Osvaldo Gervasi · Beniamino Murgante ·
Chiara Garau · David Taniar ·
Ana Maria A. C. Rocha ·
Maria Noelia Faginas Lago (Eds.)

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Hanoi, Vietnam, July 1–4, 2024
Proceedings, Part V

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Editors
Osvaldo Gervasi
Department of Mathematics and Computer Science
University of Perugia
Perugia, Italy

Chiara Garau
Department of Civil and Environmental Engineering and Architecture
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Department of Chemistry, Biology and Biotechnology
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Perugia, Italy

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Preface

These 11 volumes (LNCS volumes 14815–14825) consist of the peer-reviewed papers from the 55 Workshops of the 2024 International Conference on Computational Science and Its Applications (ICCSA 2024) which took place during July 1–4, 2024 in Hanoi (Vietnam). The peer-reviewed papers of the main conference tracks are published in a separate set consisting of two volumes (LNCS 14813–14814).

The conference was held in a hybrid form, with some participants present in person, hosted in Hanoi, Vietnam, by the Thuy Loi University. We enabled virtual participation for those who were unable to attend the event, due to logistical, political and economic problems, by adopting a technological infrastructure based on open source software (jitsi + riot), and a commercial Cloud infrastructure.

ICCSA 2024 was another successful event in the International Conference on Computational Science and Its Applications (ICCSA) conference series, previously held in Athens, Greece (2023), Malaga, Spain (2022), Cagliari, Italy (hybrid with few participants in presence in 2021 and completely online in 2020), whilst earlier editions took place in Saint Petersburg, Russia (2019), Melbourne, Australia (2018), Trieste, Italy (2017), Beijing. China (2016), Banff, Canada (2015), Guimaraes, Portugal (2014), Ho Chi Minh City, Vietnam (2013), Salvador, Brazil (2012), Santander, Spain (2011), Fukuoka, Japan (2010), Suwon, South Korea (2009), Perugia, Italy (2008), Kuala Lumpur, Malaysia (2007), Glasgow, UK (2006), Singapore (2005), Assisi, Italy (2004), Montreal, Canada (2003), and (as ICCS) Amsterdam, The Netherlands (2002) and San Francisco, USA (2001).

Computational Science is the main pillar of most of the present research, industrial and commercial applications, and plays a unique role in exploiting ICT innovative technologies, and the ICCSA conference series have been providing a venue to researchers and industry practitioners to discuss new ideas, to share complex problems and their solutions, and to shape new trends in Computational Science. As the conference mirrors society from a scientific point of view, this year's undoubtedly dominant theme was the machine learning and artificial intelligence and their applications in the most diverse economic and industrial fields.

The ICCSA 2024 conference is structured in 6 general tracks covering the fields of computational science and its applications: Computational Methods, Algorithms and Scientific Applications – High Performance Computing and Networks – Geometric Modeling, Graphics and Visualization – Advanced and Emerging Applications – Information Systems and Technologies – Urban and Regional Planning. In addition, the conference consisted of 55 workshops, focusing on very topical issues of importance to science, technology and society: from new mathematical approaches for solving complex computational systems, to information and knowledge in the Internet of Things, new statistical and optimization methods, several Artificial Intelligence approaches, sustainability issues, smart cities and related technologies.

In the Workshops proceedings we accepted 281 full papers, 17 short papers and 2 PhD Showcase papers. In the Main Conference Proceedings we accepted 53 full papers, 6 short papers and 3 PhD Showcase papers from 207 submissions to the General Tracks of the conference (acceptance rate 30%). We would like to express our appreciation to the workshops chairs and co-chairs for their hard work and dedication.

The success of the ICCSA conference series in general, and of ICCSA 2024 in particular, vitally depends on the support of many people: authors, presenters, participants, keynote speakers, workshop chairs, session chairs, organizing committee members, student volunteers, Program Committee members, Advisory Committee members, International Liaison chairs, reviewers and others in various roles. We take this opportunity to wholehartedly thank them all.

We also wish to thank our publisher, Springer, for their acceptance to publish the proceedings, for sponsoring part of the best papers awards and for their kind assistance and cooperation during the editing process.

We cordially invite you to visit the ICCSA website https://iccsa.org where you can find all the relevant information about this interesting and exciting event.

July 2024

Osvaldo Gervasi
Beniamino Murgante
Chiara Garau

Welcome Message from Organizers

After the very hard times of COVID, ICCSA continues its successful scientific endeavors in 2024, hosted in Hanoi, Vietnam. This time, ICCSA moved from the Mediterranean Region to Southeast Asia and was held in the metropolitan city of Hanoi, the capital of Vietnam. Hanoi is a vibrant urban environment known for the hospitality of its citizens, its rich history, vibrant culture, and dynamic urban life. Located in the northern part of the country, Hanoi is a bustling metropolis that combines the old with the new, offering a unique blend of ancient traditions and modern development.

ICCSA 2024 took place in a secure environment, allowing for safe and vibrant in-person participation. Combined with the active engagement of the ICCSA 2024 scientific community, this set the stage for highly motivating discussions and interactions regarding the latest developments in computer science and its applications in the real world for improving communities' quality of life.

Thuyloi University, also known as the Water Resources University, is a prominent institution in Hanoi, Vietnam, with a strong reputation in engineering and technical education, particularly in water resources and environmental engineering. In recent years, the University has expanded its academic offerings to include computer science, reflecting the growing importance of technology and digital skills in all sectors. This year, Thuyloi University had the honor of hosting ICCSA 2024. The Local Organizing Committee felt the burden and responsibility of such a demanding task and put all necessary energy into meeting participants' expectations and establishing a friendly, creative, and inspiring scientific and social/cultural environment that allowed for new ideas and perspectives to flourish.

Since all ICCSA participants, whether informatics-oriented or application-driven, realize the tremendous advancements in computer science over the last few decades and the huge potential these advancements offer in coping with the enormous challenges of humanity in a globalized, 'wired,' and highly competitive world, the expectations for ICCSA 2024 were high. The goal was to successfully match computer science progress with communities' aspirations, achieving progress that serves real, place- and people-based needs and paves the way towards a visionary, smart, sustainable, resilient, and inclusive future for both current and future generations.

On behalf of the Local Organizing Committee, I would like to sincerely thank all of you who contributed to ICCSA 2024.

Nguyen Canh Thai

Organization

ICCSA 2024 was organized by Thuyloi University (Vietnam), the University of Perugia (Italy), the University of Basilicata (Italy), Monash University (Australia), Kyushu Sangyo University (Japan), the University of Minho (Portugal), and the University of Cagliari (Italy).

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Evaluating Inner Areas Potentials (EIAP 2024)

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Econometrics and Multidimensional Evaluation of Urban Environment (EMEUE 2024)

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Environmental, Social, Governance of Energy Planning (ESGEP 2024)

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Ecosystem Services in Spatial Planning for Resilient Urban and Rural Areas (ESSP 2024)

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Ethical AI Applications for a Human-Centered Cyber Society (EthicAI 2024)

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14th International Workshop on Future Computing System Technologies and Applications (FiSTA 2024)

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Toshihiro Yamauchi	Okayama University, Japan
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Geographical Analysis, Urban Modeling, Spatial Statistics (Geog-An-Mod 2024)

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Andreas Fricke	Hasso-Plattner-Institut für Digital Engineering, Germany
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Geomatics for Resource Monitoring and Management (GRMM 2024)

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International Workshop on Information and Knowledge in the Internet of Things (IKIT 2024)

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Regenerating Brownfields Enhancing Urban Resilience Appeal (INFERENCE 2024)

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International Workshop on Territorial Planning to Integrate Risk and Urban Ontologies (IWPRO 2024)

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MaaS Solutions for Airports, Cities and Regional Connectivity (MaaS 2024)

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Martina Sinatra	University of Cagliari, Italy
Ginevra Balletto	University of Cagliari, Italy

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Brunella Brundu	Univerisity of Sassari, Italy
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Maria Ronza	University of Naples, Federico II, Italy
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Development of Urban Mobility Management and Risk Assessment (MAINTAIN 2024)

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Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2024)

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Building Multi-dimensional Models for Assessing Complex Environmental Systems (MES 2024)

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Models and Indicators for Assessing and Measuring the Urban Settlement Development in the View of Zero Net Land Take by 2050 (MOVEto0 2024)

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4th Workshop on Privacy in the Cloud/Edge/IoT World (PCEIoT 2024)

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Scientific Computing Infrastructure (SCI 2024)

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Downscale Agenda 2030 (SDGscale 2024)

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Maria Ronza	University of Naples, Federico II, Italy
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Socio-Economic and Environmental Models for Land Use Management (SEMLUM 2024)

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Paola Amoruso	LUM, Italy

Ports of the Future - Smartness and Sustainability (SmartPorts 2024)

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Marco Petrelli	Roma Tre University, Italy

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Enrico Dagostini	University of Malta, Malta
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Maria Ronza	University of Naples, Federico II, Italy
Massimiliano Bencardino	University of Salerno, Italy

Smart Transport and Logistics - Smart Supply Chains (SmarTransLog 2024)

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Giuseppe Borruso	University of Trieste, Italy
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Ginevra Balletto	University of Cagliari, Italy
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Enrico Dagostini	University of Malta, Malta
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Luca Toneatti	University of Trieste, Italy
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Smart Tourism (SmartTourism 2024)

Workshop Organizers

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Martina Sinatra	University of Cagliari, Italy
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Brunella Brundu	University of Sassari, Italy
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Tu Anh Trinh	College of Technology and Design for UEH University, Vietnam
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Massimiliano Bencardino	University of Salerno, Italy

Sustainable Evolution of Long-Distance Freight Passenger Transport (SOLIDEST 2024)

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Luigi Dall'Olio	University of Cantabria, Spain
Antonio Russo	University of Enna Kore, Italy

Sustainability Performance Assessment: Models, Approaches, and Applications Toward Interdisciplinary and Integrated Solutions (SPA 2024)

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ICCSA 2024 took place on the main campus of Thuyloi University in Hanoi, Vietnam.



Plenary Lectures

Harnessing Artificial Intelligence for Enhanced Spatial Analysis of Natural Hazard Assessments



Prof. Dr. Biswajeet Pradhan

Director - Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS), School of Civil and Environmental Engineering, Faculty of Engineering and IT, University of Technology Sydney, Australia

Abstract. In the realm of natural hazard assessments within spatial domains, the advent of Artificial Intelligence (AI) represents a paradigm shift, revolutionizing the way we conceptualize, model, and interpret environmental risks. This keynote address illuminates the profound impact of AI technologies, particularly machine learning algorithms and data-driven approaches, in reshaping our understanding and prediction capabilities concerning natural disasters.

By assimilating and scrutinizing vast spatial datasets, AI-driven models offer unparalleled accuracy and efficiency, facilitating timely and precise hazard assessments. Real-time processing of geospatial information not only enables rapid predictions but also forms the cornerstone of proactive disaster management strategies. Furthermore, AI's capacity lies in its adeptness at deciphering intricate spatial patterns inherent to natural hazards, unraveling subtle cues and previously unnoticed correlations within the data fabric.

This keynote delves into how AI's nuanced interpretation, coupled with advanced algorithms, elevates hazard modeling, providing deeper insights into the spatial dynamics of environmental risks. By augmenting traditional methodologies and revealing hidden patterns, AI fosters comprehensive risk assessments, fostering informed decision-making processes. The fusion of AI and natural hazard assessments in spatial domains heralds a more resilient approach to disaster preparedness and response.

Join us in embracing this transformative era, where AI's sophisticated modeling techniques and precise spatial interpretations converge, heralding proactive and effective mitigation strategies amidst the ever-evolving landscape of environmental challenges.

Short Bio. Distinguished Professor Dr. Biswajeet Pradhan is an internationally established scientist in the field of Geospatial Information Systems (GIS), remote sensing and image processing, complex modelling/geo-computing, machine learning and soft-computing applications, natural hazards and environmental modelling. He is the Director of the Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS) at the Faculty of Engineering and IT at the University of Technology, Sydney (Australia). He was listed as the World's Most Highly Cited Researcher by the Clarivate Analytics Report for five consecutive years, 2016–2020, as one of the world's most influential minds.

He ranked number one (1) in the field of "Geological & Geomatics Engineering" during the calendar year 2021–2023, according to the list published by Stanford University Researchers, USA. This list ranks the world's top 2% most highly cited researchers based on Scopus data. In 2018–2020, he was awarded as World Class Professor by the Ministry of Research, Technology and Higher Education, Indonesia. He is a recipient of the Alexander von Humboldt Research Fellowship from Germany. Between 2015–2021, he served as "Ambassador Scientist" for the Alexander Humboldt Foundation, Germany.

Professor Pradhan has received 58 awards since 2006 in recognition of his excellence in teaching, service and research. Out of his more than 850 articles (Google Scholar citation: 70,000, H-index: 129), more than 750 have been published in science citation index (SCI/SCIE) technical journals. He has authored/co-authored ten books and thirteen book chapters.

Software Engineering Research in a New Situation



Prof. Carl K. Chang

Professor Emeritus, Iowa State University, USA

Abstract. With the rise of Generative Artificial Intelligence (GAI), epitomized by Large Language Models (LLMs), a profound shift has unfolded in software engineering research. In this presentation, I will traverse my four-decade journey in software engineering research, focusing on situational awareness in the era of the Internet of Things (IoT). I have witnessed the turbulence brought forth by the AI community that demands changes in our approaches. Meanwhile, owing to the pervasiveness of services computing, services became the first-class citizen in modern-day software engineering methodologies.

I argue that situational awareness must permeate the entire lifecycle to consistently deliver software services that align with the dynamic needs of users and the ever-evolving environments. I will elucidate this argument by reviewing the Situ framework, offering a comprehensive illustration of my perspective. Furthermore, I will outline my vision regarding the formidable research challenges considering the rapidly shifting landscape dominated by an irresistible and profoundly disruptive generative AI tsunami.

Short Bio. Carl K. Chang is a former department chair and Professor Emeritus of Computer Science at Iowa State University. His research interests include requirements engineering, net-centric computing, situational software engineering and digital health. Chang was the 2004 President of the IEEE Computer Society. Previously he served as the Editor-in-Chief for IEEE Software (1991–1994), and as the Editor-in-Chief of IEEE Computer (2007–2010). He was the 2012 recipient of the Richard E. Merwin Medal from the IEEE Computer Society. Chang is a Life Fellow of IEEE, a Fellow of AAAS, and a Life Member of the European Academy of Sciences (EurASc).

Interpretability and Privacy Preservation in Large Language Models (LLMs)



Prof. My Thai

University of Florida (UF) Research Foundation Professor
Associate Director of UF Nelms Institute for the Connected World

Abstract. Large Language Models (LLMs) have transformed the AI landscape, captivating researchers and practitioners with their remarkable ability to generate human-like text and perform complex tasks. However, this transformative power comes with a set of critical challenges, particularly in the realms of interpretability and privacy preservation. In this keynote, we embark on an exploration of these pressing issues, shedding light on how LLMs operate, their limitations, and the strategies we can employ to mitigate risks. We begin by examining the interpretability in LLMs, which often function as enigmatic "black boxes." Their complex neural architectures make it challenging to understand how they arrive at specific outputs. This lack of transparency raises questions of trust and accountability. When deploying LLMs in real-world applications—whether for chatbots, content generation, or decision-making—it becomes crucial to demystify their decision paths.

We will use explainable AI (XAI) to offer faithful explanations, from the black-box to white-box models, and from feature-based [1, 2] to neuron circuits-based [3, 4] explanations. By visualizing attention mechanisms, feature importance, and saliency maps, we empower users to comprehend LLM predictions. XAI not only fosters trust but also encourages responsible utilization of LLMs.

We next turn our attention to one of the utmost concerns and challenges: data privacy. LLMs process vast amounts of data, raising risks of data leakage, model inversion, the right to be forgotten, and inadvertent exposure of sensitive information. Furthermore, the integration of LLMs into diverse applications also significantly brings these challenges to the next level [5]. This talk explores strategies to protect privacy, including differential privacy, federated learning, and data encryption.

Short Bio. My T. Thai is a University of Florida (UF) Research Foundation Professor, Associate Director of UF Nelms Institute for the Connected World, and a Fellow of IEEE and AAIA. Dr. Thai is a leading authority who has done transformative research in Trustworthy AI and Optimization, especially for complex systems with applications to healthcare, social media, critical networking infrastructure, and cybersecurity. The results of her work have led to 7 books and 350+ publications in highly ranked international journals and conferences, including several best paper awards from the IEEE, ACM, and AAAI.

In responding to a world-wide call for responsible and safe AI, Dr. Thai is a pioneer in designing deep explanations for black-box ML models, while defending against explanation-guided attacks, evident by her Distinguished Papers Award at the Association for the Advancement of Artificial Intelligence (AAAI) conference in 2023. At the same year, she was also awarded an ACM Web Science Trust Test-of-Time award, for her landmark work on combating misinformation in social media. In 2022, she received an IEEE Big Data Security Women of Achievement Award. In 2009, she was awarded the Young Investigator (YIP) from the Defense Threat Reduction Agency (DTRA), and in 2010 she won the NSF CAREER Award. She is presently the Editor-in-Chief of the Springer Journal of Combinatorial Optimization and the IET Blockchain Journal, and editor of the Springer book series Optimization and Its Applications.

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Evaluating Inner Areas Potentials (EIAP 2024)

Understanding Geographies of Architectural Heritage Abandonment in Inner Areas: A Multi-dimensional Investigation

Marco Rossitti[1(✉)], Annunziata Maria Oteri[2], and Francesca Torrieri[1]

[1] Politecnico Di Milano, Via Ponzio 31, 20133 Milan, Italy
marco.rossitti@polimi.it
[2] Politecnico Di Milano, Via Bonardi 3, 20133 Milan, Italy

Abstract. The international concern about narrowing territorial disparities has resulted in a new territorial policy season focusing on marginal areas. In Italy, such a concern has found a policy translation in the National Strategy for Inner Areas (NSIA), which identifies "the enhancement of natural and cultural resources" as a key sector to promote the development of inner areas. Within the wide scientific debate triggered by this planning direction about cultural capital's role in developing inner areas, a challenging discussion space has been devoted to architectural heritage conservation. Indeed, when focusing on architectural heritage's possible contribution, the planning challenge for the future of inner areas becomes even more complex due to the interaction between the fragility of these territorial systems and the one of heritage assets. Thus, the design of effective development strategies leveraging heritage's potential requires properly identifying and reading the main emerging fragility themes stemming from this interaction, such as the ongoing abandonment processes of architectural heritage. Based on this premise, the paper proposes a multi-dimensional investigation of the architectural heritage abandonment phenomenon in inner areas, aimed at understanding and evaluating its geographies, extent, and peculiar features. After providing a theoretical reflection on the causes and effects of abandonment processes of architectural heritage, the paper delves into a multi-dimensional and quantitative analysis of the phenomenon's extent and features in terms of the relationship between depopulation, built heritage use state, and decay conditions. Finally, the paper reflects on the results from such a preliminary investigation and its opportunities, limitations, and future perspectives in supporting conservation processes from a local development perspective.

Keywords: Architectural heritage · Geographies · Abandonment · Inner areas · Evaluation

1 Introduction

The international concern about narrowing territorial disparities as an essential condition for sustainable development has resulted in a new public policy season devoting attention to marginal and under-developed areas [1].

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In Italy, such a concern has found a policy translation in the National Strategy for Inner Areas (NSIA), which aims at improving life conditions and promoting local development opportunities in areas defined as "inner" according to their distance from basic services [2]. Among the different key sectors to unfolding inner areas' potential, resting on enhancing their territorial capital [3], the NSIA identifies "the enhancement of natural and cultural resources, and sustainable tourism", which are recognized as drivers for wealth and welfare creation [4].

Based on this planning direction and the consolidated recognition of the role of culture in fostering sustainable development and ensuring territorial resilience [5–9], the debate about inner areas' future has produced plenty of reflections on the possible contribution offered by their cultural capital, intended as «an asset which embodies, stores or provides cultural value in addition to whatever value it may possess» [9], in tackling the ongoing marginalization vortex. For instance, Imperiale et al. [10] and Crociata et al. [11] have reflected on the spatial distribution and the role of the Cultural and Creative Industry (CCI) in triggering culture-led development models in inner areas. Tricarico et al. [12] have discussed the opportunities of digital technologies to enhance intangible heritage as a valuable basis for socially innovative development strategies. Furthermore, different scholars have focused on the possible contribution of cultural tourism to inner areas' sustainable growth [13–15].

Within this wide scientific debate about cultural capital's role in inner areas development strategies, a fruitful and challenging discussion space has been devoted to the conservation and reuse of architectural heritage[1] [16–19].

Indeed, when focusing on the possible contribution of architectural heritage conservation, the already challenging planning mandate of tackling depopulation and reversing the ongoing marginalization dynamics in inner areas becomes even more complex [20, 21].

By embracing the extension of the fragility condition from humans to objects [22], such a complexity can be read as stemming from the interaction between the fragility of inner areas territorial systems and the intrinsic fragility of heritage assets [23]. In this sense, the local development challenge, addressed from the heritage conservation perspective, depends on properly managing the encounter between these two fragility dimensions.

If the leading approach to architectural heritage conservation rests on the idea of "removing" fragility conditions, some innovative theoretical positions in the academic debate open to the possibility of considering fragility as a value or an opportunity, thus grounding sustainable development strategies on the recognition and acceptance of the existing fragility conditions rather than on their elimination [24]. In this perspective, it becomes crucial to identify and read the main emerging fragility dimensions related to architectural heritage in inner areas as a fundamental knowledge basis for approaching

[1] In this context, the architectural heritage locution is adopted to identify both single and unique heritage assets (the ones protected by law) and other built assets witnessing traditional construction techniques and materials or relevant local activities, working as a *palimpsest* and expressing a systemic relationship with their reference territorial context, whose significance is recognized by local communities.

conservation from a co-evolutionary point of view [25] and, thus, unfolding its potential toward sustainable development.

Within the multiple fragility elements stemming from the meeting between architectural heritage and inner areas, the recent academic debate about conservation in these territorial contexts [26] has paid attention to the relationship between people and heritage assets, which has often been ignored for the misleading idea that conservation is an expert process rather than a social practice [27]. Furthermore, reflecting on the possible crisis of this relationship hints at another fundamental fragility dimension, returning to the complexity of themes placed on territorial planning for inner areas: architectural heritage abandonment processes. A clear understanding of architectural heritage abandonment processes, which result from a complex interrelation of socioeconomic factors and planning choices, thus, is a determinant research task for endorsing local development processes in inner areas leveraging on their architectural heritage's potential.

Based on this premise, the paper stands as a preliminary attempt to deal with this research task by providing a multi-dimensional investigation of the built heritage abandonment phenomenon in inner areas, aimed at understanding and evaluating its geographies, extent, and peculiar features related to different territorial realities. After providing a theoretical reflection about the causes and effects of abandonment processes of architectural heritage, the paper delves into a multi-dimensional and quantitative investigation of the phenomenon's extent and features by collecting and analyzing open-source data concerning depopulation, built heritage use state, and decay conditions, and critically interpreting their relationships. Finally, based on the results from such a multi-dimensional investigation extended to the 72 project areas selected for the NSIA's first implementation cycle (2014–2020), the paper reflects on its opportunities, limitations, and future perspectives in supporting conservation processes from a local development perspective.

2 Causes and Effects of Abandonment Processes on Architectural Heritage: A Theoretical Reading

The abandonment processes warrant close consideration when reflecting on the architectural heritage conservation issue in local development processes for inner areas. Indeed, these processes are responsible for built heritage decay and, thus, contribute to the risk of losing an extraordinary material witness of traditional architecture, erasing a historically consolidated image of places, and weakening the relationship between people and places [28]. Understanding these processes, central to the NSIA agenda [2], requires weaving architectural themes with the reading of territorial dynamics, thus looking at territories as the production of socioeconomic and historical-cultural sedimentations and as the field for social practices [29].

In this sense, it is worth deepening abandonment in inner areas and its implications for architectural heritage conservation by recognizing its complexity and overcoming the mainstream approach, which attempts to reduce its understanding to identify cause-effect relationships.

This mainstream approach already reveals its ineffectiveness when addressing the causes domain. Indeed, there are multiple causes of abandonment and depopulation processes, and it is cumbersome to identify or classify them. The basic distinctions between

functional and structural causes, natural and anthropic causes, are undoubtedly helpful to understanding the phenomena's extent but speak little for their deeper comprehension [28]. Usually, it is impossible to attribute everything to one single cause or consider a horizontal relationship between different causes [30], thus dismissing ripple effects and the specificities of local geo-historical dynamics. The limits of a causes-based approach to reading abandonment processes become evident when dealing with natural disasters (i.e., earthquakes, landslides, floods) leading to the destruction of entire towns. The existence of resilient towns, able to react to the disaster, as opposed to others dying after the destructive event, shows that it is not a single event that leads to the abandonment and decay of a place, but instead that it can work as a catalyst of ongoing shrinking dynamics [28].

For instance, some valuable studies about the Italian Apennines, hit by a severe earthquake in 2016, focus on the relationship between the disruptive event and local socioeconomic processes, thus showing how the seismic event has accelerated some ongoing dynamics [31]. At the same time, these studies reveal some common but conflicting patterns in the communities' reactions to dramatic events (i.e., resistance or resignation, disaffection or sense of belonging).

Such a finding suggests that another mistake to be avoided in addressing abandonment and depopulation lies in resorting to the similarity of these processes in terms of causes, consequences, and transformations as justification for adopting blind-to-places approaches to understanding and tackling them based on repeating knowledge and action schemes used elsewhere. While completely ignoring the complexity embedded in abandonment processes [32], these approaches report the role of policies in triggering or speeding up abandonment processes when political choices are not coherent with the needs and the specificities of a place and its local community [28]. Furthermore, it is necessary to recognize what Loughlin Kealy defines as the «new quality of abandonment settlements» [33]. Indeed, the acknowledged socio-cultural meaning of traditional settlement for contemporary societies based on a complex mechanism of values attribution rather than on a mere recognition of an aesthetic value brings along essential differences between past and present abandonment processes and, most of all, in the ways to address them [33].

3 A Multi-dimensional Evaluation of Abandonment Processes in Inner Areas: Evidence from the NSIA Pilot Areas

Given the recognized complexity of abandonment phenomena, their understanding must go through an integrated and multi-faced investigation approach. In this sense, other hints for properly framing and delving into the complexity of abandonment processes in inner areas can stem from quantitively analyzing the phenomenon's geographies, extent, and features regarding the relationship between depopulation, built heritage use state, and decay conditions. Such an analysis, although affected by all the limits of a data-based approach and the aggregated inner area territorial scale[2], can help detect specific

[2] The territorial dimension of inner areas, as defined within the NSIA's policy frame, is made up by the aggregation of different municipalities.

phenomenon's declinations to be deepened through real contact with local realities and their evolution.

The analysis refers to the 72 NSIA project areas, selected within its first cycle of implementation (2014–2020), and grounds on several factors, which are relevant metrics for assessing the abandonment phenomenon[3]:

- Percentage variation of resident population in different periods (1971–2011; 2001–2011; 2011–2017) [34];
- Buildings' potential for use, intended as the percentage ratio between the number of disused buildings and the total amount of buildings (in 2001 and 2011) [35];
- Incidence of buildings in a bad conservation state, defined as the percentage ratio between the number of residential buildings in a bad conservation state and the total amount of residential buildings (in 2001 and 2011) [35];
- Incidence of occupied historical residential buildings expressed as the percentage ratio between the occupied residential assets built before 1919 and the total of occupied residential assets [35].

Concerning the extent of abandonment processes, one of the crucial reasons for the national intervention in inner areas, it becomes immediately evident when spatially displaying the pre-mentioned factors and their variation over time. The variation in resident population between 1971 and 2011 (Fig. 1) shows that most of the project inner areas (63 out of 72) have experienced a demographic shrinking process with a different magnitude.

The phenomenon is more evident in southern Italy's regions, such as Abruzzo (with *Subequana* and *Basso Trigno*) and Calabria Region (with the *Grecanica* and *Sila e Presila*), where the population decrease is around 40%. Areas against the leading trend mainly belong to Italian north-western regions: i.e., *Alto lago di Como* e *Valli del Lario*, *Alta Valtellina* and *Valchiavenna* in Lombardia Region; *Bassa Valle* in Valle d'Aosta Region. Nevertheless, the strongest signals of positive demographic trends can be observed in two inner areas from the south of Italy: *Val Simeto* in Sicilia and *Sud Salento* in Puglia. Moving forward the observation time range, the analysis of resident population variation between 2011 and 2017 (Fig. 2) confirms the existence of a steady and ongoing demographic shrinking phenomenon. The majority of the project inner areas (62 out of 72), indeed, still experience a population decrease. Two inner areas, *Sud Salento* in Puglia Region and *Contratto di Foce Delta del Po* in Veneto Region, are affected by an inversion of the previous positive demographic trend, thus showing how this phenomenon is spreading out over the years and how, at the same, it is not possible to trace a common history of abandonment in inner areas.

The emerging unicity and heterogeneity of each inner area's condition, to be carefully considered in designing strategies to tackle abandonment and promote local development, is also evident in some cases where the shrinking trend is inverted. These cases (*Monti Simbruini* and *Alta Tuscia* in the Lazio Region and *Sud-Ovest Orvietano* in the Umbria Region) deserve a critical deepening to understand the reasons behind this path change.

[3] The years taken as reference (1971, 2001, 2011, 2017) depends on the availability of data aggregated for the inner area territorial scale.

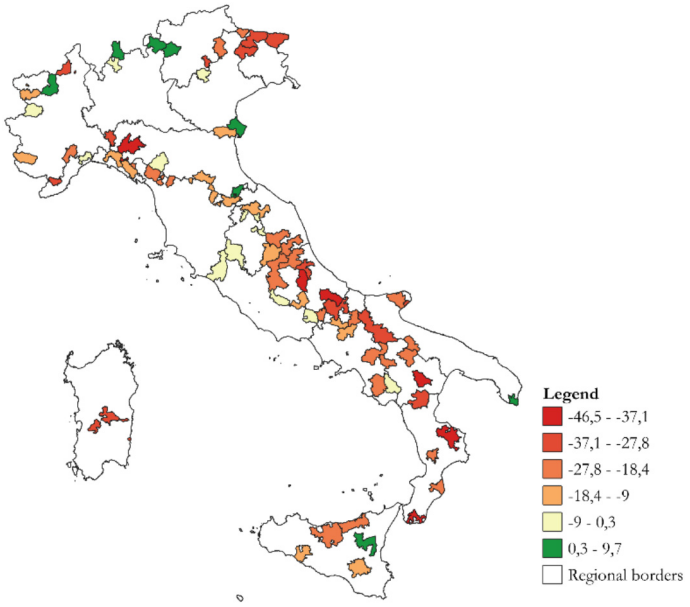

Fig. 1. Variation of the resident population between 1971 and 2011 for each project's inner area (Authors' elaboration on data retrieved from the Territorial Cohesion Agency website).

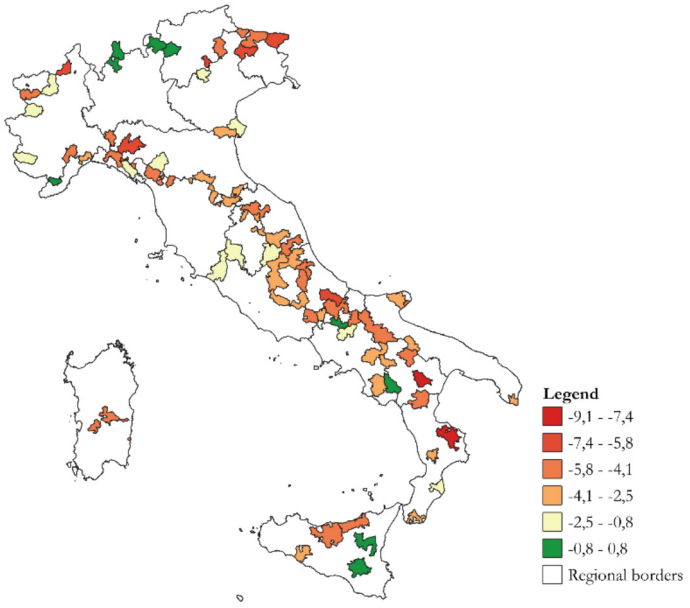

Fig. 2. Variation of the resident population between 2011 and 2017 for each project's inner area (Authors' elaboration on data retrieved from the Territorial Cohesion Agency website)

The abandonment processes under investigation can also be read in terms of effects on built heritage assets by considering buildings' potential for use in 2011, intended as the percentage ratio between the number of disused buildings and the total amount of buildings (Fig. 3). This datum, even if referred to the whole inner area's building stock, clearly reveals the consequences of demographic shrinking on real estate assets' use. Indeed, the highest incidence of disused buildings can be observed in inner areas that, as shown by the previous analyses, have experienced the most severe demographic shrinking processes: the *Subequana* inner area in the Abruzzo Region and the *Grecanica* inner area in the Calabria Region. Furthermore, most areas (52 out of 72) show an incidence of disused buildings in 2011 higher than 5%.

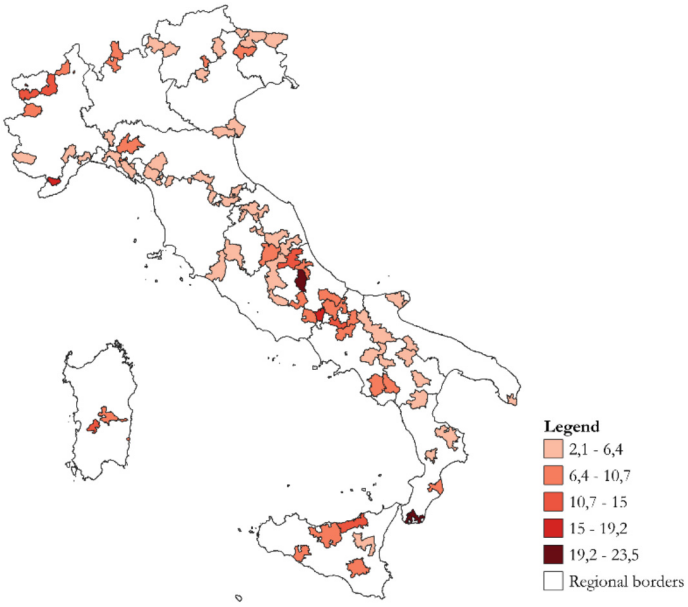

Fig. 3. Variation of the buildings' potential for use between 2001 and 2011 for each project's inner area (Authors' elaboration on data retrieved from the ISTAT 8milacensus website)

A more interesting perspective on the entity and durability of abandonment processes and their effects on architectural heritage in inner areas can be obtained by analyzing other two variables: the variation in the incidence of residential buildings in a bad conservation state between 2001 and 2011 and the variation of the incidence of occupied historical residential buildings in the same period. Concerning the variation of incidence of residential buildings in a bad conservation state for each inner area, the analysis returns a more diversified situation compared to the ones described by the previous variables (Fig. 4). Indeed, most of the inner areas (50 out of 72) have seen an improvement of their buildings' stock conservation state. This result, affected by considering the whole building stock, regardless of assets' age or heritage value, must be carefully interpreted to avoid making simplistic conclusions about a relaunch signal in inner areas. Looking at the most critical realities, they are widespread in the Italian territory: *Calatino*

in Sicilia Region; *Appennino Piacentino-Parmense* in Emilia-Romagna Region; *Val Canale-Canal del Ferro* in Friuli Venezia Giulia Region.

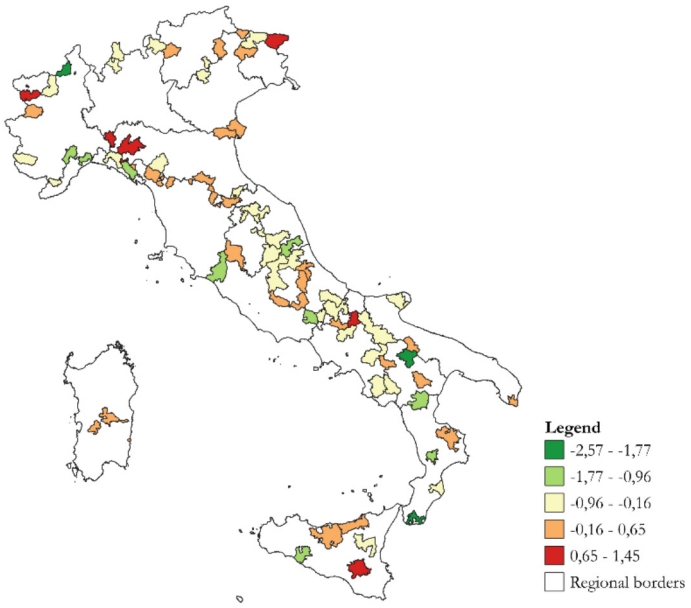

Fig. 4. Variation of the incidence of buildings in a bad conservation state for each project's inner area (Authors' elaboration on data retrieved from the ISTAT 8milacensus website)

At the same time, analyzing the variation in the incidence of occupied historical residential buildings between 2001 and 2011 provides the most interesting results related to the research themes. Indeed, considering this variable as a proxy of historical built heritage use conditions and analyzing its variation over time allows to draw out some reference points for sharply focusing on abandonment processes and their impact on architectural heritage in inner areas. The analysis shows how almost all the project inner areas have experienced a decrease in the incidence of occupied historical residential buildings on the whole number of residential buildings from 2001 to 2011 (Fig. 5). The most critical situations, with a decrease in historical building occupation higher than 10%, can be observed in southern Italian regions (*Area Reventino Savuto* in Calabria Region; *Subequana* in Abruzzo Region) and Liguria Region (*Val Di Vara* and *Valle Arroscia*).

This result deserves specific attention, not only because it stands as the most relevant quantitative reference for bridging abandonment processes to their effects on architectural heritage but also because its critical interpretation can be a starting guide in catching the specificities of each inner area's abandonment history with its implications for architectural heritage conservation from a local development perspective. With this aim, it can be helpful to correlate the incidence variation of occupied historical residential buildings between 2001 and 2011 with the resident population variation in the same period.

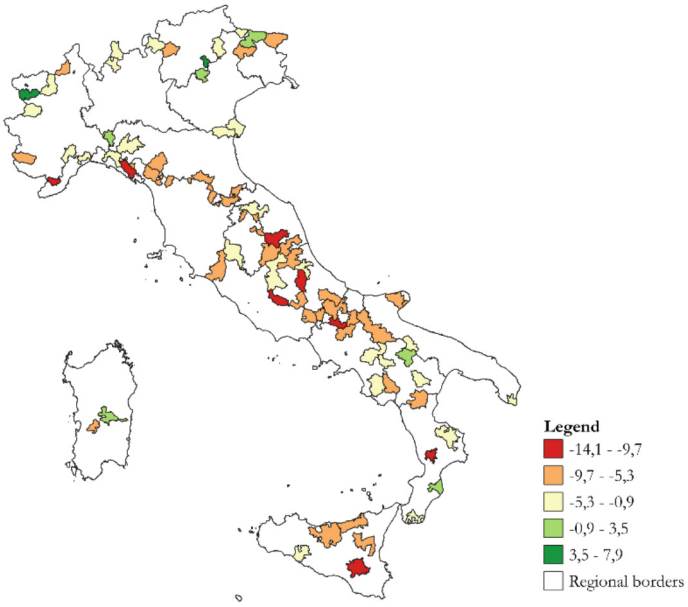

Fig. 5. Variation of the amount of occupied historical residential buildings (Authors' elaboration on data retrieved from the ISTAT 8milacensus website)

This correlation, represented through a scattered plot chart (Fig. 6), in which each project inner area stands as a point in the graph, clearly reveals the existence of heterogeneity in inner areas' abandonment processes and their effects on architectural heritage, thus hinting at the necessity to adopt a place-based approach to address them.

Indeed, based on the analysis results, it is possible to group the 72 project inner areas into four clusters:

- *Cluster 1*: *Population decreases – Occupation increases.* This cluster includes four inner areas (*Alto Bradano, Alta Carnia, Appennino lombardo-Oltre Po pavese*, *Tesino*) where the resident population decrease corresponds to an increase in the incidence of occupied historical residential buildings between 2001 and 2011. This rough result, mainly observed in northern Italy's inner areas, is remarkably interesting since it can prompt a stronger relationship between the local community and historical built heritage;
- *Cluster 2: Population decreases – Occupation decreases.* This cluster, including the majority of project inner areas (49 out of 72), especially in its southern part, reflects the mainstream trend in these territorial realities, on which the dominant narratives about abandonment processes in inner areas and their effects ground. Indeed, inner areas belonging to it are experiencing an abandonment of historical residential buildings as a consequence of a demographic shrinking process;
- *Cluster 3: Population increases – Occupation increases.* The cluster includes only one inner area (*Grand Paradis* in Valle d'Aosta Region), which is experiencing an increase in resident population, flanked by an increase in the incidence of occupied

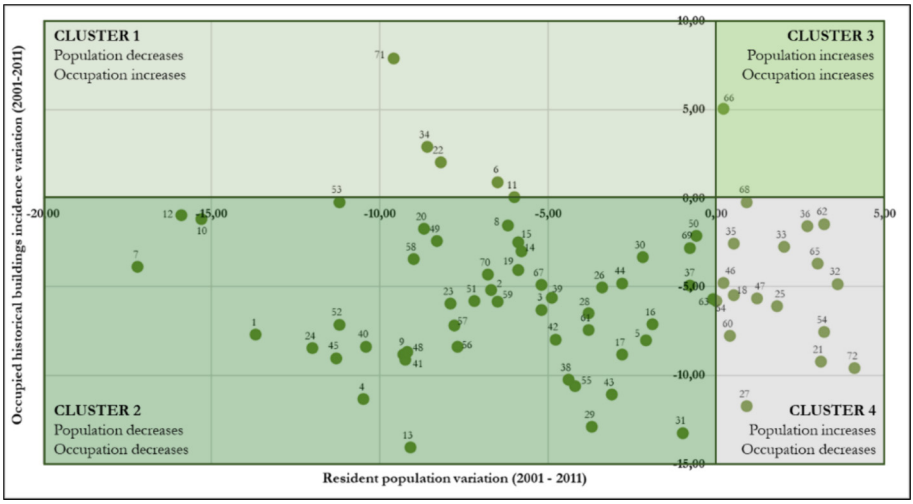

Fig. 6. Correlation between the resident population variation and the occupied historical buildings incidence between 2001 and 2011 (Author's elaboration on data retrieved from ISTAT)[4]

historical buildings. This result must be carefully examined to understand if it stems from a random process or if it finds its reasons in specific top-down or bottom-up planning actions;

- *Cluster 4: Population increases – Occupation decreases.* This cluster, including 17 inner areas, mainly located in the north or the center of Italy, returns the most critical

[4] In the scattered plot, inner areas are identified through a numeric code. The correspondence is: 1 = *Basso Sangro-Trigno*, 2 = *Valfino Vestina*, 3 = *Valle Roveto*, 4 = *Subequana*, 5 = *Alto Aterno-Gran Sasso–Laga*, 6 = *Alto Bradano*, 7 = *Montagna Materana*, 8 = *Marmo Platano*, 9 = *Mercure-Alto Sinni-Val Sarmento*, 10 = *Grecanica*, 11 = *Versante Ionico Serre*, 12 = *Sila e pre Sila,* 13 = *Area Reventino Savuto*, 14 = *Alta Irpinia*, 15 = *Cilento Interno,* 16 = *Tammaro-Titerno*, 17 = *Vallo di Diano,* 18 = *Appennino emiliano*, 19 = *Basso Ferrarese*, 20 = *Appennino Piacentino-Parmense,* 21 = *Alta Valmarecchia*, 22 = *Alta Carnia,* 23 = *Dolomiti Friulane*, 24 = *Val Canale-Canal del Ferro*, 25 = *Alta Tuscia*, 26 = *Monti Reatini*, 27 = *Monti Simbruini*, 28 = *Valle di Comino*, 29 = *Valle Arroscia*, 30 = *Beigua e Unione Sol*, 31 = *Val Di Vara*, 32 = *Antola-Tigullio*, 33 = *Valchiavenna*, 34 = *Appennino lombardo-Oltre Po pavese*, 35 = *Alta Valtellina*, 36 = *Alto lago di Como e Valli del Lario*, 37 = *Appennino Basso Pesarese e Anconetano*, 38 = *Alto Maceratese*, 39 = *Ascoli Piceno*, 40 = *Alto Medio Sannio*, 41 = *Fortore*, 42 = *Mainarde*, 43 = *Matese*, 44 = *Val Bormida*, 45 = *Valli dell'Ossola,* 46 = *Val di Lanzo*, 47 = *Valli Maira e Grana,* 48 = *Monti Dauni*, 49 = *Alta Murgia*, 50 = *Sud Salento*, 51 = *Gargano*, 52 = *Alta Marmilla*, 53 = *Gennargentu – Mandrolisai*, 54 = *Val Simeto*, 55 = *Calatino*, 56 = *Madonie*, 57 = *Nebrodi,* 58 = *Terre Sicane*, 59 = *Garfagnana,* 60 = *Valdarno e Valdisieve, Mugello e Val di Bisenzio*, 61 = *Casentino-Valtiberina,* 62 = *Sud-Ovest Orvietano*, 63 = *Nord-Est Umbria*, 64 = *Valnerina,* 65 = *Bassa Valle,* 66 = *Grand Paradis*, 67 = *Agordina,* 68 = *Spettabile Reggenza,* 69 = *Contratto di Foce Delta del Po,* 70 = *Comelico,* 71 = *Tesino,* 72 = *Val di Sole.*

situation concerning architectural heritage conservation. Indeed, a resident population increase in these areas corresponds to a decreased incidence of occupied historical buildings. This correspondence can suggest that residents favor new buildings rather than historical ones. If confirmed, thus, this result hints at the necessity to trigger a capacity-building process to guide local communities in recognizing their heritage value or to identify other drivers than architectural heritage to foster local development.

4 Discussion and Final Reflections

The paper provides a preliminary and multi-faced investigation of the extent of architectural heritage abandonment processes, their geographies, and peculiarities in inner areas as an essential knowledge basis for assessing the opportunity to leverage heritage potential in designing local development strategies and to define appropriate intervention strategies.

More in detail, it integrates a theoretical reflection about the most relevant themes related to abandonment processes in inner areas with a multi-dimensional quantitative analysis used to bring out specific phenomena that require further investigation through critical reading and questioning. By so doing, the paper attempts to overcome the traditional approach to territorial planning, which has used quantitative analysis as the only basis for policy design rather than as a guiding interpretative layer.

The critical discussion about the causes and effects of abandonment processes reveals the complexity of such a phenomenon, which can be properly addressed only by weaving architectural themes with the reading of territorial dynamics, thus looking at territories as the production of socioeconomic and historical-cultural sedimentations and as the field for social practices. Such complexity is also confirmed by quantitively analyzing the phenomenon's geographies, extent, and features regarding the relationship between depopulation, built heritage use state, and decay conditions in inner areas.

This quantitative analysis, extended to the 72 NSIA project areas, returns a heterogeneous frame in inner areas' abandonment processes and their effects on built heritage, thus revealing the necessity to adopt place-based and people-based approaches to investigating such complex phenomena [36].

Indeed, the highlighted existence of different relationships between the considered factors confirms that abandonment processes and their implication can be understood only by delving into local socioeconomic dynamics. Thus, the urgency to return a historical dimension to abandonment processes by grounding their understanding on a place's local history and reconstructing their economic and productive background is evident [37, 38]. Adopting this historical dimension doesn't mean looking at abandonment processes as concluded historical facts to be faced by protecting from and limiting their consequences in the present or as an incurable fracture in the history of a place. Instead, the historical dimension must stem from deeply considering the history of communities and places as a reservoir of knowledge for connecting with the complexity of such phenomena. At the same time, it is appropriate to address abandonment by recognizing it as an ongoing phenomenon [32] and a natural phase of a place's lifecycle.

In this sense, when declined at the architectural heritage scale, abandonment processes open complex challenges and opportunities for conservation. Indeed, such a sensitive approach to abandonment processes can provide decision-makers and experts in conservation with valuable references to critically assess the opportunity to address the local development challenge from a heritage conservation perspective [39], thus identifying appropriate actions and targets for conservation strategies or, rather, guiding and assisting architectural heritage abandonment.

Of course, the outlined investigation's results suffer from the limits of being aggregated at the inner area territorial scale, thus compensating and hiding differences between municipalities belonging to the same inner area and must be necessarily verified and deepened through direct contact with the territory and its community. In this perspective, future research efforts can be devoted to transposing the quantitative analysis within an inner area territorial context and, by integrating its results with a critical and history-based reading of its socioeconomic dynamics, better assess the opportunity to adopt its findings as guiding elements to design place-based strategies for inner areas local development.

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The Enhancement of the Alta Valsesia Territorial Potential: A Collaboration-Based Approach Between Academia and Local Actors

Diana Rolando[1(✉)], Alice Barreca[1], Giorgia Malavasi[1], and Manuela Rebaudengo[2]

[1] Architecture and Design Department, Politecnico di Torino, Viale Mattioli 39, 10125 Turin, Italy
{diana.rolando,alice.barreca,giorgia.malavasi}@polito.it
[2] Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino, Viale Mattioli 39, 10125 Turin, Italy
manuela.rebaudengo@polito.it

Abstract. Over the past decade, efforts have been made to enhance the development of Italian fragile areas, to counter social exclusion and population decline. With this purpose, the National Strategy for Inner Areas was launched in 2014, to face the challenges related to the improvement of territorial services. In the wider context of research on the issues of vulnerability and marginalization, the Branding4Resilience-B4R project defined local strategies for revitalizing inner territories and fostering partnerships and collaboration between Academia and local actors. This article describes how the Politecnico di Torino B4R Research Unit has activated a collaboration-based approach with Valsesia Mountain Union since 2020, contextually with the B4R start, and how it has supported the current SNAI strategy definition process. It emphasizes the importance of collaboration in generating insights and proposing initiatives to boost competitiveness and territorial appeal. The results show how the proposed approach supported the sharing of opportunities and threats related to the territorial context, some design ideas deriving from a collaborative process and how the ongoing interaction between Academia and local actors can trigger possible actions connected with uncertainties and risks, based on a data-driven process and not only deriving from political decisions.

Keywords: Inner Areas · Collaboration-based approach · Territorial potential

1 Introduction

The enhancement of Inner Areas was implemented in Italy for over a decade, with the particular aim of reducing the marginalisation and the demographic decline of these territories [2]. The National Strategy for Inner Areas (SNAI) was launched in 2014 and the most fragile areas (peripheral and ultra-peripheral) in the country were identified in relation to the level of offered services and the distance from the nearest service

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provider centre (pole) [5]. The first programming cycle (2014–2020) was formalised with the identification of 72 Inner Areas to be funded by the Italian government with more than 590 million euros, leading to the implementation of around 1,700 projects over the following years [46]. With the launch of the second programming cycle (2021–2027) [42], a further 43 areas were added, for which the Government allocated an additional 30 million euros.

Alongside the ongoing process, scholars have addressed these same problems over time: *vulnerability*, *fragility* and *marginality*, are frequently used keywords in theoretical and applied research on territorial, suburban and rural areas [16, 17, 19, 21, 25, 47, 48]; otherwise, the issue of *territorial resilience* seems to have been studied only lately [23, 43, 45]. In recent years, researchers have increasingly focused not only on the negative point of view (vulnerabilities) but on *vitality, vibrancy* and *quality of life,* although they appear to be themes studied in relation to urban areas [3, 4, 45].

Taking up the challenge of revitalising and enhancing inner territories, the authors of this paper have addressed these issues in previous studies [32–34, 37] in the context of the B4R - Branding4Resilience research project [9, 11, 22, 31]. B4R is a research project of national interest (PRIN 2017—Young Line), which was funded by the Italian Ministry of University and Research (MUR) for a four-year duration (2020–2024). The project (which is now concluding its planned dissemination actions) was coordinated by Università Politecnica delle Marche (principal investigator: Maddalena Ferretti) and it has involved Università degli Studi di Palermo (local coordinator: Barbara Lino), Università degli Studi di Trento (local coordinator: Sara Favargiotti) and Politecnico di Torino (local coordinator: Diana Rolando) as partners.

In particular, in almost three years of theoretical and field research the Research Unit of Politecnico di Torino (Polito RU), to which the authors belong, had the opportunity to study the area of Alta Valsesia, selected as Focus Area (FA) within the B4R project. In accordance with the goals of the B4R project, the Polito RU triggered a collaboration-based approach between Academia and the Valsesia Mountain Union, which was identified as the most important local actor for the territorial enhancement. This important collaboration has been activated since 2020, contextually with the B4R start, and it has been constantly strengthened in the next years in the context of several activities developed by the Polito RU [32–34, 37]. It is worth mentioning that the Valsesia Mountain Union has been constantly involved and consulted during the first phase of the B4R project, aimed at knowing and analysing the territorial context issues, as well as during a series of co-design activities activated to foster some municipalities' potential.

Furthermore, in June 2022 the Valsesia Mountain Union, together with the Biellese Orientale Mountain Union, achieved the important goal of being identified as one of the new "Inner Areas" (called "Valsesia"), funded in the context of the second SNAI programming cycle by the Italian Minister for Territorial Cohesion (Regional Council Resolution No. 28 of June 21, 2022), aligned with the European programming for 2021–27. This important goal has triggered a series of interesting new synergies between scholars of the Polito RU and the Valsesia Mountain Union and it fostered a further development of the ongoing collaboration towards the "Valsesia" SNAI strategy definition.

This paper offers a comprehensive overview of the collaborative and knowledge-sharing process implemented by the Polito RU which, starting from the results achieved during the 3 phases of the B4R project ("Exploration", "Co-design", "Co-visioning"), has allowed the active participation of the Academy in the SNAI strategy formulation process. The specificity of this work lies in the novelty of the collaboration-based approach (Sect. 2), able to share opportunities and threats related to the territorial context, some design ideas deriving from a collaborative process and possible actions connected with uncertainties and risks. The final objective is to support local authorities in defining priority actions and interventions around which the SNAI strategy can be oriented, correctly managing all existing levels of knowledge in order to make territories more competitive, attractive and lively for new inhabitants, tourists and economic operators. Furthermore, the paper describes the study area (Sect. 3), focusing on the pilot case (the Alta Valsesia Side Valleys), which turn out to be the most fragile areas, compared to the endowment of the main valley with services and its strong winter tourist vocation. The results (Sect. 4) summarise the analytical framework on territorial vulnerability/vibrancy generated by the quantitative and qualitative analyses carried out during the "Exploration" and illustrate the three design concepts and the main challenges, which guided the "Co-design" workshop experience and led to the identification of first design ideas for territorial development. Moreover, the results show the importance of the knowledge structuring process carried out by the Polito RU during the "Co-visioning" phase, which allowed to identify strategic axes, strategies, pilot actions, uncertainties and risks able to support the SNAI strategy construction process.

Possible future developments are discussed in the conclusion, which emphasises the flexibility of use and replicability of the proposed collaboration-based approach also in other contexts.

2 The B4R Methodological Approach for the Alta Valsesia Context

In the context of the B4R project, a methodological approach was developed and based on three main phases as previously presented in authors' publications [16–19] which focus on intermediate results of the research The "Exploration" phase supports the investigation of the territorial contexts from different perspectives, by combining and integrating different quantitative and qualitative tools and methods. The second "Co-design" phase is aimed at proposing actionable transformations of small infrastructures and operative branding actions in selected pilot cases by strictly cooperating with local actors and stakeholders. The third phase aims to develop "Co-visioning" processes in collaboration with local communities, stakeholders and institutions [11].

Each RU of the B4R project has tailored and detailed these phases focusing on the specific territorial context of a selected Focus Area (FA). Figure 1 shows the methodological approach that the Polito RU developed and applied for its FA, the Alta Valsesia territorial context.

Exploration. The "Exploration" phase mainly focused on data analyses and mapping based on data and indicators collected from literature and databases and then included in the knowledge base structured in a Geographical Information System (GIS). The quantitative results deriving from data elaborations were integrated with other qualitative

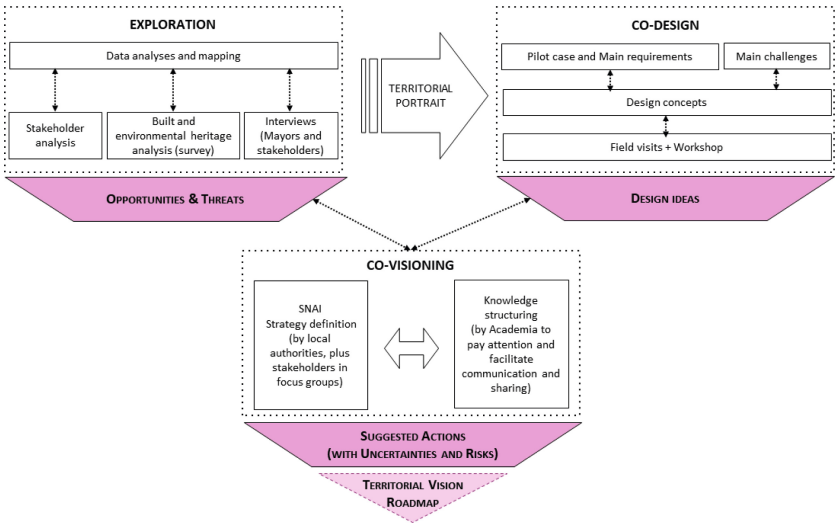

Fig. 1. The B4R methodological approach developed and applied by the Polito RU for the Alta Valsesia, in the general framework of the B4R project (Source: Authors' elaboration)

analyses: a stakeholder analysis and a survey focused on the built and environmental heritage, completed and verified by directly interviewing stakeholders and the mayors of the municipalities. The integrated results from these analyses supported the identification of a series of opportunities and threats that could orient and guide the process in the following "Co-design" and "Co-visioning" phases.

Co-design. The "Co-design" phase was focused on the organisation of a co-design workshop by assuming the explorative analysis results summed up in a territorial portrait. A paradigmatic pilot case and related requirements were identified within the larger FA, and its main challenges were explicated and shared with the public administrations involved in the process (local actors). Furthermore, the RU, jointly with the local actors, decided on three specific design concepts that guided the co-design workshop activities and the dialogue with the territorial communities during field visits. During the workshop, 3 working groups - made up of B4R researchers and students - worked in parallel on the assigned design concept and developed different design ideas able to foreshadow future enhancement strategies to be implemented in the "Co-visioning" phase.

Co-visioning. The "Co-visioning" phase aimed to implement a process focused on constructing a shared territorial vision and formulating a roadmap for the political decision-makers and local communities of the FA. In the Alta Valsesia context, two parallel processes were conducted in order to develop the Valsesia SNAI strategy. The first process consisted in a series of participatory meetings and focus groups with stakeholders organized by the Valsesia Mountain Union - in conjunction with the Biellese Orientale Mountain Union - and supported by the contribution of professionals. The second process was developed in parallel by the Polito RU to structure the acquired knowledge elements, identify uncertainties and risks and suggest strategic axes and pilot actions for the SNAI strategy definition and implementation.

3 Study Area

The Polito RU applied the methodological approach to the Alta Valsesia FA, which is located in the northern part of Piedmont, in a mountain area including 17 Municipalities (Alagna Valsesia, Alto Sermenza, Balmuccia, Boccioleto, Campertogno, Carcoforo, Cervatto, Cravagliana, Fobello, Mollia, Pila, Piode, Rassa, Rimella, Rossa, Scopa, Scopello). The Alta Valsesia includes numerous side valleys, which take their name from the respective streams that flow into the Sesia river: Val Mastallone and Val Sermenza are the most vulnerable socio-economic contexts since they are characterised by limited accessibility and facilities and by a progressive decline in population and ageing demographics. (Fig. 2).

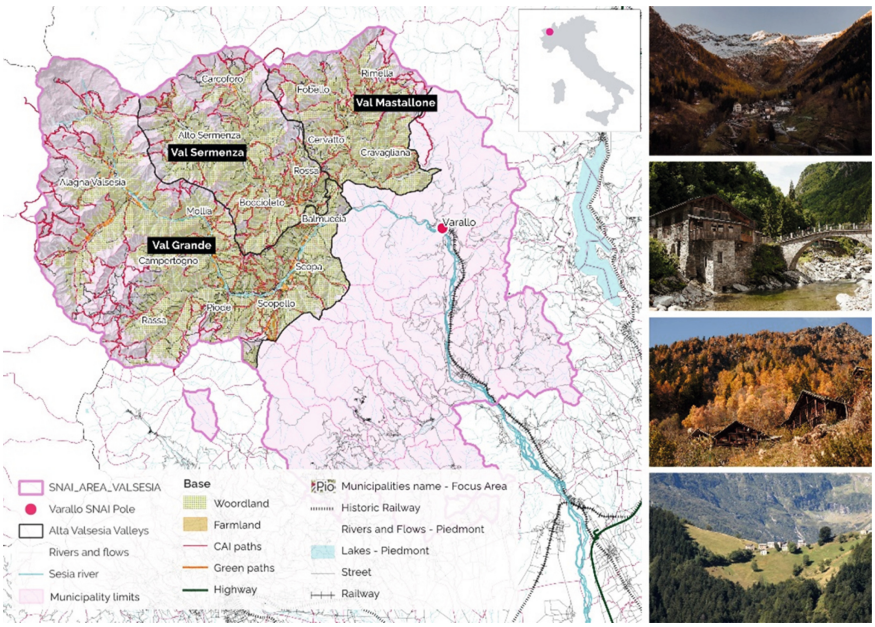

Fig. 2. The Alta Valsesia territory and the new SNAI Valsesia Inner Area (Source: Authors' elaboration; Photos: © Stefano Druetta, 2021)

A relevant territorial development project "Di Valle in Valle", partially funded with PSR funds 2014–2020, was promoted by the Polito RU to enhance the accessibility of the two lateral valleys including six municipalities (Carcoforo, Cervatto, Cravagliana, Fobello, Rimella, Rossa) [41]. This project was aimed to connect the mountain pastures located in the territories of Val Mastallone and Val Sermenza by improving the existing routes and enhancing the mountain environment and traditional Alpine architecture. Pathways and trails with different levels of difficulty cover the entire territory. A network of agro-silvo-pastoral tracks between Rossa and Cervatto serve high-altitude pastures and agricultural farms, connecting the Val Sermenza to the Val Mastallone. On these routes, there are shelters, high-altitude pastures, and votive chapels. The challenge to

increase and encourage the use of these pathways lies in improving and maintaining the trails, with the goal of ensuring maximum safety and accessibility.

The mountain that seems to divide the two side valleys actually connect them through a system of little-trodden pathways and trails and a network of villages, hamlets, mountain pastures, and shelters located at different altitudes (low, medium and high mountains). These areas necessitate restoration and reuse. The built heritage potentially subject to reuse and enhancement is consistent and typologically diverse. Numerous high-altitude pastures and residential properties are nestled within remote hamlets, posing accessibility challenges. Additionally, downstream in the town centres, abandoned properties - including former hotels, theatres, and commercial spaces—often await new opportunities for revitalization.

4 Results

The application of the B4R methodological approach in the Alta Valsesia territorial context allowed the Polito RU to strengthen the collaboration with the Valsesia Mountain Union and reach important results, shared with local authorities and communities along the four-year process, structured in its 3 main phases. In the following sub-sections particular attention was focused on the results achieved during the "Co-design" and "Co-visioning" phase, while the results achieved during the "Exploration" phase are briefly mentioned and referred to previous publications.

4.1 The Exploratory Analysis Main Results

The exploratory analyses conducted during the first year (2020) of the B4R project highlighted certain factors and critical issues in Alta Valsesia.

Over 400 indicators were analysed, and structured data within the GIS were utilized to generate more than 100 thematic maps and graphs, evaluating the territorial potential of the considered 17 municipalities [32, 35]. Furthermore, a stakeholder analysis was performed by applying the Mendelow Power-Interest matrix [26, 29] where more than 100 stakeholders (institutions, third sector organisations, companies, local associations and museums) were analysed and classified in relation to the 8 main objectives of the B4R research project [24].

In parallel, the survey on the built and environmental heritage, addressed to the Mayors of the considered municipalities, highlighted more than 40 assets or sites, both publicly or privately owned. Different asset typologies could be redeveloped to create new enhancement opportunities for the territory: rural buildings, buildings to be totally or partially reused, eco-museums, groups of buildings (hamlets), religious buildings (churches, chapels, oratories), pedestrian and cycle pathways, municipal washhouses [10]. This important knowledge base did not represent a systematic census of assets, but fostered the organisation of a series of interviews with the Mayors and meetings during field visits. These engagements were instrumental in further exploring the condition of assets and in discussing specific needs and potential redevelopment strategies.

All these exploratory analyses were developed by building a fruitful synergy with the Valsesia Mountain Union and allowed the Polito RU to better know and understand some

opportunities, threats, values and vulnerability aspects of the Alta Valsesia territory. In particular, the results revealed that the two lateral valleys (Val Sermenza and Val Mastallone) are particularly fragile areas, yet at the same time, they are strategically important for enhancing the entire Alta Valsesia. Therefore, these more fragile areas inspired the territorial portrait development and were chosen as the pilot case to be assumed during the "Co-Design" phase [10].

4.2 The Co-design Activities and Results

In the second year of the B4R project (2021), the Polito RU, in close collaboration with the Valsesia Mountain Union, decided to focus on Val Sermenza and Val Mastallone and to enhance the partially developed project "Di Valle in Valle". These fragile areas and assets were assumed as pilot case during the "Co-design" phase, facing the main challenge of reactivating and fostering the territorial vibrancy [37, 44] by counteracting demographic contraction, population aging, and the abandonment of built heritage. The Polito RU, jointly with the Valsesia Mountain Union and the six above mentioned municipalities involved as important local actors, defined other challenges, such as:

- Improving the network and the connection with the main cycle pathway (from Varallo to Alagna)
- Ensuring a mixed use (trekking, e-bike,…) and the widest accessibility (Mountain for all)
- Improving the coverage of the mobile network
- Enhancing the built and environmental heritage
- Creating job opportunities for local young people
- Strengthening and diversifying sports and cultural activities (both in winter and in summer)
- Enhancing the use of the Sesia River and its streams
- Increasing the accommodation offer
- Preserving and redeveloping mountain pastures, villages and (mixed uses)
- Promoting energy efficiency (passive houses)
- Promoting transformative tourism
- Offering events and experiences for both young residents and young tourists

Therefore, these challenges were synthesized in the following three design concepts, which emerged from a constructive dialogue (carried on during a series of online meetings) with the Valsesia Mountain Union and guided the working groups' activities during the co-design workshop:

1. "Buğési" that in the local dialect means *walking, arriving, riding*
2. "Alègru!" that in the local dialect means *having fun, connecting, sharing*
3. "Farmési" that in the local dialect means *stopping, contemplating, sleeping*

From March 18 to 21, 2022, at the Varallo Congress Center, local actors collaborated with researchers and students to identify possible new flows, economies, and enhancement strategies to resiliently "vitalize" the two lateral valleys of Alta Valsesia. The first day, during the Opening Conference, the B4R project was publicly presented, specifically highlighting the results achieved by the Polito RU during the first year of studies

and research. The main ongoing projects in the area were then presented through the testimonies of key stakeholders involved in territorial enhancement (such as the Confindustria Novara Vercelli Valsesia, Monterosa 2000, Terre del Sesia Local Action Group, Sesia Val Grande UNESCO Global Geopark, Valsesia Onlus Foundation). The Opening Conference concluded with the presentation of the "Di Valle in Valle" project and the three design concepts aimed to guide the development of revitalising projects. The second day was dedicated to field visits and meetings with the Mayors of the Municipalities. On the third day, separate working groups delved into the challenges and issues related to the visited territories and the three design concepts. Three design ideas emerged from the three working groups (Fig. 3), which were then presented on the last day to the Valsesia Mountain Union and some representatives of the key stakeholders in the area, who positively commented and envisaged real possible future developments (Fig. 3).

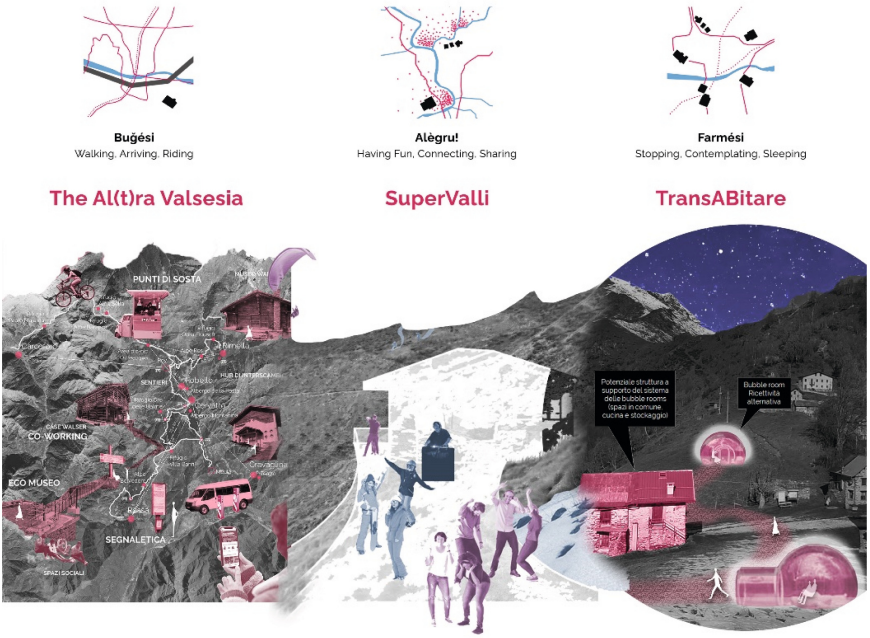

Fig. 3. Co-design workshop results (Source: Authors' elaboration)

"The Alt(r)a Valsesia. Collaborative transvalley intermodality strategy"

The concept "Buğési" addressed the challenge of soft mobility and connection between the valleys, aiming to enhance and make the existing trail network more accessible to attract slow and sustainable tourism. This form of tourism appreciates and respects the natural environment, revitalising currently more inaccessible places and the pathways leading to them. Making the ancient connecting routes between the valleys as accessible and usable as possible, on foot and by bicycle, is a key condition for enhancing the scenic beauty of these areas.

The design idea developed by this first working group was entitled "The Alt(r)a Valsesia. Collaborative transvalley intermodality strategy". It aimed to expand pedestrian and cycling routes, introduce new alternative transportation modes (such as e-bikes, on-call services, electric shuttles, cable cars, Inland Areas Uber, etc.) and integrate new mobility services coordinated through a novel management system in the municipalities of Val Sermenza and Val Mastallone. This idea represents an evolution of the "Di Valle in Valle" project. The five issues at the basis of the design idea are: 1. "Eco-sustainability" for slow tourism and sustainable use of the territory; 2. "Move" thanks to an integrated mobility network; 3. "Discover" through experiences along pathways and cycling; 4. "Arrive" thanks to a widespread distribution system for goods and people; 5. "Understand" through coordinated, open, accessible, integrated, and widespread communication.

"SuperValli. Policies, practices and places for young valleys"

The concept "Alégru!" addressed the challenge of targeting a very specific audience: the young people living or working in the FA and young tourists who predominantly visit the valley during the summer period. The socio-economic and cultural reactivation of these territories is intended to be closely connected to the goal of keeping and attracting new young people, not only as users but also as potential economic operators. The mountain, the river, the villages, and hamlets can offer strategic focal points for a range of activities and experiences - cultural and sports - and opportunities for socialising, leisure, and enjoyment.

The design idea developed by this second working group was entitled "SuperValli. Policies, practices and places for young valleys" and included a series of place-based project proposals for the implementation of innovative policies, social inclusion practices, and initiatives for young people (18–35 years old). These proposals align with national policies aimed at revitalising gathering places in inner areas. The focal points of the project concept are two places, both designed as catalysts for both resident youth and tourists: elevated meeting places for events, entertainment, and hubs for extreme sports (Yuppi-Alpe); meeting places in town centres, in the valley, which could form the nodes of a network of hybrid and flexible spaces hosting diverse functions for education and leisure (Wow-House).

"Transabitare. For a transvalley model of hospitality and living the Alta Valsesia"

The concept "Farmési" addressed the challenge of recovering local typical architecture, converting at-risk properties in villages, hamlets, and mountain pastures into accommodations or mixed-use spaces. These places can become strategic stopping points where the slow tourist can contemplate the landscape, stay overnight, experience innovative activities, or undergo transformative experiences. The goal of increasing accommodation options in the lateral valleys and smaller centers through an alternative high-altitude offering can also be well integrated with the aim of creating a replicable and extendable format (and brand) throughout the entire territory of Alta Valsesia.

The design idea developed by this third working group was entitled "Transabitare. For a transvalley model of hospitality and living the Alta Valsesia" and explored various

forms of residential living and alternative modes of habitation (including temporary ones) to reverse the depopulation trend, especially in "minor" centres, and to trigger entrepreneurial initiatives capable of creating new economic opportunities and local development in Alta Valsesia. The conceptual design was developed by analysing the quality of the local architectural heritage and the different types of residential settlements in the mountainous environment, vertically stratified into three levels (low valley, mid-mountain, and high altitude). In this system, centres at different altitudes acquire different functional and experiential characteristics, in line with "slow tourism" principles. The management of various structures in the various municipalities of the two valleys could be coordinated by the Mountain Union and the GAL (Local Action Group). At the same time, local administrations could support and promote integrated management of vertical systems, involving associations, community cooperatives, Pro Loco (local promotion associations), and industry associations.

4.3 The Co-visioning Process First Results

The key knowledge elements achieved during the "Exploration" and "Co-design" phase supported the last "Co-visioning" phase during the third and fourth years of the B4R project, which temporally coincided with a very important process that affected the Alta Valsesia FA. In 2022, in fact, the Valsesia Mountain Union, together with the Biellese Orientale Mountain Union, achieved the important goal of being identified as one of the new "inner areas" (called "Valsesia"), with over 10 million Euros funds to counteract negative socio-economic trends and promote new economic and local development strategies.

Since December 2022, the Polito RU has been involved in the SNAI strategy definition process, managed by the above mentioned two Mountain Unions with the support of an external consultant and finalised to identify a series of actions to be developed and funded to improve citizen services and local development. For this purpose, the two Mountain Unions organized six Focus Groups to dialogue with a series of local actors and stakeholders and to identify and share with them the main critical issues and opportunities related to the "Valsesia" territory. The activities of each Focus Group were related to a specific theme (1.Mobility and transport; 2.Health and personal care; 3.Agri-food chains and rural development; 4.Tourism enhancement; 5.SMEs development; 6.Education and training) and managed over two sessions. The first sessions focused on identifying critical elements and needs, while the second sessions were aimed at exploring suggestions and indications to be developed within the SNAI strategy. The first sessions were organised from December 2022 to March 2023, while the second sessions in April 2023, including also specific meetings with the Mayors of the Municipalities in order to share the results of the sessions and to collect other issues, needs or suggestions from them. Therefore, in June 2023 the Mountain Unions formed a series of Technical Groups to delve deeper into the refinement and crafting of possible actions to be integrated into the SNAI strategy, thereby advancing the initiative's development.

In parallel, the results from the Focus Groups' and Technical Groups' activities, as well as other ongoing processes in the territory, were monitored by a Control Room, formed by representatives of the Piedmont Region ("Territorial and local development

planning, inner areas and urban areas" Sector), the Province of Vercelli, the two Mountain Unions and their external consultant.

The Valsesia Mountain Union involved the Polito RU as a technical expert both in all Focus Groups' activities and in the Control Room meetings, to share the results deriving from the B4R projects and to participate in the dialogue with the local actors. Moreover, the Polito RU was also involved in the Technical Group "Transports" and in July 2023 suggested a series of possible actions, logically connected with the B4R project results and with the new knowledge elements derived from the six Focus Groups' sessions.

Since December 2022, the activities of the Polito RU were carried on two parallel sides, by actively participating to the above mentioned meetings (on field activities), and by analysing the previous results of the B4R project and elements of the ongoing process and structuring dispersed knowledge elements (internal RU team meetings) (Fig. 4).

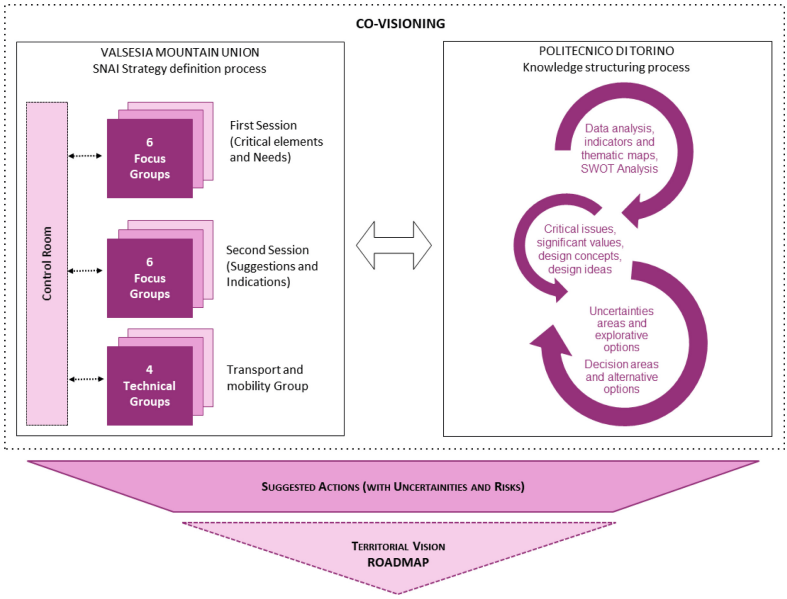

Fig. 4. The Polito knowledge structuring process in the context of the B4R "Co-visioning" phase (Source: Authors' elaboration)

The knowledge structuring process was developed with the support of a decision aid analyst, who actively participated in the RU meetings and progressively aided the group of six researchers to progress in the structured and formal elaboration of the research activities and results in relation with the B4R aims and the SNAI process.

The main B4R activities and results were:

– a survey on the built and environmental heritage, interviews with the Mayors and meetings during field visits, 400 indicators and 100 thematic maps and graphs of the territorial potential of seventeen municipalities of the area, a stakeholder analysis and a SWOT Analysis [7], applied to highlight the most critical issues and significant

values emerged from data analysis and mapping and the interviews with the Mayors (in the exploration phase);
– three design concepts identified together with the Mountain Union ("Buğési", "Alègru!" and "Farmési'") on the basis of the exploratory results and translated into design ideas during the co-design workshop, further developed and described in internal reports and conference presentations [38];
– the elements gradually originated during the first steps of the SNAI process (6 Focus Groups' sessions), which involved the Polito RU while it was operating in the B4R co-visioning phase and strengthened and increased the Polito knowledge base on the Alta Valsesia territorial potential.

All these knowledge elements, useful for establishing a preliminary territorial vision, were organised in a way able to be clearly communicated [28] during the meetings of the Control Room and the "Transport" Technical Group, and to become a road map for future decision processes.

To achieve these results, Problem Structuring Methods were selected to prepare the ground for effective interactions in the context of the SNAI Strategy definition process [6, 28, 39]. The Polito RU applied in particular the Strategic Choice Approach (SCA) [12], which has been applied in various situations (see, for instance [15, 18, 27, 30, 36]). SCA, with the support of its STRAD software tool [13, 14], is normally used to facilitate collaborative actors in managing and reducing the complexity of problem contexts characterised by a high level of uncertainty. In this case, it was used to facilitate a group of analysts in identifying and reducing elements of uncertainty that reduce the possible use of the acquired data and elements of knowledge.

SCA was used to formulate the key issues that have been proposed as main requirements by the Mountain Union and three key issues were formulated: "*How can we guarantee residents those services that an inner area must seek externally?*"; "*How can we retain or attract young people and counteract the trend towards ageing and depopulation?*"; "*How can we attract new and complementary tourism flows?*". Therefore, the application of the *Shaping* mode of SCA aided a technical association between the uncertainty level of each key issue, and related options, and the nature of knowledge about the territory, its potentiality and vulnerability.

Some structuring activities were developed and led to the formulation of a series of Decision Areas, with associated interventions around which the SNAI strategy can be oriented, and to a first debate on possible explorative actions finalised to reduce or control the uncertainty levels by means a structured use of data, information and knowledge.

The Polito knowledge structuring process is currently ongoing, in parallel to the Mountain Union's SNAI Strategy definition process, to formulate a Roadmap including strategic axes, strategies, pilot actions, uncertainties and risks able to support the Valsesia SNAI strategy implementation.

5 Conclusion

Assuming the challenge of being more attractive for new inhabitants, tourists and economic operators, inner territories can benefit from Academia's support for several aspects. For instance, Academia can effectively support them in addressing the lack of

data and information at the municipal level, particularly concerning spatial data. This support can include analysing data to identify opportunities and threats related to the territorial context, developing and sharing coherent design ideas, as well as aiding local actors in making strategic choices in complex decision contexts.

In the context of the B4R research project, the Polito RU implemented a collaboration-based approach, which represented not only a concrete opportunity for knowledge sharing with the Alta Valsesia local actors but also a chance during the definition of the Valsesia SNAI strategy, which is a complex ongoing decision-making process. In the past (and to some extent in this case), the process of defining the strategy and its interventions was mainly carried out at the political level, but the involvement of the Polito RU, providing technical expertise, facilitated enhanced collaboration throughout the process initiated and overseen by the Valsesia Mountain Union. The collaboration-based approach was particularly effective during the Focus Groups' sessions and the Control Room strategic meetings where the Polito RU's vibrancy-oriented vision, developed within the B4R project, was proposed. Since 2020 the collaboration between Academia and local actors has led to the identification of weaknesses/opportunities and to the enhancement of territorial potential by means of design ideas and possible strategic actions to be implemented in the context of the SNAI strategy definition process.

Supporting the correct identification of new territorial opportunities and enhancement strategies is only the first step in the redevelopment of an area: strategies must guarantee equal opportunities for all territories, with particular attention to those that are more fragile. According to the regional milestones, the construction process of the Valsesia SNAI strategy is ongoing. However, the initial drafts of actions and interventions and their impacts (including economic ones) on the territories reveal a limited coherence between proposals, identified vulnerabilities and actual potentials. Upcoming research developments concern:

– in the short term, specific research opportunities for project-specific studies (due to the involvement of Polito RU in the development of the "Di Valle in Valle" project, and in the feasibility study on a new local mobility system, oriented towards the experimentation of a territorial MaaS for inner areas [8, 20]);
– in the longer term, a critical remark of the (last/final) Valsesia SNAI strategy proposal in order to identify weaknesses and risks that need to be checked in order to avoid the results that were not so positive in the first programming cycle [46].

The Valsesia area is currently benefiting from other new specific funding measures. In fact, in recent years several financial potentials have emerged thanks to specific policies and public tenders: in addition to the SNAI opportunity above mentioned, there are numerous funding opportunities deriving from the National Recovery and Resilience Plan (PNRR), bank foundations and initiatives promoted by the "Terre del Sesia" Local Action Group. As a result, numerous projects have been funded and activated in some of the municipalities considered during the research carried out for the B4R project, and their implementation is currently a potential trigger for both the rehabilitation of the heritage and the promotion of new economies.

Certainly, it is worth mentioning that the enhancement of the Valsesia area is possible only if all these funding opportunities are jointly considered and coherently coordinated, avoiding managing them as separate processes. The success of the SNAI strategy cannot

be measured until the process is concluded, but the activation of equally structured processes of management, observation and monitoring of results id desirable, in order to correct the guidelines, and thus guarantee the effectiveness of the policy [1, 40, 46].

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From Data Collection to a Cross-Cutting Analysis Visualisation: Territorial Complexity Overview to Foster Responsible Tourism in Rural Areas

Asja Aulisio(✉), Silvia Barbero, Alice Barreca, Giorgia Malavasi, and Diana Rolando

Department of Architecture and Design, Politecnico Di Torino, Turin, Italy
asja.aulisio@polito.it

Abstract. In recent years, design expertise has become crucial for fostering connections between stakeholders and driving bottom-up processes to address complex challenges in fragile territorial contexts. This is evident in the struggles of both public and private organisations to strengthen collaborations and tackle territorial complexity issues faced by rural areas and fragile territories across Europe, such as depopulation, ageing populations, and unsustainable tourism patterns. While mass tourism threatens economic development in these regions, sustainable and responsible tourism strategies present an opportunity to enhance attractiveness and well-being. This paper focuses on using Systemic Design and Socio-Economic evaluation approaches to bolster responsible tourism development in rural areas by involving stakeholders within the tourism value chain and managing a structured enhancement process that starts with data collection and comes to cross-cutting analysis visualisation able to support co-design initiatives. Drawing insights from the SYSTOUR project, the paper explores ways to understand the intertwining of the elements of the system to find a balance between tourism-generated revenue and sustainable and even regenerative territorial development.

Keywords: Rural Areas development · Sustainable Tourism · Geographical Information System

1 Introduction

Design expertise has given rise to fostering connections among stakeholders, thereby catalysing value creation through bottom-up processes capable of bringing systemic change in tourism enhancement processes. This approach holds significant promise in addressing the intricate challenges inherent in fragile territories. Within these complex territorial contexts, both public and private organisations continue to grapple with the need to fortify collaborations in order to address issues related to rural areas and fragile territories effectively.

Rural areas across Europe are currently facing similar challenges. Depopulation, an ageing population, the closure of essential services, and in some cases, unmanageable

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picks in tourism and extremely seasonal visitor flows. Mass tourism is not a real opportunity for economic development in these places but rather a threat. Small villages and local communities lack the capacity to manage large influxes of visitors concentrated within limited time frames. Instead, they need to attract tourists, new inhabitants and investors who can increase the income of small businesses throughout the year, often complementing normal productive activities. Local governments agree on the promotion of strategies and actions for the implementation of sustainable tourism development policies, which could be a real driver for these territories to improve their attractiveness and well-being, not only as destinations to visit but also to live, work, and invest.

Recent literature faces the problem of practice-based and practice-led research methodologies in relation to artistic fields [52] where it is extensively discussed. While in the tourism field, there is very limited research on the methodological intricacies of practice-based research and knowledge development [8].

From these premises, this paper delves explicitly into using Systemic Design and Socio-Economic evaluation approaches to bolster responsible tourism development in rural areas by involving stakeholders within the tourism value chain and managing a structured enhancement process that starts with data collection and comes to cross-cutting analysis visualisation able to facilitate sustainable strategic planning through co-design initiatives.

In particular, critical synthesis emerges as a primary objective to be achieved also through visual elements and mapping, which act as a channel to provide an overall vision and narrative of territorial complexity. This integration complements traditional qualitative and quantitative analyses, facilitating a deeper understanding of the intricate interaction between the whole territorial system and the individual assets of the whole. By clarifying the relationships and connections inherent to the dynamics of rural territories, visual synthesis and mapping improve a holistic understanding of the territorial context. This approach has been tested in the context of the European interregional co-funded project SYSTOUR (2023–2027). Led by Politecnico di Torino (POLITO), the SYSTOUR project brings together researchers specialising in Systemic Design, Real Estate Appraisal and Economic Evaluation, collaborating with six diverse regions spanning North to South, East to West, and central Europe (https://www.interregeurope.eu/systourwebsite). Partnering with tourism regional departments (Hungary, Poland, Italy, and Finland), government foundations responsible for Tourism and Culture (Spain), and a technological centre for services related to transitions (France). Within the SYSTOUR partnership, the authors of the paper are experimenting with a research protocol to co-create data visualisation to jointly define strategies using a systemic approach for the regenerative transition of the Travel and Tourism value chain in rural areas. Specifically, the design-related component has core operational skills to combine and implement some methodologies and approaches applied in the context of the Systemic Design and Socio-Economic evaluation research fields. The approach used for this research recognises the effectiveness of a deep understanding of interconnected and interdependent elements in changes and transformation processes, often based on data, information and knowledge systems. The project expects to support territorial policies and strategies in close dialogue with stakeholders located within the selected regions.

After an international literature review (Sect. 2) on the main investigated topics (translational design, big data, geo-referenced data, GIS, and visual narrative) that brings out the lack of proper methodologies on practice-based research in the tourism field, Sect. 3 introduces the methodological approach, which was applied on Leartibai territory as a case study. Some exploratory results are illustrated in Sect. 5, while possible future developments are discussed in the conclusion, which points out the flexible use and adaptability of the proposed approach also in other contexts.

2 Background

With the aim of highlighting the methodological perspectives recently adopted by scholars to investigate sustainable territorial enhancement in rural areas by means of indicators-based analyses and translational design [15, 26, 34] a synthetic literature review is presented here.

In facilitating the integration of the design discipline, an undoubtedly crucial element, as stated by translational design [32], is to establish iterative dialogues and assess the design intervention through the active involvement of stakeholders in the process, promoting a holistic approach based on a systemic way of thinking. Synthesis turns out to be one of the main goals to be achieved through visual elements capable of mapping the territorial complexity, as integrated to pure data analysis, which helps to manage the components while understanding the whole and the parts, along with the relationships and connections that make up the dynamics of the whole [4]. Through meticulous use of data visualisation techniques and a research-though design approach, the paper demonstrates how design research can provide valuable insights into the complexity of actors that shape the tourism value chain to implement policy strategies for a sustainable and regenerative transition. This approach allows stakeholders to understand the complexities within their operational environments, enabling them to establish meaningful connections with the sector in which they work or collaborate with.

The increase of big data, coupled with high-performance computing and advanced machine learning techniques, presents unprecedented opportunities to capture the latent characteristics of territories, spanning regions, neighbourhoods, and individual buildings [18, 46, 47]. Recent studies have witnessed an exponential increase in the volume and diversity of geo-referenced data, both actively generated by users or passively collected [2, 21, 35, 44], providing deeper insights into the representation of socio-economic environments [22]. In the age of Volunteered Geographic Information (VGI) [9, 11, 16–19] and the proliferation of big geo-data [49, 50], platforms hosting user-uploaded photographs offer invaluable resources for tourists and visitors to shape their expectations, understand local landscapes, explore various routes, and unearth hidden gems [13, 14]. Moreover, the use of multi-sourced harmonised open data allows to better understand and visualise territorial features belonging to different domains [6]. This nuanced understanding of the relationship between these dimensions and visitor satisfaction rates holds big potential for policymakers to enhance the quality of tourist experiences and foster socio-economic equilibrium in rural areas [20, 36]. A wide range of literature underscores the indispensable role of Geographical Information Systems (GIS) in analysing and visualising diverse local features such as green spaces, local activities, public amenities, and touristic attractions. GIS facilitates the integration of spatial attributes, travel

times, and mobility patterns, offering insights beyond conventional databases. Proximity to positive territorial attributes yields benefits and positive impacts, while proximity to negative attributes poses vulnerabilities and threats [51]. The spatial organisation of environmental variables and community-driven processes undelights spatial correlations, co-variances, and multiplicative effects arising from the intersection of various interventions, policies and risks.

Data visualisation can be an effective communication and decision-making tool that helps people discern, distinguish, learn and understand specific topics even complex ones, in achieving this, the design and production processes are not trivial [30] they need to be planned and organised by rules to create stories. The visual narrative is what the visualisation represents to fulfil the intent of defining a story to tell someone else [39]. This allows a visual narrative to be constructed around that information combination, selection and hierarchy. Space, colour, layout, typography and annotations are all used to guide the users through the experience of processing the information [24].

By analysing specific literature and case [24] studies, which refer to the co-design data visualisation process, territorial geospatial analysis in rural areas and practice-based research in the tourism sector, some research gaps emerged. First, recent literature faces the problem of making the process of co-design strategic intervention with the support of technical experts to stakeholders more democratic, especially in the tourism sector and in geographical contexts like the rural ones where is tougher to generate change.

3 Methodological Approach

The methodological approach proposed in this paper is designed to support the territorial complexity analysis through Holistic Diagnosis [32] and to stimulate an active and effective involvement of stakeholders in different European rural contexts (Fig. 1). To this aim, it is necessary to manage data, knowledge and relationships with a diverse array of stakeholders involved in operational discussions regarding the research findings. This collaborative approach focuses primarily on the perspectives, interests, and needs of stakeholders, requiring that these participants influence the entire research process, from project design, data collection, and data analysis to the visualisation of results [23].

Despite this active participation of the stakeholders, it is crucial that the researchers organise and mediate co-design sessions to work with all the stakeholders by establishing a common language around data visualisation.

The experience in the holistic understanding of the territories [33] and dialogue with stakeholders in highlighting policy gaps, as well as good practices in terms of sustainability and regenerative territorial transitions, will provide to the experts' elements for policy roadmaps for regional models.

The first step of the methodological approach, shown in Fig. 1, includes the definition of the domain and the objective of the analyses (Phase 0), starting from a theoretical background that enables each team of the singular regional department to understand the characteristics and hidden potential of rural areas. In this phase, the technical team of researchers plays the role of practitioners by sharing practical competencies developed and coordinating the stakeholders to establish and validate a shared domain for the research.

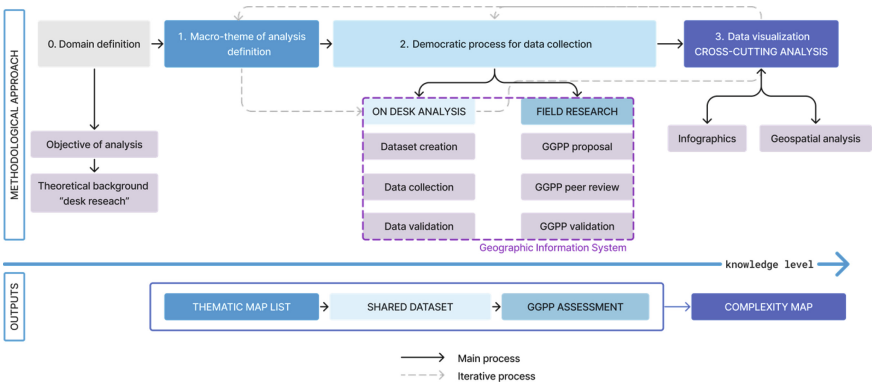

Fig. 1. SYSTOUR methodological approach (Source: Authors' elaboration)

The proposed methodological approach follows three main steps of analysis. The "Macro-themes of the analysis definition" (Phase 1) sets which kind of spatial analysis has to be carried on for understanding each specific territorial context. Based on the domain of the analyses, the macro-themes selection allows the Holistic Diagnosis method of analysis [5] by considering in parallel different fields of analysis to understand the relationship between each element and its environment.

The definition of the macro-themes of the analysis draws from two distinct approaches: the Holistic Diagnosis analytical framework [1], integrated with a selection of spatial analyses defined in the context of the Exploration phase within the "Branding 4 Resilience" national project[1] [10, 12, 25, 29, 37, 38, 43, 45]. Subsequently, for each macro-theme, it is necessary to consider the unique geographical partitions and hierarchical structures inherent to each territory involved in the investigative process. Starting from a set of indicators it is necessary to build up a list of required data at different territorial levels (e.g. national, regional, municipal). The output of this phase is the Thematic Map List, including the specific list of information, indicators, and geospatial data that needs to be collected.

In the final Thematic Map List (O1), indicators and data need to be shared with stakeholders to get their feedback and reviewed through a time of discussion on what may be elaborate, too detailed, or superfluous to activate the process of interest and involvement. Once the macro-themes of analysis are defined, the democratic process of data collection starts, which is articulated in two main parts: desk research and field research.

The democratic process of data collection (Phase 2) embodies steps and features of a participatory process aimed at fostering inclusivity and collaboration. It operates on a bottom-up principle, empowering key stakeholders to engage directly with researchers,

[1] "B4R - Branding4Resilience. Tourist infrastructure as a tool to enhance small villages by drawing resilient communities and new open habitats" is a research project of national interest (PRIN 2017 - Young Line) funded by the Ministry of Education, University and Research (MIUR) with a three-year duration (2020–2023). More information available at https://www.branding4resilience.it.

thereby facilitating the exchange of knowledge, valuable insights and the articulation of pertinent issues. Through this dynamic interaction, the outcome is not merely dictated but rather negotiated, ensuring that diverse perspectives are considered, and consensus is achieved.

It is noteworthy to mention that the technical team needs to supervise this phase in order to collect, harmonise and validate the data that the stakeholders provide during the process; moreover, it is necessary to find the right balance between the objective of the analyses and the availability of data in the different countries (O2). The outputs of Phase 3 are infographics, georeferenced maps and new spatial databases of Good Governance Practices (GGPP) scouted, mapped and assessed by stakeholders in each region (O3).

All the structured datasets are organised in a Geographic Information System (GIS) with the aim of supporting local authorities and sharing specific knowledge on each territorial context [3]. While the existence of open-access WebGIS in specific geographic regions is recognised, the proposed democratic process presents an invaluable opportunity to not only guide the acquisition of knowledge but also to shape the specific outcomes towards the focal points of analysis.

In the cross-cutting [43, 44] analysis [7, 37] visualisation (Phase 3) all the previously collected elements (territorial data, GGPP, and local stakeholders' vision) are joined to create a collective overview of the different regions with a combination of infographics and geospatial analyses to visualise the complexity of the contexts [41] in a Territorial Complexity Overview (O4).

Lastly, the aspect of democratisation of the process is again emphasised by the incremental iteration of the process itself, in which steps are being continuously refined and improved and where the outcomes of one phase informing revisions to preceding ones. This iterative approach ensures better alignment with the stakeholders' intentions and the analytical objectives [28]. The level of knowledge on the focused territorial context will increase as the process continues: it could potentially be repeated for all macro-themes of interest for future analyses.

4 Results: The Data Collection Process for Visualising and Interpreting the Territorial Complexity in SYSTOUR Project

According to the aim of SYSTOUR project, the proposed methodological approach has been implemented to address sustainable strategic planning and investments for services to improve employment and growth rates by focusing on European rural areas. This initiative seeks to increase the development of responsible tourism opportunities and the number of inhabitants (Phase 0). In this specific case, the objectives of the analyses have been addressed to identify and develop strategies in the field of sustainable tourism, a driver to improve the attractiveness and well-being of fragile territories, not only as destinations to visit but also as places to live, work, and invest.

At this time, the SYSTOUR partners are actively engaged in finalising the data collection and visualisation efforts. In light of this, the current proceedings aim to provide a preview of the final indicators for the Territorial Complexity Overview. This preview

will focus on presenting the two representative macro-themes, namely Demography and Tourism.

4.1 The Thematic Map List

To streamline project coordination and ensure the integration of project outputs into research design, the authors (POLITO) developed a protocol. This protocol, as outlined by Nanda & Wingler [31], serves as a roadmap for crafting a theoretical framework and a set of practice-based tools. It employs a dual methodology, encompassing both qualitative and quantitative approaches to data collection and cross-cutting analysis visualisation. Crucially, the protocol emphasises active involvement of stakeholders throughout the process, by fostering collaboration and ensuring comprehensive input.

The Thematic Map List (O1) in Tab. 1 is the result of the application of Phase 1 of the proposed methodological approach with the aim of stimulating an active engagement of stakeholders and creating new economic flows in different European rural contexts (Italy, France, Spain, Poland, Finland, Hungary). This outcome represents a possible result of the application of the methodological approach, but the set of indicators and spatial data can vary during the process to better match the objectives of the analyses.

The set of indicators in Table. 1 was set up assuming that the collected data would be represented through a combination of infographics and geospatial maps, hence the shared dataset (O2) includes both data for different kinds of graphs and spatial data according to the stakeholders' contribution and the open-data availability.

In SYSTOUR, the POLITO research team set up the macro-themes and indicators list (Phase 1), by assuming the results achieved in other studies [12, 37], with a combination of different open data sources such as the National Institutes of Statistics (ISTAT, INSEE, INE, etc.), Tourism Observatories and other specific dataset obtained thanks to the stakeholders' volunteer contribution (VGI).

The Thematic Map List has been provided to the European partners from the initial phases to discuss the topic of the analyses and to check the available data: this step has triggered the starting of the Democratic process for data collection (Phase 2). It began by providing a structured and shared dataset designed to collect data within the framework of several macro-themes, such as Geography, Demography, Economy, History and Culture, Tourism, and Education.

To enhance the depth and scope of data compilation, the protocol foresees intermediate reviews with advisors, enabling the inclusion of additional subcategories that stakeholders, actively involved in the process, identified as relevant [48].

This collaborative effort (Fig. 2) ensured that the dataset comprehensively reflected the complexity of the subject matter. Once the Excel spreadsheet has been fully populated by the regional project partners and stakeholders involved, the POLITO research team reorganised and analysed the collected data and indicators to create graphs, geospatial analyses and infographics that follow a precise logic by referring to their expertise and consulting "The Data Visualisation Catalogue" [42].

Table. 1 Thematic map list from the macro-theme selection. (Source: Authors' elaboration)

Macro-theme	Theme	Spatial data type	Territorial level
GEOGRAPHY	land use	polygon	regional
	rivers	polygon/line	regional
	orography	polygon	regional
	streets/connection	line	regional
	population density	polygon	municipal
DEMOGRAPHY	migration balance	polygon	municipal
	middle age	polygon	municipal
ECONOMY	employment rate	polygon	municipal
	real estate market (sales prices)	point/polygon	municipal
	GDP	polygon	municipal
HISTORY-CULTURE	Museums	point/polygon	national
	UNESCO sites	point/polygon	regional
	National parks	polygon	national
	Natura 2000 sites	polygon	national
	Protected areas no-UNESCO	point/polygon	national
TOURISM	Average stay	polygon	municipal
	Accommodation	point	municipal
	Tourist classification of municipalities	polygon	municipal
	Touristic flows	polygon	municipal
	Sport and leisure points of interest	point	municipal
	Other points of interest	point	local/national
	SYSTOUR Scouted/selected/visited best practices	point	local/regional
EDUCATION	Schools	points	local/municipal
	University districts	polygon	municipal
	Average level of education	polygon	municipal

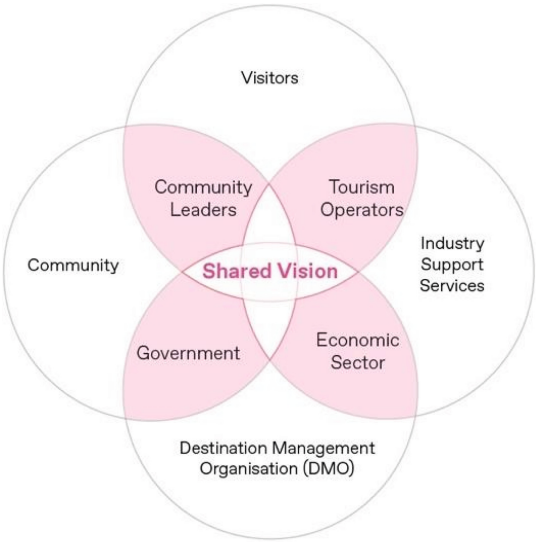

Fig. 2. Defining a shared and democratic multi-stakeholders' vision (Source: Authors' elaboration)

4.2 Shared Dataset and GGPP Assessment

After the definition of the Thematic Map List (O1), the process continues with the collaborative input from the partners (Fig. 3).

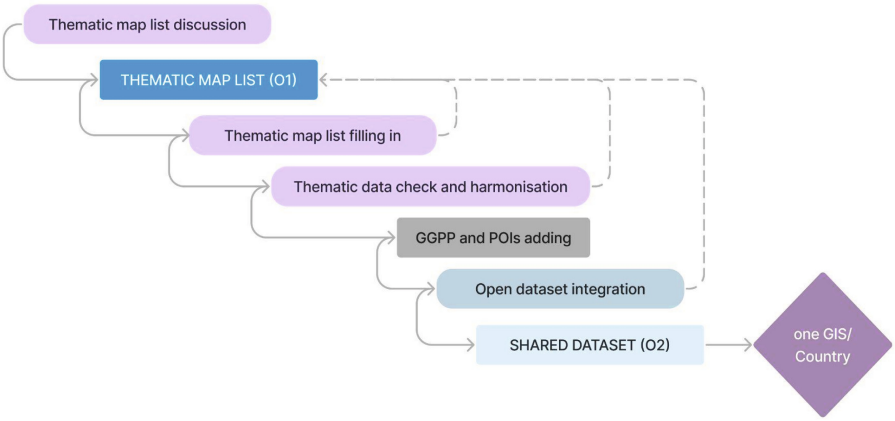

Fig. 3. Shared dataset (O2) achievement (Source: Authors' elaboration)

Currently, the SYSTOUR partners are actively engaged in finalising the data collection process, ensuring the completion of all data tables and sheets. Following this crucial step, the POLITO research team will work to check and review the data's completeness

in order to ensure that all the countries' datasets are comparable by harmonising data and standardising their specific ontologies.

The original contribution of each GIS project is the inclusion of the two new spatial databases. The GGPP, discussed and approved by all the partners trough a peer review process of assessment, and the mapping of Point of Interest (POIs) mostly related to the Tourism topic. Lastly, the POLITO team would provide some integration by consulting online open datasets and new geographic data. The final result of the shared dataset (O2) process is the creation of six GIS (one for each country) that could be bequeathed to local authorities to guarantee the equity of information between the different territorial contexts.

4.3 Territorial Complexity Overview

To address specific analyses, a list of indicators for each macro-theme has been developed by providing a mix of data to be represented both with the use of images or graphs (infographics) and maps thanks to the GIS developed for each country of the project.

At this moment, the SYSTOUR partners are working to finalise the data collection and the cross-cutting analysis visualisation; so the Territorial Complexity Overview (O4) here presented is a draft, focused only of on two main representative macro-themes: Demography and Tourism (Tab. 2).

Table 2 highlights the complementarity between infographics and maps: it is not possible to represent each singular indicator by the use of graphs due to the necessity of showing the spatial relationship between the elements as could be done with maps; meanwhile, the use of infographics allows to light up the dependency between the different territorial levels.

Tab. 2. Territorial Complexity Overview: focus on selected data for Tourism and Demography analysis. (Source: Authors' elaboration)

Macro-theme	Theme	Spatial data type	Infographic	Map	Sources
MAP BASE	Administrative boundaries of the region, comarcas, municipalities	polygon		X	Eu Commission
	Buildings	polygon		X	Regional WebGIS
	Railway lines networks	line		X	
	Main and secondary road network	Line		X	
	Pedestrian and cycling lane network	Line		X	
	Blue infrastructures	Line/polygon			

(*continued*)

Tab. 2. (*continued*)

Macro-theme	Theme	Spatial data type	Infographic	Map	Sources
	Digital Terrain Model	Tiff		X	OpenDem
	Land Cover	Polygon		X	Corine
	Parks	Polygon		X	
	Natura 2000 sites	polygon		X	Eu Union
DEMOGRAPHY	population density	polygon	X		National institute of statistic
	Migration balance	polygon	X		National institute of statistic
	middle age	polygon	X		National institute of statistic
TOURISM	Avarage stay	polygon	X	NA	National institute of statistic
	Accomodations	point	NA	NA	-
	Tourist classification of municipalities	polygon	NA	NA	-
	Touristic flows	polygon	X	X	National institute of statistic
	Sport and leisure points of interest	point		X	Regional online GIS
	Other points of interest	point		X	Partners survey
	SYSTOUR Scouted/selected/visited best practices	point		X	Partners survey

The issues and potential of an area are highlighted by the intersection of geospatial elements and the integration of infographics with specific focuses that emerge from the data provided by the stakeholders who live, administer, and know the area.

The narrative approach is employed to craft a compelling storytelling component for the Territorial Complexity Overview, making the findings more accessible and meaningful to a broader audience [27]. The research Protocol defined also emphasises the importance of sharing the results with stakeholders, dedicating specific moments for feedback and involvement. To gather valuable insights and ensure a well-rounded analysis, several moments of review within multi-stakeholder group sessions are being conducted

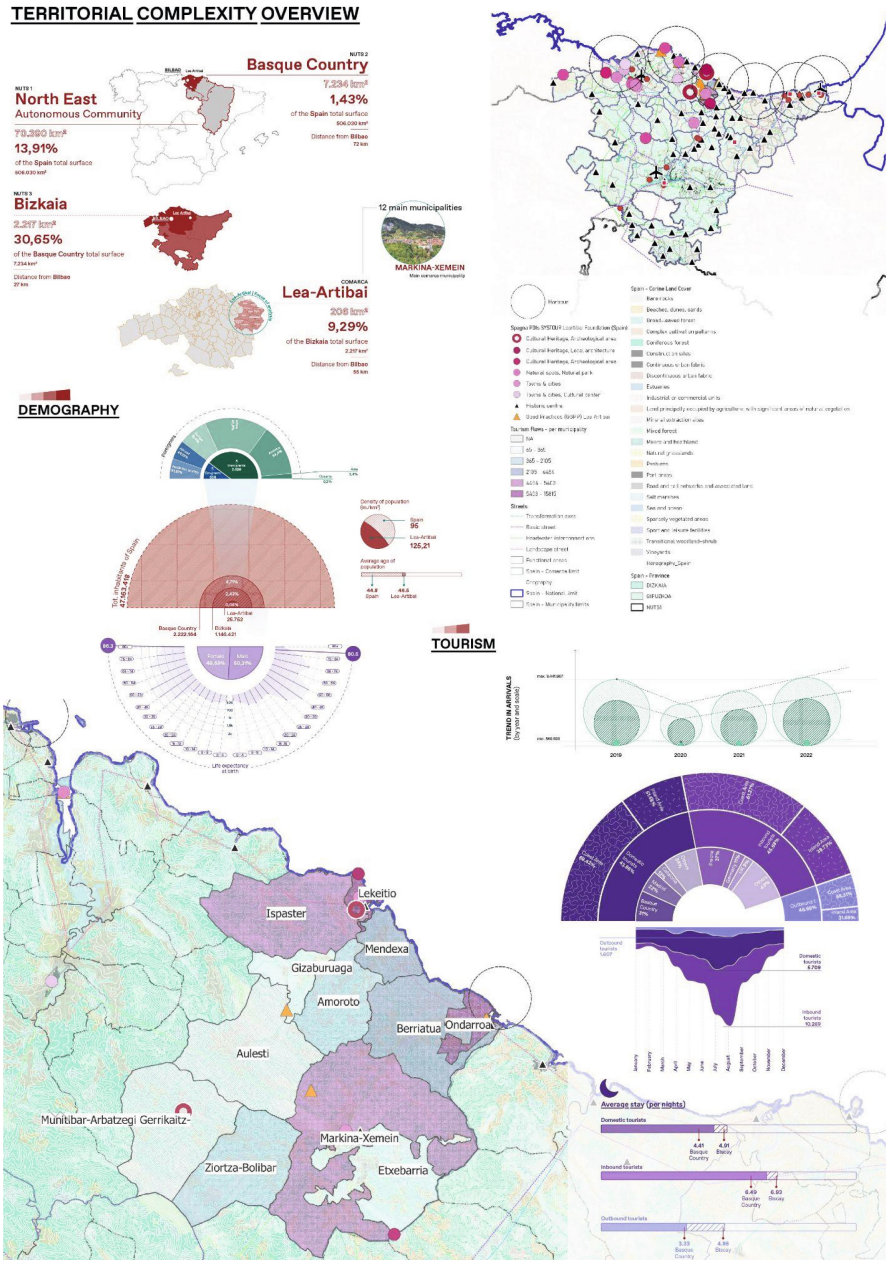

Fig. 4. Preliminary Territorial Complexity Overview of Lea Artibai - Spain. (Source: Authors' elaboration)

to integrate their feedback and foster a democratic and inclusive approach to the study. This comprehensive Protocol ensures that the research process is structured, inclusive, and well-informed, leading to robust and meaningful results.

The Territorial Complexity Overview example reported in Fig. 4 shows preliminary results elaborated for the Spanish territorial area, specifically afferent to the Basque Country (NUT 2), the Biscay region (NUT 3), in the rural area of Lea Artibai. The selection of representing this context stems from the fruitful collaboration, selection, and sharing of information and data, which demonstrates a very high level of propensity to access the data itself, which should be considered when designing using local, regional, and national data. The partner, Lea Artibai Foundation, contracted an external agency qualified in tourism industry data analysis to support them in acquiring the data and information required by the POLITO research team.

The region's online geoportal (https://www.geo.euskadi.eus/inicio/) boasts an extensive array of data, offering the opportunity to access specific geospatial datasets for map creation. This resource not only identifies existing gaps but also facilitates ongoing work to address them, in accordance with the outlined methodological approach.

The ultimate outcome is a comprehensive territorial complexity overview of the region, empowering readers to meticulously examine and analyse the multifaceted issues that define a specific geographic area or region.

The preliminary Territorial Complexity Overview in Fig. 4 delves into two key dimensions: demographic and touristic factors, which collectively shape the complexity of the territory. This approach involves examining the relationships, interconnections, and contradictions within the region. The spatial aspect of data allows for a detailed analysis at a local level, while also presenting a broader regional perspective, also demonstrating the presence of hierarchical relations between different areas.

This panoramic overview provides valuable information on the challenges, opportunities, and trends within a region, creating a solid foundation for informed decision-making processes, long-term planning, and the development of sustainable growth strategies.

5 Conclusion, Discussion and Limits

Rural communities across Europe face common challenges such as aging populations, depopulation, closure of essential services, and unsustainable tourism picks. While tourism offers economic potential, mass tourism often overwhelms small towns and villages. To thrive, these communities need sustainable and responsible tourism approaches that support local businesses year-round, rather than seasonal spikes in visitor numbers.

Local authorities concur to foster plans and initiatives for implementing sustainable and responsible tourism development policies. This could be a major factor in making these regions more attractive places to live, work, and invest in addition to being popular sustainable travel destinations.

To support these processes, different research profiles within academia, can explore the territorial complexity and better understand users' needs and behaviour, going beyond mere data retrieval. The [52]cross-pollination among design and non-design research

fields in studying a complex territorial context is based on the integration between qualitative and quantitative approaches, to analyse and visualise different contexts, stories, human and non-human needs, addressing solutions better suited to real-world circumstances [40]. Moreover, as a collaborative discipline, design is particularly suited to these challenges by translating complex messaging, meanings, and narratives of experience. The objective is, therefore, to understand the intertwining of the elements of the system to find a balance between tourism-generated revenue and sustainable and even regenerative territorial development.

This research emphasises that initiating this transition process requires a collaboration with the stakeholders involved in data collection and cross-cutting analysis visualisation. This collaborative effort gives rise to comprehensive and nuanced interpretations of the context in which actions are undertaken, fostering the holistic and complex view of transition dynamics.

The present research has shown the first results of the territorial complexity overview with an explanation of the overall methodological approach to data collection, analysis and visualisation through a democratic process. The collaboration between the POLITO research team and the local partners during the definition of the macro-theme and the data structuring has allowed to combine open online data with other new data provided directly by the stakeholders (VGS).

The Territorial Complexity Overview is the examination of the intricate and multilayered aspects that characterise the SYSTOUR geographic areas. This assessment examines various dimensions such as geographical, economic, cultural and educational issues that make up the territorial complexity. On this regard, the results of this research try to understand the connections, interconnections, and contradictions between the different layers of analyses (macro-themes) within the analysed territorial contexts, by taking into account the state of the art and future developments to provide insights into the challenges, opportunities and dynamics for informed decision-making processes.

At this aim, the six GIS projects - one for each SYSTOUR country - would be delivered to the partners to guarantee a baseline for future analyses concerning rural areas and opportunities for responsible tourism development. The provision of a geographical information system on sustainable tourism with common ontologies could encourage stakeholders to identify solutions and develop guidelines for new policies and strategies not only at municipal but at regional or national scales. Moreover, the SYSTOUR GIS projects can provide knowledge bases for all countries that do not have any open access to online information systems, in order to guarantee fairness in data organization.

Despite this crucial result, the gap between the objective of the analyses and the availability of information at the different territorial levels needs to be mentioned: future developments could try to improve the GIS in the different countries by adding new macro-themes of analysis or improved indicators to better compare the countries.

The current paper underscores the significance of engaging stakeholders through the utilisation of co-design practices and participatory approaches. By embracing alternative and cross-disciplinary methodologies, such as the Territorial Complexity Overview, the research endeavours to catalyse impactful and enduring change, thereby paving the way for fresh perspectives in the strategic development of European rural areas.

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Resistance to Sardinia's Guarded Capacity: Multicriterial Mapping for Strategies and Valorization of Abandoned Places

Cheren Cappello(✉)

Department of Architecture Design an Urban Planning, University of Sassari, Piazza Duomo, 6, 07041 Alghero, Italy
c.cappello@studenti.uniss.it

Abstract. This contribution fits into the context of studies on perspectives for eco-oriented territorial rebalancing involving city networks in inland areas. These areas are characterized by the contrast between socio-territorial disadvantages and opportunities for reusing physical resources within the framework of city redevelopment and the promotion of local identities. This is in response to challenges that lead to the exclusion of both small municipalities and growing cities from territorial, urban, social, and economic communication. In this study, the concept of "reconnection" is glimpsed in the project's potential bring about a return to the land essences and the significance of places through the establishment of new value-based relationships.

The research aims to construct a structured knowledge model focused on identifying and describing the causes and motivations behind the loss of recognizability of urban and territorial forms. This is done to identify possible trends reversals or to justify the motivation for discontinuation. The initial results consist of 1) the formation of an integrated set of maps highlighting the Capacities and resistances describing the profiles of each territorial unit under study, and 2) the design synthesis representing the convergence or divergence of the two forces expressing the willingness of each unit to adopt revitalization strategies for the eco-oriented development of abandoned municipalities.

Keywords: Abandoned places · Aggregated Joint Capacity/Resistance Index · Territorial strategies

1 Introduction

1.1 Territorial Reconnections

The issue of abandonment in vulnerable Italian territories persists despite increased efforts to enhance accessibility through the National Strategy for Inner Areas and energy-efficient building retrofitting in the National Recovery and Resilience Plan (NRRP), part of the Next Generation EU program, and aligned with the United Nations Sustainable Development Goals, specifically Goal 11 and Goal 12 [1].

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Faced with the increasing exposure of the human-nature system to dissipative processes at the eco-socio-systemic level, it becomes imperative to rethink the issues related to urban and territorial planning oriented towards ecological transition, focusing in particular on the issue of 'waste' in territorial, urban (and social) terms, i.e. on certain aspects of the 'closing of cycles' issue concerning the relationship between the value of local resources and their efficient and equitable use [2].

The overarching perspective of sustainability, towards which research has been increasingly consistently oriented for many years, is specified here in the forms of recovering smaller territorial-urban aggregates that carry testimonial and landscape values predominantly linked to local material culture. The recovery of the local material culture, especially in abandoned territories, plays a prioritized role in the dimension of inclusion, i.e., territorial justice [3]. Literature has identified the improvement of quality of life and the enhancement of the attractiveness of places as key factors capable of reversing this trend [4–6]. Recognizing the value of local material culture as a unique and irreplaceable expression of community identity implies reference and "re-affection" towards tangible and intangible resources that have defined and continue to define the distinctiveness of a place [7].

However, in today's global cultural and economic trends, there is resistance to the quiet flow of history in small communities, far removed from metropolitan dynamics. This distance, in the era of crisis and confusion, represents "the opportunity" for the rediscovery of a sense of shared purpose between socio-economic and environmental systems (constructed and natural) [8]. The recognition of the value of the human-nature relationship constitutes the root of the impulse for change to address environmental urgencies that are increasingly at the center of scientific community attention.

The possibility of guiding a return to the land through the creation of new value-based relationships is identified in the concept of "reconnection". If it is true that images inform and shape the preference system, then the task of project and planning choices is to advocate for the ethics of the "aesthetics of sobriety" and the importance of judicious renunciation. When discussing small villages and inland communities abandoned because they are not suitable for contemporary living, what does it mean to intervene for their "revitalization"? Can a dead place come back to life? Considering these reflections, the question of this study is reframed as: what abandoned aspects are sustainable to recover?

In this perspective, the landscape represents a crucial reference element, in terms of both extent and complexity, in analyzing territorial phenomena of both natural and anthropogenic origin. This study aims to capture significant elements – criteria – for evaluating the city's resistance to its essence, i.e., that social identity recognizable in the territorial continuum [6]. These criteria provide a description/representation, through a structured set of metrics and semantics, of the degree of capacity and resistance of the most significant dimensions of the city-territory-landscape system.

1.2 Contents and Aims

With the support of spatial analysis tools (GIS) and based on official data accessible through the portals of relevant national institutions – along with observers providing aggregations for specific purposes – the study provides structured analyses

aimed at a synthetic interpretation of the arrangement of natural, urban, and socio-economic components in the studied area through indices and maps at different levels of aggregation.

The methodology is developed within the perspective of multicriteria analysis, particularly referring to aggregate operational research approaches [9]. The result is the establishment of an interrogable information system that allows the calculation of complex indices for comparing the municipalities of the province. This comparison is done from the perspective of criteria that facilitate the connection between different aspects of the current structure of the territory [10].

The paper is structured into six sections: Sect. 2 (Materials) outlines the study's context, highlighting recent socio-economic resistances in the face of strong capacities within the natural system and the inland city network; Sect. 3 (Methods) presents the descriptive and evaluative model, from the selection and organization of basic information to the setting of significant indices representing the oppositions between resistances and capacities; Sect. 4 (Application and Results) presents the results of comparisons in terms of and proposes interpretations of natural, urban, and socio-economic contexts; Sect. 5 (Discussions and Conclusions) critically analyzes the results, correlating landscape risk and causes of abandonment.

2 Materials

2.1 The Uncontaminated Territory of Sardinia

Sardinia region consists of 377 municipalities divided into four provinces, over 24,100 km^2. The island's geographical position, eccentric to the main routes of the Mediterranean sea, has allowed for natural development protected from contaminations, hybridizations, and constructions. With 1,213,250 hectares, it is the first in Italy for forested area. The essence of the territory is evident in the deserted beaches, endless forests and shrubs, and the rugged hills marked by dry stone walls bordering pasture areas and a few rare farmhouse cottages. Stone is the essence of Sardinia, a resilient and durable material, characterized by magnificent chromatic variations.

Demographically, Sardinia has always been sparsely populated. It went through a period of intense growth between 1920 and the post-war period, maintaining the highest birth rate in Italy, but with the beginning of the 21st century the trend reversed [11].

Due to demographic, social and economic fluctuations, 317 out of 377 municipalities in Sardinia have been identified as municipalities at risk by the National Strategy for Inner Areas. In line with national and European trends, Sardinia is also characterised not so much by a decline in population as by its transfer from the hinterland to the large metropolitan and coastal centres.

Mining and cork processing in the inland areas, along with salt production in coastal zones, have historically characterized the economies of Sardinia, alongside agro-pastoral activities. However, in the post-World War II period, to revive the island's socioeconomic fortunes and as a measure to counteract banditry, the "Renaissance Plan" was conceived in 1962 (Law 11 June 1962, no. 588). This plan implemented special legislative measures for financing the industrialization of Sardinia, leading to the establishment of the two petrochemical settlement in Porto Torres, Sarroch and Ottana. Today, the economy of

Sardinia is mainly based on the tertiary sector (78%), driven particularly by the tourism and seaside sector [12].

2.2 Selecting the Case Study

The study concerns the urban-territory system of the Sassari Province which since 2016 includes the province of Olbia Tempio (Regional L. 2 /2016), thus becoming the largest province in Italy, covering an area of 7,692 sq. km, and the most populous province in the region with 493,788 inhabitants (see Fig. 1).



Fig. 1. Spatial framework of the study area: the Province of Sassari, Sardinia, Italy.

Some issues of landscape risk such as abandonment of productive activities and migratory phenomena affected the province mainly due to the abandonment of the former productive landscapes: the petrochemical settlement of Porto Torres and the historical area of Nurra, which was reclaimed in the 1950s but never recovered in economic and productive terms; various productive landscapes linked to mining (quarries and mines), such as Argentiera. The district of Gallura is known for the "economic miracle" of the Costa Smeralda, the epicenter of elite tourism, created in 1961 at the behest of the Ishmaelite Prince, the Aga Khan and other wealthy investors. This part of the region can be seen as a separate entity, bucking the economic and demographic trend of the rest of the island, and is therefore interesting to study. On the other hand, Gallura is also known for its cork and granite districts, that flourished until the 1990s and now declined, leaving large parts of the territory profoundly altered and abandoned.

The proposed model, which is presented immediately below, analyses the 92 municipalities of the province (Fig. 2), summarizing for each one the information that characterizes it in terms of its ability to maintain a strong link with the place or, on the contrary, its resistance to the natural transformation of the landforms in harmony with the environment.

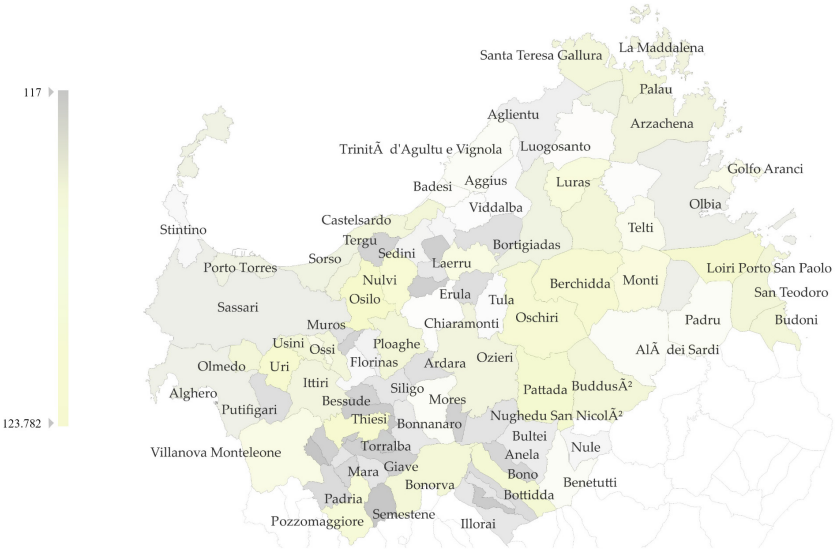

Fig. 2. Municipalities of Sassari Province and resident inhabitants.

3 Methods

3.1 Information-Units and Information-Bearers: Denotation and Connotation

The proposed model coordinates units of information at different levels of description and evaluation. The information system is structured in the form of a database where the records (rows) are the study units (sU) bearing information, and the fields (columns) are the attributes, namely the information units (iU). Attributes are distinguished between denoted and connoted, the former being predominantly descriptive (observations and indices), and the latter being predominantly evaluative. Indeed, the latter constitute value representations of the sU from the perspective of the upstream criteria that describe their value in terms of capacities or resistances to integrated evolutionary processes of the natural, urban, social and economic systems (see Sect. 3.4).

3.2 Denotative Attributes: Official Sources of Data and Indices

The denotative attributes come from the data and indices coming from the following official sources.

1. For the natural context, the Landscape Territorial Plan (PPTR) of the Region of Sardinia, the Geological Map, and the Land Use Map provide accessible information on the Sardegna Geoportal website. These sources highlight the arrangement of systems and provide quantitative data on abiotic and biotic components.
2. The database of the National Institute of Statistics (NSI) was scrutinized for the municipality and Census Section data, using the "8000Census" and "Italy in detail" sections to represent vulnerability and obtain critical data for the social and urban system.

3. Portals such as "Comuni Italiani" were consulted for demographic and income dynamics. The Statistical Atlas of Municipalities, with reference to ATECO data, describes the productive system.
4. The Observatory of the Italian Real Estate Market (OMI) provides information on the arrangement of real estate assets, analysing data for Micro zones and typology.
5. The database of the Regional Plan of Extractive Activities (PRAE) surveys the Sardinian extractive industry in 2004, assessing the anthropization of the territory linked to historical construction and prospects for recovery to preserve local identities.

Additional information related to climate, peculiarities of production processes and the wealth distribution disparity index (Gini Index) were retrieved through platforms like certifico.com and Urban Index.

3.3 Connotative Attribute: Informative Aggregate System and Hierarchical Evaluation

The evaluative synthesis refers, on the one hand, to the capacities of economic and institutional actors to highlight and valorise the vocations implicit in the landscape combinations of natural data and anthropic substrate; on the other hand, to the manifestations of impoverishment and territorial disadvantage that characterise the hinterland, and to the effects of the superimposition of the real estate and seasonal economy on a production economy with little consistency, especially in the coastal areas; in short, to the forms of resistance to the eco-oriented and inclusive development of the urban-territory-landscape system.

3.3.1 Capacity and Resistance Indexes

The iUs function as attributes, each with a specific explanatory capacity at every level of the WBS to which they are assigned (see Fig. 3). At the first level, they represent the value of the Municipality from the perspective of each System. At the second level, the attributes reflect the aggregated value of the main components into which these systems can be broken down. At the third level, the attributes express the sub-components, and at the fourth level, type and quality specifications. Finally, the fifth level reports the above-mentioned elementary denotative information units.

Natural/Lad System

The natural system capacities are divided into abiotic and biotic components. The former, are represented through the sub-components "soil", "elevation", "water resources" and "climate" of the area under study. The biotic components are disaggregated into "fauna" and "vegetation". The vegetation sub-component is described at the fourth level based on the grouping of the most common spontaneous or cultivated botanical species, considering their importance in view of development patterns and lifestyles aimed at the compatibility of livelihood needs and biodiversity.

The resistances of the Land System are identified as those components that betray local capacities and hinder the *continuum* of the territorial milieu [18]. These include the "abandonment of stone economies", the "abandonment of agricultural economies",

and the "anthropic imprint on the landscape". The latter is calculated based on the environmental footprint of unsustainable development patterns, relating to "productive and urban settlements", "infrastructure systems" and "major facilities".

Urban/City System

The Urban System, conceived as an open system, is defined by the flows of "matter, energy and information" [19] that characterize the territory. The key components of this system are the built heritage, the housing system, and the settled communities. Regarding the built heritage, physical-quantitative and partly qualitative aspects are examined, including "building density", "state of conservation", "use status", and "testimonial" and "material value" related to the age of the buildings and the technological and material coherence of their formal structure. The component related to the state of housing focuses on residential dwellings, evaluating building density and the housing occupancy rate. Finally, the third component describes settled communities in quantitative terms (crowding index) and qualitative terms, considering the family as a reference and home-ownership as a significant aspect of attachment to the city and the territory. The overall score of the system aggregates the three components, recognising the importance of the built heritage - emphasising the physical and symbolic support in which communities recognise themselves - and the owner/tenant ratio for the importance highlighted above.

The resistances to the City System (see Fig. 9) are identified as those components that prevent the system from expressing its landscape ("state of degradation of historic centers"), functional ("state of use of buildings and dwellings"), and identity ("abandonment of the family's housing dimension") capacities.

Social/Community System

The analysis of the resident communities in the studied municipalities aims to identify the demographic dimension of local social realities and the overall skills of their inhabitants. It assesses the demographic consistency of the settlement in relation to its attractiveness, highlighted by intercensal variation. Various aspects of families are explored, considering the presence and consistency of family units, as well as the risks associated with young single-parent families or elderly individuals living alone.

The resistance of Social System is represented from a high index of "intercensual variation", which indicates the inability of the system to maintain identities, and for the same reason a high "index of unemployment".

Economic/Resources System

Lastly, the general concept of the Economic System encompasses all interconnected elements, including actors, resources, technologies, and knowledge, which collectively contribute to the creation of wealth and subsequently to its circulation, use, and accumulation. The observations are organized into three sub-components of production: first, regarding the presence and dimensions of entrepreneurial activities in various sectors (primary, with reference to extraction, secondary, and tertiary); second, concerning the real estate sector, focusing on urban areas; third, regarding individuals and personal income, with specific attention to its distribution.

In contrast, economic resistance is visible in indicators that express aspects of low efficiency and prosperity, as measured by low productivity and low-income indices.

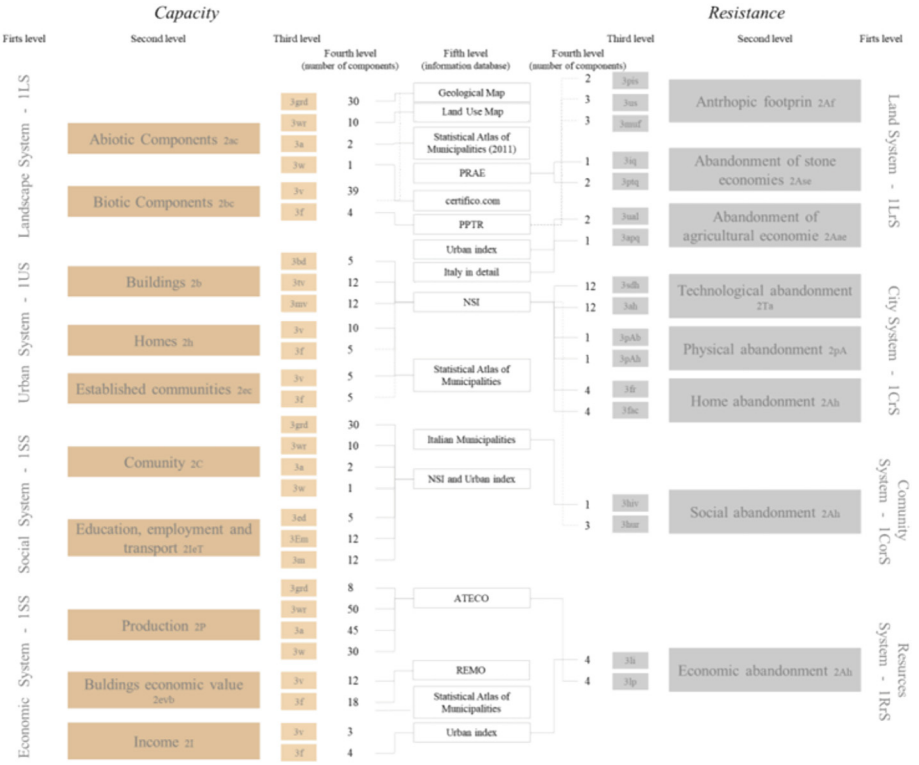

Fig. 3. Dendrogram representing the distribution of the indices od capacity and resistance.

3.3.2 The MAVT Model

A multi-criteria analysis model based on the Multi Attribute Value Theory (MAVT) has been developed to characterize and compare various key information units (tUs) based on different capacities to provide value, i.e., different evaluation criteria [13–15].

The proposed evaluation model is part of the operational research tools in the field of multidimensional analysis to support decision-making processes, extending utility knowledge to the sphere of values. Among these, the MAVT provides methods for structuring and analysing decision problems through Work Breakdown Structures (WBS) [16] according to the relative importance of different and sometimes conflicting criteria [17]. The two WBS schemes (one for capacities and one for resistances) used for the informational organization of this study are represented in the dendrogram in figure.

The overall value of each sU is the weighted average score of all attributes, progressing from the elementary level to the highest level of aggregation.

$$V_k = \sum_{i=1}^{n} w_i v_{iU_i} \tag{1}$$

The (1) refers to the aggregation of level 5 of the model where each information from official sources is transformed into a standard score and associated with an elementary weight. This elementary weight is calculated as the product of the weights at the higher levels as follows:

$$w_i = w_h w_g w_f w_e; \sum_{i=1}^{n} w_i = 1 \tag{2}$$

where w_h is the weight of the corresponding iUs group at level 4, w_g the weight of the corresponding iUs group at level 3, w_f for the level 2 and w_e for the level 1.

3.4 Joint Capacity/Resistance Index

The results of the first level of territorial capacities, on the one hand, and of resistances, on the other, converge in the planning synthesis, i.e. the JCRI; the latter measures the attitude of each tUs to a revitalisation profile that can be defined between the two extremes of transformation and conservation. JCRI is calculated as the product of the two previous indices, the Capacity Index and the Resistance Index.

1. A JCRI below the second quartile of the total sample indicates either 1) a situation where modest capacities are not able to overcome even a slight resistance from a territorial context that is nevertheless promising; 2) or a situation where high capacities are not able to emerge from a highly degraded and therefore highly resistant environment. The municipalities in this band are those in which: 1) or the territorial system is in a state of "downward" equilibrium; 2) or significant capacities – such as attachment to the place and a favourable socio-economic condition – do not support the recovery of an old town that is inaccessible, severely degraded and consequently abandoned in favour of suburbs of low architectural-urban value and significant landscape impact.
2. A JCRI equal to or greater than the third quartile indicates a general state in which both forces are above their mean and one of them is at its maximum: 1) if the best capacities meet with little resistance – as in the case of a community with a strong territorial identity that is confronted with an urban and landscape context that is not severely degraded – an ecologically oriented redevelopment model can be driven by local resources and initiatives; in this case, the development model will be coherent with the local economic, social or urban trends, in which the disused resources will find a new location (medium-low conservation); 2) if the capacities are not excellent, especially in local communities in slight socio-economic and demographic decline, confronted with highly valuable local resources, it is likely that an eco-oriented development can only be sustained by public incentives and/or external investments, with the risk of transformations that are not always controlled. In this case, planning is called upon to revise the development model, which must be redirected in the circular logic of the recovery of territorial relations (medium-low transformation).

3. A JCRI between the second and third quartile reports a condition in which one of the two forces records a medium-high value while the other a medium-low value. In this case, if the medium-low value concerns capacity, the project effort will be minimal and will have to adhere to local guidelines (medium-high conservation); if the medium-low value concerns resistance, a radical intervention is required to consolidate the renewed relationships of the human-nature system (medium-high transformation).
4. A final and illustrative consideration concerns the hypothesis of the highest value of JCRI, which refers to a solid and thriving community and a spatial, urban and landscape system of absolute value; this is the condition in which ecologically oriented development and self-centred development are mutually supportive, requiring neither incompatible transformations nor external interventions that interfere with local capacities.

4 Applications and Results

4.1 Evaluation Synthesis

Capacity

The investigation into the natural system of the examined territory focuses on the physical characteristics of the area as described in Sect. 3.3.2.

In the ranking (see Fig. 4), Alà dei Sardi is at the top, followed by Berchidda, Arzachena, Olbia and Ozieri. In fact, Alà dei Sardi is situated in a mainly hilly and mountainous environment, often covered by Mediterranean vegetation, and it hosts natural reserves that contribute to the conservation of the local flora and fauna. Not far away is the municipality of Berchidda, which reflects the local agricultural traditions. Ozieri scores well for the importance of its water resources, which is lacking in the other municipalities, of which only the last quartile has above-average values. Arzachena and Olbia, already more urbanised, add to the landscape values the advantages of the coastline. At the bottom are the municipalities of Tissi, Semestene, Muros Borutta and Valledoria. This is explained by the small size of the municipalities, whose boundaries tend to coincide with those of the urbanised area, overlapping with the natural component.

For the Urban System, the resulting ranking (Fig. 5) places the Municipality of Sassari in the first position, followed by Olbia, Alghero, Porto Torres, and Ozieri. The first four are indeed the most developed cities in northern Sardinia characterized by their historical significance (Sassari, Olbia, and Porto Torres) and linguistic diversity (Alghero and Ozieri). With very low scores are the cities of Semestene, Bulzi, Romania, and Tergu, with few buildings and, by now, few inhabitants.

The analysis of population characteristics is particularly significant, reflecting the vitality, plurality, and heterogeneity of settled communities. The ranking (see Fig. 6) confirms the residential well-being in the municipalities of Olbia, Ozieri, and Sassari, while highlighting challenges in smaller municipalities such as Padria, Monteleone Rocca Doria, Bulzi, and Semestene, characterized by high unemployment and low population density. The ranking of the Economic System (see Fig. 7) places Olbia, Sassari, and Porto Torres among the top positions, confirming the strength of their territorial system from all four perspectives. On the other hand, Alà dei Sardi, Romana, Monteleone Rocca Doria, Nule, and Borutta occupy the last five positions, confirming the disadvantage of

smaller municipalities located in the rugged territories of the Sardinian hinterland and thus "removed" from infrastructure, digital, economic, and social communication.

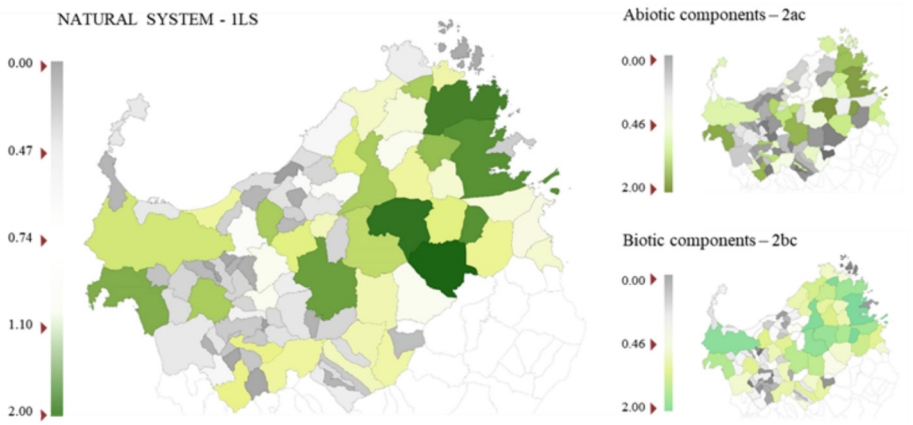

Fig. 4. Map of the capacity scores of the municipalities in the Natural System with mapping of the aggregate values at the second and third level.

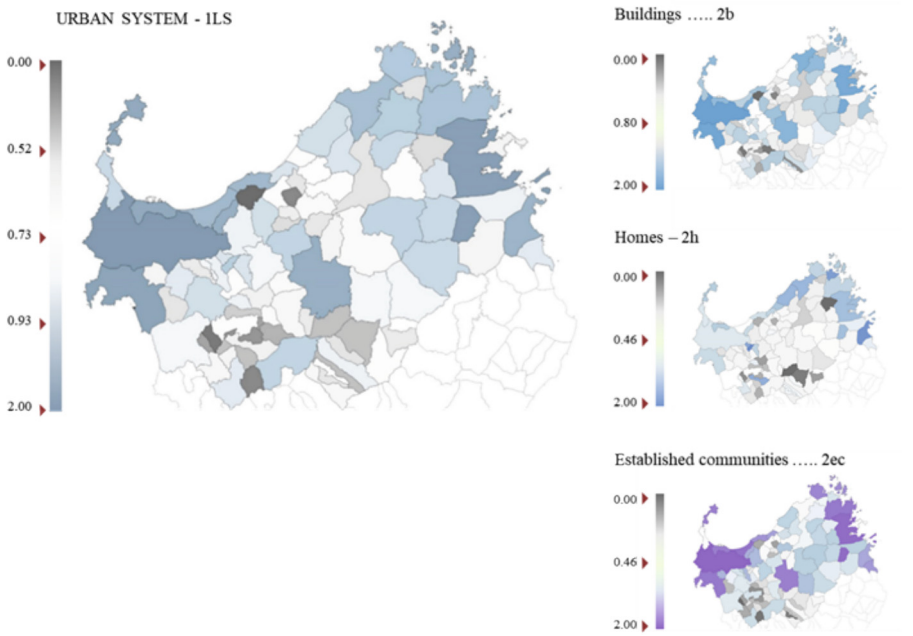

Fig. 5. Map of the capacity scores of the municipalities in the Urban System with mapping of the aggregate values at the second and third level.

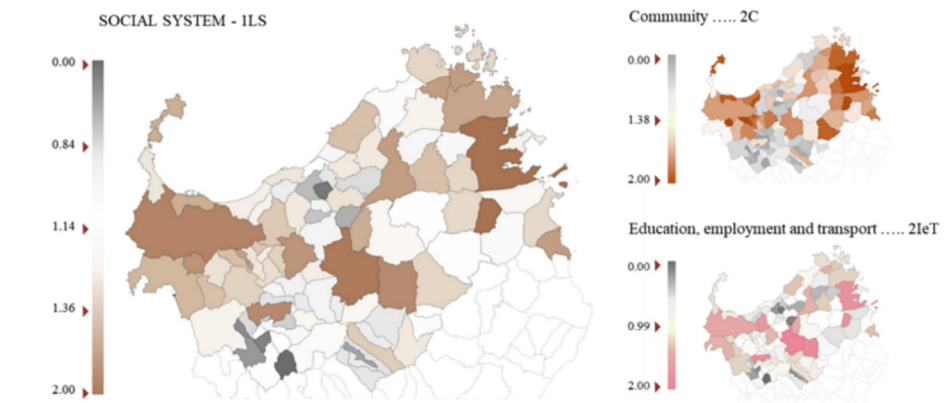

Fig. 6. Map of the capacity scores of the municipalities in the Social System with mapping of the aggregate values at the second and third level.

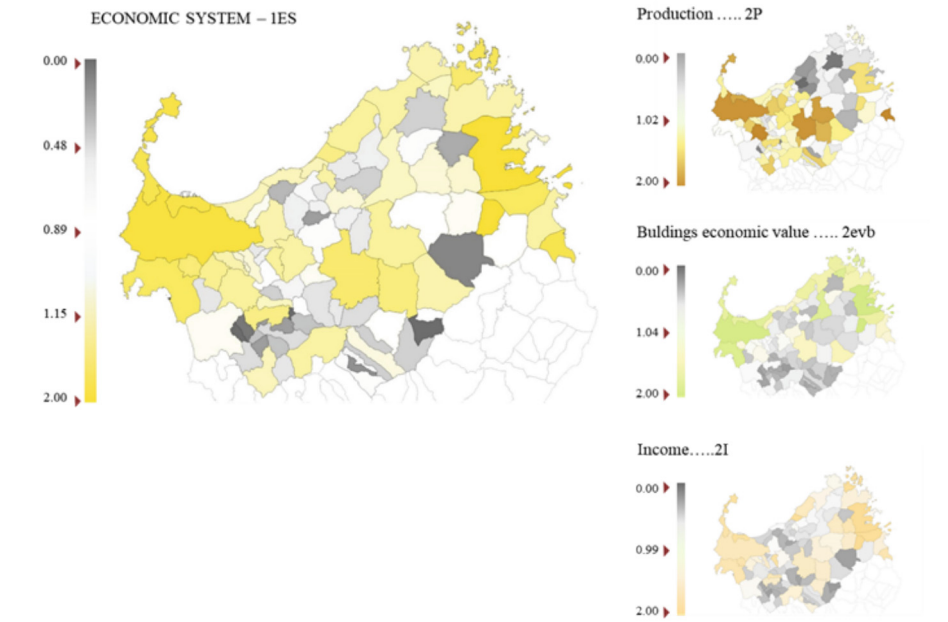

Fig. 7. Map of the capacity scores of the municipalities in the Economic System with mapping of the aggregate values at the second and third level.

The property sector is characterised by the disparity between the average market values of the most prestigious coastal towns and those of the inland municipalities. This phenomenon indicates the prevalence of external demand for high-value property, which cannot be met by internal demand.

Resistance

Regarding land system resistance, Fig. 8 shows that Costa Smeralda's economic shift contributed to abandoning agricultural economies in municipalities like Aggius, Luogosanto, Aglientu, Calangianus and Sant'Antonio di Gallura. It has also affected the "stone economies" of Palau, Berchidda, Monti and Trinità d'Agultu e Vignola, as well as other municipalities southwest of the study area.

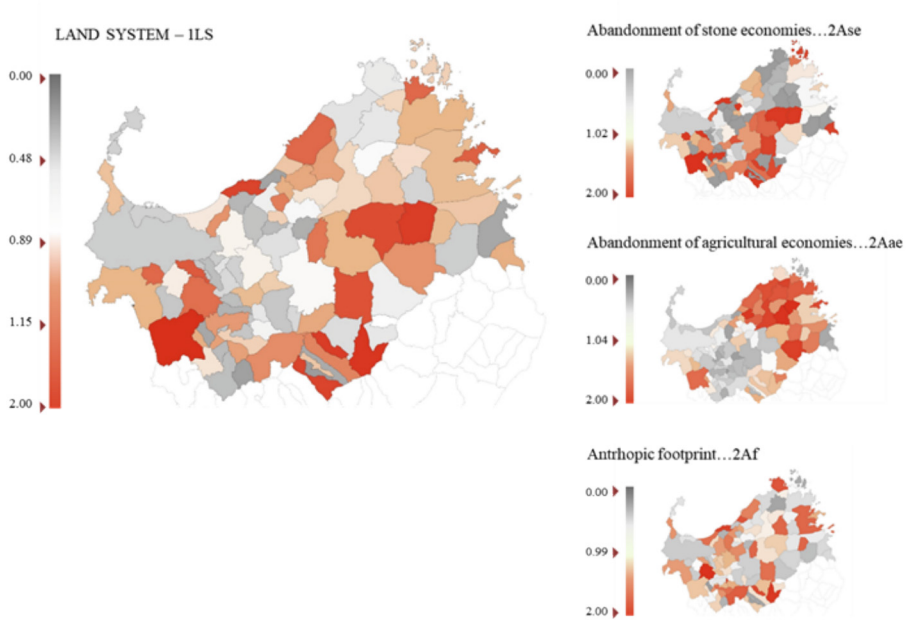

Fig. 8. Map of the resistance scores of the municipalities in the Land System with mapping of the aggregate values at the second and third level.

Concerning the resistance of the City System, "technological abandonment" mainly affects the hinterland. As for "physical abandonment" and "home abandonment", the situation is difficult to classify clearly. Some interesting considerations involve, for example, the municipalities of Sassari and Arzachena, which report low values of physical abandonment but high rates of housing abandonment. This means that occupancy is high but mainly non-resident, unlike Stintino and Porto Torres, which keep both indices high despite not reporting serious technical problems.

The resistances to the community system are identified in the components describing intercensal variation and the unemployment rate, while those of the resource system are represented in the indices of low income and low productivity (see Fig. 10).

Despite the demographic problems already mentioned, in some cases there has been growth, as in Golfo Aranci (due to the opportunities offered by industrial development linked to the port) and Olmedo (due to the spill-over effects of the real estate sector of the nearby and more important area), while in most cases it has been constant and significantly decreasing, as in the cases of Ardara, Benetutti and Pattada. Thematic

maps representing the second dimension highlight the profound transformation of the economy in many centers in northern Sardinia (see Fig. 11), which has increasingly become tertiary, confirmed by a generalized population growth around the two economic poles of Sassari and Olbia.

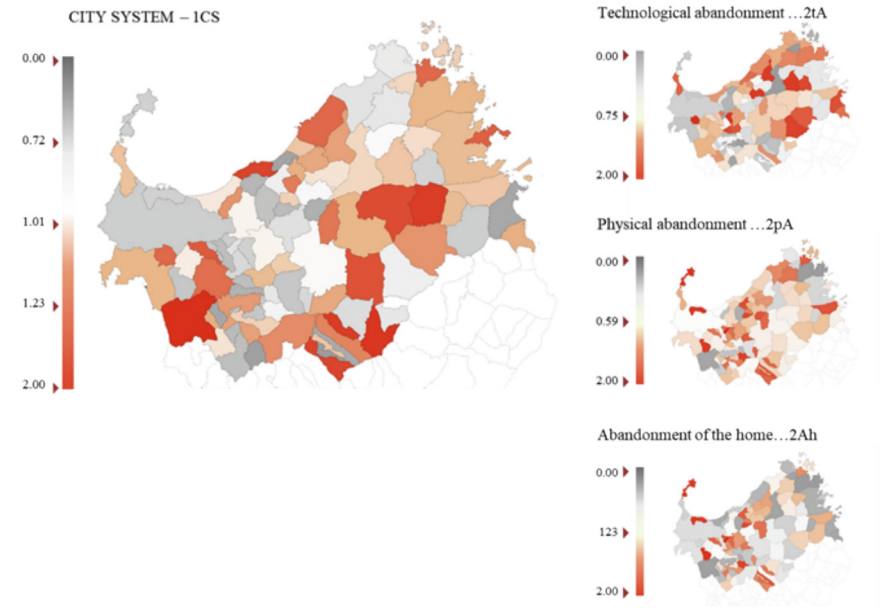

Fig. 9. Map of the resistance scores of the municipalities in the City System with mapping of the aggregate values at the second and third level.

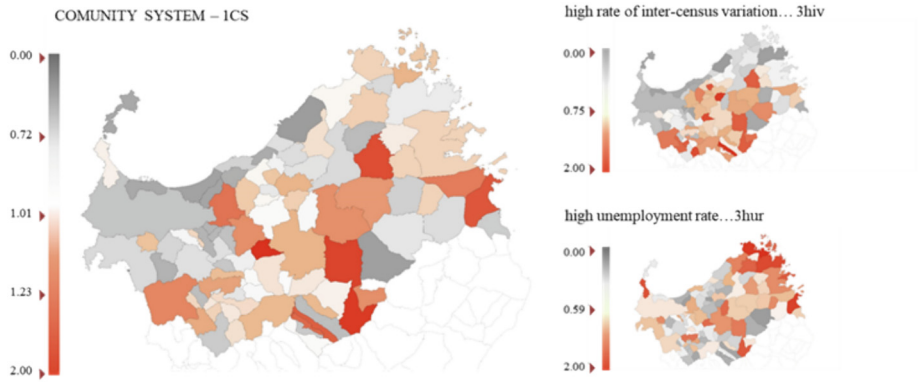

Fig. 10. Map of the resistance scores of the municipalities in the Community System with mapping of the aggregate values at the second/third level.

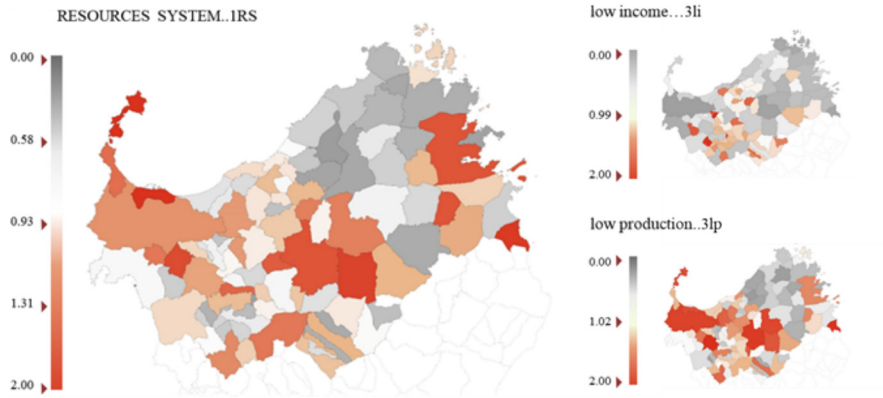

Fig. 11. Map of the resistance scores of the municipalities in the Resources System with mapping of the aggregate values at the second/third level.

4.2 Design Synthesis

The results of this critical observation are summarised in the JCRI. Figure 12 shows that the municipalities most capable of preserving natural capacity are concentrated in eastern northern Sardinia, Sassari, Alghero and the entire central area, which includes the municipalities of Ozieri, Chiaramonti, Erula and Nulvi. The synthesis of the two indices reveals the high capacity of the natural system and the almost total absence of resistance to the expansion of its maximum potential. Thus, in the case of the coastal municipalities, it can be observed that the potential for integrated development has been almost fully exploited. On the contrary, for the above-mentioned municipalities, the very lack of traditional economic development suggests opportunities for implementation of place-based models.

The low scores reflect the combination of low capacity and high resistance, particularly in the municipalities of Villanova Monteleone, Illorai, Aggius, Benetutti, Bono and Tergu. Moreover, these municipalities are in inaccessible areas, so that agricultural and pastoral production activities have always been limited. These same municipalities are also more characterised by significant forms of urban resistance. Located in the most rugged part of the territory, most of them suffer from accessibility problems that make it difficult for the local population to stay. On the other hand, from a social point of view, except for a few municipalities (such as Buddusò and Bortigiadas), resistance is concentrated in inland areas, which are typically less accessible and less urbanised, and therefore lack the facilities and services that typically characterise metropolitan and coastal areas. The best performing systems are those of Sassari, Trinità d'Agultu e Vignola, Buddusò, Puttifigari and Budoni. Apart from Sassari, where the social capacity is strong thanks to the work and research pole that the city represents, the other municipalities are examples of care and affection for the place, despite the conditions of degradation. The economic resistance of the inland municipalities is similar to the previous case, while in terms of capacity, the municipalities of the Costa Smeralda stand out.

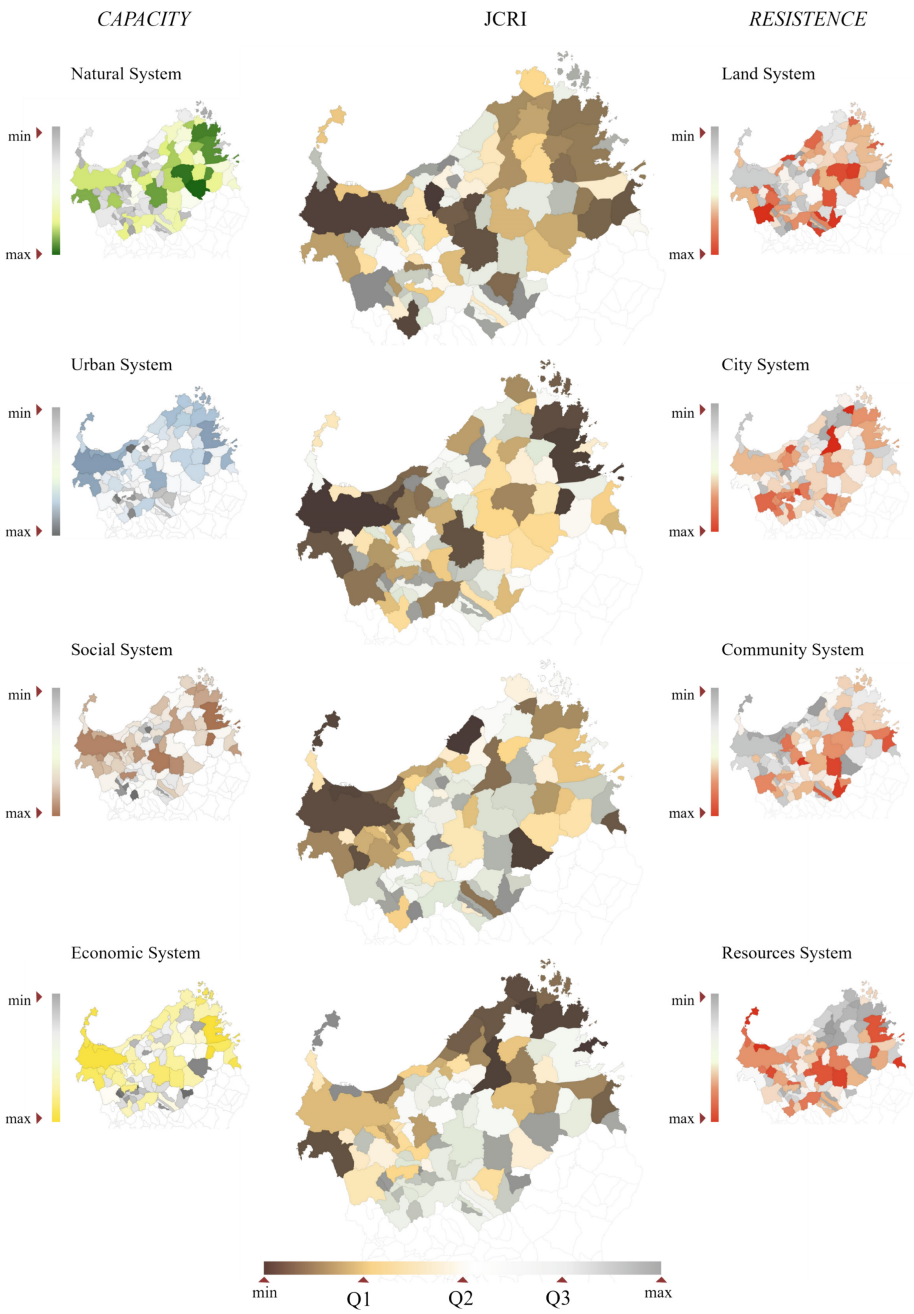

Fig. 12. Map of the Joint Capacity/Resistance Index of the municipalities.

5 Discussions and Conclusion

This study has provided a framework for observing and interpreting the phenomenon of abandonment in term of its complexity and articulation in the territorial context of Northern Sardinia. In line with the cognitive path structured by means of a Multi Attribute Value Theory-based approaches, the results consist in having defined and delimited two converging syntheses, the evaluative one and the design one.

In the evaluation synthesis, capacities were identified the factors which could prefigure integrated development lines between human and natural capital. On the other hand, resistances were identified in all the conditions and processes, whose inertia and dissolving power hinder the above-mentioned redevelopment paths.

This conceptual framework coordinates: 1. The critical observation of the capacity of actors to highlight the possible integration of natural datum and anthropic substratum; 2. The dialectic between settled communities and their original territorial contexts, manifested in the impoverishment and territorial disadvantage of the hinterland in relation to the metropolitan and coastal areas.

On the basis of these results, the design synthesis by means of the joint capacity/resistance index has made it possible to show how, in some cases (in the coastal areas of some important urban centres), the effects of this overlap have been metabolised by the capacity system, which has been able to overcome the resistance due to the change in the relationship between the resident population and the seasonal tourist flows and the loss of some of the original landscape characteristics; on the other hand, in some inland areas, although the capacities of the original urban and natural landscapes have been preserved, the resistance due to the fragility of the local economy and the consequent neglect of the built heritage makes it difficult to plan integrated regeneration strategies.

Furthermore, this index have measured favourable conditions for integrated development in the inland areas of Gallura, also showing how the natural capacities – in particular those due to the geological character that has shaped the granite landscapes and that is reflected in the forms of the urban landscape through the architectural languages – have overcome the resistance due to the partial transformation of the economy of local production, in particular the abandonment of the "stone economy".

The evaluation and design syntheses also identified the areas where the prevalence of resistance claims economic and territorial policies aimed at infrastructure and equipment. In the light of these findings, the reflection on values focuses on the possibilities and ways of mediating between the codes of the land and those of modernity.

Furthermore, the JCRI highlighted situation in which the coexistence of low capacity and high resistance, can make inaction acceptable as a conscious choice of a possible way to interpret sustainable development policies [20].

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Intermunicipal Co-operation in Marginal Territories for the Rebalancing of Territorial Gaps. The Sicani Area in Sicily (Italy)

Barbara Lino(✉) and Annalisa Contato

Department of Architecture, University of Palermo, Palermo, Italy
{barbara.lino,annalisa.contato}@unipa.it

Abstract. The scientific debate in the field of territorial policies shows a renewed interest in marginal territories as hybrid contexts that need to raise awareness of hidden qualities in order to re-balance existing territorial gaps.

Starting from the framework of the B4R Branding4Resilience research project of national interest, the contribution of the University of Palermo explores the Sicani Area in Sicily (Italy) as a paradigmatic case of marginality for which territorial branding strategies need to be developed. The paper discusses case study analyses and the results of the co-visioning phase of the research project: a process of strategic spatial visioning to recompose the existing system of relationships in a coherent territorial vision, identify a branding strategy and show that effective cooperation and networking can represent the path to development that can lead marginal territories out of isolation.

The work in the Sicani Focus Area in Sicily provides a framework that can support administrations in the formulation of development strategies and policies.

Keywords: Marginal Territories · Territorial Co-operation · Resilience

1 The Background

1.1 Territorial Inequalities

Throughout Europe, as a result of the polarisation of settlement processes, development gaps have gradually widened between catalysing urban formations and areas undergoing progressive depopulation in which pockets of marginality are spreading [1, 2]. Throughout Europe, the polarisation of settlement processes has gradually widened the development gap between the catalysing urban formations and the areas of progressive depopulation where the marginal areas are spreading [1, 2].

Although the population of the EU has grown by 4% over the last twenty years, this growth has been uneven and has widened the gap between urban and rural areas in countries. This is due to the polarisation of settlement processes and transformation dynamics around central urban areas and rural-urban migration leading to the desertification of villages and towns, the phenomenon of brain drain and the fact that the population is on average significantly older than that of cities. Rural areas account for 83% of the EU's

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total surface area, home to almost 30% of Europe's population (137 million people), and more than half of these rural areas are located far from cities [3]. In these areas, increasing social and economic marginalisation and territorial and environmental imbalances have highlighted the urgent need to re-engage with territorial cohesion policies and their possible developments by placing the issue of the development of marginal territories at the centre of scientific debate and public policies.

In addition, it should be emphasised that what these areas have in common is that their overall performance, level of development, access to services or quality of life of the population is relatively poor compared to neighbouring areas, which means that there is a risk that some areas will become inner peripheries in the future [4]. This risk is particularly high in those territories that have access to basic services (such as education and health) but this access is already poor or depends on a single service centre that, if it gets into difficulties, would undermine the entire territory. These conditions must be assessed in the territorial development policies in order to reduce the current disparities and the level of peripherality and create the development conditions necessary for at least basic services in the current peripheral areas.

In Italy, where marginality and abandonment in inner territories are the result of a temporally stratified process in which long-term and very long-term dynamics are interwoven and overlap [5], the issues of territorial imbalances and spatial inequalities have been at the centre of disciplinary debate for several years and are at the heart of the interesting experience of the SNAI - Strategia Nazionale per le Aree Interne [6, 7], that had the merit of recognising these territories as (material and immaterial) identities to be exploited and as important opportunities for economic growth. However, although the SNAI has undoubtedly opened an important innovation path that attempts to translate the place-based approach to local development into an organic policy design, it also encounters numerous critical aspects that highlight the limitations of the parameters that lead to standardisation and normalisation of complex phenomena [8] and the limitations of the predefined territorial context. The rigidity of the administrative boundaries of the inner areas defined by the SNAI, which does not recognise the systems of relationships that exist within a sub-regional territory and hinders their development, but stops at purely statistical data that do not take into account the often-virtuous diverse realities of cooperation that exist in the territories in question. This limitation and the deterioration in the level of peripherality of Italian municipalities – the analysis was carried out in 2020 compared to 2014 – that concerns 1,272 municipalities and 7,894,871 inhabitants, confirms the risk that some areas will become inner peripheries if no specific territorial development policies are taken and emphasises that the development planning of these areas must go beyond data, beyond administrative boundaries and beyond the mere provision of basic services.

Even if the expression 'inner areas', which emerged in the context of these ongoing experiments in relation to the classification of what was defined as the 'level of peripherality' of the municipalities, has gradually taken on a polysemic character and has been enriched with a complexity of meaning that alludes to the inherent qualities of these territories, 'different' from those of large urban centres, where global flows and

more dynamic demographic processes are intertwined [9, 10], it is necessary to recognise the intrinsic values of these territories and to strongly consider the already existing inter-municipal cooperative relationships, that represent an important strength.

The aim of this article is to analyse how inter-municipal cooperation intervenes in the construction of an integrated territorial development strategy aimed at equalisation and enhancement, how these cooperations are supported and where, on the other hand, they have difficulties in converging and integrating due to the excessive presence of fragmented policies that exist in the same territory.

1.2 The B4R Research Project

Against this background, the research "B4R Branding4Resilience. Tourist infrastructure as a tool to enhance small towns by drawing resilient communities and new open habitats" proposes to shift the concept from the narrow definition of inner areas to the broader concept of inner territories, which encompasses the contexts affected by depopulation, peripherality, ageing and lack of services and infrastructure as fragile and hybrid spaces with a high territorial complexity both in terms of spatial development strategies and governance issues [11].

Inner territories are understood as areas that need to be sensitised to their hidden qualities and spaces of opportunity, which require a process-oriented and multi-sectoral approach that is able to bring together interests, conflicts, but also different potentials and resources.

The B4R research project takes up this change of perspective by focussing on marginal areas as drivers of innovation and testing grounds for new development dynamics and scenarios [12] and examining the potentials and resources specifically in connection with space, settlements and landscapes [13].

As part of the B4R project, the areas were viewed through different interpretative lenses. One of these lenses was the analysis of governance processes with a particular focus on the capacity expressed by the territories to join forces beyond individual municipal competences to work on common issues.

The project therefore aimed to assess the extent to which there was a propensity for inter-municipal aggregation and, if there was, how this propensity, which is considered an important lever for the implementation of effective development measures, was articulated and with what objectives.

It was assumed that institutional fragmentation is an obstacle for marginal territories to overcome and that the ability to co-operate and 'join forces' are crucial levers to overcome the territorial gaps of these areas compared to medium and large cities in order to achieve critical mass.

2 Methodology

2.1 The B4R Methodology

At the beginning of the research project, each Research Unit (RU) selected a Focus Area (FA) to be analysed and compared in order to obtain a meaningful sample of fragile inner territories and to sketch a portrait of the current situation in Italy. The four FAs are

located in the Italian regions of the four RUs, Marche, Sicily, Trentino, Piedmont, and represent two Alpine and two Mediterranean regions.

B4R is based on three main phases, each corresponding to a research work package:

1. Exploration; 2. Co-design; 3. Co-visioning.

The "Exploration" phase, carried out in the first year of the research, served to investigate the territorial contexts from different points of view, focussing on spatial interactions, and it combines and integrates different quantitative and qualitative tools and methods, thus offering a unique methodological approach. The second phase is the co-design with communities, with the aim of proposing useful transformations of small infrastructures and operational branding actions in selected focus areas. Four "Co-design" workshops were conceived as a way to approach the areas through project-based explorations, uncovering key questions of the research topic which will be reviewed and deepened through the design. Indeed, during the co-design workshops, transformations and minimal interventions in the urban and territorial context are summarised in project proposals. In each workshop, proposals are developed that address the specificities of each area and succeed in analysing the paradigmatic nature of each pilot case and identifying possible branding actions. The third phase is the development of co-visioning processes in collaboration with local actors and institutions.

2.2 The Co-visioning Phase

In the "Co-visioning" phase, B4R proposes a process of strategic spatial co-visioning to reformulate the current system of relationships in a coherent territorial vision and identify a brand strategy that can uncover and activate territorial capital in all its dimensions (natural, cultural, built, financial, social, institutional) to increase the transformative capacity of communities.

In this phase, a collaborative process is set in motion in which citizens, local communities and other stakeholders actively work together to design and develop a shared vision of territorial development that transcends individual administrative boundaries.

The co-visioning phase is organised in a sequence of methodological steps (Fig. 1).

The first step involves the elaboration of a Criticality and Values Matrix, which is necessary to summarise the potential of the territory and identify the most critical issues to be resolved, based on the results of the analyses carried out in the "Exploration" and "Co-Design" phases.

The second step is oriented towards the construction of the strategic programme by defining a sequence of strategic axes - strategies - project actions that outline a long-term vision for the development of the territory. In this phase, a first mapping draft of the strategies is drawn up, the so-called Territorial Vision Draft, which aims to concisely summarise all the themes and the location of the project actions that have emerged during the elaboration of the strategic vision.

The third step provides for the organisation and implementation of a phase of collective planning and validation of the work carried out through the so-called "co-vision dialogues", which can be carried out according to different methodologies, such as expert interviews, focus groups or the organisation of face-to-face workshops, and which aim to validate the strategic programme and the draft territorial vision realised in the previous

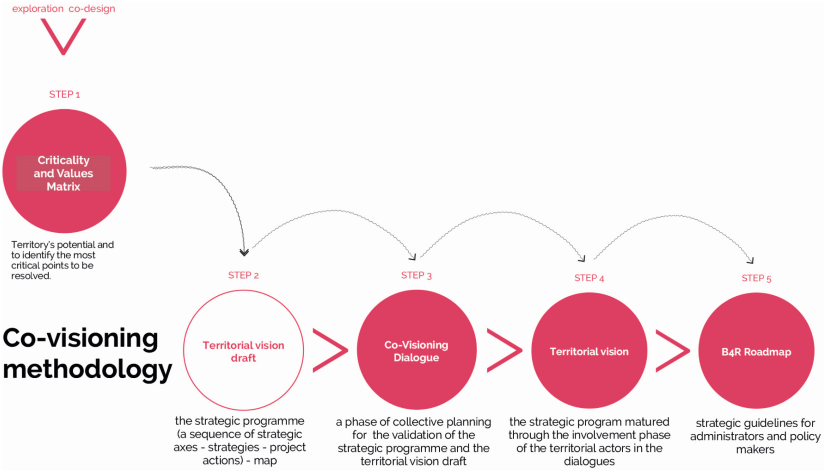

Fig. 1. The Co-visioning methodology scheme.

step. In the collective strategic validation and co-design phase, both the territorial vision programme and its spatialisation are reassembled in a coherent way.

In the final two steps, in the light of what has matured in the phase of participation of the territorial actors in the dialogues, the final version of the strategic programme and the Territorial Vision will be elaborated, as well as a Road Map, strategic guidelines as a result of the co-visioning phase that will accompany the administrations in the formulation of support policies in which the strategic programmes of all 4 strategic programmes of all 4 Focus Areas involved in the research project. The branding strategy will seek to achieve a coherent spatial vision of development in order to increase the area's capacity for interaction and to valorise and connect the tangible and intangible heritage and resources. In other words, a new development path that enhances the value of the different territorial capitals through design.

The co-visioning phase therefore aims to actively experiment in the territories the definition of transformation visions that go beyond the boundaries of individual administrations and aim at cooperation between actors by calling for collaborative forms.

3 The Co-visioning Phase in the Sicani Focus Area

3.1 The Sicani Focus Area

The Sicani Focus Area (Fig. 2) is part of a large part of the regional territory on the edge of the polarisation of the large urban coastal areas (Palermo, Catania and Messina). The selected area is composed of 18 municipalities that are not coastal, hilly or mountainous, have a spatially contiguous area and each have fewer than 7,000 inhabitants, a total population of 52,156 inhabitants (31 December 2021) and an average density of 54.9 inhabitants per square kilometre. The 18 municipalities are experiencing a progressive population decline (−15.8% between 2011 and 2021), an ageing population (the average age index in 2020 is 279.79, compared to the regional value of 159), are characterised

by economic weakness (the average per capita income is 12,469 euros, compared to the regional value of 15,846 euros), difficult accessibility in terms of mobility and low access to primary services. Looking at this area from the perspective of the SNAI (updated classification of the level of peripherality of municipalities by 2022), 7 municipalities are categorised as Ultra-peripheral, 10 as Peripheral and 1 as Intermediate, of which only 8 belong to the Sicani Inner Area.

The analyses conducted in the Sicani Focus Area through site inspections, mapping, interviews, other qualitative explorations and the co-design workshop [14, 15] revealed resources, critical factors, actors and dynamics operating in the area as a result of both informal processes and ongoing formal policies and projects.

The trends reveal a fragile and complex area, but one in which transformative sparks of interest can be recognised that can be harnessed to develop a possible vision of the future.

The experiments in the field of relational tourism, the ability to attract new inhabitants, the strong impetus for active association and the ongoing efforts to valorise the rural and artisanal traditions of this territory, which are generating new economic sectors, should be used as levers to create a future based on the regenerative rediscovery of the many environmental and cultural resources available, but also on a new role for this territory in relation to the coastal and metropolitan areas, to activate forms of collaboration and integration. Thus, interpreting this area as a "constellation of people and places", the Sicani Focus Area has multiple opportunities to create new networks and socio-institutional structures that can catalyse the capacity of local communities to mobilise resources and specific assets present in the area, thus improving the quality of life and development opportunities.

Today, the various policies and projects act in an uncoordinated manner: each of them pursues objectives set by national and/or regional policies to which it has adhered to obtain funding, without having a truly unified development strategy. The aggregated geometry is therefore variable and constantly subject to change depending on the funding opportunities that present themselves.

So while on the one hand we can observe a very active territory (especially in bottom-up actions) and a tendency towards inter-municipal collaboration and co-operation, on the other hand there is no integrated, coherent and shared development vision, but rather a fragmentation of policies, projects and partial visions of the future. This picture, which is constant in marginal territories where individual municipalities are looking for associative forms to obtain development potential through funding opportunities, leads us to reflect on some important questions: what instruments and approaches can be used to achieve a common vision of development? How can we develop effective shared visions for territorial and community development? And how can communities be involved to implement place-based transformative practises and promote co-learning and co-design activities?

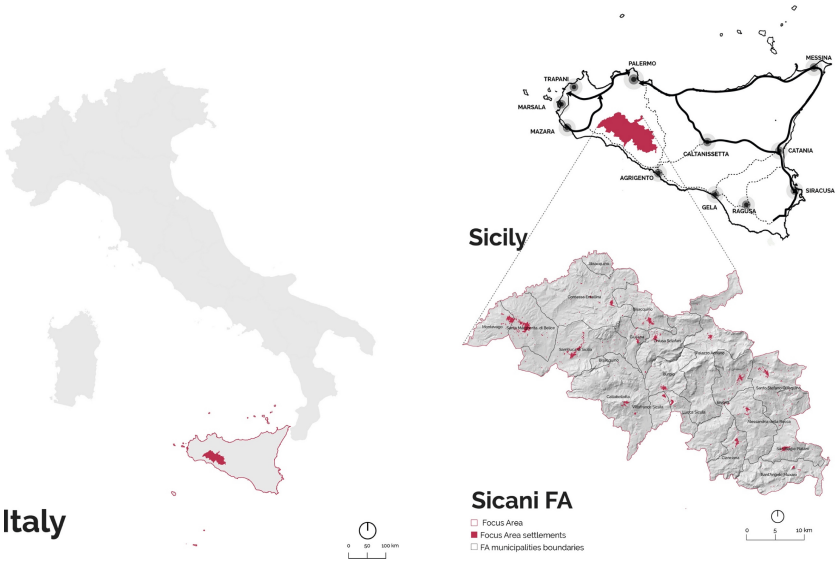

Fig. 2. Sicani Focus Area (FA) in Sicily (Italy).

3.2 A Fragmented Governance

In the Sicani territory, in line with what has happened in other Italian contexts, the renewed interest in the inner areas that has emerged in the field of territorial policies has led to the launching of numerous projects aimed at giving centrality and impetus to those areas of the country that are far from the essential service poles and whose fragility is the result of complex and stratified dynamics over time.

This scenario presents a complex and fragmented landscape, characterized by a variable geometry pacts between a plurality of actors and the application of different planning tools (Fig. 3).

The centrality of the National Strategy for Inner Areas must undoubtedly be acknowledged. Now in its second phase of action, facilitated by the continuity ensured by the 2021–2027 programming period, the strategy has made significant efforts to redefine the development trajectories of inner territories. Its focus lies on fostering greater sustainable territorial competitiveness and fight against demographic decline. In the Sicani territory, alongside the inner area bearing the same name, which is also reaffirmed in the 2021–2027 programming period, there exists a new Inner Area adjacent to the existing one.

In addition to the undeniable centrality of the National Strategy for Inner Areas (SNAI), the prominence of a second-level actor such as the Local Action Group (LAG) is evident in the area. By its own nature, the LAG operates as an extended form of inter-municipal aggregation (the Sicani LAG has 29 member municipalities) and is capable of fostering direct community participation through regular meetings and various forms of involvement outlined by the LEADER methodology itself. The LAG offers itself as an example of integrated inter-municipal cooperation, operating on a voluntary basis (the adhesion of the municipalities is voluntary) that also includes private actors such

as companies and associations. While the LAG pursues multiple objectives, its focus remains centred on rural production issues. The Sicani LAG has emerged as a significant intermediary actor, excelling in establishing a shared and participatory vision of the area, more so than others.

More recently, there has been the implementation of programming linked to the National Recovery and Resilience Plan (PNRR), including the so-called 'Bando Borghi' aimed at supporting marginal territories. This initiative focuses on the selection of cultural and social regeneration projects for small historical villages. However, this has led to a fragmentation of initiatives due to the absence of an overall strategic vision for the territories. Additionally, local administrations face considerable difficulties in coordinating actions and resources [16].

The variety of policies and aggregative forms observed, while showing a complex liveliness of the territory, returns an area with variable geometry, according to development themes and specific opportunities that from time to time create different directional cabins and, more in general, spaces of interaction between public and private subjects, as a result of the declination on the territory of different negotiated programming tools.

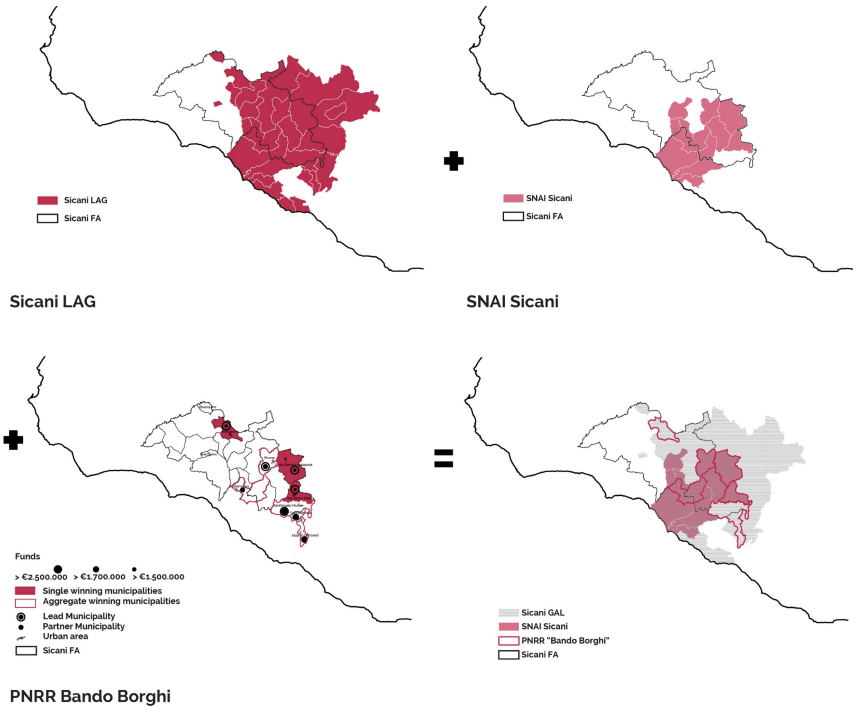

Fig. 3. A fragmented governance: The Sicani National Inner Area, the Sicani LAG and the so-called "Bando Borghi" areas.

3.3 The Co-visionig Method Applied in the Sicani Focus Area

The methodology applied for the definition of a shared territorial development vision for the Sicani Focus Area involved the development of four phases.

The first phase involved the drafting of a Matrix of Resources and Values, which highlighted the endogenous peculiarities that emerged during the Exploration phase. These peculiarities concern not only material aspects, but also - if not primarily - intangible ones such as the strength of the communities, the experiences of territorial enhancement promoted by associations, experiments to attract new inhabitants, and the capacity to build horizontal relations. However, these aspects clash with the objective difficulties faced by these marginal territories in providing services, both material and virtual (such as broadband access). Alongside these, the matrix also highlights ongoing projects, which, while presenting opportunities for the territory's development, contribute to an increasingly fragmented vision of the territory overlaid by numerous different municipal aggregations that intersect with each other but hardly engage in dialogue.

This matrix served as the starting point for the Territorial Vision Draft, which identified strategic axes and possible actions within a long-term vision. This proposal is not intended to address all the critical issues that emerged from the previous phases and were summarised in the matrix, but rather aims to build an integrated and shared vision of the Sicani Focus Area. This vision respects, enhances, and implements the resources present, with the community playing a key role in the co-definition and co-planning phases of development.

The Territorial Vision Draft was subsequently shared, discussed, and implemented through a crucial step of this methodological phase: the co-visioning dialogues. These dialogues served as moments of engagement with communities, institutional stakeholders, associations, and other actors, providing opportunities for discussion and collaboration[1] (Fig. 4). These dialogues with the territory commenced from the theoretical and operational implications arising from the juxtaposition of various initiatives and the imperative to harmonize project interventions in governance. This was aimed at constructing shared visions and implementing place-based transformative practices.

In these meetings, the emphasis was placed on recognizing marginal territories not as mere 'backdrops' to metropolitan areas or destinations for slow travellers' tourism consumption. Instead, they were viewed as territories ripe for regeneration, where cooperative economic models, alternative lifestyles, and cohesive community dimensions can be explored.

In particular, during these meetings, attention was focused on 'co-creative communities' and 'collaborative processes' - factors that the Palermo Research Unit intends to propose as distinctive and characterizing elements of the future development of the Sicani Focus Area. These are understood as emerging forms and indicators of an organisational and cultural shift that points towards local resilience rooted in the territorial context. These concepts embody key features of social innovation, with the aim of identifying

[1] The dialogue activities were conducted both within the framework of activities organised exclusively by the B4R research group and in collaboration with the Sicani LAG within the framework of further research activities and scientific collaboration in which the authors of this article are involved as members of the research unit of the Department of Architecture of the University of Palermo.

culturally-based regeneration projects, community cooperatives, renewed approaches to welfare, interactions with the environment and agriculture, as well as new models of living and working that can revitalize established communities towards new forms of residency or return to inner territories.

These moments of dialogue and engagement followed a structured operational mode: presentation of the results of the analyses carried out; presentation or proposal of initial insights into potential territorial strategies; initiation of dialogue/confrontation through the input of questions, such as:

- What are the theoretical and operational implications arising from the juxtaposition of various initiatives within inner territories?
- Which tools and approaches can facilitate the harmonization of project interventions?
- How can effective shared visions of territorial and community development be formulated?
- In what ways can communities be actively engaged in implementing place-based transformative practices and fostering co-learning and co-design activities?
- How can public institutions serve as intermediary agents, facilitating knowledge and information exchange with communities and enhancing their participatory, propositional, planning, and implementation capacities?

The process of sharing initial results, listening to participants, and collecting proposals was organized through both plenary meetings and the utilization of Open Space Technology technique. This latter methodology, which integrates plenary sessions with thematic discussion tables, fosters open participation in discussions and innovation. It serves as an informal learning tool that facilitates the exchange of information, knowledge, experiences, and innovative ideas. By enhancing the capacity of individuals and groups to address specific issues, strengthening connections among participants, promoting continuous learning, and fostering collective dialogue to find solutions, this technique facilitated genuine participatory co-creation, evaluation, and validation of innovative ideas. This approach aimed to construct a medium to long-term vision for a sustainable future for the territory.

These meetings served to reinforce and amplify, within the strategies and actions, the strong sense of community prevalent in these territories, as well as the experiences of innovation and resilience. They also emphasized the relational and associative capabilities that render these areas fertile ground for the development of co-creative communities, with social and cultural regeneration at the core of a territorial development and regeneration process grounded in inter-municipal cooperation networks. While recognizing the importance of enhancing services and infrastructure, the overarching focus was on networking, cooperation, and collaboration.

The moments of engagement with the Sicani Local Action Group (LAG) were particularly significant, as the LAG is the primary entity responsible for implementing development and regeneration strategies, policies, and interventions in the territory. Moreover, the LAG's activities within the territory entail a substantial participatory process, which equips them not only with comprehensive territorial knowledge beyond analytical and statistical aspects but also with credibility among inhabitants and local administrations. This credibility distinguishes the LAG and positions it as one of the most experienced territorial entities in the area to date. These meetings underscored the emphasis on

community, identity, and territorial excellences, leveraging existing resources as fertile ground for new development and innovation processes.

The outcomes of these meetings extend beyond the mere generation of development ideas for the formulation of a shared and integrated territorial strategy. They also played a crucial role in empowering citizens and enhancing their influence in activities: inhabitants, users, and stakeholders were placed at the forefront of initiatives and became co-creators of strategies.

As a result of the dialogue and engagement process with the territory, strategic axes, strategies, and actions were defined to propose a 'collaborative Sicans' strategy. This approach positions communities, collaborative management forms, dialogue spaces, the establishment of networks, and community cooperatives as the primary drivers of development actions in the Sicani territory.



Fig. 4. The Sicani LAG thematic discussion tables in Santo Stefano Quisquina (1–2) and in Siculiana (3).

3.4 Collaboration as the Connective Tissue of the Territory

The co-visioning of the B4R research proposes a strategic spatial visioning process aimed at consolidating a coherent territorial vision by reassembling the existing system of relationships. This process involves identifying a branding strategy that can reveal and leverage the territorial capital of the Sicani Focus Area across all its dimensions: natural, cultural, built, financial, social, institutional, etc.. The overarching goal is to enhance the community's transformative capacity.

In the context of the B4R research project, branding, typically interpreted through a competitive, quasi-mercantilistic lens, is understood differently. It's seen as a complex socio-political construct and a process of reconstructing the shared imaginary of communities, composed of a multiple interdependency in spatial and temporal dimensions among actors, different types of users, and stakeholders. Based on this approach, the research project conducted dialogue activities with key stakeholders in each research area. The aim was to gather opinions on draft visions and strategies, prioritize and evaluate potential alternatives, and assess the sustainability levels of envisioned choices. This process can be seen as a form of collaborative branding.

In the Sicani Focus Area, the qualitative-quantitative analyses conducted have highlighted two significant findings. Firstly, there exists a fragmented transformative framework, indicating a lack of cohesion in development efforts; secondly, there is a propensity for the emergence of innovative organizational models based on associationism and

cooperation. This is exemplified by the rich network of local associations present in the area.

Based on this observation and recognizing that effective cooperation and networking are essential to lead marginal territories out of isolation, collaboration was deemed the guiding principle for spatial development and transformation actions in the Sicani Focus Area. Hence, the concept of "Collaborative Sicani" (see Fig. 5) was embraced as a central theme (Fig. 5).

Small centres should work together because they need to be part of a "larger location" in order to reach a critical mass [17, 18] necessary not to succumb in the competition with the metropolitan areas and to claim centrality in the policies for the rebalancing of territorial gaps. Forming new inter-municipal alliances and adopting branding strategies that transcend administrative boundaries can lead to a positive-sum outcome. In this scenario, even non-capital areas can achieve critical mass by pooling resources. The objective extends beyond merely attracting capital or residents; it encompasses a complex political and socio-economic dimension.

The Unipa B4R "Collaborative Sicani" strategy aims to stimulate the emergence of collaborative branding initiatives in the territory, looking beyond administrative borders.

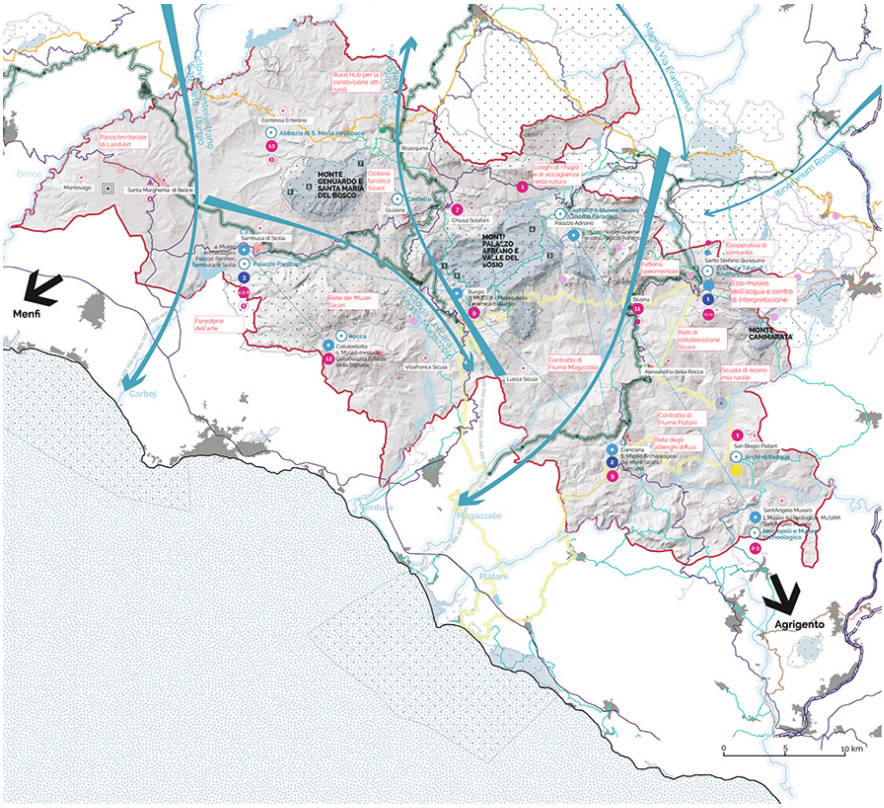

Fig. 5. The Unipa B4R "Collaborative Sicani" strategy.

This approach seeks to enhance visibility and strengthen a shared vision. Some of the strategies discussed with communities and stakeholders revolve around the theme of networks as spaces of opportunity. Among the main strategies proposed are: organizing a new model of mobility as an enabling factor, such as implementing transport-on-demand services and establishing a coast-mountain network of new cycle routes; promoting new collaborative forms of managing disused resources implementing co-operation agreements; strengthening the encounter tourism model thanks to a new hospitality network based on initiatives such as Art Foresterias and "diffuse hotel" network; supporting social and cultural circular economy initiatives, including community cooperatives, a school of circular rural economy, and energy communities.

To attract and retain visitors and talents, small and peripheral Sicani's communities should engage in inter-territorial cooperation in order to enhance their competitiveness and cohesion/resilience.

4 Discussion

The observation of the Sicani Focus Area has revealed the coexistence of various groups that don't always complement each other effectively in terms of goals and actions. Multiple coalitions and flexible alliances form, each pursuing objectives defined at times by national and/or regional policies or projects they've joined to secure funding, lacking a coordinated territorial vision and a clear, long-term development framework.

Over time, the Sicani Local Action Group (LAG) has served as an intermediary entity striving to harmonize the actions resulting from different projects, employing a co-planning approach that emphasizes community involvement. It's within this process that B4R's involvement has been integrated, contributing to the formulation of an integrated strategic vision known as the Sicani Unipa B4R Territorial Vision. This represented a tangible input to the formulation of the LAG Sicani's Strategy for the 2021–2027 programming cycle.

During the co-visioning phase, researchers actively engaged in co-planning processes with local communities to develop branding strategies and operational actions that organize existing projects within a unified vision of territorial development, emphasizing stronger inter-municipal cooperation. Indeed, fostering cooperation among inner territories' municipalities presents a significant challenge. Only through effective collaboration and networking can these areas break free from isolation, avoiding direct competition with metropolitan areas and asserting their centrality in policies aimed at addressing territorial disparities.

The emerging results thus far serve to underline, on one hand, the crucial role played by intermediary entities in fostering genuine inter-municipal cooperation in these territories, and on the other hand, to emphasize the necessity of experimenting with solutions that support co-planning processes with local communities and shared, long-term visions capable of transcending existing administrative fragmentation, thanks to a holistic and integrated perspective.

Acknowledgments. This contribution is the result of the research activities of the Unipa Unit whose scientific coordination is by Barbara Lino. Both authors contributed to the formulation and

conceptualisation of the survey problem and the construction of the empirical basis of the article. However, the drafting of paragraphs 1.2; 2.1; 3.2; 3.4; 4 is to be attributed to Barbara Lino; the drafting of the paragraph 1.1; 3.1; 3.3 is to be attributed to Annalisa Contato.

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Exploring Mobility in Rural Areas. A Case Study in the Marche Region's Central Apennine

Muhammad Junaid[1(✉)], Maddalena Ferretti[1], Sabine Garrone[2], and Daniel Gorokhov[2]

[1] DICEA Department of Construction, Civil Engineering and Architecture, UNIVPM, Ancona, Italy
m.junaid@pm.univpm.it
[2] MIC-HUB, Mobility in Chain, Milan, Italy

Abstract. This study investigates the critical role of rural mobility in combating the risk of rural abandonment and facilitating the re-population of the pilot inner area of the Marche Region, Italy, for the Italian National Strategy for Inner Areas (SNAI). The research delves into the primary reasons behind residents' mobility, including daily needs, socializing, work, and leisure, spanning municipalities and nearby urban areas. Using qualitative and quantitative methods alongside tools like QGIS, Komoot, Moovit, TomTom, and Python, the study aims for a thorough analysis and evaluation of current mobility patterns. It seeks to reveal detailed insights into travel behaviors, including off-peak private vehicle usage, peak travel times, and trip lengths, with the goal of highlighting critical conditions and potential opportunities for redevelopment strategies. Ultimately, the study aims to contribute to evaluating the region's transportation infrastructure and identifying areas for improvement. Furthermore, it explores alternatives, such as micromobility options, to effectively substitute short-distance trips, thereby fostering sustainable rural mobility practices that will help re-inhabit the region.

Keywords: Rural areas · inner areas · sustainable mobility · Marche region Central Apennine

1 Introduction

Mobility in rural areas is a topic that has been left behind in discussion and research as compared to mobility in urban areas. The rural areas have been facing the issue of mobility for decades. The public transport options cannot satisfy the user demands, and the public transport operators themselves are not willing to offer them any transport options due to some reasons. Their scattered and uneven distribution of the population, low population density, low travel distances, and low demand for transport make it very difficult for public transport operators to offer them any public transportation because it's not economical for them. One of the factors that affect the demand for rural areas is the seasonality of the tourists that visit rural areas at specific times of the year, which creates problems and challenges for responding to the needs of the residents with sustainable and efficient public transport as an alternative to private cars. The seasonality

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also affects the actual demand for transportation. According to Robertson, seasonality in the transportation sector has a number of significant and varied effects, some of which include traffic jams on major thoroughfares, infrastructure damage, extreme pollution, energy loss, longer travel times, harm to historical sites, and low-quality services for tourists [1]. Thus, managing seasonal traffic peaks well is crucial to preventing a decline in tourism in these areas and, consequently, preserving the high revenue generated by the tourism industry [2].

Most rural residents need transportation for healthcare purposes, groceries, education, shopping, social life, etc., which remains unmet or the possibility of meeting those needs is limited. Due to limited mobility options, residents in rural areas mostly use their own cars. Residents with reduced mobility are the most affected group. Rural communities in the United Kingdom have become more dependent on privately owned cars as a result of a reduction in investment in public transportation. This has led to an increase in carbon emissions per passenger per kilometer (DfT, 2020), car trips per person (33% more than the national average), and miles traveled per person (66% more than urban cities and towns). While having a look at the Italian data, approximately four fifths of Italians own at least one automobile. Since the economic boom and the introduction of the Fiat 500, cars have been an essential aspect of Italian culture and daily life. As a matter of fact, the majority of Italians commute to work using private vehicles [1]. According to Eurostat data, there are 684 passenger cars per 1000 inhabitants in Italy in 2021 [3].

Regarding the transport policies for rural areas, there has been no specific attention given to rural and mountainous areas in the transport policy so far. Furthermore, the orientation given for EU mobility in the 2011 white paper is specific for urban mobility; there is no specific policy orientation document for rural mobility. Indeed, in the new 2014–2020 programming period, rural mobility does not appear as a priority, neither in the general strategy of EU2020, nor in the rural development policy or the cohesion policy [2]. There is neither a policy for rural mobility at the European level nor any obligation for member states to have such a policy [4]. Currently, the EU is starting a project about sustainable mobility policies in rural areas with the title “A long-term vision for the EU’s rural areas up to 2040.” The objectives of this initiative are: 1) Sustainable multimodal mobility best practices for rural areas will be developed to support rural municipalities in identifying best practices and replicating them in their territory, 2) Rural digital futures will address digital connectivity issues by closing the gap between rural and urban areas, encouraging digital innovation and the use of new technologies, boosting new competencies needed for the digital transformation, and measuring progress towards closing the digital gap [5].

This study aims to delve into the transport infrastructure of the selected Apennine region, evaluating the utilization of various mobility options by residents, and identify gaps for future intervention and improvement. By conducting an in-depth analysis of transportation patterns, infrastructure limitations, and community needs, this research seeks the complexities of rural mobility.

2 Literature Exploration

A person's ability to access employment, education, services, society, and all other aspects of their existence is known as their "mobility." Stated differently, one of the most important factors that makes a community function is mobility, particularly in rural areas where a lot of necessities are spread out across a large area. Increasing the availability of environmentally friendly transportation options can also significantly aid in climate change mitigation. Nonetheless, policymakers have given rural mobility far less consideration than urban mobility, and many metropolitan regions suffer from a severe lack of both traditional transportation and the different shared mobility options available. In many rural places, the fact is that there are very few train stations, few buses, and a near entire reliance on cars. People are compelled by this to travel more expensively and to utilize private transportation instead of more environmentally friendly options [6].

The lack of transport infrastructure and mobility options can lead to a high number of residents migrating from rural areas [7]. In order to reduce social exclusion and youth migration from rural areas, better transport options are essential [8–10].

In the modern world, owning a private vehicle is largely necessary for mobility. Social inclusion and employment opportunities are severely limited for anyone without a car, according to Soder and Peer [11]. The flexibility that a car offers is something that neither public transportation nor car sharing can match, according to Berg and Ihlström [12]. Vern and Taegen [13] assert that the dearth of public transportation makes owning a car essential. Despite the fact that owning a car is frequently the only option available to replace public transportation, less well-off rural residents also have trouble using this form of transportation [14]. A person who does not own a car is more likely to experience social exclusion [15]. Lower-class people frequently live in rural areas. They spend a sizable amount of their income on transportation, which creates a financial barrier to mobility. Additionally, low-income households are more likely to live in suburban areas with little access to public transportation [16, 17]. To keep low-income people from being excluded and to increase their mobility, a variety of financial supports are available [18]. People with low incomes seem to find financial incentives especially appealing [19]. It is important to remember, though, that low-income citizens of small towns and rural areas also have fewer needs when it comes to daily travel and commuting to work [20].

Furthermore, senior citizens' concerns are an important topic of mobility research since they are frequently the majority population in rural areas. Elderly people are a group that needs extra care. Older people exhibit low levels of activity and are typically accustomed to the mobility conditions in their community [21]. A study by Varadi [22] claims that elderly people have a variety of needs. Owing to the particular requirements of that specific group of people, there is a lot of interest in unique forms of transportation, particularly on-demand options that can hold multiple passengers at once. The lack of infrastructure and public transportation options that suit the needs of the elderly, especially those with disabilities, is one of the factors contributing to their low mobility. Seniors' use of public transportation is primarily driven by social and health-related factors, such as shopping, medical appointments, and rehabilitation [22]. As per the research conducted by Shergold and Parkhurst [23], the elderly in rural areas had trouble getting to service places such as specialized hospitals or movie theaters. An increased risk

of social exclusion is linked to living in a rural area and becoming older; an increasing number of elderly people also mention the growing inaccessibility of transportation options.

Some researchers suggest alternative solutions for rural areas; demand responsive transport is one of them. In urban and suburban areas, Demand Responsive Transport (DRT) serves as a feeder service for local public transportation (PT), making it a viable alternative to expand the reach of PT [24–26]. When PT is completely absent in rural areas, DRT may be the only option available. In these cases, local governments often subsidize DRT. Alternatively, DRT can be co-located with mass transit stations (either bus or rail hubs) under the "hub and spoke" business model, which increases user visibility of the service [27]. To give rural and semi-rural communities more options and access to more sustainable options through new modes of transportation, higher levels of subsidies are necessary if on-demand mobility services are unable to draw in the necessary amount of demand. Studies conducted on the periphery of rural and urban areas, where there seems to be less demand for travel, have indicated that larger vehicles with eight or ten seats are needed to meet demand [28, 29]. Additionally, DRT services can be more economical than traditional bus routes by reducing CO2 emissions [29, 30]. This is mostly because of the area's features and the demand that already exists [31]. Passengers are likely to be drawn to a DRT that operates in areas of transport poverty where PT services are inadequate and integrates with pre-existing PT services [32, 33].

In addition, there are other ways to travel, like ride-sharing, vanpooling, and hitchhiking, which are examples of alternative mobility options that could establish the necessary connection with other villages and regions [34–36]. Hitchhiking, entails going with someone else on a journey with basic amenities [37]. For their travels, hitchhikers rely on the assistance of others [38]. However, drivers and passengers must consider their privacy and safety when using such shared modes of transportation. Drivers are less likely to share their cars with strangers because of their attachment to them [39]. In addition, passengers worry about crimes like violence and robbery as well as their own safety. Robbery and violent crimes are typically more likely to occur during hitchhiking.

3 Methodological Approach

This study is carried out as part of the larger PhD research project "Habitat matters. Managing and reducing the risk of built heritage by promoting the ecological transition, accessibility, and sustainable mobility in rural areas". The methodology for the larger research project encompasses three main steps. Firstly, a background study was conducted to identify reference studies and best practices related to sustainable mobility in rural areas. From these studies, guidelines and valuable insights about rural mobility were extracted, leading to the publication of a conference paper. Secondly, an analysis of the existing transport conditions was carried out at the MIC-HUB Company, utilizing skills and tools acquired during the period in the industry. This article focuses on this part of the research. Lastly, the final phase of the PhD project will involve an overarching analysis of rural areas across the EU, aiming to highlight gaps, criticalities, issues, and opportunities in the transport system and the policies that different European governments are setting in place to solve the issues related to mobility in rural areas.

The methodological approach employed in this study involves a combination of qualitative and quantitative tools. The strategy entails gathering data both on-site and from diverse online and offline sources and tools. Qualitative data collection methods include visiting the case study area, conducting on-site research analyses, and performing photographic surveys during the Rail to Land project site visit [40]. Additional on-site data were collected as part of the Branding 4 Resilience project. [41]. The specific qualitative tools used for the collection and analysis of the data are: the QGIS (QGIS (Quantum Geographic Information System) is a free, open-source software that allows users to create, edit, visualize, analyze, and publish geospatial information), the Komoot app (a mobile app for navigation and route planning which Map your bicycle, walking and running adventures with the GPS tracker), Moovit (a mobility as a service provider and journey planner app which is more than a train and bus time *app*, helpful for public transit navigation, maps, schedules, real-time arrivals and more) and Tom Tom (a leading independent geolocation technology specialist, shaping mobility with highly accurate maps, navigation, real-time traffic info etc.). With the help of QGIS, we analyze the transport infrastructure of the area. The road infrastructure, which is further categorized into different types of roads, i.e., motorways, highways, primary roads, secondary roads, and tertiary roads, the railway infrastructure available in the area, and some abandoned railway lines in the region, might play a vital role in the development of this territory [42]. The Komoot app is used to analyze the bicycle infrastructure in the area. There are several bike ways available in the area, which is presented in a map through QGIS tool in this research. Moovit is another tool that is used to analyze the public transport in the area. The public transport system is not frequent in the area, but we still need to analyze and assess it in detail. Another useful tool is the Tom Tom. The Tom Tom is used to analyze private trips, specifically car trips that were taken by the residents. The car trip data are taken only for the month of October 2022. Unfortunately, we did not get all the data we originally planned for the study, due to its high cost. Indeed, accessing a wider spectrum of data would have meant to purchase specific and detailed datasets from TomTom's database, which was financially unfeasible as it exceeded our budgetary limitations and available resources for the research project. Yet, we acquired data for different specific days in the month of October 2022 and we systematized and categorized them as follows, in order to extrapolate possible useful information from their analysis. The first set corresponds to the first Monday of October (03 Oct), the second set to the middle of the week (12 Oct), the third set to the weekend (15 and 16 Oct), and the fourth set to the end of the month and week (28 Oct). These sets include trips between the Apennines and nearby cities. Additionally, we collect two data sets, one focusing solely on trips within the Apennine region for October 18 and the other for October 22 and 23. Car trips is particularly important in this study, given that private vehicles are the predominant mode of transportation in rural areas.

The data collected from these sources is compared for further analysis. Specifically, TomTom's data provide us some insights into trends regarding the increase or decrease in private trips during the day. Additionally, analyzing the demand for trips during non-operating hours and the length of the trips also shed light on potential opportunities for micromobility solutions.

This research was conducted at MIC HUB Company [43] on mobility in the peripheral and rural areas of the Marche region, which is the pilot inner area of the Marche Region, for the Italian National Strategy for Inner Areas (SNAI). The area is specifically named "Appennino basso Pesarese e Anconetano," which comprises nine municipalities, a total population of 33,146, and a land area of 846.16 sq. km. The demographic variation according to the ISTAT census for 2011–2017 is −5.23%. The inner areas are those areas that are significantly distant from the supply centers of essential services (education, health, and mobility) but rich in important environmental [44] and cultural resources. These areas are usually characterized by low population densities. The average density of the area is 39.17 person/km^2, which is much less than the Marche region density of 158.5 person/km^2 compared to 200 person/km^2 in the entire Italy. The area is far from essential services, i.e., there is no hospital in any of its nine municipalities except for a healthcare center in Cagli. The absence of a railway line makes it more difficult to reach the area and hinder its overall accessibility. There are some existing railway tracks that pass through-the area, i.e., the Fano-Fermignano-Urbino line, the Fabriano-Pergola line, and the Pergola-Fermignano line. These lines are abandoned due to landslides, suffered in World War II and other natural disasters [45]. The Fabriano-Pergola line was opened for tourists in September 2021. Two of the authors themselves traveled with this historic tourist train in June 2022. It was a very nice experience witnessing and experiencing the majestic and phenomenal landscapes of the area, which is not possible with any other mode of transport. Regarding major roads and highways, there is no highway passing through these areas. The nearby airports are Umbria International Airport in Perugia and Ancona International Airport, which are 1 h and 15 min, and 1 h and 30 min, respectively. The distance from Rome is 231 km, 73 km from Ancona, and 48 km from Pesaro. The study was conducted to examine the role of rural mobility, the ways in which people move around in the Apennine region, and how inefficient mobility can contribute to the abandonment and depopulation of these areas. A comprehensive review of the existing literature regarding the context analysis highlighted gaps and areas requiring further investigation. From this literature and from the overall study of the context, several research questions were derived, aiming to address key aspects of the study area's transportation system.

- What are the different options to move around the Apennines mountain area in the inland of Ancona?
- How frequently do residents in the area utilize cars for transportation?

The questions are directly aligned with the broader research objectives of understanding rural mobility patterns and their implications for community development. By examining the available transport infrastructure, modes of transport, and dominant usage patterns, the study seeks to provide insights into current mobility dynamics and inform future interventions aimed at enhancing transportation accessibility and efficiency in the area.

4 Research Findings

In the picturesque landscapes of the Apennine Marche region of Italy, the dynamics of mobility take on a unique significance, weaving through the idyllic countryside and quaint villages nestled amidst rolling hills [42]. This research shedding light on the diverse modes of transportation and infrastructure utilized by residents to navigate their surroundings in the Marche Central Apennines. There are different types of infrastructure and modes of mobility that is explored in this study, and the results are presented in this chapter. The research findings will be presented in two parts: the first part will focus on the transport infrastructure, while the second part is about the findings from different modes of mobility in the region.

In the first part, the transport infrastructure of the Marche region, particularly the central Apennines, is examined. Figure 1 illustrates the road and rail network of the Marche region, showcasing various types of roads and railways. The Autostrada Adriatica (Motorway A14) traverses the Marche region, providing a major transportation route. Additionally, other roads such as Strade Statali (State roads SS), Strade Provinciali (Provincial roads SP), and Strade Bianche & Comunale (white and Municipal roads) contribute to the region's road network.

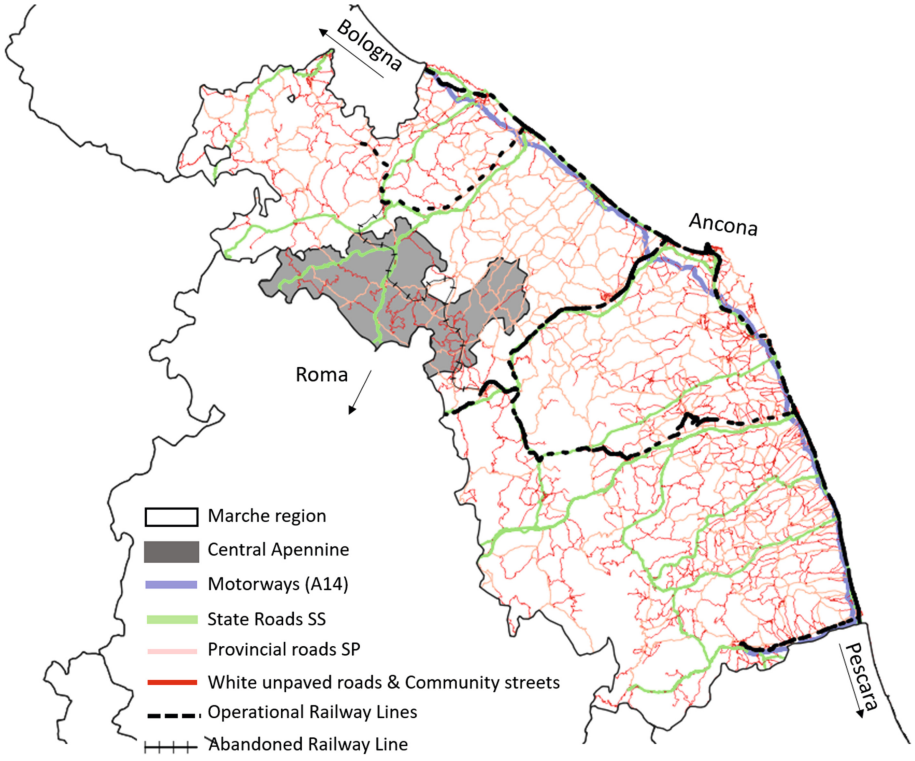

Fig. 1. Marche region Road and Rail Infrastructure @ *Junaid M., 2023* (Data source: EU Environment Agency & Humanitarian Open Street Map)

However, it is noteworthy that the Autostrada A14 does not extend into the central Apennines, but it is longitudinal along the coastline. Instead, only SS3 and SS257 pass through this mountainous region, specifically in the municipalities of Cagli, Piobbico, and Apecchio. Other roads, like Strade Bianche and Comunale, also play a role in the local transportation network. In addition to roads, there are also railway lines in the Marche region. The important railway lines include the coastal Milan-Bari line, which connects most of the seaside resorts, and the trans-Italy Ancona-Rome line, which links a few of the larger towns in the central part of the region. However, none of these train lines pass through the Apennine region. In fact, there are some abandoned railway lines in the region.

Other infrastructures include cycling paths, pedestrian routes, and hiking paths, as presented in Fig. 2. The central Apennines of the Marche region boast numerous cycling routes, including the ciclovia alte Marche. This cycling route project is of great interest, connecting nine municipalities in the central Apennines in the provinces of Pesaro, Urbino, and Ancona. It winds through an area rich in natural and cultural attractions, comprising ten sections of the Apennine Cycle that form a ring. While some parts of this project have been realized, others are yet to be completed. Additionally, besides these cycling routes, there are pedestrian paths and hiking trails both in the Marche region and specifically in the central Apennines.

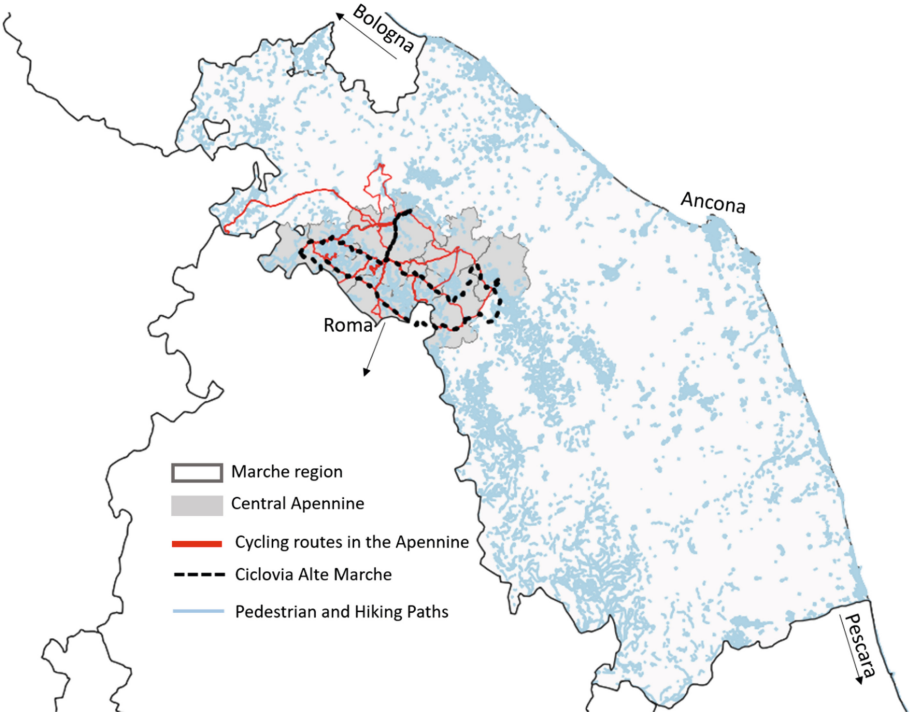

Fig. 2. Appennino Basso Pesarese e Anconetano Cycling, Pedestrian and Hiking Paths @Junaid M, 2023 (Data source: Komoot App & Humanitarian Open Street Map)

In the second part of the research, various modes of mobility utilize the aforementioned infrastructure. However, this section will specifically focus on the private trips taken by residents, primarily due to limited mobility options.

In the first section of this part, we analyze the schedule of public services and their frequency in the central Apennine region, along with their connections to nearby cities. Tables 1, 2 and 3 present detailed schedules of these services. Table 1 illustrates connections for travel to nearby cities, Table 2 outlines return connections to the Apennines from nearby cities, and Table 3 displays the schedule and frequency of services within the Apennines.

It is evident from the service schedule that services are non-operational on Sundays, with some also non-operational on both Saturdays and Sundays. Another notable observation is the gap in service frequency, particularly between the hours of 6:00 or 7:00 and 13:00, resulting in approximately a 6–7 h hiatus in service. While it may be assumed that there is limited demand for service during these hours, further investigation will cross-check this assumption by analyzing private car trips during the same time frame.

Furthermore, connections with nearby cities are infrequent, with some cities having only a single departure per day. Similarly, connections within the Apennines are also not very frequent, with gaps of 3–4 h between departures, especially during the morning and evening hours.

Table 1. Connections of Apennines with the nearby cities @Junaid M, 2024 (Data Source: Moovit App)

Line	From	To	Schedule	Frequency
VI1	Pergola	Fabriano	Mon–Sat: 06:00, 06:40, 06:55, 14:05, 15:35	
VI3	Arcevia terminal	Jesi Bus Station	Mon–Sat:	Only bus at 06:27
BS2	Arcevia	Senigallia	Mon–Sat: 05:52, 06:52, 13:37, 14:33	
35	Pergola	Marotta Mondolfo	All week 05:10–17:35	Every 60 min
24	Acqualagna	Fossombrone	Mon–Fri: 07:00, 14:20	
25V	Acqualagna	Urbino Park St. Lucia	Mon, Tue: 07:10, 07:15	Every 30 min
23	Acqualagna, Piobbico, Apecchio	Citta di Castello	Mon–Sat: 06:48, 18:07	-

The next part involves analyzing the TomTom data for private car trips made by residents. This analysis encompasses six types of data collected on different days throughout October 2022.

Table 2. Connections to move back to Apennines from nearby cities @Junaid M, 2024 (Data Source: Moovit App)

Connection	From	To	Schedule	Frequency
VI1/SFB/22R	Fabriano	Sassoferrato/Pergola/Urbino	Mon–Sat: 07:17, 09:01, 12:41, 13(31, 36, 38) 16: 40, 18:02	
VI3	Jesi	Arcevia	Mon–Sat:	Only bus at 14:35
BS2	Senigallia	Arcevia	Mon–Sat: 06:40, 13:45, 19:30	–
BS2	Marotta Mondolfo	Pergola	All week: 07:05–19:30	Every 60 min
25S	Fano	Fossombrone	Mon–Sat:	Only bus at 06:30
25	Fossombrone	Acqualagna	Mon–Sat: 07:32, 13:13, 13:50, 14:50	
LV	Pesaro	Urbino Park S. Lucia	Tue–Sun: 06:25–20:30	Every 30 min
20/22R	Urbino Park S. Lucia	Acqualagna	Mon–Fri: 06:00, 14:20, 17:35	
23	Citta di Castello	Acqualagna, Piobbico, Apecchio	Mon–Sat: 06:04, 13:04, 13:44, 15:39	

The first set of data is from the beginning of the month and week (03-10-2022), followed by the second set from the middle of the month and week (12-10-2022), the third set for weekend data (15/16-10-2022), and the fourth set from the end of the month and week (28-10-2022). These four sets of data include trips taken within the Apennines, as well as trips to nearby cities.

Additionally, our study incorporates two distinct datasets focusing exclusively on trips within the Apennine municipalities. These datasets were collected for the dates of October 18th, 2022, and October 22nd to 23rd, 2022. Furthermore the TomTom data was normalized, knowing that TomTom claims to have data for around 20% of existing vehicles. This means that if TomTom shows that there were 5 trips, we say it was 25 (multiplying all number by 5).

The results derived from the initial dataset are depicted in Figs. 3, 4, and 5, highlighting a predominant occurrence of trips within the cities and intra-city travels. Additionally, a notable number of trips were observed within the Apennines and between cities,

Table 3. Connections inside the Apennines @Junaid M, 2024 (Data Source: Moovit App)

Line	Connection	Schedule
20/52/24	Acqualagna to Cagli	Mon: 06:40, 08:30, 08:48, 09:00, 11:48, 12:48 (12:48–19:45 every 1 h)
21	Frontone to Serra San't Abbondio	Mon: 06:12, 06:55, 11:43
BS2	Arcevia to Sassoferrato	Mon: 07:40, 12:45, 13:45, 14:45, 21:00
VI1	Sassoferrato to Serra San't Abbondio	Mon: 06:15
VI3	Arcevia to Sassoferrato	Mon: 06:53 & 16:43
23	Acqualagna to Piobbico & Apecchio	Mon–Sat: 06:48, 13:48, 14:40, 15:12, 18:07

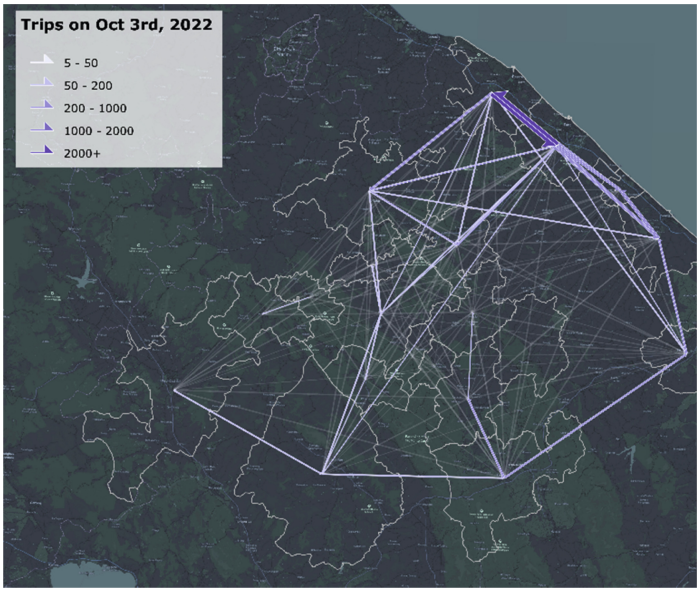

Fig. 3. Showing the trips taken on 3rd Oct 2022 in the Apennines and with other cities ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

ranging from 5 to over 200 trips. Further examination of trip lengths and starting hours reveals additional insights. Analysis of trip lengths reveals that approximately 33% of trips are under 10 km in length, with around 46–47% of trips under 20 km. Regarding trip initiation times, peak hours are identified between 7–9:00 a.m., 13–14:00 p.m., and 17–19:00 p.m. However, significant trip volumes persist between these peak hours; for instance, between 9:00 a.m. to 12:00 p.m., approximately 2500 trips were recorded each hour. Notably, despite this substantial activity during off-peak hours, many public bus lines remain non-operational, indicating potential gaps in transportation service coverage during these periods.

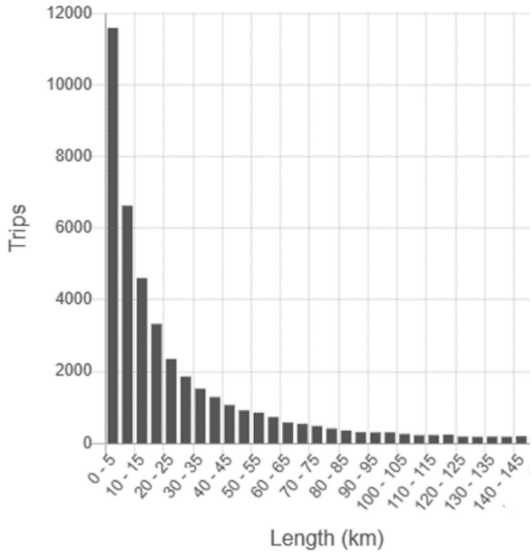

Fig. 4. Showing length of these trips on 3rd Oct 2022 ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

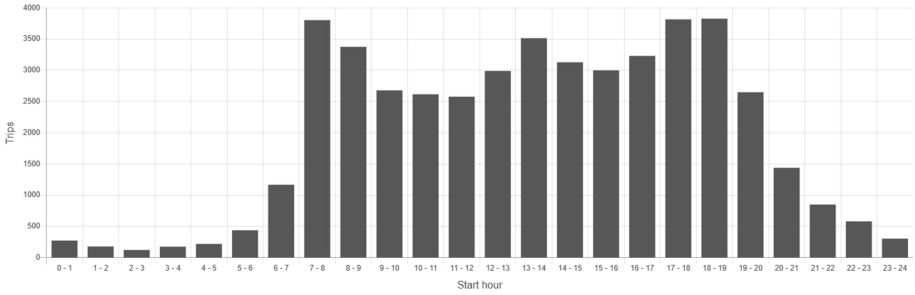

Fig. 5. Showing the starting hour of trips on 3rd Oct 2022 in the Apennines and with other cities (Data Source: Tom Tom)

The findings extracted from the second dataset are showcased in Figs. 6, 7, and 8, revealing a similar trip pattern to the preceding dataset. Once again, the majority of trips exhibit lengths under 10 and 20 km. Peak travel hours mirror those identified in the previous dataset.

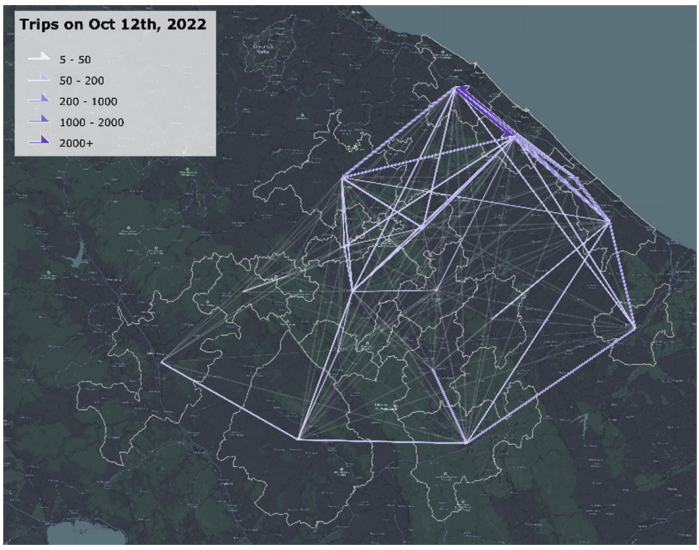

Fig. 6. Showing the trips taken on 12th Oct 2022 in the Apennines and with other cities ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

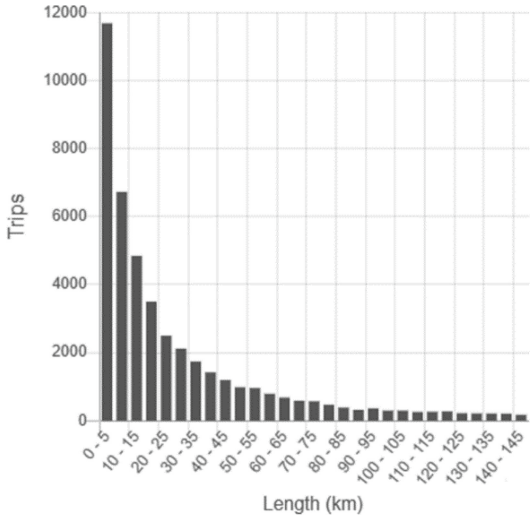

Fig. 7. Showing length of these trips on 12th Oct 2022 ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

The third dataset, representing weekend data, is illustrated in Figs. 9, 10, and 11. Notably, the trip pattern lines appear darker, indicating a higher volume of trips during the weekend compared to weekdays. Within the Apennines, the number of trips ranges from 5 to 800 over the two-day period, suggesting potential destinations such as grocery

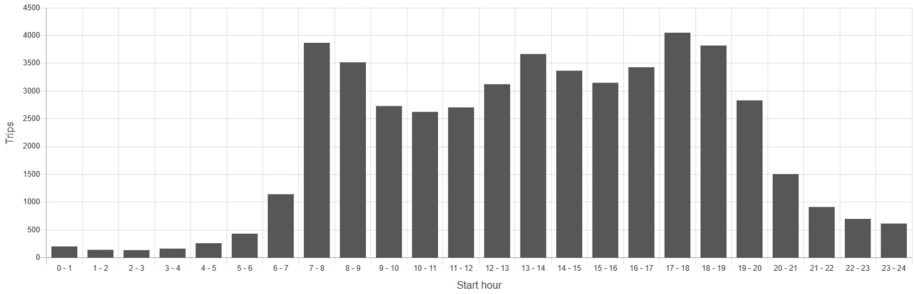

Fig. 8. Showing the starting hour of trips on 12th Oct 2022 in the Apennines and with other cities (Data Source: Tom Tom)

stores and social activities. Trip lengths exhibit a similar distribution to previous datasets, with the majority falling within the 0–10 km and 11–20 km ranges.

Interestingly, there is a shift in peak hours during the weekend. Morning peak hours are displaced towards the afternoon, with new peak hours observed between 10:00 and 13:00. Following a slight decrease in trips, another peak is observed from 15:00 until 20:00. This shift in peak hours highlights the altered travel behavior and activity patterns during weekends compared to weekdays.

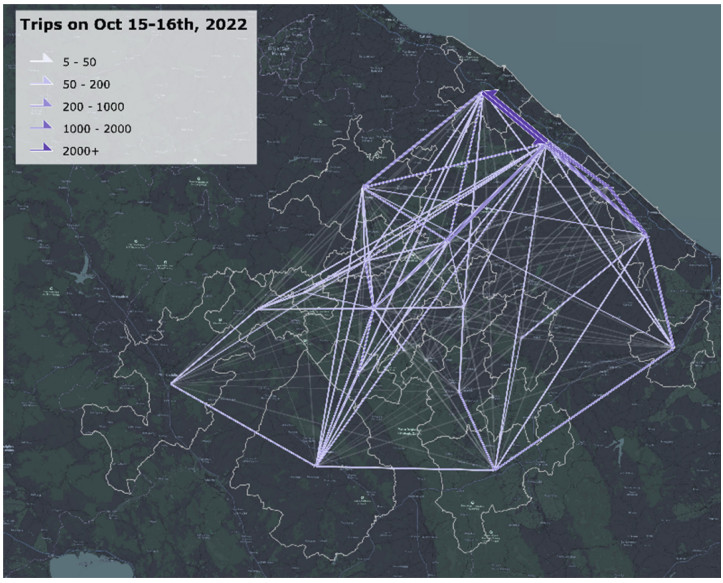

Fig. 9. Showing the trips taken on 15th and 16th Oct 2022 in the Apennines and with other cities ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

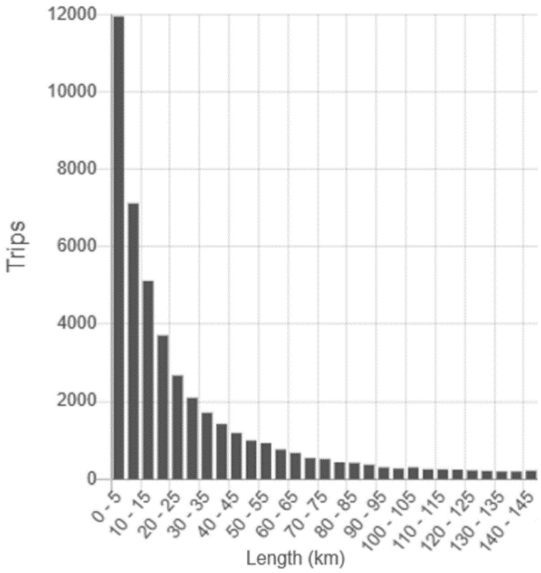

Fig. 10. Showing length of these trips on 15th and 16th Oct 2022 ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

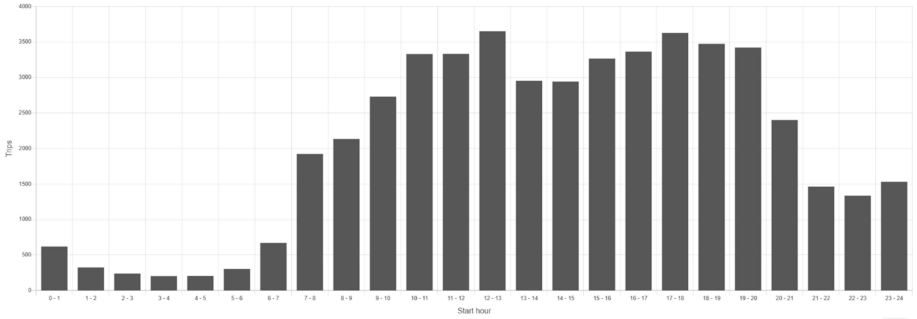

Fig. 11. Showing the starting hour of trips on 15th &16th Oct 2022 in the Apennines and with other cities (Data Source: Tom Tom)

The fourth dataset, collected at the end of the month and week, is depicted in Figs. 12, 13, and 14. Interestingly, there is a slightly higher volume of trips compared to the first two datasets. However, upon closer examination, it is evident that there are no significant differences in trip patterns across different times of the month on weekdays and various days of the week.

Overall, the analysis indicates a consistent trend in trip frequency and peak hours across the datasets. Despite a slight increase in the number of trips in this dataset, the peak hours remain unchanged. This suggests a stable mobility pattern irrespective of the specific timing within the month or week, with the exception of weekends, where distinct shifts in peak hours and increment in number of trips were observed.

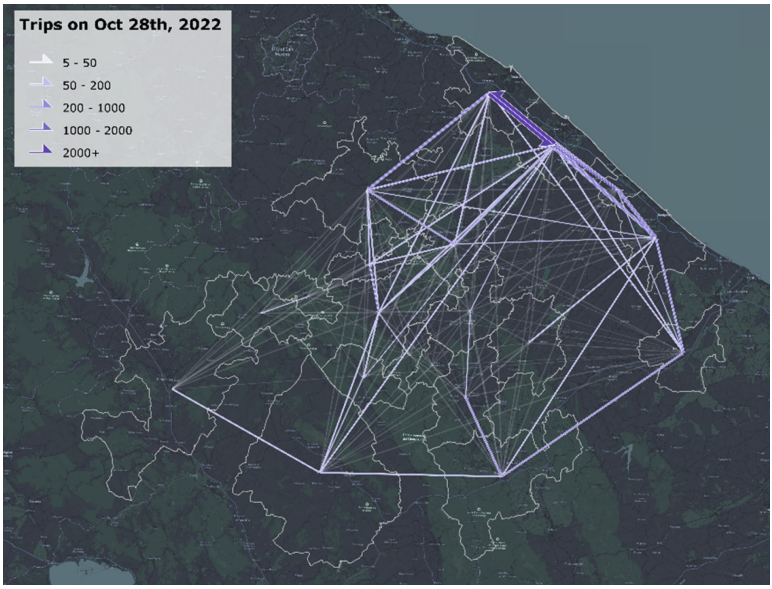

Fig. 12. Showing the trips taken on 28th Oct 2022 in the Apennines and with other cities ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

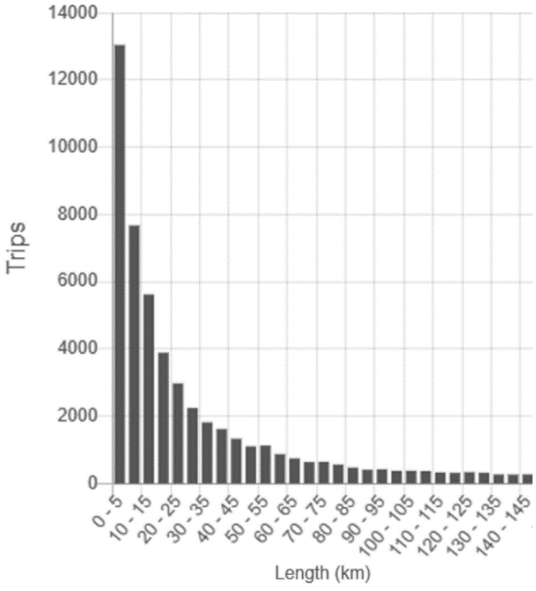

Fig. 13. Showing length of these trips on 28th Oct 2022 ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

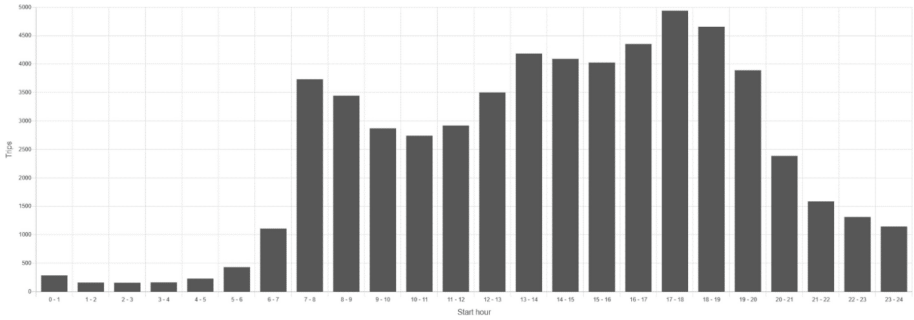

Fig. 14. Showing the starting hour of trips on 28th Oct 2022 in the Apennines and with other cities (Data Source: Tom Tom)

The fifth dataset exclusively comprises trips taken within the Apennines municipalities, depicted in Figs. 15, 16, and 17. Results indicate a considerable number of trips, exceeding 50 trips in a single day across various areas. Trip lengths align with previous data, predominantly falling under 10 km and extending to 20 or 25 km. Peak hours exhibit similar trends, with a slight alteration in the afternoon hours, including the addition of 12:00 PM as part of the peak period.

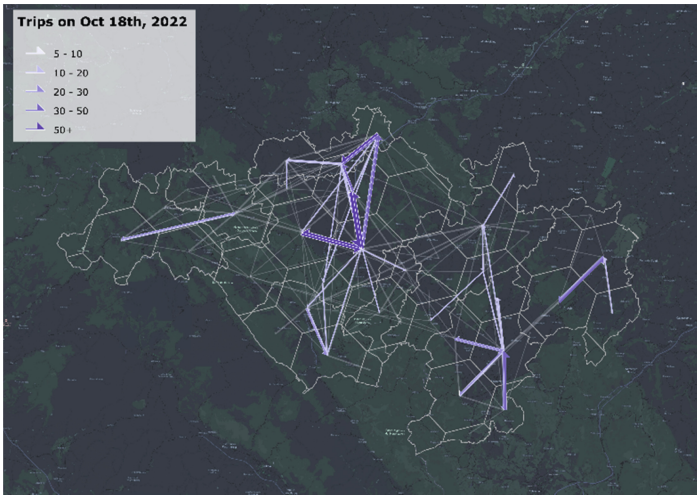

Fig. 15. Showing the trips taken on 18th Oct 2022 inside the Apennines ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

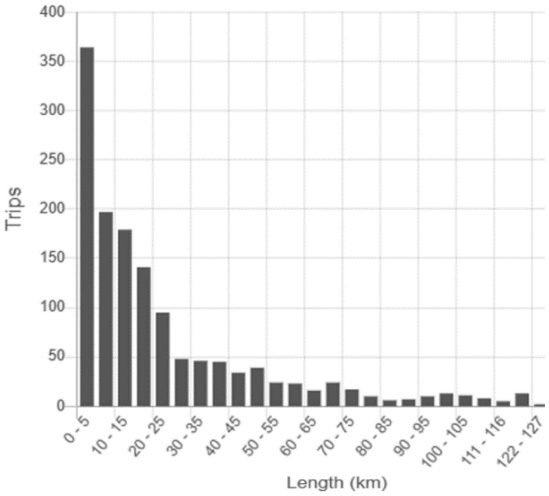

Fig. 16. Showing length of these trips on 18th Oct 2022 ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom)

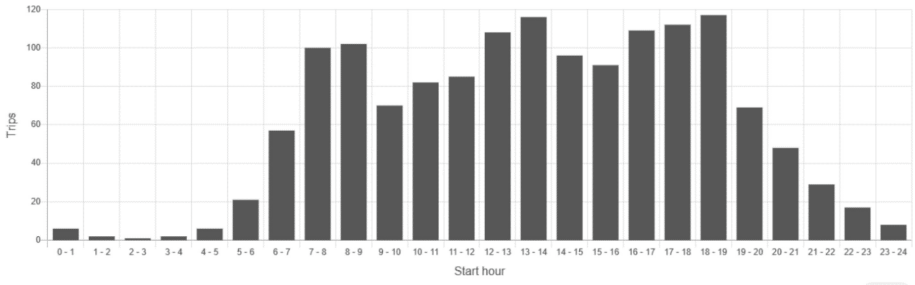

Fig. 17. Showing the starting hour of trips on 18th Oct 2022 inside the Apennines (Data Source: Tom Tom)

The last dataset examines weekend trips within the Apennines, showing varying trip volumes across different areas, with consistent trip lengths predominantly categorized as short. Unlike previous datasets, peak hours are observed at 12:00 p.m. and between 15:00 and 18:00. Despite public bus lines not operating, significant resident movement, mainly facilitated by private cars, is evident. This highlights the potential for reducing private car usage by offering alternative transportation means during non-operating hours, leading to a substantial decrease in private car trips and promoting sustainable mobility practices within the Apennines municipalities (Figs. 18, 19 and 20).

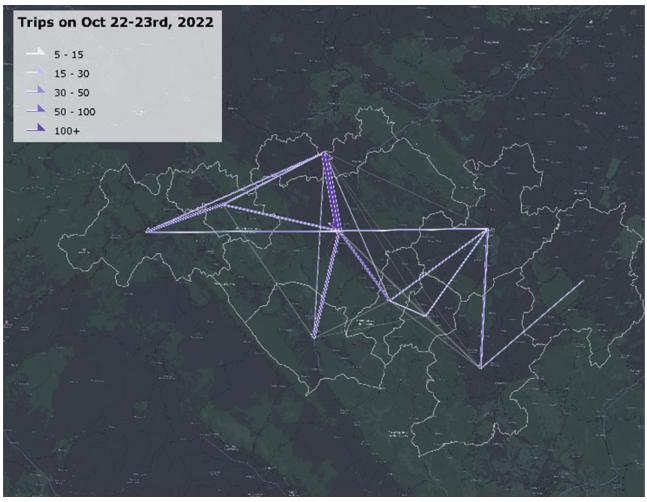

Fig. 18. Showing the trips taken on 22nd and 23rd Oct 2022 (weekend) Inside the Apennines ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom).

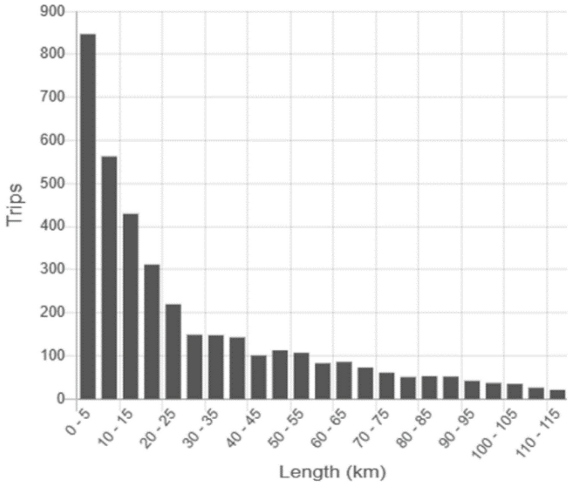

Fig. 19. Showing length of these trips on 22nd and 23rd Oct 2022 (weekend) ©Elaboration by Gorokhov D, 2024 (Data Source: Tom Tom).

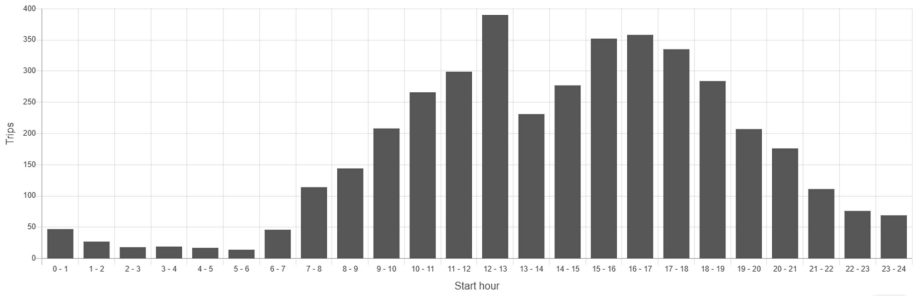

Fig. 20. Showing the starting hour of trips on 22nd and 23rd Oct 2022 (Weekend) inside the Apennines (Data Source: Tom Tom)

5 Discussion and Conclusion

The research on rural mobility in the Central Apennine of the Marche Region aim to discuss the crucial role of transportation infrastructure in preventing rural abandonment and promoting sustainable mobility practices. The study delves into the residents' mobility, emphasizing the challenges faced due to limited public transport options, particularly in rural and mountainous areas. One of the central focal points of our investigation is the examination of the transportation infrastructure network crossing the Apennine region. From the well-traveled Strada Statale (state roads) to the more localized Strade Provinciali (provincial roads) and the smaller Strada Comunali (municipal roads), the territorial analysis has shown qualities, potentials as well as criticalities in the connectivity and accessibility of the area. Despite the abundance of bicycle routes, hiking trails, and pedestrian paths, the absence of public transport, such as the railway, is a fact that is made even more evident by the territorial footprints of the rail remnants of the abandoned historical line. Within this intricate web of infrastructure lies a mosaic of mobility behaviors, each with its own nuances and challenges. While cyclists and pedestrians navigate the winding paths of the Apennines, public bus lines and private cars emerge as the lifelines connecting remote villages to urban centers. However, our focus narrows to dissecting the dynamics of public bus lines and private car usage, recognizing their pivotal roles in shaping the area's mobility landscape. The analysis of bus line schedules reveals temporal gaps, particularly during non-operating hours sandwiched between morning and afternoon peak periods. This temporal asymmetry underscores the need for a nuanced understanding of mobility demand throughout the day, prompting us to delve deeper into private car trip data sourced from TomTom. The aim of analyzing the TomTom data is to examine car trip data at various times of the year, particularly during public holidays and summer vacations, in order to uncover trends in private car usage. Tourist activity in these areas may influence fluctuations and trends in private car trips. Unfortunately, obtaining the necessary data proved to be too expensive. Such specific and detailed data from TomTom likely required purchasing access to their database, which is beyond our research project's budget constraints and resources. In the future, the required analysis might become feasible if specific funded projects will provide the necessary financial support. These projects will enable the gathering of the necessary resources and capabilities required to conduct comprehensive analysis of TomTom data

at various times of the year. As a result, researchers will be able to delve deeper into understanding car travel patterns and behaviors, particularly during critical times such as public holidays and summer vacations.

For this study, as mentioned, we focused only on data from October 2022, which is freely accessible. Our aim with this data is to uncover the complexities of car travel patterns, particularly during crucial non-operating hours of public transport, which could reveal hidden insights into residents' mobility preferences and behaviors. Beyond the confines of daily routines, our study aspires in the future to capture the essence of seasonal fluctuations in travel patterns. By performing an analysis spanning through different seasons, including the bustling tourist season, we aim to glean insights into how external factors, such as tourism flows, influence residents' travel choices and mobility planners' decisions. Regrettably, the unavailability of specific TomTom data hindered our ability to delve into these seasonal nuances, leaving an open way for future exploration. Nevertheless, the findings gathered from our analysis cast a revealing light on the pervasive reliance of the area's population on private vehicles for a myriad of purposes, ranging from essential errands to social engagements, work commitments, and leisure pursuits. This reliance underscores the pressing need for innovative, sustainable alternatives that not only mitigate the environmental effects of transport in the area, but more generally foster a greener, more inclusive mobility landscape for the residents of the Apennine region.

5.1 Mobility Pattern and Challenges

The analysis reveals an interesting trend: a significant portion of trips within the region span distances of less than 10 km. This finding hints at a promising opportunity for embracing micromobility solutions tailored to efficiently cater to these short-distance journeys. Whether it's zipping through narrow village streets or navigating scenic pathways, micromobility options like electric scooters, bicycles, or even innovative shared mobility schemes could offer convenient and eco-friendly alternatives for residents and visitors alike. Moreover, the prevalence of private trips during the non-operating hours of public bus lines highlights a critical gap in the current transportation ecosystem. During these periods, when traditional public transit services are limited or unavailable, the need for alternative modes of transport becomes glaringly apparent. This is where the concept of transport-on-demand comes to light. With its flexibility and responsiveness to individual travel needs, transport-on-demand emerges as a compelling solution to supplement existing public transportation services and bridge the gaps in service coverage. By leveraging modern technologies such as ride-hailing apps or community-based shuttle services, transport-on-demand can offer residents the convenience of tailored mobility solutions precisely when and where they need them. This not only enhances accessibility for underserved communities but also promotes a more integrated and resilient transportation network for the entire region [24, 25].

5.2 Implications for Rural Mobility Policies

The TomTom data is limited to only one month due to the limited scope discussed above in this article. However, even from this restricted data, when studying the challenges and

opportunities in the region, we can still assume this conclusion that there is an urgent need for tailored policies and interventions to address the unique mobility challenges faced by rural communities. While current EU mobility strategies predominantly focus on urban areas, there is a glaring absence of specific policies catering to the needs of rural and mountainous regions. Initiatives such as the "A Long-Term Vision for the EU's Rural Areas up to 2040" project represent a step towards rectifying this gap by promoting sustainable multimodal mobility practices and bridging the digital divide between rural and urban areas.

Furthermore, our research advocates for a holistic approach to rural mobility that goes beyond infrastructure development to encompass digital connectivity enhancement and the promotion of alternative transportation modes. By diversifying mobility solutions and addressing the multifaceted needs of rural communities, policymakers can foster inclusive and sustainable mobility practices that contribute to economic growth and social cohesion in rural areas.

5.3 Limitations and Future Recommendations

The study relies on existing data sources and methodologies for analyzing mobility patterns, which may have inherent limitations such as data accuracy, completeness, and reliability, as well as constraints in availability. Additionally, the study's findings are based on data collected within a specific timeframe, and mobility patterns and infrastructure may evolve over time, potentially leading to an incomplete depiction of long-term trends or changes in mobility behavior beyond the study period.

Looking ahead, it is imperative to continue exploring innovative mobility solutions tailored to the specific needs and challenges of rural communities. Initiatives such as transport-on-demand services and the integration of micromobility options hold promise in enhancing accessibility and reducing dependence on private vehicles, particularly during non-operating hours of public transit.

Furthermore, ongoing collaboration between policymakers, researchers, and local stakeholders is crucial to ensuring the effective implementation of rural mobility policies and interventions. By fostering a participatory approach and leveraging insights from interdisciplinary research, stakeholders can work together to design and implement sustainable mobility solutions that address the diverse needs of rural communities and contribute to the long-term prosperity of rural areas.

In conclusion, our study serves as a foundational step towards understanding and addressing the complex dynamics of rural mobility in the Marche Region's Central Apennine. By shedding light on existing challenges and opportunities, it provides a roadmap for future research aimed at fostering sustainable and inclusive mobility practices in rural areas. Through collaborative efforts and innovative solutions, we can pave the way towards a more accessible, resilient, and vibrant rural landscape.

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Ethical AI Applications for a Human-Centered Cyber Society (EthicAI 2024)

Aspects of Digital Transformation of Higher Education in the Republic of Kazakhstan

Bekmanova Gulmira, Mussina Gulmira, Omarbekova Assel(✉), Ospanova Aigerim, Zulkhazhav Altanbek, and Sultan Beibarys

L.N. Gumilyov Eurasian National University, 2 Satbaev Street, Astana, Kazakhstan
omarbekova_as@enu.kz

Abstract. The scientific article analyzes current trends in the digital transformation of higher education in the Republic of Kazakhstan. The digital transformation of the education system in any country is based on the integration of digital technologies and solutions into the processes of the organization. New solutions, in turn, make it possible to comprehensively modernize university models, as well as increase the efficiency of their activities and develop their competitive advantages. In the context of the global digitalization of higher education, it is important for Kazakhstan to use technological potential to ensure a leading position in the educational industry of the region, as well as, with the help of innovative systems, to solve internal issues of a socio-economic nature. Since the processes of digital transformation of higher education are based on digitalization, the key concepts and practices of "digitalization" and its role in the higher education system have been studied. The authors, along with the Kazakh experience, also considered the strategies of digital transformation of higher education in foreign countries: Italy and Norway. During the study, a set of general scientific and special methods of cognition was used, with the help of which the processes and phenomena considered in the work were analyzed. Despite the differences in the level of development, in comparison with foreign countries, Kazakhstan has similar approaches to determining priorities for the digital transformation of the university system. Digitalization provides significant opportunities for Kazakhstan to improve educational innovation. The analysis shows that digital technologies in education make it possible to ensure a change in discourse from the model when the university taught, to the model when the university is transformed into a space for self-development of students in professional and business activities, as well as a zone of influence on sectors of the economy. In an environment of increasing multidisciplinarity, the active role of the state in digital transformation makes it possible to orient universities to the new needs of stakeholders. This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant no. BR21882302 Kazakhstani society in the context of digital transformation: prospects and risks).

Keywords: digital transformation · digital technologies · higher education · e-learning · e-transformation

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1 Introduction

Background of the study. At the present stage of the country's development, digitalization is an integral part of the life of society and the state, including the spheres of education and science. Kazakhstan, as a country striving for innovative development and modernization, today is actively introducing digital technologies into various sectors of the economy, including higher education. For this reason, digitalization, as a key term, closely penetrates the higher education system, because this process has a profound impact on the educational environment, changing the ways of learning, knowledge transfer and research. It provides new opportunities for the educational process, enriching it with digital tools, platforms and resources. In addition, digitalization is changing approaches to managing universities, transforming business models and internal ecosystems.

Thus, digitalization in the context of higher education is the process of integrating digital technologies, tools and resources into educational and management processes in order to improve the quality of learning, the availability of knowledge and the development of the education system.

The relevance of the research topic is due to the fact that the introduction of digital technologies is currently being actively promoted at the state level in Kazakhstan. Strategic and program documents are being adopted aimed at the innovative development of the country in the digital era. However, it is important to identify whether the priorities of Kazakhstan's digital transformation correspond to global challenges and megatrends. For example, do the content of education and educational formats correlate with such megatrends as a change in the technological structure, a change in management models, a change in the structure of employment and lifestyle, a new financial architecture, a new model of family and childhood? [1].

It should also be noted that in the 2023 Digital Competitiveness Ranking of the International Institute of Management Development (IMD), which assesses the extent to which countries are studying and assimilating digital technologies leading to the transformation of public policies, business models and society as a whole, Kazakhstan ranked 34th out of 64 countries. At the same time, the highest indicators were achieved in the direction of "Knowledge", that is, training and education [2]. In this regard, it seems relevant to analyze what factors associated with the higher education system influence the improvement of Kazakhstan's position in the world ranking of digital competitiveness.

Review of the theoretical basis of the study. Kazakh authors quite often in recent years have turned to studying the experience of digitalization of higher education in order to scientifically substantiate the introduction of certain innovations in the area under consideration in our country. However, the analysis shows the lack of systematic research into the processes of digital transformation of higher education. Selected aspects are studied: online learning, the use of ICT in teaching, etc.

The digitalization of higher education in Kazakhstan plays a key role in transforming the educational environment, contributing to the development of new approaches to learning and enriching the educational process with new opportunities, which ultimately leads to an increase in the quality of education in the country. In other words, the digitalization of higher education in Kazakhstan is a complex process covering several key aspects that play an important role in modernizing and improving the educational system.

And at the same time, digitalization stimulates research activities and innovative projects in universities, facilitating access to scientific resources and promoting the development of new technologies and teaching methods.

Therefore, R. Bugubaeva et al. conclude that digitalization opens up more opportunities for access to education and improvement of the educational process and content. Thanks to the digitalization process, the teacher turns from a carrier of knowledge and skills into a navigator who helps navigate certain knowledge bases [3].

A. Cherniavsky analyzes the digitalization of higher education in Kazakhstan from the perspective of three main principles for universities: "Digital education and research" - it is recommended to teach and research using digital technologies; "Strategy and partnerships" - it is recommended to consider digitalization as part of your overall strategy, to adapt business models for digitalization; "Infrastructure and campus" - it is recommended to create a technological environment for activities at the university (Wi-Fi availability, data centers, smart buildings, etc.) [4].

At the same time, A. Ibraeva and S. Egemberdieva highlight problems that can affect the processes of digital transformation in education:

- insufficient level of digital skills of teachers;
- low level of preparedness of the university infrastructure for the introduction of modern educational technologies;
- insufficient quality of electronic educational materials for online learning;
- low level of students' readiness for self-study [5].

Positive practices of implementing modern technologies in the educational process are described by N. Kushzhanov, K. Balginova and others [6]. Thus, in their opinion, in many countries digitalization is a strategic development priority. Increasing digital literacy at all levels of the education system is becoming a priority. Therefore, it seems important to use modern IT technologies in training, including mobile applications on smartphones and tablets and social networks. The Kazakhstani higher education system requires digitalization not only in terms of the development of IT universities, digitalization should fundamentally affect all universities: economics, law, and natural sciences. Thus, the emphasis on knowledge in the field of IT technologies among economists and lawyers will allow us to move to a qualitatively new high level of education [7].

However, if Kazakh authors primarily consider individual aspects of digitalization and digital transformation of universities, then foreign researchers have a more systematic approach to defining digital transformation, including in the context of education. Thus, G. Vial, having systematized more than 20 existing definitions of the definition of "digital transformation", concludes that digital transformation is a process in which digital technologies create disruptions that cause strategic reactions from organizations that seek to change their ways of creating value, at the same time managing structural changes and organizational barriers that influence the positive and negative outcomes of this process [8]. Based on the research of G. Vial, F. Martin and K. Xie define digital transformation for digital learning in the context of higher education as the use of digital technologies to achieve significant improvements in education, improve the experience of students and teachers, and create new models of learning through policies, planning, partnership and support [9].

Digital transformation is also defined as "a series of profound and coordinated changes in culture, workforce and technology that enable the creation of new educational and operating models and transform an institution's business model, strategic directions. And value proposition." Digital transformation can make educational institutions more resilient, flexible and relevant as they face a host of increasingly complex challenges, including declining student enrollment and rising public skepticism [10].

In the works of Russian researchers, digital technologies in higher education are considered as a tool for creating interactive educational materials that make the learning process more fun and effective. This includes multimedia lectures, virtual laboratories, animations and educational games [11].

In addition, the use of digital technologies allows us to customize the educational process to the individual needs of each student. The use of adaptive programs and systems allows each student to go at his own pace and delve into topics that interest him.

Another key problem in the field of digital transformation of the education system is viewing digitalization as a means, and not as a catalyst for systemic changes. Point solutions prevent the full potential of digital solutions from being realized. When considering the problems of digitalization and digital transformation, higher education systems often focus on successful models in the field of secondary education and/or the business environment, which can contribute to the formation of negative consequences when adapting approaches without taking into account their own specifics [12].

It is necessary to take into account these challenges and actively work to overcome them in order to maximize the potential of digitalization of education. At the same time, attention should be paid to the prospects that digital transformation opens up, such as improving the quality of education, expanding the accessibility and flexibility of the educational process, as well as the development of innovative teaching methods.

It is also important to determine what requirements must be placed on modern teachers and students, what models of university management are effective in the context of digitalization, and what actions need to be taken to mitigate the negative consequences of digitalization of higher education (for example, the ability to use modern information technologies by teachers in the educational process, readiness students for independent work, etc.) [13].

The novelty of the study lies in the systematic analysis of the experience of digital transformation of higher education in the Republic of Kazakhstan, including in comparison with foreign experience in order to identify the most successful cases for their possible implementation in Kazakhstan.

The research hypothesis lies in the assumption of the possibility of improving approaches to managing Kazakhstani universities, building the educational process, developing university infrastructure, technology platforms and university laboratories under the influence of digital transformation.

The purpose of the scientific article is to analyze the Kazakh and foreign experience of digital transformation of higher education in Kazakhstan to compare compliance with current needs and identify promising opportunities.

Achieving the stated goal will be facilitated by the following tasks:

– study the experience of digital transformation of the higher education system of Kazakhstan and the best practices of foreign countries;

– determine the directions for further development of the digital transformation strategy in Kazakhstani higher education.

2 Digital Transformation of Higher Education in the Republic of Kazakhstan

In the Republic of Kazakhstan, the concept of "digitalization" in the context of the higher education system is enshrined in regulations and strategic program documents. One of such acts is the Law of the Republic of Kazakhstan "On Education", which reflects the introduction of digital technologies into the educational process, as well as the creation of conditions for the development of digital educational platforms and infrastructure [14].

In general, the Law "On Education" is a key document of modern educational policy, including the introduction of digital technologies in education. It helps provide more effective learning, preparation for future jobs and the development of competencies needed in the digital age.

At the same time, the term "digitalization" was found in the State Program "Digital Kazakhstan" [15]. As part of this program, the Government of Kazakhstan created and implemented education management systems (organization of a single, centralized repository of subjects and objects of education at the levels of preschool, secondary, technical and vocational, higher education; subsystem "Automation of public services of the Ministry of Education and Science of the Republic of Kazakhstan"; subsystem "Activity Control educational organizations"; subsystem "Planning and analysis of educational development", etc.).

In addition, according to the Ministry of Education and Science of the Republic of Kazakhstan (currently the Ministry of Education and the Ministry of Science and Higher Education), starting from the academic year 2018–2019, updated educational content has been gradually introduced. At the same time, in 2018 the number of graduates with basic IT competencies amounted to 271.8 thousand people (of which 130 thousand people were in universities), in 2019 - 283,191 people (of which 142,435 people were in universities), in 2020 year - 320,828 people (of which 176,445 people are in universities). To increase the number of graduates with IT competencies, the disciplines "Digitalization in Education" and "IT and Digital Resources" were added for pedagogical specialties. At the same time, together with universities, educational programs in leading specialties were updated taking into account modern trends. Along with this, as part of the digitalization of education, special training courses on digital literacy were introduced for teachers.

In addition, in 2019, the "OpenU" project was implemented - an educational platform that provides free access to online courses from leading universities and teachers of the country for everyone without restrictions, to which all universities in Kazakhstan were connected. Meanwhile, in 2020, as part of the rapid adoption of measures to respond to the emergency situation caused by the coronavirus pandemic in the country, the platform "online.edu.kz" was implemented for posting video lessons for students [16].

The nationwide Strategy "Kazakhstan-2050" in the context of digitalization of education pays significant attention to the development of information technology and the digital economy [17].

Key priorities and initiatives related to higher education are reflected in the annual Messages of the Head of State K. Tokayev. An example is the Message of the Head of State dated September 1, 2020, in which he emphasized the importance of developing digital platforms for the development of distance education, which received impetus due to the spread of the coronavirus pandemic [18].

In his Address dated September 1, 2021, the President noted that within the framework of the National Digitalization Project, it is necessary to train at least 100 thousand highly qualified IT specialists, as well as improve the quality of information systems for remote learning formats [19].

In the Address of September 1, 2023, digitalization received the greatest attention. Thus, the Head of State stated that it is necessary to transform Kazakhstan into an IT country, increase the export of IT services to $1 billion by 2026, apply artificial intelligence technologies, which, in turn, implies not only the active introduction of information technologies into educational process, but also the creation of a favorable environment for the development of the innovative IT sector and the training of qualified personnel in this area through the higher education system [20].

In the post-pandemic period, approaches to the development of higher education were significantly revised, taking into account digitalization trends. In June 2022, the Ministry of Science and Higher Education of the Republic of Kazakhstan was created in Kazakhstan; one of the key areas of activity was the digitalization of science, higher and postgraduate education [21].

The Concept for the Development of Higher Education and Science in the Republic of Kazakhstan for 2023–2029, adopted in March 2023, identified the development of digital technologies in education and access to any digital educational resources in the world for retraining and obtaining the necessary competencies as a weakness – deficit of digital skills. One of the priorities of the Concept is the development of infrastructure and digital architecture of higher education, as well as increasing the digital competencies of citizens [22].

Correlated with the digitalization of higher education is the Concept of digital transformation, development of the information and communication technologies and cybersecurity industry for 2023–2029, for the needs of which by 2029 the training of highly qualified IT personnel should increase from 35 thousand to 40 thousand. For these purposes, it is planned to organize the patronage of specialized universities over regional universities in order to improve the quality of education to a higher level [23].

Since the Republic of Kazakhstan officially joined the Bologna Declaration in 2010 and became a member of the European Higher Education Area, we will consider the experience of digital transformation of higher education in individual countries participating in the European Higher Education Area, including Italy and Norway. These countries were among the first to adopt Digital Transformation Strategies specifically for higher education. While in most countries, including Kazakhstan, the digitalization of higher education is part of national strategies or included in strategies for the formation of a digital society.

Italy

Italy was one of the first to adopt a strategy of using new technologies in teaching and learning for higher education [24].

At the same time, the main national participants in digital transformation are:

- Italian universities,
- Ministry of Education, Universities and Research and Ministry of Economic Development,
- Agency for Digital Italy, created to support the achievement of the goals of the Italian digital agenda, the diffusion of digital technologies and digital innovation,
- Manifesto of the Conference of Italian University Rectors – National Plan for Digital Universities and Open Science Initiatives. The manifesto presents a vision and strategy for promoting digital technologies in universities.
- CINECA is a non-profit consortium formed by 68 Italian universities, 9 Italian research institutes and the Ministry of Education, Universities and Research. This organization supports technology transfer by connecting universities with industry and government agencies.

In 2018, the Conference of University Rectors proposed the adoption of a National Plan for the Development of Digital Universities. The plan is a comprehensive strategy for addressing the challenges and opportunities of new digital technologies. Its goal is to bridge the gap between the Italian higher education system and other higher education systems in European countries. The plan covers areas such as teaching and learning, competencies, research, national action and coordinated governance.

As a result, Italy managed to achieve the following successes:

- in organizing digital learning using massive open online courses (our own online learning platforms have been developed);
- in the use of blockchain technology (issuance of authentic electronic certificates and diplomas confirming skills);
- in the formation of "open" university science (wider dissemination of research results in digital format through the "open access" model);
- in strengthening the role of universities as centers of the digital ecosystem in the digital transformation of non-academic institutions through the broadcast of digital culture and knowledge exchange [25].

In 2020, Italy adopted the National Strategy for Digital Skills until 2025, the main priorities of which are: digitalization of the school system; development of digital skills and digital culture among students; digital teacher training; strengthening ICT training as part of cross-cutting skills and pathways; strengthening orientation programs for high school graduates together with IT companies; cooperation between universities and schools on vocational guidance; implementation of digital portfolio; cooperation between universities and the business community; strengthening human capital and infrastructure; re-design of training programs taking into account digital transformation [26].

Norway

In order to maximize the use of new technologies in higher education and research, Norway has adopted the Digitalization Strategy for the Higher Education Sector 2017–2021. The Norwegian government has highlighted the digitalization of higher education as a separate strategic document, since each sector of the economy is responsible for using

common solutions and complying with common frameworks and requirements. Each sector has a responsibility to create solutions that can be shared with other businesses and sectors. The industry goals of digitalization and ICT in the higher education sector were identified:

– High quality education and research.
– Research and education for well-being, value creation and adaptation.
– Good access to education.
– An efficient, diverse and robust higher education sector and research system [27].

In 2023, Norway presented a new Strategy for Digital Transformation in Higher Education, based on the lessons of the COVID-19 pandemic. This strategy replaces the Higher Education Sector Digitalization Strategy 2017–2021. Analysis of the Strategy allows us to conclude that the policy of digital transformation of higher education has been significantly revised. If previously the emphasis was on digital skills and infrastructure, now approaches are oriented taking into account the needs and capabilities of participants in the educational process. Thus, six strategic directions have been identified:

1. Digitalization for flexible education: introduction of such learning concepts as "physical presence", "fully digital learning", "blended learning" (some classes take place online, some classes take place offline) and "hybrid learning" (part of the group participates online, some are offline).
2. Digital innovation in teaching and learning: Digital skills acquired by teachers should be developed to promote innovation in all forms of teaching, learning and assessment, and digital technologies should be used to facilitate the learning process.
3. Digital topics, methods and skills in all disciplines: Regardless of the field of study, students should study topics related to digitalization in interaction with the rest of the academic content of the course.
4. Open science and new research opportunities: improving the quality of research through digital technologies and the use of new research methods and analysis tools, the availability of research results, subject to ensuring reliable data confidentiality and respect for security, intellectual property rights and trade secrets.
5. Using education and research data: Using data to conduct higher education research to drive even more innovative decisions and economic growth, while respecting confidentiality.
6. Management and culture of digital transformation: digital transformation in higher education should be rooted in management at all levels and contribute to improving the quality of education, research and knowledge dissemination, digital culture should contribute to improving the quality of education and research [28].

Discussion

Digitalization of higher education in Kazakhstan plays a key role in the modernization of the educational system, influencing teaching methods, accessibility, quality of educational processes and preparing students for the challenges of the modern world.

Consideration of the historiographical and source study base, the key concept of "digitalization" and its role in the higher education system of Kazakhstan made it possible to see how digital technologies are transforming the educational environment. They

increase access to knowledge, make learning more flexible and interactive, and help students develop modern skills.

In Kazakhstan, the digital transformation of higher education can be divided into two levels: national at the level of the Ministry of Science and Higher Education and local at the university level. Table 1 characterizes current processes and promising development trends at both levels. At the same time, elements of digital transformation are reflected in various documents, that is, there is no unified strategic approach to determining priorities for digitalization of higher education.

Table 1. Digital architecture of higher education in the Republic of Kazakhstan

National level of digital transformation of higher education	University level of digital transformation of higher education
Implementation of national information systems for monitoring and management: National Educational Database, Unified Higher Education Management System, Unified Platform for Higher Education Automation of public services and implementation of digital tools	Implementation of learning management systems (LMS) and their integration with government information systems and databases Formation of a student's digital profile
Determining national digitalization priorities taking into account the needs of the economy ("digital university")	Implementation of digital tools of the Ministry of Science and Higher Education (digital diplomas, digital forms of strict reporting, online provision of public services, statistical data)
Funding innovative forms of access to information (online educational platforms, global digital libraries)	Monitoring and optimization of current business processes
	Using Big Data for Decision Making
	Introduction of digital services and solutions ("digital" HR, online admission to studies, online distribution of dormitories, Face ID, electronic library card, etc.)

However, there are challenges such as limited digital access, poor infrastructure and cybersecurity issues that require attention and further improvements. A broader initiative is needed to ensure accessibility and development of education from a digital perspective.

However, the digital transformation of education is not only challenges, but also huge prospects. The development of new technologies, the creation of high-quality educational platforms, as well as the development of flexible and innovative teaching methods, the transition from a "digital university" to a "smart university" can become key factors in the further improvement of the educational system and the development of a new economy in Kazakhstan.

Thus, digitalization in higher education in Kazakhstan is a process that requires not only technological innovation, but also broad social support and strategic planning.

It opens the door to new educational horizons, but requires constant development and adaptation to ensure equal educational opportunities for all participants in the system.

In this regard, it seems necessary to develop a separate sectoral Digital Transformation Strategy in Kazakhstan, which will allow to maximally cover all levels of the digital architecture of higher education. This approach will allow us to focus on digitalization and move to a qualitatively new level of management and organization of processes in the country's universities.

3 The Ethical Side of Digital Transformation of Higher Education

The digital transformation of higher education in the Republic of Kazakhstan is accompanied by a number of ethical issues and challenges that require attention and solutions.

The adopted "Concept for the Development of Higher Education and Science in the Republic of Kazakhstan for 2023–2029" pays special attention to the issue of privacy and data protection, since with the development of digital technologies new opportunities arise for collecting, storing and analyzing student data. However, this also raises questions about the privacy and security of this data, especially given sensitive information such as grades, personal data and research results [29].

Digital transformation in the Republic of Kazakhstan must take into account the needs of all students, including those who have limited access to technology or who have special needs. It is important to ensure that online resources and tools are accessible to all students, regardless of their physical or technological limitations.

According to the Concept, the creation of digital campuses is one of the tools that are used to develop the digital architecture of Universities. Citizens are given the opportunity to gain knowledge, skills and competencies through various forms of education, including through massive open online courses (hereinafter referred to as MOOCs), offered by such global providers as Coursera, edX, Udacity, MOOCs have a variety of topics and provide a flexible schedule training and accessible to the general public. Higher education institutions have also developed MOOCs and provide online educational services. To ensure access to online learning for the wider population, existing platforms will be integrated and repurposed to issue electronic certificates.

Digital technologies can create new opportunities for cheating and breaches of academic integrity, for example through plagiarism or illegal use of online resources during exams. Universities in Kazakhstan are actively using tools to combat these problems and ensure fair conditions for all students.

Also, in the process of digital transformation of higher education, it is necessary to take into account the possible increase in digital inequality between different groups of students. This may be due to uneven access to technology, insufficient digital literacy skills, or other factors. Universities are taking action to reduce these inequalities and ensure equal opportunities for all students.

Ethical standards are followed when using digital technologies to collect and analyze student data, and research is conducted with the consent and benefit of the participants. There is also transparency and openness regarding the use of data and research results.

Addressing ethical issues in the context of the digital transformation of higher education in Kazakhstan requires careful analysis, broad discussion and the development of appropriate policies and strategies that will promote the development of the educational system and protect the interests of students and teachers.

4 Conclusion

The work uses methods of dialectics of knowledge of the process of digitalization and digital transformation of higher education. The use of a systematic approach during the study made it possible to consider the experience of Kazakhstan in the use of digital technologies in the educational process to identify the most suitable ways for further development. To highlight the pros and cons of introducing digital solutions in the field of education, a systematic bibliographic analysis of scientific literature was carried out. The method of comparative analysis helped to determine the common and distinctive features of digitalization of education in foreign countries. Other methods of scientific knowledge used in the work were the methods of comparative analysis, induction and deduction.

An integrated approach to the digitalization of higher education, used in Kazakhstan, makes it possible to create an educational environment that promotes the development of modern knowledge.

Thus, digital technologies are making significant changes to the educational environment of higher education in Kazakhstan, stimulating the transformation and development of educational practices, infrastructure and teaching methodologies.

They allow you to create a flexible educational environment, providing access to knowledge at any time and from anywhere in the world. Students can study online, choose their learning format, and create flexible schedules to suit their needs. And digital libraries and databases provide broad access to educational materials, articles, scientific publications and up-to-date information, which significantly enriches research work and student learning. At the same time, the development of mobile applications for education makes learning more accessible, as students can receive educational content through their mobile devices, which increases the flexibility and convenience of the learning process.

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Ethical Principles in Artificial Intelligence for Children: A Protocol for a Scoping Review

Aurora Castellani[1](✉), Mariagrazia Benassi[2], and Giulia Balboni[1]

[1] University of Perugia, 06123 Perugia, PG, Italy
{aurora.castellani,giulia.balboni}@unipg.it
[2] University of Bologna, 40127 Bologna, BO, Italy
mariagrazia.benassi@unibo.it

Abstract. Artificial intelligence (AI) is leading a new era of technological progress with significant ethical implications. Furthermore, AI is playing an increasingly important role in the lives of children. Nonetheless, it is noteworthy that most national and international ethical guidelines on AI only superficially address children and their needs. This article proposes a protocol for reviewing ethical guidelines on AI with children as users. The objective was to map the guidelines, ethical principles, and literature recommendations for using AI with children as primary users. We employed a methodological approach based on the discovery and eligibility protocol, adapted from the Joanna Briggs Institute's PRISMA extension for scoping reviews. Our research involved a multi-stage screening process using various sources, including online collections and search engines. We applied specific inclusion and exclusion criteria to identify relevant documents defining ethical principles for AI use, particularly concerning children. We analyzed the data using linguistic analysis software and qualitative content analysis to identify and summarize emerging ethical principles and their frequency. In this way, we established a comprehensive and specific framework of ethical principles that should guide AI in this context.

Keywords: Artificial Intelligence · Ethics · Children · Ethical Guidelines · Ethical Principles · Scoping Review Protocol

1 Introduction

1.1 Ethics of Artificial Intelligence

The emergence of Artificial Intelligence (AI) has marked the beginning of a new era of technological progress, with significant implications not only in scientific and social domains [1–3] but also in ethical considerations [4, 5].

The increasing complexity of AI systems [6–9] has prompted fundamental inquiries, such as understanding how humans can coexist with AI, its impact across diverse contexts, and the ethical principles that should govern its development and implementation [10, 11]. Concurrently with AI's technological advancement, AI ethics has evolved,

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delineating guidelines and principles to steer the design and use of intelligent systems [12].

Various national and international organizations have convened expert committees dedicated to AI [13–15]. These organizations, spanning both the public and private sectors [16, 17], have produced reports and guidance documents on AI that fall within the realm of soft law. Soft law establishes standards or principles that guide AI's ethical and responsible management [18].

Despite a burgeoning international focus on AI ethics for adults, the escalating integration of AI into children's daily lives gives rise to additional ethical issues [19]. AI is taking a significant role in children's lives through various applications, including personalized educational tools [20, 21], interactive games [22], and monitoring devices [23]. Nonetheless, most national AI strategies superficially touch upon children and their specific needs [24]. In contrast, several documents emphasize the imperative of affording exceptional protection to children, given their potential vulnerability to the impacts of technology [25, 26].

These considerations highlight the need to ascertain what ethical principles should govern when children are the primary users of AI technology and their prioritization [27]. Addressing ethical challenges associated with using AI with children as users demands a comprehensive and unified perspective on the ethical principles involved.

To this end, we have reviewed ethical guidelines for AI with children as users.

1.2 Limits and Resources of Gray Literature

One of the challenges in achieving a unified vision of AI ethics for children pertains to the nature of AI guidance documents. Usually, these documents are classified as soft laws [18]. Soft laws encompass documents such as reports and guidelines issued by public and private entities without legal constraints. They may be considered part of the broad range of grey literature materials [28]. This literature presents numerous advantages, including encompassing a wide variety of documents, providing a fundamental contribution to literature reviews, expanding the scope of scientific syntheses, helping to reduce publication bias, and ensuring greater completeness and representativeness of the evidence considered [29, 30].

Although valuable, grey literature presents various challenges in its retrieval, such as rapid online publication, difficulty finding documents outside conventional editorial channels, and diversifying formats and target audiences [31–33]. Furthermore, grey literature lacks legal constraints, originates from various sources, and is less accessible than traditional literature [34]. These factors make searching for such materials more complex and may result in lower documentation and archiving than official documents [35]. Despite these challenges, the benefits of studying grey literature outweigh the efforts required to retrieve it.

A well-planned research strategy can be an aid in overcoming these difficulties and exploiting this source of information [33].

1.3 Scoping Review as a Literature Synthesis Methodology

Choosing how to synthesize the retrieved documents presents an additional challenge. Literature syntheses aim to summarize all relevant studies on a specific research question, improve understanding of discrepancies among various pieces of evidence obtained, and identify literature gaps to guide future research projects [36]. In recent years, many works have proposed different methods of knowledge synthesis in the literature, each aimed at addressing various types of questions in heterogeneous disciplines [37].

To understand ethical principles with children as the primary users of AI technology, we have opted for the scoping review method as the mode of literature synthesis. The scoping review represents a valuable research tool for systematically and comprehensively exploring the extensive reference literature [38], including grey literature documents, guidelines, and government reports [39]. The scoping review is a legitimate and rigorous methodology for providing an overview of the state of evidence on broader research questions and emerging, less-known, interdisciplinary, complex, or multi-methodology topics [40–43].

The ethics of AI for children is broad and still needs to be widely explored. It is a new and complex multidisciplinary research topic. Therefore, we opted for a scoping review focusing on ethical guidelines for AI with children as primary users. To our knowledge, no published scoping studies exist on ethical guidelines for AI with children as users. Our proposed review aimed to address this research gap.

Although the scoping review is an excellent method of literature synthesis, it presents several limitations that researchers must consider. Scoping review exhibits variations in its approaches and methodologies, which may increase the potential for bias [44]. It does not include a critical appraisal or an analysis of the risk of bias, which could affect the confidence and validity of the review results, and only a few reviews include a priori protocols [45, 46].

Therefore, a priori review protocol becomes essential as it provides clear guidance on the direction and execution of the review itself. A protocol can be likened to a recipe for the review, outlining inclusion criteria, search methods, and data management in advance [47]. This procedure can help reviewers avoid bias and reduce the risk of arbitrary decisions and duplications of previous reviews.

An optimal scoping review should be characterized by procedural and methodological rigor. A lack of clarity or transparency regarding the methodology can make it difficult to distinguish between errors in result synthesis or research design [48]. Therefore, authors of scoping reviews must account for processes, procedures, and any limitations of their approach to provide reviewers with the necessary information to evaluate the work [49].

To overcome the limitations of scoping reviews and gray literature searches [50, 51], this paper describes our protocol inspired by the PRISMA extension for scoping reviews (PRISMA-ScR) [39, 47].

2 Methodology

2.1 Eligibility Criteria

The concept of AI has evolved, leading to various definitions that reflect the rapid development of the technology [52]. For instance, in 2019, the European Union defined AI as a collection of software or hardware systems designed by humans capable of operating in physical and digital environments through data acquisition. These systems have complex objectives, interpret data, make decisions, and act based on predetermined goals [53]. This definition was also endorsed by the OECD [54]. To accommodate the rapid changes in this field, we included all documents containing the term *AI* rather than selecting only those adhering to a specific definition of AI.

We adopted the definition proposed by Fjeld et al. (2020) [55] for ethical principles. According to these authors, *principles* refer to statements on how AI should be developed, utilized, and disseminated to influence the behavior of specific recipients. Consequently, we included documents conforming to this definition, even if they used different terminology, such as requirements, recommendations, or guidelines. If a document contained only one or more, but not all, sections of guidelines, principles, or recommendations aligning with this definition, we included only that section (not the entire document).

Considering our objective of constructing a comprehensive and consistent framework for the ethical principles guiding the development and implementation of AI used by children, we included documents that exclusively refer to children as the primary recipients. This decision led to the exclusion of documents that treat children as use cases [56] or that consider children only when dealing with specific ethical principles (for example, Morgan's treatment of the privacy principle for children [57]).

We also included documents that addressed AI for children within specific application domains, such as guidelines for educational contexts. These documents comprehensively described the principles involved in children's use of AI, including the roles of children, teachers, and families. On the contrary, we excluded documents that did not refer to AI, such as general guidelines to protect children's rights in digital environments [58]. Furthermore, we excluded documents focusing on a particular type of technology, such as robotics [59] or facial recognition [60], as the application of ethical principles depended strictly on the type of technology.

To keep pace with the rapid evolution of AI ethics, we have selected only documents published since 2018.

Finally, to facilitate the comparison of documents through linguistic analysis with the software, we excluded documents that were not in English or lacked translation options.

2.2 Information Sources and Search Strategy

Without a specific database of ethical guidelines for AI, we drew inspiration from the search strategy used by Jobin et al. (2019) [50]. The authors used a multistage screening strategy to map and analyze the principles and guidelines on ethical AI.

Our search strategy involved four sequential screening processes to retrieve relevant documents:

1. We manually searched the AI Ethics Guidelines Global Inventory by Algorithm Watch, a comprehensive list of ethics guidelines [61]. Subsequently, we manually searched Linking Artificial Intelligence Principles (LAIP) [62], an initiative and platform dedicated to integrating, synthesizing, analyzing, and promoting global AI principles from various research institutions and organizations. To determine if the documents explicitly referenced children, we utilized keywords such as "Children," "Child," "Minor," "Youth," "Adolescent," and "Young."
2. After logging out of personal accounts, we conducted a keyword-based web search using the Google.com search engine in incognito mode. Keywords such as "AI principles for children," "Artificial Intelligence principles for children," "AI guidelines for children," "Artificial Intelligence guidelines for children," "Ethical AI for children," and "Ethical Artificial Intelligence for children" were utilized to search for relevant documents. Each link within the first fifty search results underwent analysis for the title, abstract (if available), document summary, and table of contents. Subsequently, the remaining Google results up to the 200th listing for each search were screened only for the title and the table of contents based on a pre-determined selection [50].
3. Finally, we searched the Scopus database using search terms tailored to the research topic (AI), target population (children, youth, minors, and pediatric populations), and document type (guidelines).

An example search string used for the database included terms such as (TITLE-ABS-KEY (((AI AND principles) OR ("Artificial Intelligence" AND principles) OR (AI AND guidelines) OR ("Artificial Intelligence" AND guidelines) OR (AI AND guidelines AND ethic*) OR ("Artificial Intelligence" AND guidelines AND ethic*)) AND (Child OR Adolescent OR child* OR boy* OR girl* OR toddler* OR kid* OR minor* OR preschooler* OR schooler* OR schoolchild* OR preadolescent* OR adolescent* OR "young people" OR "youth*"O "giovane*" OR teen* OR juvenile* OR student* OR underage OR under-age OR schoolage* OR "pre-puberty" OR prepuberty OR "pre-pubescent*" OR prepubescent*))) AND (LIMIT-TO(LANGUAGE, "English")) AND (LIMIT-TO(PUBYEAR > 2017))).

4. Once the relevant documents were identified, we employed the citation chaining technique to manually examine the full texts and identify further pertinent documents [63].

All citations were imported into Excel, and duplicate citations (including those found later in the process) were manually removed.

2.3 Data Management and Selection Process

The lead author assumed an active role in conducting the screening, eligibility assessment, and inclusion operations of the identified documents under the supervision of the co-authors. Any uncertainties regarding inclusion/exclusion were resolved through discussions among all authors until a consensus was reached. This approach was designed to ensure a precise and comprehensive analysis of the documents included in the review and a balanced evaluation of inclusion and exclusion criteria.

For each relevant document identified, we systematically extracted and compiled the following information into an Excel spreadsheet:

(a) Document title
(b) Year of publication
(c) Organizations that commissioned or produced the document
(d) Geographical locations referenced in the document
(e) Specific paragraphs or chapters of the documents included in the content analysis.

We employed two sequential strategies to extract principles, requirements, and ethical recommendations. Initially, we conducted a content analysis of the documents using SketchEngine software [64]. Subsequently, we performed a qualitative content analysis (QCA) [65] to verify the following:

(a) Correspondence with principles identified through software analysis
(b) Identification of any additional principles not captured by the software.

2.4 Data Items

We chose to use SketchEngine software because of its capabilities in linguistic analysis and information extraction from extensive text corpora. This software provides users with tools for linguistic analysis, lexical information extraction, and linguistic resource generation.

A feature of the software is its *keywords* function, which allows for the extraction of single and multi-word terms. Moreover, it facilitates the comparison of two text documents by identifying unique elements present in one corpus but absent in the other. This function explicitly compares a user-uploaded focus corpus with a reference corpus to identify distinctive elements, such as multi-word terms or expressions occurring more frequently in the focus corpus than in the reference corpus.

We specifically utilized the *multi-word terms* mode within the *keyword* function because it can analyze the most significant terms in documents while providing some contextual information to aid interpretation.

Table 1 shows the output of the software's *keyword* function. The output includes the number of occurrences (F) of single and multiple salient words in the focus corpus (user-loaded document) and the reference corpus.

Table 1. SketchEngine software output example for keywords function.

KEYWORDS					
Single-Word			Multi-Word		
Word	Focus Corpus (F)	Reference Corpus (F)	Word	Focus Corpus (F)	Reference Corpus (F)
Data	326	720	Data Protection	295	189
Bias	289	543	Gender Bias	202	97

For our reference corpus, we selected the English Web 2021 (enTenTen21), a vast collection of 52 billion words from various online sources. This corpus was chosen

because it extensively covers web-based language and reflects contemporary English usage.

Subsequently, we analyzed each extracted item to identify and categorize the underlying principles represented by the terms. For example, terms like *data protection* were linked to *privacy and data protection* principles. Items with no corresponding identifiable principle were categorized as *other* (e.g., continuous assessment, designated safe space, marginalized group). Each entry in this category was further analyzed using SketchEngine's *concordance* function to understand its context within the text and determine the corresponding principle. This feature allows for exploring each item within its usage context, specifically, the sentences where it appears in the text, while extending the context forward and backward to enhance understanding.

Figure 1 provides an example of the software's output for the *concordance* function. The output shows each occurrence of the *multi-word term* in the focus corpus and the sentence in which it appears in the text.

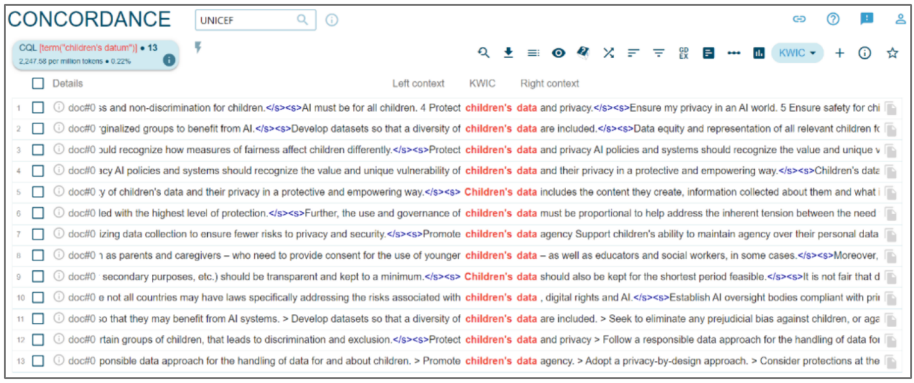

Fig. 1. SketchEngine software output example for concordance function

In the second phase of our analysis, we conducted a qualitative content analysis (QCA) on the text of the documents [65], employing an inductive approach to category formation [66]. This coding strategy enabled us to identify different classification categories based on recurring thematic areas in the documents. According to our adopted definition, the categories corresponded to ethical principles (cf. Eligibility Criteria) (e.g., Environmental Well-Being, Transparency, Non-Discrimination). As our analysis progressed, new categories were created to accommodate data that did not fit into existing ones.

2.5 Synthesis of Results

Once we identified all the ethical principles in the documents, we analyzed how they relate. This analysis allowed us to develop overarching categories to group and summarize the initial categories [67].

For example, the overarching category, *Provide Transparency, Explainability, and Accountability for Children,* could encompass principles such as *Explainability and Transparency,* which are often related [68].

Additionally, to assess the representation of each principle across different documents, we calculated the presence or absence of each category for every document as a percentage.

Finally, we analyzed the documents' application areas (e.g., social care or education), the countries in which they were developed, and whether their dissemination was national, continental, or global.

2.6 Risk of Biases

The document selection process and analysis methodology may introduce bias. The chosen documents are part of grey literature, often not indexed in academic databases. This lack of indexing could lead to non-systematic selection and the exclusion of relevant guidelines or research [30–33]. Moreover, limiting the inclusion criteria to English-language documents risks overlooking valuable information in other languages.

We adhered to a protocol for document discovery and eligibility to mitigate the risk of missing pertinent sources during the selection process [47]. We continuously monitored the literature, employed multiple screening strategies, and engaged in discussions among all authors.

Furthermore, qualitative document analysis is susceptible to arbitrary interpretations and potential information loss [69]. We incorporated linguistic analysis software alongside qualitative content analysis to address this concern.

While we cannot completely eliminate the risk of subjective interpretations influencing data analysis, this methodology can help mitigate it.

3 Discussion

Given the growing international discourse on AI ethics and its increasing presence in children's lives, reaching a consensus on the ethical principles guiding the development and use of AI for children is imperative [70]. This article proposes a protocol for a scoping review aimed at mapping the breadth, variety, and nature of documents offering guidelines, ethical principles, and recommendations for AI use by children.

Conducting this scoping review may enable the development of a comprehensive and targeted framework for understanding which ethical principles should govern AI use by children and in what order of priority. Such a framework could enhance children's comprehension of AI ethics from diverse perspectives and contribute to advancing research in this domain.

The methodology outlined herein and the ongoing review may show how different countries are represented in guidance documents on AI ethics for children. This insight could deepen our understanding of issues related to disparities in resource access across nations. Moreover, identifying countries with ethical guidelines on AI for children may help elucidate cultural and social priorities, potentially leading to a narrower focus on specific ethical concerns [71].

The scoping review may also help understand disparities in regulatory frameworks; countries with more robust regulations may produce fewer ethical documents, as ethical standards may already be embedded in existing laws [72].

Additionally, the scoping review can assist in identifying the selected documents' primary application areas. The prevalence of ethical guidelines in domains such as education or healthcare may highlight specific pressing issues, such as privacy, security, equal access to educational resources, and the impact on children's learning and development [73, 74].

Furthermore, the scoping review may underscore a widespread acknowledgment of core principles guiding AI development, implementation, and utilization in child-related contexts, irrespective of cultural, regulatory, and technological disparities. However, the analysis may also reveal the underrepresentation of certain ethical principles warranting further examination.

Deciding to focus solely on English documents or those with available translations could potentially exclude significant guidelines and constitute a limitation. This may lead to underrepresenting cultural perspectives from non-Western regions, resulting in a distorted understanding of ethical principles applicable to using AI with children globally. However, preliminary findings of the review have identified documents aimed at influencing a global audience [75, 76] and documents from countries such as India and Australia [77, 78]. This points to a geographically extensive representation of the selected guidelines.

Additionally, gray literature is not always peer-reviewed, which may lead to the inclusion of materials that do not meet the high standards associated with academic research.

However, establishing a protocol for our study aims to provide a robust framework for mapping the current research landscape, ensuring rigor in document screening and selection, improving research clarity, minimizing duplication of investigative efforts, and ultimately contributing to developing a comprehensive ethical framework [79].

Given the complexity of AI ethics for children, addressing it necessitates ongoing international dialogue, interdisciplinary collaboration, and incorporation of diverse cultural and sectoral perspectives. Integrating diverse viewpoints is essential for formulating ethical guidelines that resonate with the values of a diverse society [80].

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Ethical Aspects of Analyzing Kazakh Political Discourse

Gulmira Bekmanova[1,2(✉)], Banu Yergesh[1,2], Assel Omarbekova[1,2], Yerkyn Ongarbayev[2], and Altanbek Zulkhazhav[1,2]

[1] Faculty of Information Technologies, L.N. Gumilyov Eurasian National University, 010000 Astana, Kazakhstan
gulmira-r@yandex.kz

[2] L.N. Gumilyov Eurasian National University, 010000 Astana, Kazakhstan

Abstract. This article delves into the analysis of hotbeds points in political discourse, examining the diverse forms they can take. The primary focus revolves around the officiality and openness of these discourse sources. When addressing open sources, particularly instances where candidates in various elections openly and officially express their viewpoints, the article asserts that there is no violation of legal or ethical norms in the scientific analysis of texts, videos, or audio information for research purposes. The article emphasizes transparency, ethical considerations, and adherence to legal regulations in the context of studying and analyzing political discourse, particularly within the dynamic landscape of social networks. The guiding principles outlined here aim to ensure an ethical and responsible approach to the analysis of Kazakhstani political discourse in social media platforms. (funding by grant № AP19679847).

Keywords: Political Discourse · Database · Kazakh Language · Ontology · Ethical aspects of analyzing Kazakh political discourse

1 Introduction

The premise for this research is grounded in works related to the identification of terrorist threats on social media [1], sentiment analysis of texts [2–6], and the development of morphological analyzers [7, 8]. Researchers from various countries actively engage in this topic, recognizing that citizens often obtain information about state policies from mass media. In the era of widespread internet usage, where users not only communicate but also express opinions on social platforms, the discourse of politicians through social media has become a primary means for individuals to articulate their civic and political positions.

Efforts have been made to analyze the content flow concerning political discourse. For instance, a study [9] investigates the pragmatic and social functions of specific forms of ironic quotes used by social media users to mock political voices. Methods are applied for quantitatively assessing media bias regarding preferred stances on economic policies and consistency with the ideological positions of different political parties, influencing public understanding of politics [10].

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Publicly available data has been analyzed to critically evaluate how platforms targeting voters through online advertising either amplify or moderate the spread of political advertisements [11]. Another study [12] examines how language used by members of the UK Parliament changes after social media posts and reactions on the internet.

Sentiment analysis methods at the aspect level (ALSA - Aspect-level sentiment analysis) are employed to determine subjective sentiments of entities within texts [13]. Additionally, deep semantic and contextual knowledge networks (DSCNet) are explored in research [14], introducing a novel model with deep context.

An analysis of fake content, based on a frequency model of abstract terms in a reverse context using a diffuse neural network (Surf Scale), is proposed in a study [15], focusing on social content from public forums.

In Kazakhstan, sentiment analysis of official and unofficial information sources based on mood analysis of texts has been studied by researchers from L.N. Gumilyov Eurasian National University [16, 17], Al-Farabi Kazakh National University [18], and the International University of Information Technologies [19].

The literature review and analysis of journal articles from the first and second quartiles over the last three years indicate a significant interest in extracting meaning from texts and understanding conversation contexts. While some works on artificial intelligence related to political discourse exist, available applications do not yet fulfill functions such as emotion analysis or conversation context extraction. In Kazakhstan, few studies focus on sentiment analysis and cyberbullying, but comprehensive research on detecting political discourse, extracting semantics, and sentiments in social networks for the Kazakh language has not been conducted.

The scientific results obtained are crucial for addressing the scientific and technological needs of Kazakhstan in the context of ubiquitous digitization. As active activities transition from real life to the digital realm, which is prominently represented in social networks, monitoring and analyzing activities in social networks have become essential. Leading global social networks, like Twitter and Facebook, and individual states, such as the USA, the UK, and Russia, actively develop such tools.

The fundamental difference of the project idea from existing global analogs lies in the fact that for each natural language, such systems are created almost from scratch due to the grammatical, syntactic, and semantic peculiarities of each language. To conduct any semantic natural language processing, it is necessary to create software tools for its implementation, such as morphological analyzers, syntactic analyzers, sentiment analyzers, and various synonymizers within subject domains. For the effective operation of such tools, formalized morphological, syntactic, and sentiment models of natural language, as well as extensive knowledge bases within subject domains, such as political discourse, are required.

2 Related Works

In the article [20] investigates a network of social media accounts orchestrated by Russian operatives during the 2016 American presidential elections. These accounts aimed to manipulate political discourse by masquerading as legitimate social actors. The authors propose a novel method for tracking the “social footprint” left by these actors, utilizing

artificial intelligence to achieve an impressive 88% prediction accuracy. In work [21] authors delve into motivational speech acts within Joe Biden's political speeches. By analyzing language use and persuasion techniques, the study sheds light on communication strategies employed by the U.S. President. Article [22] explores the intersection of lobbying and environmental crimes, focusing on the Brazilian mining sector. The authors examine how corporate political activities impact environmental offenses. In the paper article [23] investigates the use of scientific discourses and markers in managing shark attack risks on Reunion Island. By analyzing language patterns, the study provides insights into risk communication strategies. Article [24] dissects how routine government releases and clarifications unexpectedly impact public opinion. Using a Chinese Ministry of Commerce release encouraging the storage of necessities as a case study, the authors explore shifts from panic to banter in public perception. Manuscript [25] explores feminist political economy and feminist critical discourse analysis as methodologies in critical nursing research. The author examines how these approaches can enhance understanding within the nursing field. This article [26] investigates how Nigerian female political leaders (NFPLs) use self-presentation strategies on social media to present themselves as powerful voices for the voiceless and active alternative leaders. The study analyzes discursive strategies such as self-promotion, ingratiation, exemplification, intimidation, and supplication1. "In Other News: China's International Media Strategy on Xinjiang—CGTN and New China TV on YouTube" [27] study delves into China's foreign-facing propaganda through the YouTube channels of CGTN and New China TV, focusing on Xinjiang2. "The multinational as a myth-prince of the global south: Writing back an emancipating imaginary to the global north" by Manuel Hensmans in Organization. In research [28] theorizes multinationals' role in writing back an emancipating imaginary from the Global South to the Global North, using the case of Huawei in China and the European Union3. The article [29] explores the negotiation of boundaries between state and society in early Republican Turkish cities.

3 Research Methods

Achieving the research goal is carried out through computer processing of the Kazakh language, which includes:

– construction of formal models describing grammar and sentiment, as well as the creation of knowledge bases (concepts and their relationships) on election topics within given subject areas.

Expected results:

1. A text corpus of political discourse of at least 300,000 words.
2. Ontological models for election topics: "Election advertising", "Speech of political candidates", "Election debates".
3. Knowledge bases on election topics: "Election advertising", "Speech of political candidates", "Election debates" with a volume of at least 2000 dictionary entries.
4. Logical rules of inference from knowledge bases.
5. Software application for a processor for processing official and unofficial information sources of political discourse based on a graphematic, morphological, syntactic

analyzer of texts in the Kazakh language with a synonymizer function on election topics: “Election advertising”, “Speech of political candidates”, “Election debates”.
6. Software application sentiment analyzer of official and unofficial information sources of political discourse based on sentiment analysis of texts in the Kazakh language.

The research hypothesis is Ontological models on election topics: “Election advertising”, “Speech of political candidates”, “Election debates”, knowledge bases on these topics, as well as rules for logical inference from knowledge bases.

The expected results are given in the order in which the studies were conducted.

The most important experiments include the verification and refinement of ontological models on election topics, the correctness and completeness of the logical rules of knowledge bases, and then the knowledge base built according to these models for the correctness and completeness of semantic features.

– collecting data to create a text corpus of political discourse;
– collection of primary information on election topics: “Pre-election advertising”, “Speech of political candidates”, “Pre-election debates”;
– Ontological modeling;
– computational logic methods for creating knowledge bases based on formal rules
– methods for formalizing the grammar of the Kazakh language and recording logical rules of inference from the knowledge base;
– graphematic analysis [32];
– morphological analysis [7, 8, 33];
– syntactic analysis [34];
– sentiment analysis [2, 3, 6].

The collection of primary (source) information is carried out on the Internet, as well as through the analysis of printed media publications. Ontological models will also be created on election topics, including concepts and relationships.

Previously, a group of authors was developing methods for analyzing political discourse in social networks in the Kazakh language. Ontological models were chosen for modeling, since this model allows taking into account different aspects of the subject area and taking into account semantics [30, 31].

The reliability and reproducibility of information is ensured by the use of only official sources to create ontological models and knowledge bases, as well as cross-verification of the created knowledge bases by members of the research group and discussion of the results at researchers’ seminars. The knowledge base also contains a database of words and dictionary entries of the subject area with semantic features.

4 Ethical Aspects of Analyzing Kazakh Political Discourse

When analyzing hotbeds of political discourse, which can be of different types, the officiality and openness of these sources of discourse are first taken into account. When we are talking about open sources, where, for example, candidates in various elections openly and officially express their point of view, we are not talking about violation of any legal or ethical standards in the scientific analysis of texts, video, audio information in scientific purposes.

Political discourse analysis in social media necessitates a careful examination of ethical considerations. This paper outlines key principles to be observed during the analysis, focusing on privacy, transparency, fairness, informed consent, cultural sensitivity, and compliance with legal regulations.

In the analysis of open sources of political discourse, where candidates express their views openly and officially, no legal or ethical norms are violated. However, when processing comments, consent is obtained, and the confidentiality of participants is strictly maintained.

Achieving transparency and openness involves providing clear information about the analysis methods, openly stating the research objectives, and ensuring clarity regarding the study's context.

Fairness and impartiality are paramount, excluding bias during the analysis and interpretation of data. Multiple perspectives and political beliefs are considered.

Informed consent is sought from participants where possible, ensuring a comprehensive understanding of the research goals by all stakeholders.

Minimizing potential negative consequences for participants in discussions is a priority, protecting against psychological or social impacts.

Cultural sensitivity is crucial, avoiding stereotypes or biased assessments in the analysis.

Transparency in the use of Artificial Intelligence (AI) technologies is maintained by openly discussing the analysis conducted through AI and addressing possible algorithm limitations and errors.

Discrimination based on political beliefs, social status, or other factors is strictly prohibited.

Ethical review of research projects is conducted before the analysis begins.

Adherence to laws and regulations governing data usage and research conduct is mandatory.

These aspects should be considered as guiding principles to ensure the ethical and responsible nature of the analysis of Kazakh political discourse in social media.

5 Conclusion

In conclusion, the ethical considerations outlined in this article serve as a foundational framework for the analysis of political discourse, specifically within the context of social networks. Emphasizing the principles of officiality, openness, and respect for privacy, the article underscores the importance of maintaining ethical standards while conducting scientific analyses of various media types. The principles of transparency, fairness, informed consent, and cultural sensitivity are pivotal in navigating the complexities of political discourse analysis in the Kazakhstani context. As technology and artificial intelligence play integral roles in these analyses, an ongoing commitment to transparency and adherence to ethical guidelines becomes imperative for responsible and conscientious research in the ever-evolving landscape of political discourse in social media.

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Can One Model Fit All? An Exploration of Wav2Lip's Lip-Syncing Generalizability Across Culturally Distinct Languages

Amirkia Rafiei Oskooei[1(✉)], Ezgi Yahsi[2], Mehmet Sungur[2], and Mehmet S. Aktas[1]

[1] Computer Engineering Department, Yildiz Technical University, Istanbul, Turkey
aktas@yildiz.edu.tr, amirkia.oskooei@std.yildiz.edu.tr
[2] Aktifbank Research and Development Center, Istanbul, Turkey
{ezgi.yahsi,mehmet.sungur}@aktifbank.com.tr

Abstract. This study explores the potential of Wav2Lip, a state-of-the-art lip-sync model, in multilingual environments. We assess its performance in generating lip-synchronized videos for Turkish, Persian, and Arabic languages. The evaluation results reveal promising language independence for Wav2Lip, achieving comparable accuracy to English. The research identifies the gap in research on lip-sync models for diverse languages and emphasizes the need for broader exploration. Additionally, we introduce a comprehensive Face-to-Face Translation workflow, outlining the fundamental elements for a seamless cross-lingual communication system. This work highlights the importance of Lip Sync models and the potential of Wav2Lip within such a system. By acknowledging current limitations and advocating for advancements in real-time models and high-resolution datasets, this study lays the groundwork for the development of revolutionary Face-to-Face Translation systems, fostering a future of barrier-free communication.

Keywords: Talking-face Generation · Lip Sync · Face-to-Face Translation · Generative AI · Deep Learning · Computer Vision

1 Introduction

The recent advancements in Artificial Intelligence (AI), particularly Deep Neural Networks (DNNs), have revolutionized the field of audio-driven talking-face generation. This surge in research and development is driven by the diverse and valuable applications of such technology. With the emergence of virtual worlds like the Metaverse, signified by the rebranding of Facebook to Meta, and the introduction of tools like Apple Vision Pro and Meta Quest to enhance virtual world experiences, the need for realistic talking avatars has become increasingly critical [1–3].

Generating a talking face from an audio input (audio-driven talking-face generation) involves synchronizing various facial movements, including the head, eyes, and most importantly, the lips. Lip synchronization (lip-sync) plays a vital

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role in this process, as the mouth area exhibits the most significant motion during facial expression and is crucial for effective communication.

Prior to the rise of deep learning, techniques like Visiomes [4] and Timecode-based [5] Systems were employed for lip-sync. However, the advancements in deep learning, fueled by factors like the dramatic improvement in neural network computations enabled by powerful GPUs and technologies like Nvidia CUDA, have shifted the research focus towards DNN-based lip-sync models [6]. Various architectures have been devised and trained for this purpose, as extensively discussed in the Related Works section.

With the proliferation of these models, there arises a critical need for performance evaluation. These models are typically assessed using two main categories of metrics: 1) Image Quality metrics that evaluate the visual fidelity of the generated lip and mouth area 2) Lip-Sync Error metrics that measure the temporal accuracy of lip movements with respect to the audio.

Among the leading Lip-Sync models, Wav2Lip stands out for achieving state-of-the-art results in both categories [7]. Despite the introduction of numerous models with varying architectures since its release, Wav2Lip remains a benchmark for open-source models in terms of Lip-Sync accuracy metrics. A key strength of Wav2Lip is its unconstrained nature, allowing it to function with any arbitrary audio, language, or facial type.

While this model is language independent, it is important to note that Wav2Lip's training data, the LRS2 dataset [8], is entirely English-based. Similarly, many evaluation datasets used in research focus primarily on English. Emerging studies and observations indicate that these models may fail to generalize to certain input speech languages [9], raising concerns about the robustness of these models and emphasizing the need for comprehensive evaluation across diverse linguistic contexts. This gap in research motivates our current investigation. We aim to evaluate Wav2Lip's efficacy with Turkish, Persian, and Arabic, languages from varied origins and linguistic families, that have received less research attention in this context.

Beyond this gap, another intriguing area demanding further attention is the use of lip-sync for Multilingual Talking Face Generation and Face-to-Face Translation [10]. Face-to-Face translation involves translating input audio to a target language and generating a talking face synchronized with the translated speech. Lip-sync has traditionally presented a significant hurdle in achieving this functionality. However, with the ongoing advancements in lip-sync technology, it can now be integrated into this process. We believe such a workflow holds immense potential and could revolutionize communication across various domains, including education, business, video conferencing, and emerging environments like the Metaverse.

Our paper presents two primary contributions. Firstly, we evaluate the performance of Wav2Lip, a highly successful open source lip-sync model, in the context of Turkish, Persian, and Arabic languages. Secondly, we propose a Face-to-Face Translation workflow that leverages advancements in lip-sync technology.

2 Related Works

Lip synchronization (lip-sync) is a critical area within computer vision and multimedia, experiencing a surge in interest due to its expanding influence across diverse and often novel applications. Research explores a multitude of uses, encompassing audio-to-video generation, live video conferencing, accessibility tools, animation, dubbing and subtitling, and even entertainment, satire, and artistic storytelling [11].

Prior to the deep learning revolution, lip-sync relied on methods such as rule-based approaches and viseme-based techniques [12]. However, the emergence of deep neural networks (DNNs) marked a turning point, triggering a surge in deep learning-based methods. This has significantly advanced the field, unlocking exciting possibilities for speech-related applications.

Early Attempts: One of the early attempts was **ObamaNet** [13], a groundbreaking architecture that utilized a time-delayed Long Short-Term Memory (LSTM) network to generate synchronized lip-sync videos from text input. However, ObamaNet suffered from a significant limitation - speaker dependency. This meant it could only effectively generate lip-sync for a single speaker, in this case, former US President Barack Obama. Another significant model, **Speech2Vid** [14], aimed to generate talking face videos from still images and speech segments. While not inherently speaker-dependent, its reliance on a large audio-visual dataset introduced language dependency concerns.

Wav2Lip and its Derivatives: The pursuit of seamless lip synchronization in videos has fueled the development of sophisticated models, with **Wav2Lip** emerging as a game-changer. This speaker-independent framework, an evolution of **LipGAN** [10], overcomes its predecessor's limitations by incorporating temporal context and a pre-trained discriminator. LipGAN, while utilizing audio and face encoders, a decoder, and a discriminator, was hindered by speaker dependency, limited accuracy, and a focus on visual artifacts.

Wav2Lip addresses these shortcomings by leveraging five consecutive frames for temporal context and employing a SyncNet-based pre-trained discriminator [15]. This strategic shift from lip region reconstruction loss to audio-lip correspondence significantly improves accuracy, ensuring lips move in perfect harmony with the audio, regardless of the speaker.

The success of Wav2Lip spurred the development of numerous derivative models focused on various aspects of improvement. Two models built upon Wav2Lip aimed to enhance lip-sync video quality using super-resolution image processing frameworks. **Wav2Lip-HD** [16] utilizes **Real-ESRGAN** [17] to improve frame quality after inference, achieving excellent results. Alternatively, **Wav2Lip-HR** [18] addresses these issues by focusing on training a powerful model rather than post-processing improvements. It recognizes the importance of high-quality training data and leverages **GFP-GAN** [19], another super-resolution model, to enhance the training dataset itself. This allows the model to inherently generate higher-quality lip-sync videos with accurate synchronization, eliminating the need for post-processing and maintaining real-time usability. Unlike models focused on enhancing lip-sync quality, the **compressed-**

Wav2Lip [20] addresses computational limitations hindering real-world applications.

The quest for even more refined lip synthesis has led to the integration of attention mechanisms. [21] exemplify this with **AttnWav2Lip**, which incorporates an attention module into Wav2Lip, resulting in superior accuracy. This enhanced model guides the network to "pay attention" to specific features and suppress irrelevant ones, further optimizing lip-sync quality. Another noteworthy variation is **LPIPS-AttnWav2Lip** [22], which builds upon AttnWav2Lip by incorporating the LPIPS loss function. Similarly, the **CA-Wav2Lip** [23] model deployed attention mechanisms in the speech-to-lip synthesis system by embedding CBAM and Coordinate Attention into the convolution layers. They also utilized the Structural Similarity Index measurement (SSIM) in the loss function of the Visual Quality Discriminator.

Other Approaches: Beyond attention mechanisms, researchers have explored a variety of techniques and architectures to enhance lip-sync performance. One study investigates a Transformer-based model called **AV-CAT** [24], which capitalizes on the Transformer's ability to capture long-range dependencies within both audio and visual features. **Diff2Lip** [26] utilizes diffusion models to address lip-sync tasks while aiming for improved visual quality compared to traditional Generative Adversarial Networks (GANs). Another approach is **MakeItTalk** [27], which offers a simple and realistic audio-driven option using an LSTM network with a self-attention encoder.

More recently, researchers have turned their attention to neural radiance fields (NeRFs) as a promising avenue for lip synchronization. Unlike GAN-based methods, NeRFs represent scenes using a 3D volume, enabling more accurate modeling of facial geometry. **AD-NeRF** [28], an audio-driven NeRF model, addresses cross-modal mapping issues without additional intermediate representations, facilitating seamless talking head video editing, including pose manipulation and background replacement, which is crucial for virtual reality applications. However, AD-NeRF initially struggled with dynamic scenes and motion blur, leading to the development of **DFA-NeRF** [29]. DFA-NeRF introduces deformation capabilities to handle dynamic changes, utilizing a hierarchical architecture for efficient representation of complex scenes, making it ideal for dynamic object and scene generation.

Despite these advancements, NeRF-based approaches, including DFA-NeRF, face limitations in lip synchronization compared to GAN-based methods. In response to this challenge, **LipNeRF** [30] was introduced, capable of high-quality lip-syncing trained on cinematic content, even with minimal video data, offering promising potential for lip synchronization. **NeRF-AD** [31], surpasses LipNeRF in capturing the full spectrum of facial expressions. While LipNeRF excels in lip-syncing, it may neglect other aspects. NeRF-AD addresses this through attention-based disentanglement, separating the face into regions for audio-driven lip movements and preserving speaker identity.

This paper delves into the universality of the Wav2Lip lip-sync model across various languages, contrasting with the focus of the referenced studies on specific

technological and computational methodologies. The authors of [32] primarily concentrates on optimizing user interface testing through graph data analysis within big data projects. This is different from the lip-sync evaluation across languages presented in this paper. The authors of [33] surveys the structural code clone detection problem, a study that is more aligned with software engineering and code analysis, whereas the Wav2Lip paper investigates the application of lip-sync models in language translation and communication, showcasing the diversity in applications of machine learning and artificial intelligence. The authors of [34] discuss a distinct area of data processing and management compared to the linguistic and communicative focus of this paper, illustrating the varied use cases of data technologies. The authors of [35] and [36] emphasize user behavior analysis and data representation, differing from the exploration of lip-sync models' adaptability across languages, thus highlighting the cross-disciplinary nature of contemporary computational research. The authors of [37,44–48] discuss grid and web services, focusing on infrastructure and computational support, which is a contrast to the linguistic and phonetic analysis undertaken in this study, underscoring the breadth of research within the field of computer science and technology.

In conclusion, advancements in lip synchronization driven by deep learning methods and innovative models like **Wav2Lip** have revolutionized the field. Despite challenges such as speaker dependency and computational constraints, these developments hold great promise for more accurate and seamless lip-syncing, benefiting various applications in computer vision and multimedia.

3 Methodology

This section details the methodology employed in our research, encompassing two key contributions. First, we evaluate the performance of the Wav2Lip model in generating lip-synchronized talking faces across multiple languages. Second, we propose a novel Face-to-Face translation workflow leveraging recent advancements. We hypothesize that the Wav2Lip model, despite being trained on an English dataset, can effectively generate lip-synchronized talking faces for various languages due to its claimed language-independent nature. We follow this methodology to evaluate the claim.

3.1 Wav2Lip Overview

The underlying architecture of the Wav2Lip model revolves around the concept of generating accurate lip-sync by learning from a well-trained lip-sync expert, as precisely outlined in the original paper. The model comprises a generator responsible for generating video frames, which utilizes two encoders and a decoder. The video encoder (V) processes visual information, extracting a latent representation of the face and mouth region, while the audio encoder (A) analyzes the mel-spectrogram, capturing audio features. These latent representations from both encoders (V & A) are combined to generate new video

frames with lip movements synchronized to the audio. During training, the generator minimizes the **L1** reconstruction loss between the generated frames and ground-truth frames. To further refine the model and penalize the generator architecture, a pre-trained lip-sync expert, derived from a modified **SyncNet** with different loss function trained on the **LRS2** dataset, is employed. Finally, to enhance overall visual quality and mitigate issues such as blurry generated lips, a visual quality discriminator with binary cross-entropy loss is utilized.

3.2 Data Collection

For our evaluation, we collected a dataset that encompasses three languages: **Turkish**, **Persian**, and **Arabic**. Each language belongs to a distinct language family (Turkic, Indo-Iranian, and Semitic, respectively), ensuring dataset diversity and providing a robust test for Wav2Lip's language independence. These languages, although widely spoken globally, haven't received significant attention in lip-sync research. Addressing this gap is crucial as the Middle East region, where these languages dominate, represents a rapidly growing market with increasing technological adoption and digital content creation. Evaluating Wav2Lip on these languages can facilitate the development of localized applications, enhance accessibility for speakers of these languages, and drive innovation in communication technologies.

For Turkish and Arabic, we selected the **MediaSpeech** [38] dataset, comprising short speech segments automatically extracted from media videos available on YouTube. For the Persian language, we opted for the **Persian Speech Corpus** [39], recorded in a Tehrani accent using a professional studio setup. Our evaluation dataset consists of one-hour audio for each language, randomly selected from the original datasets, providing a diverse and representative sample for evaluation purposes.

3.3 Video Generation

Wav2Lip requires two inputs for video generation:

1) Driving Audio: This audio track determines the speech patterns for the talking face. In our experiment, we utilized approximately one hour of speech for each language, sourced from the dataset described in the "Data Collection" subsection.

2) Target Image/Video: This input provides the visual foundation for which the lip movements will be generated. Wav2Lip can accept either a static image (single frame) or a video (multiple frames). We opted to utilize static images for this study. This decision was primarily driven by two factors. Firstly, our primary focus was on analyzing the movements of the mouth region, specifically the lips. Static images provided a clear and isolated view of this area, facilitating a more focused evaluation. Secondly, generating lip movements for videos requires significantly more computational resources compared to static images.

To generate the videos, we employed an Nvidia A100 (40GB) GPU. This powerful GPU was chosen due to its ability to handle the computationally intensive nature of Wav2Lip processing.

3.4 Evaluation

As discussed earlier, lip-sync evaluation metrics can be broadly categorized into **Lip-Sync Accuracy** and **Visual Quality** metrics. With advancements in image and video processing technologies like super-resolution and image quality enhancement, coupled with pre-processing techniques mentioned in the Related Work section, it becomes even more critical to prioritize Lip-Sync Accuracy (Error) metrics. Established metrics like **SSIM**, **PSNR**, and **FID** are not lip-sync specific and primarily assess overall image quality. The **SSIM** (Structural Similarity Index Metric) quantifies the similarity between two images based on their luminance, contrast, and structure, providing a measure of perceptual quality and detecting artifacts or distortions. The **PSNR** (Peak Signal-to-Noise Ratio) compares the maximum possible power of a signal (e.g., original image) to the power of noise introduced by distortion (e.g., synthesis), offering a measure of overall fidelity and noise level in synthesized content. The **FID** (Fréchet Inception Distance) measures the similarity between distributions of feature representations of real and generated images to evaluate the overall visual quality and diversity of synthesized content.

The Wav2Lip authors introduced **Lip Sync Error Distance (LSE-D)** and **Lip Sync Error Confidence (LSE-C)** as more suitable metrics for assessing the accuracy of generated lip movements in relation to the input audio. LSE-D represents the average error measure calculated based on the distance between the lip and audio representations. A lower LSE-D value signifies a higher audio-visual match. It is calculated as the negative value of the similarity score obtained from SyncNet . The LSE-D score is calculated by the following Eq. 1:

$$\boldsymbol{LSE_D = -S(A(t), V(t))} \tag{1}$$

where $\boldsymbol{A(t)}$ **:** Audio feature vector at time step $\boldsymbol{t}$ and $\boldsymbol{V(t)}$ **:** Lip movement feature vector at time step $\boldsymbol{t}$ and $\boldsymbol{S(A(t), V(t))}$ **:** Similarity score between $\boldsymbol{A(t)}$ and $\boldsymbol{V(t)}$.

Conversely, LSE-C reflects the average confidence score, where a higher value indicates better audio-video correlation. Lower confidence scores suggest significant portions of the video exhibit out-of-sync lip movements. LSE-C derived from the variability of the similarity scores obtained across different time steps in the video, calculated by the following Eq. 2:

$$\boldsymbol{LSE_C = \sigma\{(S(A(t)),\ t = 1 \text{ to } T)\}} \tag{2}$$

where $\boldsymbol{\sigma}$ **:** represents standard deviation and $\boldsymbol{A(t)}$ **:** Audio feature vector at time step $\boldsymbol{t}$ and $\boldsymbol{V(t)}$ **:** Lip movement feature vector at time step $\boldsymbol{t}$ and $\boldsymbol{S(A(t))}$ **:** represents the similarity score between $\boldsymbol{A(t)}$ and $\boldsymbol{V(t)}$ at each time step $\boldsymbol{t}$.

We leverage a pre-trained **SyncNet** model to calculate these two metrics for our evaluation dataset. SyncNet boasts an accuracy of around 99% [15], making it a powerful tool for measuring lip-sync error. It's worth noting that SyncNet models are pre-trained, eliminating the need for ground-truth videos in our evaluation methodology. We can calculate LSE-D and LSE-C solely by providing the generated lip-synced videos, without the need for ground-truth. Our evaluation process involves utilizing Wav2Lip to generate talking faces using the evaluation dataset and a randomly generated avatar from DALL-E. Subsequently, we employ the provided method to calculate LSE-D and LSE-C for the generated videos.

In addition to this **quantitative** evaluation approach, we will incorporate **qualitative** evaluation by human observer into our research. While SyncNet and the LSE metrics offer a robust system for assessing lip-sync accuracy, potential biases towards specific languages may exist, considering SyncNet's potential training on primarily English or a limited set of languages. Therefore, conducting human evaluation serves as a complementary approach.

Similar to quantitative evaluation, selecting appropriate metrics or criteria for human observers is crucial in qualitative evaluation. When assessing lip-synced videos, human observers can consider various criteria. However, for this study, which evaluates Wav2Lip's performance across different languages, choosing criteria sensitive to the input audio's language is essential. For instance, a criterion like "Artifacts", which refers to visual distortions or irregularities in the video, is not suitable. This is because artifacts depend on the model's architecture rather than the spoken language. Therefore, selecting language-dependent criteria for qualitative evaluation is critical.

We identified and selected two suitable criteria for this task: Adequacy and Naturalness. In this context, **Adequacy** refers to how well the lip movements match the spoken words and sounds in the audio. A lip-synced video is considered adequate if the lip movements closely align with the phonetic content of the speech, effectively conveying the intended words and sounds. Adequacy essentially assesses the accuracy of the lip-syncing process in visually reproducing the spoken content. **Naturalness** refers to the degree of realism and lifelikeness in the synthesized video's lip movements, resembling natural movements observed in real-life speech. For lip-syncing, naturalness evaluates whether the lip movements are fluid, smooth, and contextually appropriate, enhancing the overall believability and authenticity of the video. A lip-synced video is considered natural if the lip movements align with the rhythm, pacing, and intonation of the spoken words, creating a seamless and convincing visual representation of speech.

By considering the strengths and limitations of both quantitative and qualitative evaluation methods, and by selecting appropriate metrics and criteria, we ensured a comprehensive, robust, and reliable evaluation methodology.

3.5 Face-to-Face Translation Workflow

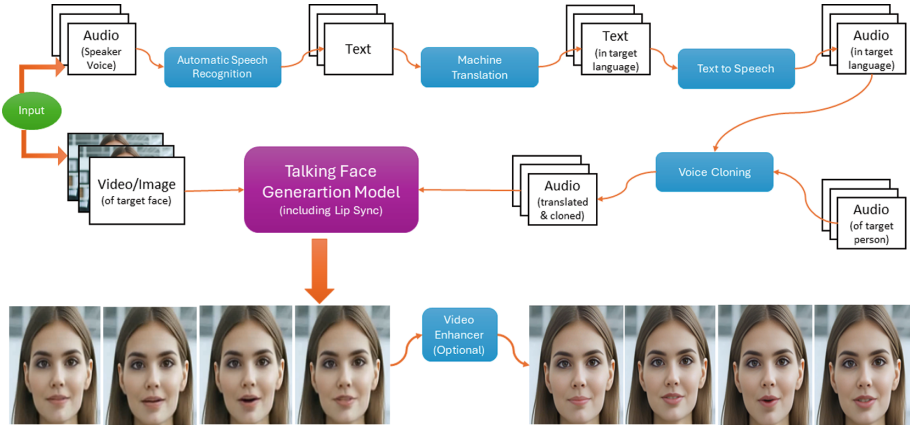

Fig. 1. Face-to-Face Translation Workflow

The concept of Face-to-Face translation entails translating all communication aspects of a speaker, including language, voice, mimics, and lip movements, into another language. The modular workflow in Fig. 1 illustrates how this can be achieved. Firstly, the speaker's voice is captured and recognized by an **Automatic Speech Recognition (ASR)** tool. The resulting text output is then translated to the target language using **Machine Translation (MT)**. Subsequently, employing a **Text-to-Speech (TTS)** model along with a **Voice Cloning (VC)** model, the speaker's voice is translated into the target language, constituting the **Speech-to-Speech (S2S)** translation step. After S2S, the generated audio and the target face (which may belong to the speaker or another person or avatar) are inputted into the **Talking Face Generation** model, with Lip Sync as a crucial component. Finally, a talking face is generated, and if necessary, an **Image/Video Enhancer** framework can be employed to improve the visual quality of the generated video, addressing potential issues arising from low-quality input images/videos, weaknesses in the talking face generation model, or insufficient computational resources.

While such a system incorporating all these modules is achievable considering current advancements, it's important to acknowledge the significant computational resources it would require. While the applications for such a system are vast, encompassing both real-time and non-real-time use cases, there is still a significant need for further improvements across all the modules. This study specifically focuses on the Talking Face Generation module within this larger workflow. We present this comprehensive workflow to provide a valuable outline for researchers, companies, and individuals interested in developing a Face-to-Face Translation system. We believe such a system has the potential to revolutionize the way we communicate

4 Experiments and Results

In this section, we evaluate the performance of Wav2Lip on generating lip-synced videos for languages beyond English. Initially, we generated approximately one hour of talking face videos for each language (Persian, Arabic, and Turkish) using Wav2Lip. The model configuration remained consistent, producing videos at 25 fps and a resolution of 96×96 pixels for the lips. Subsequently, we carried out a thorough assessment encompassing both quantitative and qualitative evaluation.

4.1 Quantitative Evaluation

To assess the quality of the generated lip-syncing, we employed the pre-trained SyncNet model and calculated two metrics: LSE-D (distance) and LSE-C (confidence). It's important to note that this pre-trained SyncNet instance differs from the Lip Sync Expert used within Wav2Lip itself, which was trained on the LRS2 [8] dataset. The pre-trained SyncNet achieves a reported accuracy of 99%, suggesting reliable evaluation results. Table 1 presents the quantitative evaluation results. Persian emerges as the language with the best scores in both LSE-D (distance) and LSE-C (confidence) by a significant margin. Arabic follows closely in second place, while Turkish exhibits the lowest scores.

Table 1. Quantitative evaluation results

Language	Length (minutes)	LSE-D ↓	LSE-C ↑
Turkish	67	7.088657544	7.265054778
Persian	59	6.235052688	8.389725332
Arabic	54	7.011181367	7.410812804

We acknowledge that previous studies and models have utilized various datasets, primarily focused on English (LRW, LRS2, LRS3, VoxCeleb2) [40] [41]. However, a comparison of their results with ours suggests promising performance by Wav2Lip for Persian, Turkish, and Arabic languages. Despite being trained on an English dataset, Wav2Lip demonstrates remarkable performance and accuracy across these different languages, validating the claim of its language-independence, at least within the context of our selected languages.

4.2 Qualitative Evaluation

While our quantitative evaluation using SyncNet provides valuable insights, it's crucial to acknowledge its limitations. Firstly, SyncNet's potential bias towards English or similar languages could lead to underestimating the quality of lip-syncing for languages like Persian, Turkish, and Arabic, overlooking their specific pronunciation nuances. Secondly, quantitative metrics might struggle with

subtleties in natural lip movements, prioritizing high similarity scores even if the generated movements appear unnatural for a particular language. Finally, the recording environment can impact results. In our case, the Persian dataset's superior performance might be attributed to its professional studio recording with minimal noise and background sounds. The Turkish and Arabic datasets come from news broadcasts, where environments are less controlled compared to studios. These factors highlight the importance of human evaluation alongside quantitative measures.

Human evaluators, ideally native speakers or those highly familiar with the languages, can assess the generated lip movements' alignment with natural pronunciation and mouth shapes specific to each language. For instance, Persian has distinct sounds like "qaf" and "khe"that require unique lip movements not commonly seen in English. Similarly, Turkish vowel harmony influences pronunciation and potentially lip shapes across words. Lastly, emphatic consonants in Arabic involve forceful pronunciation that translates to distinct lip movements. Human evaluation ensures the generated lip movements not only achieve technical accuracy but also appear natural, culturally appropriate, and capture the nuances of the target languages.

In our study, native speakers of each language evaluated a subset of generated videos for **Adequacy** and **Naturalness** criteria.

In terms of **Adequacy**, Persian evaluators reported excellent synchronization for most of the video, including the distinct sounds not found in English. Turkish evaluations indicated generally well-generated and accurate lip movements with some subtle errors. Interestingly, users noted instances of faster-than-usual lip movement transitions, potentially due to the vowel harmony characteristic of Turkic languages. Arabic reviewers reported high lip-sync accuracy even with forceful pronunciations, although some errors were present. Additionally, a participant fluent in all three languages evaluated the videos. Their assessment confirmed the best adequacy for Persian with minimal errors, followed by Turkish and then Arabic.

While the human evaluation indicated good adequacy, the **Naturalness** scores were generally lower. This is interesting because the evaluated videos featured an artificial talking avatar, and users likely didn't expect perfectly realistic lip movements. Despite this, observers reported weaknesses in motion and pacing. Most observers noted that in some instances, even though lip movements precisely matched the audio timing and accuracy (adequacy), they appeared overly responsive to the speech. This means the lips reacted to even subtle sounds that wouldn't necessarily require a visible change in lip position. Consequently, the videos sometimes exhibited faster-than-usual and unexpected transitions, impacting the overall naturalness.

Finally, participants rated the Lip Synced videos based on the selected criteria on a scale from 1 to 5. Results of the user rating is provided in the Table 2.

Table 2. Qualitative evaluation by human observer results

Language	No. of Participants	Length	Adequacy	Naturalness	Overall
Turkish	12	3 min	4.2/5.0	3.4/5.0	**3.8/5.0**
Persian	7	3 min	4.6/5.0	3.6/5.0	**4.1/5.0**
Arabic	6	3 min	4.1/5.0	3.3/5.0	**3.7/5.0**

These human evaluations complement the quantitative results, highlighting the strengths and weaknesses of Wav2Lip's performance across different languages. They emphasize the importance of considering language-specific nuances beyond solely relying on metrics potentially biased towards certain languages.

5 Discussion

Our experiments and results demonstrate that Wav2Lip, despite being trained on an English dataset, exhibits remarkable lip-sync accuracy across our chosen languages (Turkish, Persian, and Arabic). This reinforces the model's language-independence claims, as it achieves comparable performance to English within our language set. The scarcity of research exploring the use of lip-sync models for diverse languages is noteworthy. One study [9] focused on real-time multilingual talking face generation, employing a dataset encompassing Korean, Chinese, Japanese, and English. While their findings regarding real-time systems are valuable, they lacked quantitative evaluation. Another example [25] utilized a dataset containing French alongside English. For a comprehensive Face-to-Face Translation system, a wider range of languages needs to be considered in future research.

The potential of an end-to-end Face-to-Face Translation system encompassing all the modules in our proposed workflow is immense due to its vast range of applications. Advancements in neural networks have yielded well-established models for each module, catering to both real-time scenarios where efficiency reigns supreme and high-quality setups prioritizing performance. Currently, lip-sync remains the most crucial component within a Face-to-Face translation system. While several models prioritize visual quality, this often comes at the expense of lip-sync accuracy [26,31,42]. Wav2Lip and its derivatives excel in generating highly synchronized lips, but may necessitate post-processing with video enhancement models like Real-ESRGAN or GFP-GAN, which require significant computational power and time. Pre-processing techniques, such as those employed in [18], also exist. They utilize a modified Wav2Lip model trained on a pre-processed 4K dataset achieved through image enhancement models. Training Wav2Lip on high-resolution datasets directly generates high-resolution videos, eliminating the lengthy inference times associated with post-processing. However, the computational cost of image enhancement models, even during pre-processing, remains high. Therefore, the development of high-resolution speech datasets is crucial.

To the best of our knowledge, there are no existing real-time, end-to-end models encompassing all the steps in our workflow. While a recent work by [43] incorporates intriguing modules like face swapping, creating a user-friendly, end-to-end system with all the proposed steps, its real-time performance falls short, potentially requiring hours to generate a 10-minute talking face even on high-end hardware.

An end-to-end Face-to-Face Translation system that effectively balances factors such as lip-sync accuracy, visual quality, computational cost, and inference time would be groundbreaking, revolutionizing communication methods. Imagine real-time systems within the Metaverse or video conferencing platforms, enabling seamless communication between individuals across languages, utilizing any desired face or avatar. Considering the current state of these technologies and advancements in hardware and processing units, achieving such a system seems like a foreseeable future reality. By overcoming the challenges and limitations discussed, we pave the way for the development of such a transformative system.

6 Conclusion and Future Works

In conclusion, our study demonstrates the promising performance of existing Lip Sync models, particularly Wav2Lip, in multilingual environments. Despite variations across languages, our evaluation of Wav2Lip in Turkish, Persian, and Arabic showcases its adequacy both quantitatively and qualitatively. By outlining a comprehensive workflow, we provide clarity on the essential components required for Face-to-Face Translation systems. Our experiments underscore the potential of language-agnostic Lip Sync models like Wav2Lip in integrating seamlessly within such workflows.

Moving forward, addressing current limitations and challenges is paramount. This includes the necessity for high-resolution speech datasets and the development of real-time models. These insights can guide future research efforts and empower researchers, developers, and companies to contribute to this evolving field.

In the broader context, our findings offer valuable insights that can pave the way for the realization of end-to-end, real-time solutions for Face-to-Face translation systems. Such advancements hold immense potential to revolutionize communication methods significantly, marking a pivotal shift in how individuals interact and connect with one another.

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Internet of Things Implemented with Mruby

Hattapat Silangern and Kazuaki Tanaka(✉)

Kyushu Institute of Technology Iizuka, Fukuoka 820-8205, Japan
silangern.hattapat647@mail.kyutech.jp kazuaki@ics.kyutech.ac.jp

Abstract. The objective of this paper is to develop an Internet of Things (IoT) system that utilizes fusion sensors implemented with Mruby, a lightweight implementation of the Ruby programming language specifically designed for microcontrollers. The Mruby has been adapted to function on compact devices such as the Internet of Things (IoT) and other embedded systems. In addition, to improve communication efficiency in the IoT system. Thus, LoRa is well-suited for integration with the IoT system. The LoRa module, a low-power transmission technology, facilitates communication between embedded systems and other systems. LoRa is a technology that allows communication over long distances while consuming little energy, which is suitable for integration with IoT systems. As a result, this research has focused on embedded system development, which involves creating software and hardware components for IoT and embedded systems through design, coding, and testing processes. This involves a combination of software and hardware engineering, with an emphasis on creating systems that are efficient and reliable and able to satisfy specific performance standards. The microcontroller has successfully created a functional environment for running Mruby. This involves running the Mruby code in the microcontroller environment. The experiment demonstrates the procedure for setting up a Mruby environment and directory structure, along with the creation of a test program that can access real-time data.

Keywords: Embedded system · Mruby · Ruby · Long Range communication

1 Introduction

Nowadays, electronic devices are rapidly advancing and widely utilized to support customers. The demands of customers today extend beyond mere functionality. They seek seamless integration, emotional interfaces, and innovative features that enhance their overall experience. Thus, integrating electronic devices has become an indispensable part of daily consumer life. For example, a dishwasher machine simplifies their lives. Instead of washing dishes by hand, which can be time-consuming, this electronic device efficiently cleans and dries our plates and utensils. Thus, washing with a dishwasher machine not only saves time but also ensures a thorough cleaning, leaving consumers with more time to do things.

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On the other hand, when consumers have a desire to use functions in electronic devices, a variety of devices. Therefore, developers emphasize developing systems that meet the requirements of various consumers. Developing each system will be quite expensive, depending on the system. Several years ago, the Information Technology Promotion Agency (IPA) in Japan released reports indicating that the production costs of systems and electronic devices were notably high. Because the production costs depend on the software and hardware architecture and development, the software development cost is a large proportion of the system. In fact, there is a lot of source code for the software available on the internet right now, which makes it simple to implement. However, the source code remains complex and hard to fully understand within a short period of time. Thus, designing smaller and easier software for the system can significantly reduce production costs and conditions for users. Software development is an attractive area for developing embedded systems. To reduce production costs.

Therefore, this research focuses on Mruby, a lightweight implementation of Ruby, which is an object-oriented programming language and scripting language for microcontrollers employed in IoT and embedded systems. This study investigates the potential applications of Mruby within embedded systems, examining its advantages and challenges, particularly in terms of the design of the software and hardware. This research is poised to contribute to more cost-effective and efficient designs, driving advancements in embedded system technologies.

2 Literature Review

This section aims to closely review the work and related information in order to gain a more comprehensive understanding of each important part of this research. Utilizing the relationship between the Internet of Things and embedded systems. Furthermore, this study also emphasizes the selection of suitable microcontrollers and sensors. While analyzing the utilization of long-range and short-range communication to enhance the communication capacity among individual systems to align with the particular system's conditions. The most important part of this section is to focus on developing and designing the programming language Mruby to be suitable for the IoT embedded system that has been planned and designed to meet the goals and objectives that have been set.

2.1 Internet of Things

The Internet of Things (IoT) is an integrated network of devices connected to the Internet, or the linking of smart devices across the Internet to the cloud. To be able to share information between devices, a general IoT system involves collecting and exchanging information in real time and consists of three parts: smart devices, IoT applications, and graphical user interfaces. This research will focus on designing and developing intelligent devices that implement with the programming language Mruby, which will be divided into two parts: hardware and software development.

Embedded System. An embedded system is a system that consists of a computer that has a specific function, namely, a computational system. using microcontrollers that are specifically designed to have pre-defined functionality with specific requirements, for example, smart devices that have small computers embedded in them and control them.

- **Systems design and Development**. This part describes the design and development of the system. From the information provided, it can be concluded that the microcontroller is a crucial component in the design and development of an embedded system. A microcontroller functions akin to a compact computer, brimming with integrated circuits (ICs) that comprise diverse components like memory and peripherals. Therefore, the system design in each system will depend on the purpose of each task that has been designed and programmed into the controller chip to perform a specific task. For example, reading the temperature value from temperature sensor by changing the input of the sensor into output using a microcontroller to read and process the data.

Embedded Software. This part emphasizes the significance of software in facilitating communication between the program and the microcontroller. The design of software specifically caters to the specific microcontroller it operates on. Typically, we employ embedded software to control the specific and programmed operations of a microcontroller.

- **Programing languages**. Programming languages are typically well-suited for writing programs that can communicate with microcontrollers. There are a wide range of options available nowadays. For example, the C programming language is the most widely used programming language for embedded devices. Built to be fast and efficient, C is a low-level language. Therefore, it is a powerful language that allows developers to write code that communicates with the hardware. However, the choice of programming language in software development is dependent on the developer's understanding of programming complexities and the specific requirements of the software. Consequently, the decision about which programming languages to use involves various elements, allowing developers to determine the suitability of each language.

2.2 Microcontroller

This section describes the microcontroller, which is a key part of IoT embedded systems. Microcontroller is a small and low-cost microcomputer. that is designed to control specific tasks within an electronic system. Microcontroller provide a combination of functionality through a central processing unit (CPU), memory (RAM, ROM, and EPROM), input/output interface ports, and other peripherals.

ESP32. Over the years, there have been many microcontrollers designed for use in IoT embedded systems, such as the ESP32, ESP8266, Arduino, Nano,

and the Raspberry Pi Pico. From experimentation and comparison with other microcontrollers. Therefore, we can conclude that the ESP32 is suitable and capable of achieving the objectives of this research. The ESP32 has a combination of performance built-in Wi-Fi and Bluetooth connectivity and is easily integrated with local networks and the Internet. It also comes with a dual-core processor running at up to 240 MHz. which provides more processing power than a single-core processor running at 16 MHz. In addition, ESP32 has a large development community, which has a tutorial library and development tools that can support developers comprehensively. Therefore, making it easier for developers to start ESP32-based projects.

– **Espressif IoT Development Framework (ESP-IDF)**. This part describes the Espressif IoT Development Framework (ESP-IDF) as the official development framework for Espressif Systems' ESP32 and ESP32-S series microcontrollers. This development framework provides a comprehensive set of tools, libraries, and documentation for developers who want to develop firmware and applications for microcontrollers. Therefore, the Espressif development framework is for developing Internet of Things (IoT) applications with Wi-Fi, Bluetooth, power management. and other features of the system. Which is a good help for developers. The framework provides basic hardware and software resources to help application developers realize their ideas using the ESP32 series hardware[1] .

2.3 Software Integration with Mruby

This part focuses on the efficient development of software for integration with microcontrollers. C is currently the most commonly used programming language for communicating with microcontrollers. This is due to the fact that C serves as a general-purpose language for a diverse range of applications, encompassing systems programming, application development, and low-level system programming. On the other hand, C syntax is complicated. Therefore, designing applications for each project requires more time and resources.

At this point, it is necessary to focus on the development of programming languages that are both user-friendly and easy to use. In order to reduce the loss of resources in the design process for each project, the Mruby is the right choice. This is because it has a non-absorbent scripting style and dynamic behavior. It allows developers to create and run Ruby scripts.

Ruby Programming Language. This part describes the Ruby programming language. Ruby is a dynamic, object-oriented programming language known for its simplicity and productivity. Yukihiro Matsumoto publicly released Ruby in 1995. Ruby's main features include dynamic typing, object-oriented principles, clean syntax, meta-programming capabilities, automatic memory management through garbage collection, and a standard library. Therefore, Ruby is widely used for web development, scripting, automation, prototyping, etc., which makes Ruby a popular choice among developers.

On the other hand, Ruby's need for automatic memory management can result in slower execution times and higher memory usage. This is especially true in resource-intensive applications that consume a lot of resources in their operation. However, many Ruby applications are web applications, so there are no problems with consuming resources on the server machine[2]. Ruby retains its powerful meta-programming capabilities and extensive ecosystem. This appeals to developers, who value developer productivity over raw performance.

Mruby. This part describes Mruby. Mruby is a lightweight implementation of the Ruby programming language, compliant with ISO 30170, released under the MIT license[3]. Mruby has different uses than others. Mruby outperforms Ruby due to its compactness and optimization for use cases with limited memory and processing power. Mruby is generally designed specifically for embedded systems, IoT devices, and other scenarios. that focus on efficiency and suitability in using resources in a limited environment.

However, Mruby also aims to achieve this goal by providing a smaller standard library and offering features for customizing the language runtime. Although reduced in size, Mruby retains many of Ruby's core features, such as dynamic typing. Object-oriented programming has meta-programming capabilities.

Mruby Compiler. This part focuses on the functionality of the Mruby compiler, which is an important part of developing a programming language suitable for use with ESP32. The Mruby compiler, or "mrbc," is a tool that can compile Ruby programs into byte code. The byte-code features are compact and efficient, independent of the device. Thus, compiling Ruby programs using the Mruby compiler tool. This process will produce byte code. The next procedure byte code is executed by the Mruby Virtual Machine (VM). The steps for compiling and executing are shown in Fig. 1. MrubyVM is responsible for executing byte code, managing memory, and arranging the environment for the target device. In general, byte code that is compiled does not depend on the target device architecture because MrubyVM is designed to be able to run byte code on various hardware architectures and operating systems. On the other hand, MrubyVM also needs to be optimized for the device because MrubyVM needs to specify a target device. So the bytecode can be used on another device, but MrubyVM must be optimized for the device.

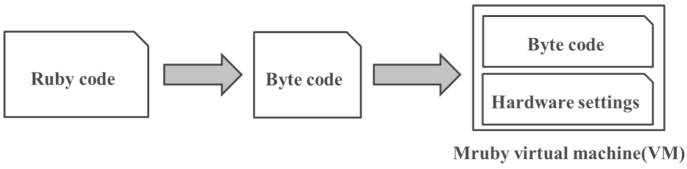

Fig. 1. Mruby compiler

Mrbgems. This part focuses on the capabilities of mrbgems. Mrubgems is a Mruby library that integrates C and Ruby. Which is important in expanding Mruby's functionality and increasing its ability to develop multiple applications. Developers have developed mrbgems with easy-to-use steps and a clear user manual available for download from Github. Therefore, mrbgems has an important function that helps in developing applications. By focusing on the integration of C and Ruby, it extends Mruby's ability to more easily access control of embedded systems, IoT devices, or various hardware architectures.

2.4 Long Range Communication

This section focuses on the use of long-range communication technology to increase the communication and data transmission limits between devices. LoRa is a technology that provides long-range communication and low power consumption. Which is suitable for deployment with IoT systems that require connectivity over extended distances. As mentioned in the Microcontroller section, the ESP32 has a combination of built-in Wi-Fi and Bluetooth connectivity, providing high-speed communication over short to medium ranges that is easy to integrate into local networks and the Internet. But ESP32 still has limitations in terms of communication distance [4]. Therefore, long-range communication technology is a suitable option to increase the communication limit. However, each technology has different strengths and suitability. As shown in the Fig. 2. Therefore, the selection of each technology depends on its suitability for each task, which can be determined by many factors such as range, power consumption, data rates, and usage requirements.

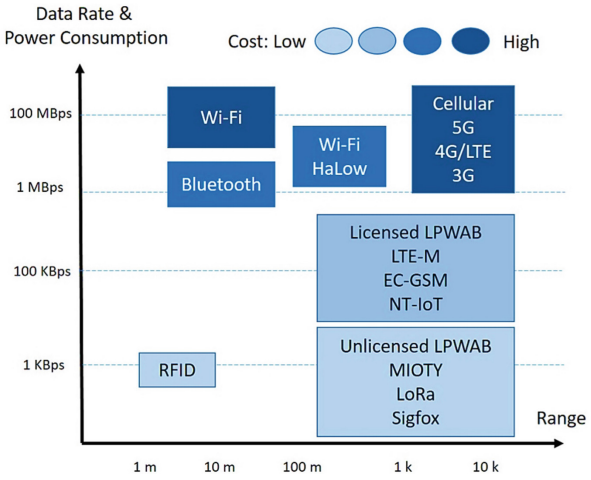

Fig. 2. Comparison between LoRa and other wireless technologies [4]

RYLR896 Lora Module. After studying about long-range communication technology, the RYLR896 module was found to be an appropriate choice. The RYLR896 transceiver module features the LoRa long-range modem, which provides ultra-long-range spread spectrum communication and high interference immunity while minimizing current consumption. The RYLR896 is certified by the NCC and FCC [5].

The RYLR896 module has many functionalities that allow users to design LoRa wireless transceiver applications and to design different network architectures such as "Point to Point", "Point to Multipoint" or "Point to Multipoint". The flexibility of network design is shown in the Fig. 3, the figure shows the structure of network design. Each module can communicate with each other, but only modules that are set to the same network ID can communicate with each other. However, each module's address section prevents communication between data receivers belonging to different groups.

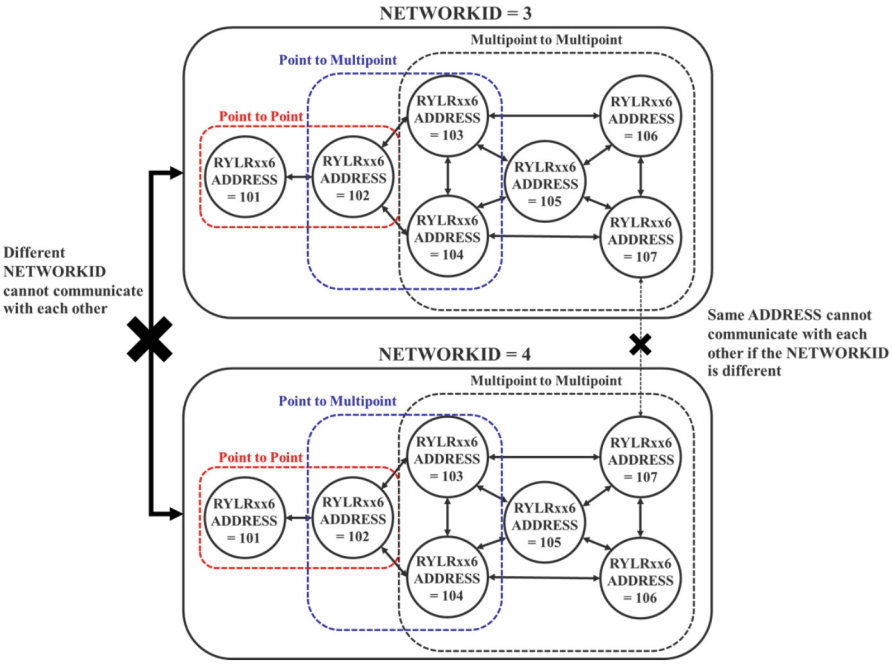

Fig. 3. RYLR896_RYLR406 network structure

Therefore, the LoRa RYLR896 module is an ideal choice for long-range wireless communications applications in IoT applications, providing a balanced range. The module exhibits energy efficiency and facilitates easy configuration.

3 Methodology

This section describes the integration of low-cost and low-power System on a Chip (SoC) microcontrollers called ESP32 which use the object-oriented and scripting programming language Mruby, which was designed specifically for the implementation of an Espresso IoT Development Framework (ESP-IDF)-based microcontroller. Additionally, this section describes the system overview, focusing on the software and hardware design that integrates with Mruby by installing various IoT devices used in the IoT embedded system to design the system to work efficiently. Effective according to requirements.

Furthermore, this section provides a comprehensive overview of the system, with a specific focus on the software and hardware design. Integration with Mruby is achieved by installing various Internet of Things (IoT) devices in the IoT embedded system. The aim is to design a system that functions efficiently and meets the specified requirements.

3.1 Implementing the ESP32 Microcontroller with Mruby

The microcontroller known as ESP32 is employed in the research because of its widespread application and relevance on the Internet of Things and embedded systems. The ESP32 empowers programming developers with a flexible platform by providing a dual-core processor, wireless connectivity, and a variety of embedded application-compatible peripherals. As a result, for developers to integrate the Mruby programming language with ESP32, the ESP-IDF framework, which facilitates application development, must be utilized. The ESP-IDF is the designated development framework for the ESP32. It provides a comprehensive environment for the development of applications based on the ESP32 and includes all the necessary tools and resources.

Another thing to consider is Mruby integration. The integration of Mruby means implementation of a lightweight Ruby programming language into the ESP32 environment. This requires the adaptation of Mruby to the ESP32 architecture in order to optimize Mruby's performance and ensure its compatibility with embedded systems with limited resources. Therefore, the ESP32 environment requires the following three components in order for Mruby to function:

The first component is a virtual machine of Mruby. The runtime environment is the location where the Mruby code is carried out. Mruby scripts are interpreted and executed by the Virtual Machine (VM), which is an embeddable and lightweight framework. By providing an abstraction layer, the virtual machine enables Mruby code to execute on the ESP-IDF framework. It is simple to incorporate the Mruby VM into C and C++ applications. For situations in which scripting capabilities are desired as part of a larger software system, this feature renders it suitable. Due to its compact memory footprint, Mruby is well-suited for environments with limited resources.

The second component can be referred to as 'Collection of Garbage in Increments'. It is a method for modifying unused memory in a program and managing

memory without resulting in significant interruptions in program execution. An important aspect of programming languages

with automatic memory management is garbage collection. To minimize the development of memory leaks and prevent the occurrence of Mruby, Incremental GC possesses the capability to detect and recover unused memory. Furthermore, it effectively manages memory in a manner that is resource-constrained, responsive, and efficient. It enhances the performance and dependability of Mruby applications as a whole, by implementing a system that consistently detects and releases unused memory while the program is running.

The third component is Interface in C library. The software controls the hardware in an embedded system or ESP32 framework using C; therefore, Mruby implementation for ESP32 or embedded systems is significant. A function of Mruby provides support for the C library. The C interface in Mruby serves as an interface between Mruby scripts and C code, allowing for the exchange of data and facilitating integration between the two environments. This includes the management of complex data structures, the passing of arguments, and the return of values. This feature enables Mruby scripts to execute C functions.

As a consequence, upon assembling every component of the Mruby system, which is built upon the ESP32 framework, it becomes apparent that programs can be compiled and executed on the ESP32. One possible application of Ruby language syntax is to instruct the program to display messages according to the user-specified criteria. Concurrently, the written message is displayed on the screen. The outcome, nevertheless, is the compilation and execution of Ruby code on ESP32, which prevents access to ESP32 control as it solely executes and compiles Ruby code. This is the issue that must be resolved in the next phase of Mruby's design in order to access and control the operation of ESP32.

The ability to access the ESP32 library. To get access to implementing the ESP32 library, the most important task in resolving the previously mentioned issue concerning Mruby's design is to establish access to and regulate the functioning of ESP32. Alternatively, one might come up with Mrbgems optimized for ESP32. Mrbgems is a library manager that simplifies the procedure of integrating C and Ruby extensions with Mruby, making it easier to follow standardized and straightforward procedures. Mruby facilitates the interaction and control of ESP32 hardware components and peripherals, including GPIO pins, sensors, actuators, communication interfaces (such as UART, SPI, I2C), and wireless capabilities. Wired technologies, such as Wi-Fi and Bluetooth. As a result, in order to allow Mruby access the functioning of the ESP32, the developer must initially create the architecture of Mrbgems. For example, in order to enable Mruby access the GPIO port of the ESP32, the initial course of action involves creating the Mrbgems directory, an essential structure through which Mruby is able to access the C library. Subsequently, the C library that is approved by the C Interface and lies within the responsibility of the Mruby C function is designed.

3.2 Overview of Systems

This section describes an overview of the system designed by combining hardware and software that have already been designed and developed together. In building IoT embedded systems, it is especially important to take into consideration the system's objectives, efficiency, and reliability. This section focuses on the design and development of IoT embedded systems that work efficiently and reliably.

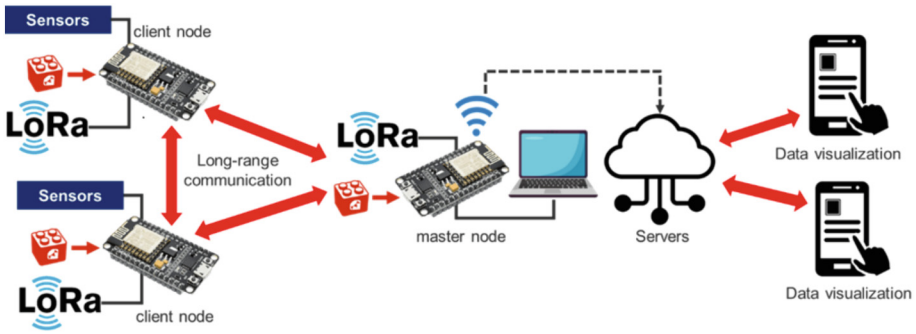

Fig. 4. Overview of the ESP32-designed system's structure

The Fig. 4 provides an overview of the ESP32-designed system's structure, which serves as the prototype structure for the IoT system. This system operates through two separate parts: client nodes and master node, each assigned a specific function. Client nodes have the responsibility of monitoring, collecting data, and controlling electronic devices. The number of client nodes can be more than one node, based on the particular function assigned to each node. For example, the first node is tasked with collecting data from sensors, while the second node is responsible for controlling the other devices in the system. Master node is responsible for remotely combining data from client nodes. Master node is the main node in the system, with the ability to send commands to client nodes. Furthermore, Master node has the capability to establish a connection with Wi-Fi and transmit data to servers in order to display the information collected from client nodes. Additionally, this IoT system possesses the capability to establish communication between client nodes and master node by the utilization of long-range communication technologies, enabling seamless operation within each node.

Consequently, in order to achieve the objective of designing and developing IoT embedded systems, implement the Mruby programming language. The Smart Farm system is a great option due to its excellent compatibility with the designed structure of the system.

3.3 Smart Farm System Design

Smart Farm or Smart Agriculture, refers to the application of advanced technologies to efficiently manage agricultural activities. The entity responsible for collecting, analyzing, and processing data until it achieves a state of automation. Currently, there are many technologies that can be applied to Smart Farm, such as: Greenhouse Automation is a small indoor farm. This technology is used to actively monitor and control the conditions in which plants develop, providing real-time monitoring and control. that can analyze and evaluate many physical characteristics and get access to phenomena of nature[6]. Moreover, artificial intelligence (AI) technology is used to help with data sharing and the management of systems. This technology has the ability to communicate with the Internet of Things, which is accessible in Smart Farm environments, and is efficient in managing and evaluating huge quantities of data [7].

Therefore,the objective of the Smart Farm system is to improve agricultural productivity by increasing crop yields, improving crop quality, reducing unnecessary operational expenses, and increasing profits. In general, the Smart Farm application has multiple functions, including monitoring soil moisture and temperature, controlling water systems, and controlling electrical equipment.

At this point, the objective is to design and develop the Smart Farm system in the form of Greenhouse Automation to operate with optimal efficiency. By expanding the communication limits among nodes, utilizing long-range communication technology, and displaying various data, in order to enhance the reliability of the system. The Fig. 5 provides an overview of the Smart Farm system, which is divided into two parts: the client node and the master node.

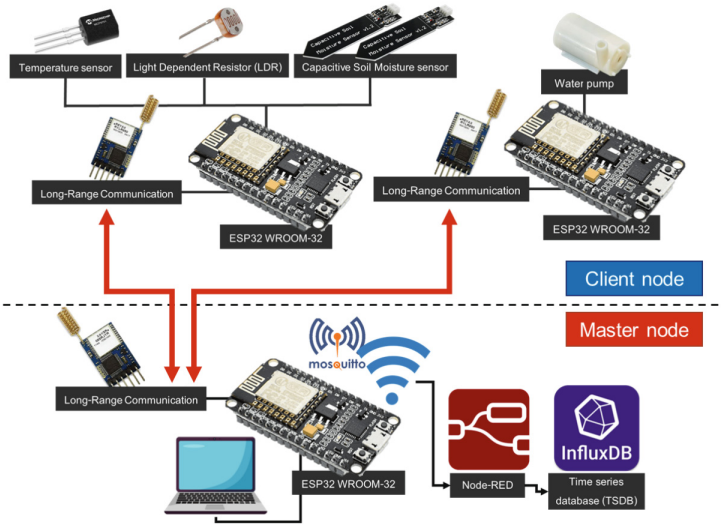

Fig. 5. Overview of the the Smart Farm system

The first part, the client node, has the responsibility of monitoring, collecting data, and controlling the water flow. The client node divides into two sub-nodes. The first node is responsible for measuring the soil moisture, measuring the temperature, and measuring the level of light. The second node is responsible for controlling the water system. Each node has the capability to communicate and send data with other client nodes or master node using long-range communication technology.

The second part, the master node, has the main task of facilitating the transmission of data between client nodes using long-range communication technology. that facilitates long-range communication. Furthermore, master nodes have the capability to establish an internet connection in order to utilize the MQTT protocol for transmitting received data to the time series database (TSDB) via Node-RED. Node-RED is a data bridge that facilitates the transfer of data from MQTT to TSDB. In order to be able to efficiently display information on environmental factors that affect plant growth.

4 Experiments and Results

This section describes an overview of the experiment, which emphasizes the objective of developing a system that can operate with high efficiency. The experiment is divided into two parts: the software and the hardware.

The first part is to carry out a software experiment. The purpose of this part is to evaluate the functionality of the software developed for the Smart Farm system. In general, the software of the Smart Farm system combines with sensors for collecting environmental data. As a result, the software must possess functionalities to facilitate effortless communication with the LoRa module and various sensors such as GPIO, ADC, PWM, UART, Wi-Fi, and MQTT. Each function is designed to be interoperable with Mruby, functioning as a library or Mrbgems.

Listing 1.1 provides a demonstration of utilizing a program in the client node. This node is responsible for monitoring and collecting data. The program utilizes the ADC and LoRa libraries. As shown in Fig. 5, the left client node is connected with four sensors: a temperature sensor, a Light Dependent Resistor (LDR), and two capacitive soil moisture sensors. All of these sensors are connected to the ADC port of the ESP32. Thus, the program operates by utilizing a function to read the analog signal from each sensor and convert it into a digital signal. The signal that is read is a voltage level from 0-3.3 V. Afterwards, the program will send voltage levels to the master node using the LoRa function. The results of the program are shown in Fig. 6.

```
include ESP32::STANDARD
include LORA
lora = LoRa.new NUM_1,25,26,115200
lora.set_node 1,10
lora.set_cmode MODE_1
```

```
while true
    Tv = ADC.read_temp 6
    Tv = Tv.round(2)
    puts "Temp_Volt:#{Tv}V"
    Sv = ADC.sun_check 7
    Sv = Sv.round(2)
    puts "Sun_Volt:#{Sv}V"
    Sr = ADC.soil_R 5
    Sr = Sr.round(2)
    puts "soil_R_Volt:#{Sr}V"
    Sl = ADC.soil_L 4
    Sl = Sl.round(2)
    puts "soil_L_Volt:#{Sl}V"

    Msg = "Sun:"+Sv.to_s+"|"+"Temp:"+Tv.to_s+"|"+"soilL
       :"+Sl.to_s+"|"+"soilR:"+Sr.to_s
    lora.send 3,Msg.to_s
    sleep 15
end
```

Listing 1.1. Demonstration of using the program in the client node

```
######################################################################
Temp_Volt : 0.81V
Sun_Volt : 1.65V
soil_R_Volt : 2.03V
soil_L_Volt : 1.86V
LoRa send : AT+SEND=3,40,Sun:1.65|Temp:0.81|soilL:1.86|soilR:2.03
######################################################################
Temp_Volt : 0.8V
Sun_Volt : 1.64V
soil_R_Volt : 2.02V
soil_L_Volt : 1.85V
LoRa send : AT+SEND=3,39,Sun:1.64|Temp:0.8|soilL:1.85|soilR:2.02
######################################################################
Temp_Volt : 0.81V
Sun_Volt : 1.65V
soil_R_Volt : 2.01V
soil_L_Volt : 1.85V
LoRa send : AT+SEND=3,40,Sun:1.65|Temp:0.81|soilL:1.85|soilR:2.01
######################################################################
```

Fig. 6. the result of the client node program

The second part involves carrying out a hardware experiment. The purpose of this section is to evaluate the system's ability to function efficiently within the Smart Farm system. This section emphasizes the incorporation of embedded systems that are capable of accurately responding to and collecting data from each device, as will be further described in the Application section.

4.1 Application

This section describes the details of the test procedure performed on the system. Therefore, from Fig. 5 presents an overview of the Smart Farm system, dividing it into two main parts: the client node and the master node.

The task of client nodes is to monitor, collect information about the conditions that affect the growth of plants, and control the water flow. Figure 7 provides the installation of two client nodes for the task of collecting data from the real-world environment. Through performing experiments to collect data from small garden plants. The operation of the first node is used to collect data from three types of sensors. The first sensor, which is the temperature sensor, is tasked with measuring the temperature and recording any variations in temperature. The second sensor, known as the Light Dependent Resistor (LDR), is responsible for measuring the intensity of light in real time. To record the illumination level. The third sensor, the capacitive soil moisture sensor, is utilized for measuring the moisture level in the soil. To determine the suitability of the soil moisture for plant growth. Furthermore, the second node has the additional responsibility of controlling the water system by adjusting the water flow according to the soil moisture measured by the soil moisture sensor. In order for this node to control the flow, this node needs to wait for commands from the master node.

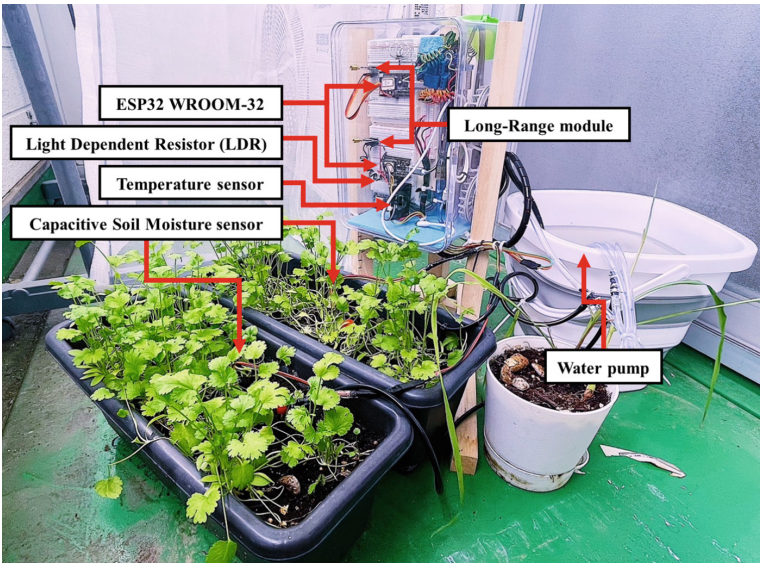

Fig. 7. The installation of client nodes to collect data from small garden plants.

Finally, the client node prepares the data received from the three sensors, and all the data is organized in string format. Subsequently, the client node will

transmit data regarding temperature, light intensity, and soil moisture through the LoRa module. The LoRa module will transmit data to another LoRa module installed on the master node. Figure 8 provides the transmission of data between the client node and master node using the LoRa module.

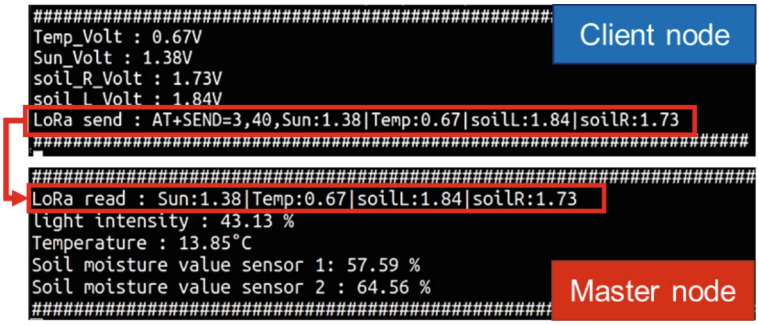

Fig. 8. the transmission of data between nodes using the LoRa module

According to Fig. 8, when the master node receives data from the client node, the program will separate the data into three categories: temperature, light intensity, and soil moisture. Furthermore, the data had been organized in order to calculate light intensity and soil moisture as percentages, which would simplify the process of analyzing the data. Subsequently, the program will make the necessary preparations to transmit the data to the next step, which is to visualize the data on InfluxDB. InfluxDB is a time-series database designed for the purpose of storing and analyzing time series data. It is especially suitable for applications that involve monitoring and recording sensor data in Internet of Things (IoT) systems.

In order to transfer data to InfluxDB, Therefore, utilize the MQTT protocol function to publish data to the MQTT Broker and subscribe a topic by Node-RED. Node-RED is a web-based visual programming tool that enables users to create flow designs and integrate them with various systems. At this point, the main function of Node-RED is to interact with InfluxDB by sending data from Node-RED to InfluxDB for visualization of the data. The data visualization results are provided in Fig. 9. In this figure, the InfluxDB will display a time series of data showing measurements of soil moisture, temperature, and light intensity. These measurements are collected using a temperature sensor, a Light Dependent Resistor (LDR), and two capacitive soil moisture sensors. The data from each sensor will be shown in the form of a line graph and a gauge view. The line graphs display time-series changes in measurement data from several sensors. Users can easily realize this by observing changes in the graph. Moreover, the gauge view represents only the latest data for a time series. The gauge view provides a visual representation of the gauge at scale and allows for customization, making it easy to understand current data.

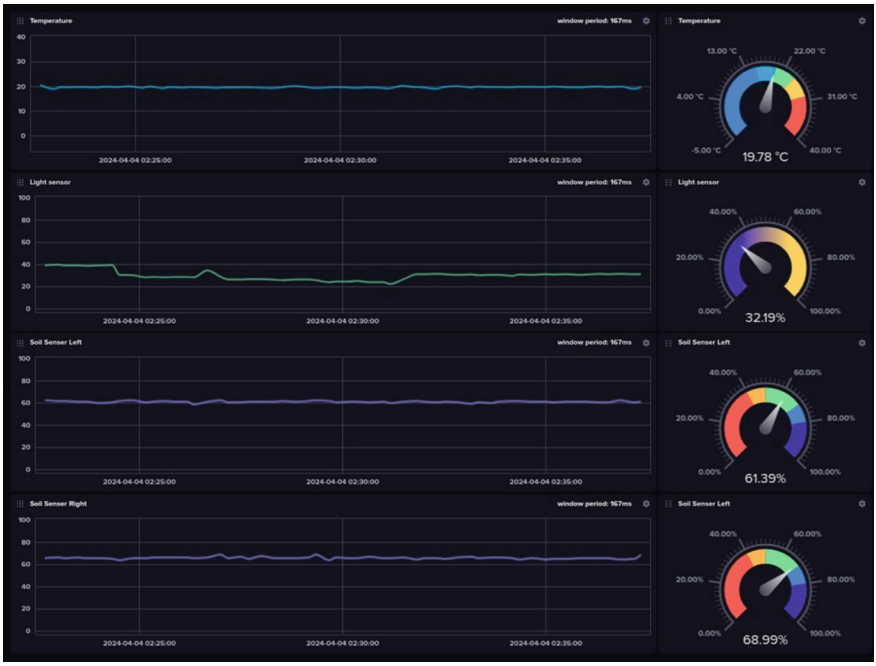

Fig. 9. Visualization of data with InfluxDB

5 Conclusion

This paper presents the design and development of an embedded system with long-range communication technology designed for the Internet of Things (IoT), with a focus on using it in Smart Farm systems. The operation of the Smart Farm system is able to monitoring, collecting, and visualizing environmental data that affects plant growth.

Additionally, the system's software has been implemented with Mruby because of its compactness and optimization for use cases with limited memory and processing power. Mruby's design specifically caters to embedded systems. However, Mruby maintains the features and syntax of Ruby, facilitating users ability to write simple scripts using Ruby's syntax. Thus, using Mruby to program embedded systems is an alternative choice for users.

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Geomatics for Resource Monitoring and Management (GRMM 2024)

Estimating Urban Growth from Landsat 8 Data Using Post-classification and Albedo Change Analysis in GEE Environment

Carlo Barletta, Alessandra Capolupo(✉), and Eufemia Tarantino

Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Politecnico di Bari, Via Orabona 4, 70125 Bari, Italy
{carlo.barletta,alessandra.capolupo,eufemia.tarantino}@poliba.it

Abstract. Urban growth, defined as the increase of artificial surfaces in cities or towns, is now considered critical for the environmental impacts it can generate. Mapping and monitoring the soil sealing phenomenon provides researchers, planners and decision-makers with useful information for sustainable development. Moreover, Earth observation remote sensing images, such as medium-resolution Landsat data, is widely adopted for short to long term urban change analysis. The aim of this paper is to extract information on land consumption occurred on urban areas (period 2015–2023) from Landsat 8 data using GEE cloud platform. The territory of the municipality of Bitritto, in Apulia region (Italy), was chosen as the study site. To achieve the objective of this work, a change detection approach, including both "post-classification comparison" and "image differencing" methods, was applied. To classify Landsat 8 multispectral images into a binary scheme ("urban areas" and "non-urban areas"), a decision tree approach using STRed and SwiRed indices, NIR/SWIR2 ratio and NIR band was developed and implemented in GEE environment. The "image differencing" step was, instead, performed by subtracting two land surface albedo maps, obtained from winter Landsat 8 images, for the two reference years. A neighborhood filter to remove isolated "changed" pixels was also applied to improve the outcome. The results were promising (P.A. 85% and U.A. 77% for the "urban growth" category, with an O.A. of 92%) even though some misclassifications were identified, probably due to "mixed" pixels or to some spectral confusion among certain land cover classes.

Keywords: Land consumption · Earth observation · change detection · soil sealing

1 Introduction

The urbanization process, which transforms natural landscapes into artificial areas, is recognized as one of the main drivers of land use and land cover (LU/LC) changes worldwide. The increase in man-made surfaces (such as rooftops, roads, parking lots, and so on) as a result of the construction of new buildings, transportation networks or other layers of totally or partly impermeable materials (i.e. concrete and asphalt) leads

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to the "soil sealing" phenomenon (understood as the covering of soil with impervious surfaces), which is now considered a serious environmental threat. Indeed, soil sealing affects several issues, including urban runoff, heat island effect, water and soil pollution, and biodiversity loss [1–5].

Detailed monitoring of LU/LC and urban growth provides valuable information for a sustainable land management. In particular, mapping the amount of impervious surfaces and detecting their changes over time through multi-temporal analyses helps planners, managers and researchers to understand urban patterns and processes and to assess the effectiveness of current policies in addressing the negative impacts of soil sealing.

Remote sensing data are well suited to acquire continuous information on the land surface at local, regional and global scales, and, also, over short to long time periods [1–6]. In addition, LU/LC changes can be detected and quantified from multi-date satellite observations that allow to measure the shift over time in biophysical variables such as the land surface albedo, which represents the proportion of solar radiation reflected from the Earth surface. For example, since more solar radiation is absorbed by vegetation, deforestation can be detected from albedo increase [7–12].

Various techniques have been developed over the years to perform change detection analyses from multi-temporal satellite images, including "image differencing", "image ratioing", "image classification and post-classification comparison", "change vector analysis", "image regression", and so on [6]. "Image differencing" and "image ratioing" between multi-temporal images are effective for a quick and quantitative assessment of changes but are limited by the difficulties in interpreting different type of LU/LC transformation characterized by similar reflectance change. "Image classification and post-classification comparison", consisting, instead, in comparing multi-date LU/LC classified maps on a pixel-by-pixel basis, is a simple, effective, and very used method but it suffers from the error propagation from the independently classified maps. "Change vector analysis" measures the magnitude and direction of change but it is challenged by multi-temporal illumination differences and the presence of noise in the result. Lastly, "image regression" method can provide better results than simple "image differencing"; however, its application suffers from non-stationary relationships (typical in geographical data) in the spatial structure of data [6, 13, 14].

These techniques have been largely tested on satellite images provided by multispectral platforms. However, Landsat mission appears as an optimal solution to address such issues since it is the only source of free images acquired in more than 50 years with a geometric, spectral and temporal resolution adapt for urban analysis. Hence, Landsat multi-decadal observations of the Earth surface are among the most suitable for short to long-term analysis of environmental and land changes like, for example, forest cover and biodiversity changes, or the expansion of urban areas [3, 6, 15–18].

The rise of geospatial big data in recent years leads to different challenges such as difficulties in their acquisition, storage, visualization, processing and analysis. To overcome these problems, cloud-based platform, such as Google Earth Engine (GEE), have been introduced to speed up the operations and provide better access to the data [3, 7, 19–22].

The objective of this research is to quantify the expansion of urban areas using Landsat 8 (L8) satellite data from 2015 to 2023. This is achieved through the development

of a hierarchical model integrating the index-based method for LU/LC extraction and albedo change analysis. A custom JavaScript code was created and implemented within the GEE platform to facilitate this analysis. The municipality of Bitritto, located in southern Italy, was selected as the pilot site for testing such a methodology.

2 Materials and Methods

This section describes the materials and methods used in this research. Moreover, Sect. 2.1 briefly introduces the study area of Bitritto, while Sect. 2.2 provides information on the GEE cloud platform and the satellite data selected. Subsequently, Sects. 2.3, 2.4 and 2.5 present, respectively, the LU/LC classification and post-classification comparison phase, the image differencing and isolated pixel phase, and the algorithm for the land surface albedo estimation. Lastly, in Sect. 2.6 is described the method for the accuracy assessment of the urban change map.

To accomplish the objective of this study, a combined approach using two widely recognized change detection methods "image classification and post-classification comparison" and "image differencing" was employed. The proposed methodology consists of four main steps:

- initially, cloud-free L8 images for each reference year underwent classification. This classification involved a hierarchical method involving SwirTirRed (STRed) and SwiRed indices, near infrared (NIR)/shortwave infrared band 2 (SWIR2) ratio, and the NIR band;
- subsequently, the resulting classified maps underwent a pixel-by-pixel comparison;
- areas identified as potential changes from "non-urban" to "urban" underwent further analysis using the "image differencing" method. This entailed comparing two land surface albedo maps, derived from single 2015 and 2023 winter L8 images. To enhance accuracy, appropriate thresholds were established to eliminate false "changed" pixels;
- lastly, a filtering process was implemented on the final "urban change map" to eliminate isolated "changed" pixels and refine the results.

This methodological approach integrates both classification and change detection techniques, offering a comprehensive analysis of urban growth dynamics over time. This approach is synthetically represented in Fig. 1.

After collecting the L8 Surface Reflectance (SR) and raw satellite images dated 29 August 2015 and 19 August 2023 from the GEE data catalogue, the LU/LC maps were obtained using the decision tree algorithm detailed in Sect. 2.4.

The extracted classes were then aggregated in binary maps to delineate "urban" and "non-urban" areas and, the "post-classification comparison" method was applied. Subsequently, the "image differencing" method was applied to the resulting potential "changed" pixels (transitioning from "non-urban" to "urban") to refine change detection, thereby eliminating false "changed" areas attributed to misclassifications present in the 2015 and 2023 LU/LC maps.

To this purpose, two winter Top-Of-Atmosphere (TOA) L8 images, acquired on 18 February 2015 and 24 February 2023, were used to retrieve the land surface albedo

maps. Therefore, after subtracting the 2015 from 2023 albedo maps and defining an appropriate threshold representing significant changes in LU/LC, this phase effectively identified and removed several false "changed" areas.

Lastly, a filter to remove isolated pixels was applied to improve the final change map.

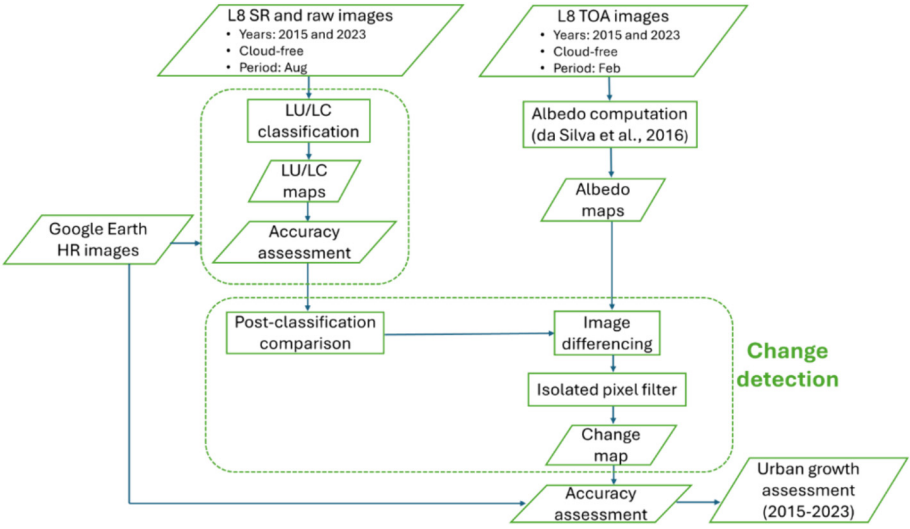

Fig. 1. Workflow. HR: High-resolution.

2.1 Study Area

The territory of the municipality of Bitritto (Fig. 2), in southern Italy, was selected as study site. This area of about 18 km^2, part of the Metropolitan City of Bari, in the center of the Apulia region, is characterized by a mainly flat topography and a land cover with a high proportion of agricultural fields or other green spaces and a relatively low proportion of built-up land. Nevertheless, like many other areas in the region, it has experienced significant land consumption in recent decades. The climate of Bitritto is Mediterranean, with hot and dry summers and mild winters [25–27].

2.2 GEE Platform and Input Data

The present work was carried out in GEE cloud platform. GEE consists of a high-performance computing service connected with a multi-petabyte data catalog of Earth observation imagery (including Landsat raw and preprocessed data), with an interactive environment for rapidly storing, managing and processing a large volume of geospatial data. The available Application Programming Interfaces (APIs) are JavaScript and Python [7, 19, 21–23]. In particular, the JavaScript interface was chosen for this study.

Table 1 highlights the data selected for this study. Cloud-free SR and raw L8 satellite images, for the reference years 2015 and 2023, acquired in the summer period,

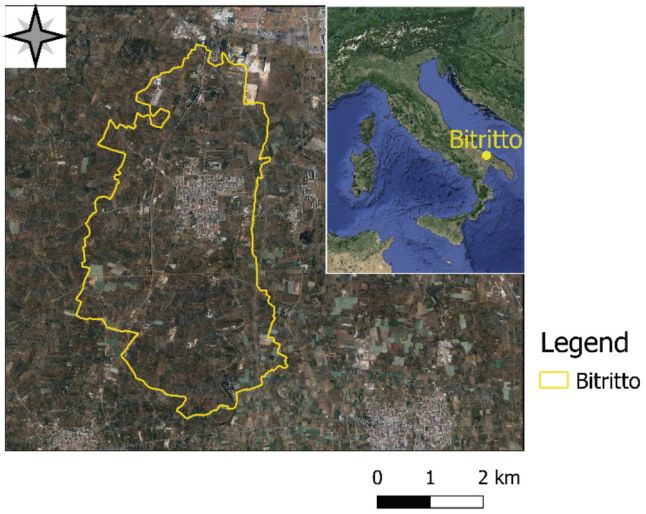

Fig. 2. Study area.

were selected from the GEE data catalogue. These images were used for the LU/LC classification of the study site, as elaborated upon in subsequent sections.

Moreover, the analysis of two additional high-resolution images available in Google Earth Pro [28], encompassing the study area and acquired on 29 August 2015 and 27 April 2023, respectively, proved beneficial for selecting training and testing pixels for the LU/LC classification, as well as for the accuracy assessment of the maps.

Finally, one TOA winter L8 image was selected for each reference year to compute land surface albedo maps. These maps were then used for the "image differencing" change detection phase, as discussed in Sect. 2.5.

Table 1. Selected data. HR: High Resolution.

ID	Data	Period	Phase
1	L8 SR and raw images	29 Aug 2015	LU/LC classification
2	L8 SR and raw images	19 Aug 2023	LU/LC classification
3	Google Earth HR image	29 Aug 2015	Training stage and validation
4	Google Earth HR image	27 Apr 2023	Training stage and validation
5	L8 TOA image	18 Feb 2015	Albedo computation
6	L8 TOA image	24 Feb 2023	Albedo computation

2.3 Image Classification and Post-classification Comparison

In this study, a decision tree LU/LC classification was developed and implemented in GEE cloud environment by writing a proper JavaScript code.

The chosen classification scheme includes four LU/LC categories to be discriminated: "vegetation", "plastic greenhouses", "urban areas" and "bare soil".

The method proposed (Fig. 3) implies the sequential application of three binary decision rules including the STRed and SwiRed spectral indices (developed for the Landsat Image Classification Algorithm [LICA] in 2020 [23]), the NIR/SWIR2 ratio and the NIR band. Therefore, the LU/LC classes were distinguished in the following order: 1) "vegetation" (using STRed, SwiRed and NIR band), 2) "plastic greenhouses" (using NIR/SWIR2 ratio and NIR band), and 3) "urban areas" and "bare soil" (using SwiRed).

The STRed and SwiRed indices are expressed as follows:

$$STRed = \frac{SWIR1 + Red - TIR1}{SWIR1 + Red + TIR1}, \tag{1}$$

$$SwiRed = \frac{SWIR1 - Red}{SWIR1 + Red} \tag{2}$$

where SWIR1, Red and TIR1 are Landsat shortwave infrared band 1, red band and thermal infrared band 1, respectively [23].

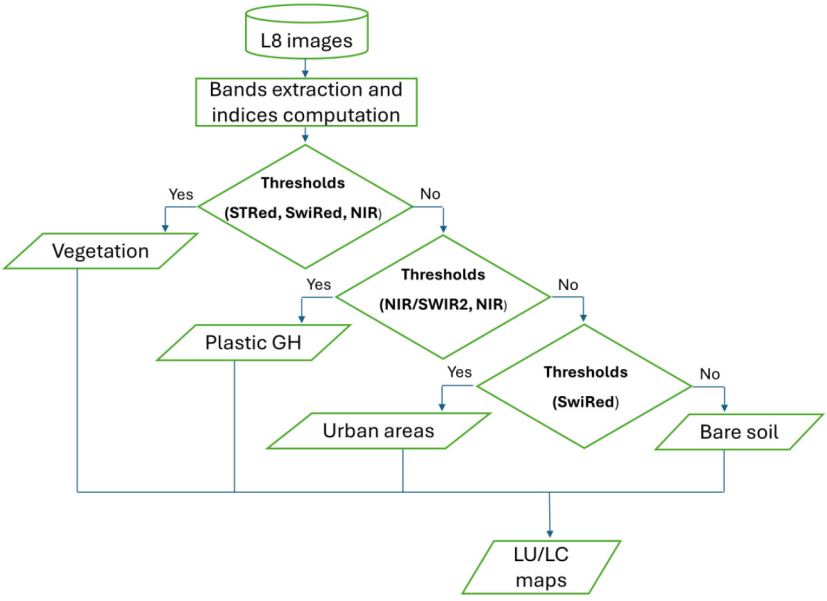

Fig. 3. Flowchart of the algorithm for the LU/LC classification.

A consistent number of training pixels for each of the four LU/LC categories were selected on Landsat 8 SR images. The visualization of Google Earth high-resolution

images, available in Google Earth Pro [28], was very useful to correctly distinguish each category on the ground.

Average spectral signature plots (Fig. 4) were then retrieved in the GEE platform:

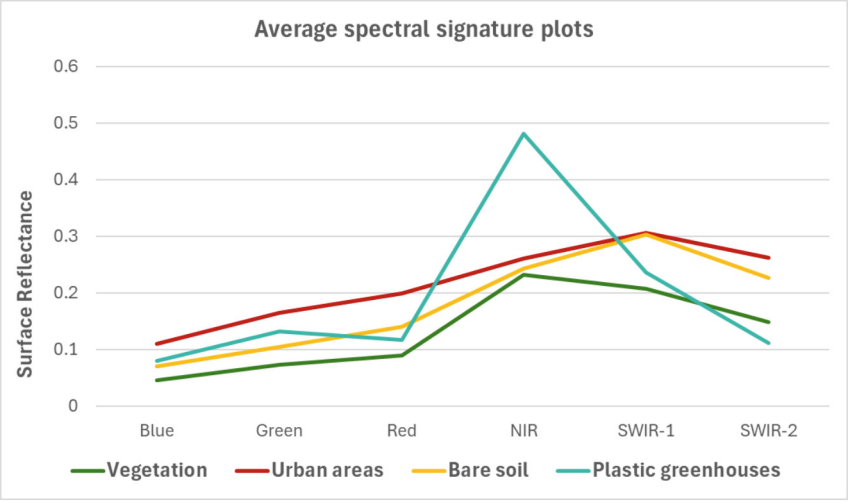

Fig. 4. Average spectral signature plots for training pixels of "vegetation", "urban areas", "bare soil" and "plastic greenhouses" categories obtained from Landsat 8 SR images for the study area of Bitritto.

A scatter diagram between STRed and SwiRed indices (Fig. 5) was obtained to analyze the separability of the four thematic classes and to choose suitable thresholds for the decision rules. This analysis suggested the selection of SwiRed thresholds (used in LICA [23] only for extracting built-up areas) to better discriminate the "vegetation" class (including both sparse and dense vegetated areas) from other categories, in addition to the STRed index (already adopted in LICA [23] for the vegetation extraction).

Moreover, in order to extract the "plastic greenhouses", the analysis of Fig. 4 suggested that the NIR and SWIR2 bands could be the most suitable for identifying them with a good accuracy, due to the relative reversal of their spectral response for these bands compared to those of the other three classes. The scatter diagram between NIR and SWIR2 confirmed this hypothesis, as shown in Fig. 6, where the spectral separability of plastics from the other categories is very evident.

Therefore, thresholds of NIR and NIR/SWIR2 ratio from Landsat 8 SR images were set to extract the "plastic greenhouses" LU/LC category.

After distinguishing "vegetation" and "plastic greenhouses", the SwiRed index was applied on Landsat 8 SR images to discriminate the "urban areas" class (including the LICA "built-up" and "mining areas" categories). Finally, the remaining part of the images was classified as "bare soil".

The resulting classified maps were then aggregated into a binary map containing only "urban areas" and "non-urban areas" categories (the latter resulting from the aggregation

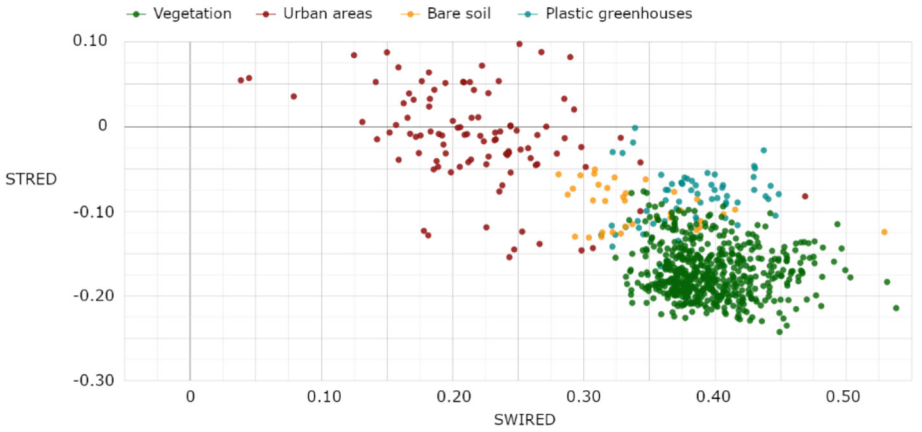

Fig. 5. Scatter diagram (STRed/SwiRed) for training pixels of "vegetation", "urban areas", "bare soil" and "plastic greenhouses" categories obtained from Landsat 8 SR images for the study area of Bitritto.

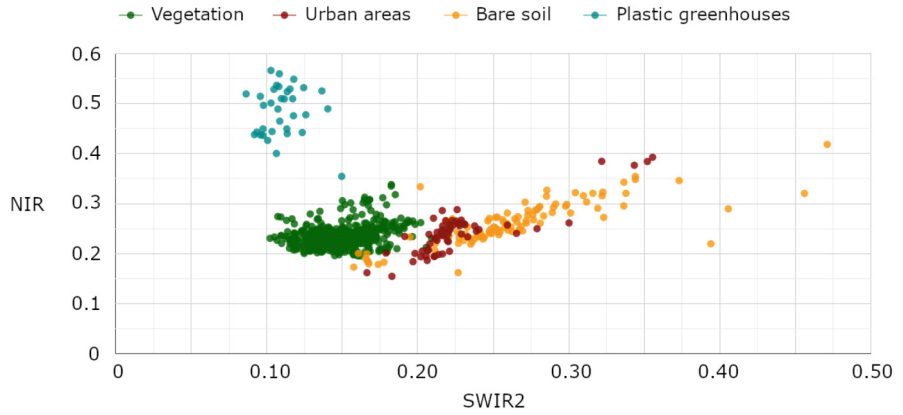

Fig. 6. Scatter diagrams (NIR/SWIR2) for training pixels of "vegetation", "urban areas", "bare soil" and "plastic greenhouses" categories obtained from Landsat 8 SR images for the study area of Bitritto.

of "vegetation", "plastic greenhouses" and "bare soil"), in order to perform the change detection and the evaluation of the urban growth (2015–2023).

After aggregating the 2015 and 2023 LU/LC maps into a binary classification scheme ("urban areas" and "non-urban areas"), the two resulting maps (the "soil sealing maps") were compared pixel-by-pixel. In this way, the possible outcomes were "no change" (in case of the same classification in both 2015 and 2023 maps) or "change" (for pixels classified differently in 2015 and in the 2023 map).

2.4 Image Differencing and Isolated Pixel Filter

After the post-classification comparison, for the resulting "changed" pixels (specifically, for pixels changed from "non-urban" in 2015 to "urban" in 2023), the "image differencing" method was applied calculating the difference images between the two land surface albedo maps, estimated from single cloud-free L8 TOA winter images (acquired on 18 February 2015 and on 24 February, respectively, for the reference years 2015 and 2023). A suitable threshold of albedo change, possibly representative of significant LU/LC changes, from "non-urban" to "urban", was found. Late winter imagery was preferred over other seasons because changes from bare or sparsely vegetated land to built-up areas may be most apparent due to the higher moisture content and green cover (resulting in lower albedo value) of the former in this season, since higher rainfall during the autumn/winter period is typical for the climate of the study area [26, 33–39]. Therefore, an increase in albedo, from 2015 to 2023 images, could be a sign of a land cover transformation from non-artificialized land to urbanized land (urban growth) [40–42].

After the "image differencing" phase, a connected neighbors filter to remove isolated "changed" pixels was implemented in GEE to further clean the change map from remaining misclassifications, and to obtain the "urban change map" (2015–2023), representing two categories: "urban growth" and "no growth".

2.5 Albedo Estimation

The land surface albedo maps were retrieved by applying the da Silva et al. algorithm (2016) [24], developed specifically for Landsat 8 data, expressed as follows:

$$\alpha = \frac{(\alpha_{TOA} - \alpha_{ATM})}{\tau^2} \tag{3}$$

where α_{TOA} is the TOA albedo, computed on Landsat 8 TOA reflectances, α_{ATM} is the atmospheric albedo, which was set equal to 0.03 as discussed in [19], and τ^2 is the square of the atmospheric transmissivity for shortwave radiation [19, 24, 33, 43]. The value of α_{TOA} is calculated with the following equation:

$$\alpha_{TOA} = p_2 * Blue + p_3 * Green + p_4 * Red + p_5 * NIR + p_6 * SWIR1 + p_7 * SWIR2 \tag{4}$$

where p_i are weighting coefficients [24, 33].

2.6 Accuracy Assessment of the Urban Change Map

To evaluate the accuracies of the classified maps, a multi-temporal dataset of test pixels was generated using the stratified random sampling method. A total number of 245 "pure" pixels were selected, according to the extent of each class, in the following proportions: 140 for "vegetation", 55 for "urban areas", 30 for "bare soil" and 20 for "plastic greenhouses". A visual interpretation of the high-resolution Google Earth images, chosen as "reference" data, was performed to assign each sample pixel to the correct category, based on its location. The metrics calculated to assess the accuracy were overall accuracy (O.A.), producer accuracy (P.A.), and user accuracy (U.A.) [19, 25–28].

To evaluate the accuracy of the change map, which shows the land consumption occurred in Bitritto for the period 2015–2023, a dataset of 100 test pixels, representing "urban growth" and "no growth", was obtained with the stratified random sampling method, after the visual interpretation of the multitemporal high-resolution Google Earth images [28]. According to the extent of each class, the pixels were selected in the following proportions: 20 for "urban growth" category, and 80 for "no growth" class. The metrics calculated to evaluate the accuracy were O.A., P.A. and U.A.

3 Results and Discussion

In this section, Sect. 3.1 presents and discusses the results of the LU/LC classification obtained from the decision tree approach described in Sect. 2, while Sect. 3.2 presents and discusses the results of the change detection method applied to extract the urban growth map (2015–2023) for the Bitritto study area.

3.1 LU/LC Classification Maps and Accuracy Assessment

The LU/LC maps, retrieved for the years 2015 and 2023 in GEE after applying the method described in Sect. 2.4, are shown in Fig. 7. The accuracy metrics, instead, obtained for the validation of the thematic maps, are reported in Table 2.

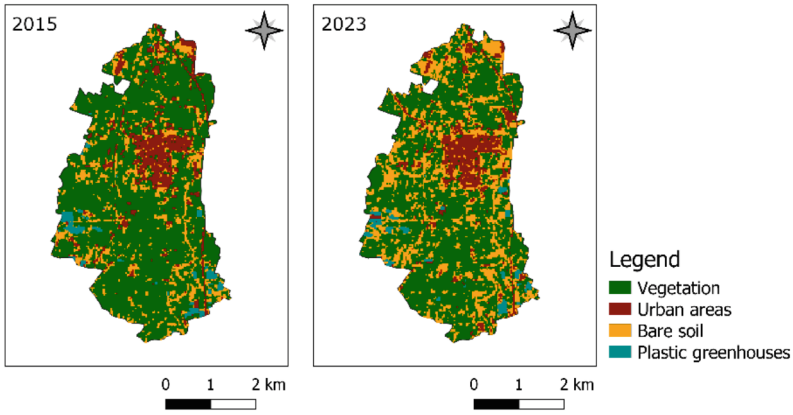

Fig. 7. LU/LC maps of 2015 and 2023 for the study area.

The analysis of the accuracy metrics highlights that the O.A. was quite high for both classification maps (about 90%), while plastic greenhouses and vegetation were those classes with both O.A. and U.A. higher than 90%. The extraction of urban areas was very good with P.A. accuracies of 85% and 84% for 2015 and 2023, respectively, while the U.A. accuracies were very high totaling 98% in 2015 maps and 96% for the 2023 classification. Lower accuracies characterize, instead, the bare soil extraction (P.A. $>$ 70% and U.A. $>$ 55%).

Table 2. Accuracy metrics for the LU/LC maps.

	2015		2023	
LU/LC class	P.A. [%]	U.A. [%]	P.A. [%]	U.A. [%]
Vegetation	95	92	93	94
Urban areas	85	98	84	96
Bare soil	70	64	73	56
Plastic greenhouses	100	100	95	100
O.A. [%]	90		89	

3.2 Change Detection

The 2015 and 2023 LU/LC maps were subsequently aggregated into a binary classification (where the two classes are: "non-urban areas" including vegetation, bare soil and plastic greenhouses, and "urban areas"). The "soil sealing maps" obtained after this aggregation are shown in Fig. 8. The visual analysis of these outcomes suggests that, probably, only little changes occurred in the period 2015–2023.

To estimate the urban growth, a "post-classification" comparison change detection was first performed between these maps. Since some misclassifications are present in both outcomes, this step was not sufficient to detect the land consumption with a good accuracy. Therefore, a second step ("image differencing" between two albedo maps retrieved from winter images, as explained in Sect. 2.5), and a third step consisting in a filter of isolated "changed" pixels, was necessary.

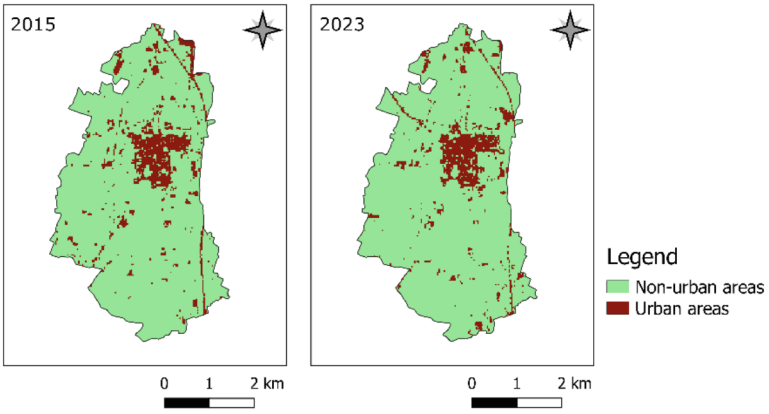

Fig. 8. Soil sealing maps of 2015 and 2023 for the study area.

Figure 9 show the land surface albedo maps retrieved by applying the da Silva et al. (2016) algorithm [24].

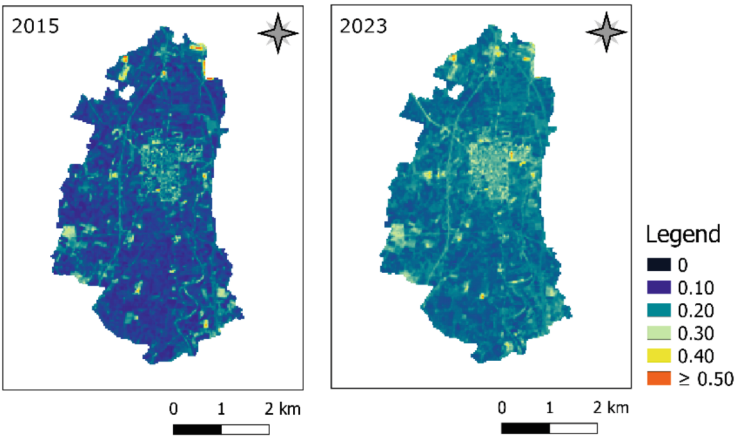

Fig. 9. Land surface albedo maps of 2015 and 2023 for the study area.

These two images were subtracted in the GEE platform, and an albedo increase greater than 0.055 between 2015 and 2023 was selected as the threshold for the urban growth detection.

Finally, a filter to eliminate isolated changed pixels were applied to further improve the outcome.

The final "urban change map", obtained using the change detection approach described above, is shown in Fig. 10, while the accuracy metrics for the change map are reported in Table 3.

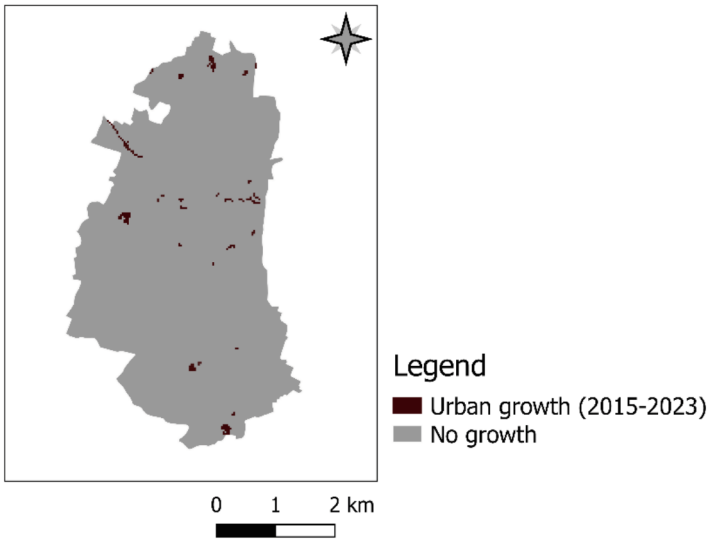

Fig. 10. Urban change map 2015–2023 for the study area.

Table 3. Accuracy metrics for the urban change map.

	2015–2023	
Class	P.A. [%]	U.A. [%]
Urban growth	85	77
No growth	94	96
O.A. [%]	92	

From Table 3 it can be noticed that the O.A. for the urban change map was high (92%). Regarding the estimation of the "urban growth" (2015–2023), satisfactory results were found, with a P.A. of 85% and a U.A. of 77%. Moreover, the analysis of the map confirms that the land consumption for the Bitritto study area is moderate for the period 2015–2023. However, a few mis-changed areas are still present in the map, probably due to the "mixed" pixels issue (typical for the classification of medium-resolution images [2, 44], such as Landsat data) or to the little spectral confusion that persists among certain classes (in particular, between "urban areas" and "bare soil").

The methodology proposed in this study, developed for free and open medium-resolution Landsat satellite data, provided, therefore, promising results in terms of automatically extracting information on land consumption occurring at the urban scale. The high values of the accuracy metrics, obtained for the change map, suggest that it could be reasonably applied in the future to contribute, thanks to its relative simplicity and feasibility, to the rapid monitoring of urban development and the soil sealing phenomenon, both at regional and local levels.

4 Conclusion

The increase in artificialized surfaces caused by urbanization has a direct impact on many environmental issues (i.e., the soil sealing phenomenon) [1, 4, 5, 27, 44].

Remote sensing data are very useful for mapping impervious surfaces and estimating urban growth using various techniques [4, 6]. In particular, Landsat medium-resolution multispectral imagery has been widely adopted to identify land cover transformations, such as detecting the expansion of artificial areas [15, 16, 19, 45, 46].

In this work, it has been possible to extract land consumption information for the study territory of Bitritto, in the central Apulia region (Italy), from 2015 to 2023, where a moderate soil consumption was found to have occurred during the period considered.

A combined approach between a "post-classification comparison" among two LU/LC maps (obtained through an index-based decision tree approach) and the "image differencing" of late winter albedo maps, retrieved from Landsat 8 data, provided satisfactory results in terms of accuracy of the urban growth map.

Furthermore, the GEE platform, used in this study to minimize the acquisition and operational time required for satellite image processing (thanks to cloud technology), was confirmed to be optimal for analyzing and monitoring the evolution of land surface features [7, 47, 48].

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Exploiting Medium-Resolution Sentinel Data in Google Earth Engine for Burned Area Reflectance Classification

Alessandra Capolupo(✉), Pietro Marco Santoro, and Eufemia Tarantino

Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Politecnico di Bari, Via Orabona 4, 70125 Bari, Italy
alessandra.capolupo@poliba.it

Abstract. To analyze and forecast changes triggered by a fire in a natural ecosystem, it is critical to look into the extent of specific traceable physical indicators, such as fire intensity, fire severity, and burn severity. Previous research has shown that Earth observation data plays an important role in quickly assessing burnt regions. Despite several technological constraints, especially related to geospatial and temporal resolution, these data enable the development of burned area reflectance categorization maps with a strong correlation with ground-truth fire severity. Thus, this research is aimed at investigating the damages induced by fire in two Apulian municipalities (Bitonto and Vico del Gargano) by exploiting the potentialities of Sentinel images. To accomplish this purpose, a custom JavaScript code was created in the Google Earth Engine environment to calculate two indices: the Delta Normalized Burn Ratio (dNBR) and the Relativized Burn Ratio (RBR). The resulting thematic maps' accuracy was assessed using both the ground truth given by the European Forest Fire Information System (EFFIS) and those obtained by applying a photointerpretation technique. Both indices performed well in extracting burnt regions using the two ground-truth datasets, even though EFFIS perimeters had low-quality categorization, indicating poor data accuracy. Nonetheless, in both situations, RBR outperformed dNBR, and hence may be suggested as a reliable method for swiftly quantifying burnt zones. Finally, the Javascript code could be easily transferred to handle data from multiple research zones based on geographical location and size. Google Earth Engine appears to be a feasible option for storing and processing a large amount of geospatial big data.

Keywords: Burn Severity · Delta Normalized Burn Ratio (dNBR) · Relativized Burn Ratio (RBR) · European Forest Fire Information System (EFFIS) · Copernicus Program

1 Introduction

Natural and built environments have always been affected by fires. To some researchers, such as Stephen Pyne [1], fire is an important natural process that regenerates and boosts biodiversity, contradicting the common conviction that all fires are negative. By

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releasing nutrients into the soil, controlled burns can allow certain plants to thrive [2, 3]. Additionally, sometimes they may prevent invasive species from growing by enabling their native counterparts to flourish [4, 5]. However, large forests can be destroyed due to wildfires, resulting in the loss of habitats and the extinction of several organisms found therein [6, 7]. These flames also destroy houses and infrastructure, and they could bring huge suffering to those who live nearby, socially and economically [8, 9]. This implies that uncontrolled bushfires should be monitored so that intervention measures happen at the right time.

To properly plan and execute maintenance and restoration strategies, accurate data is essential for evaluating and monitoring the extent and severity of fire damage in real-time whenever possible [10]. Initially, such data was primarily collected through ground-based methods, which often imposed limitations on the scope and reliability of assessments. However, recent advancements in remote sensing technologies have overcome these constraints, revolutionizing the ability to gather critical data on a global scale. Transitioning from field measurements to remote sensing and modeling introduces various challenges in assessing burn severity. Within remote sensing, a range of data types, including optical, RADAR, LiDAR, and methodologies for evaluating burned areas, exists [11]. Among them, multispectral missions provide a continuous stream of images that allow for monitoring the location and behavior of fires, as well as the assessment of burn severity and post-fire impacts on vegetation and ecosystems [11]. These images are typically used to generate a burn severity map of conditions on the ground, which can be referred to as the Burned Area Reflectance Classification (BARC). There appears to be a reasonably good correlation between these BARC classification categories and field assessments of fire severity [12, 13]. However, since these assessments must be conducted shortly after the fire, it is not always possible to avoid cloud cover and ensure clear skies. Beyond this limit, three additional primary challenges need to be addressed:

i) developing and implementing the optimal classification approach to generate a BARC map;
ii) detecting the most adequate satellite images in terms of spatial, temporal and spectral resolution; and,
iii) selecting an appropriate geospatial big data handling platform.

Addressing the first issue involves testing various classification methods to generate a reliable BARC map. Typically, index-based methods are preferred as they facilitate the swift extraction of land use/cover categories and comparison of multi-temporal outcomes [14–17]. In this regard, both the Normalized Burn Ratio (NBR) and delta NBR (dNBR) indices are considered the gold standard for producing BARC products [18] due to their promising results, which are highly correlated with field measurements of burn severity. However, in the field validation of BARC maps, [12] found dNBR to be no more accurate than NBR. In 2014, a new metrics was introduced to estimate the fire severity: the Relativized Burn Ratio (RBR) [19].

Performance indices are closely correlated with the spatial and spectral resolution of satellite images [20]. Indeed, higher resolution leads to a better ability to accurately delineate the boundaries of areas affected by fire events and extract the damages caused by them on both natural and built ecosystems. Nevertheless, it is important to find a good compromise between spatial and temporal resolution. Ideally, to optimize monitoring

policies, high spatial and temporal resolutions are required. However, these variables are inversely proportional, meaning that increasing one implies reducing the other [21]. The Sentinel-2 mission, launched by the European Space Agency (ESA) in 2015 and comprising two twin satellites (Sentinel-2A and Sentinel-2B), offers a viable solution to address this challenge. It is characterized by thirteen spectral bands, with four bands at a resolution of 10 m, six bands at 20 m, and three bands at 60 m. Its temporal resolution is approximately 10 days (or 5 days if images collected by both Sentinel-2A and Sentinel-2B are considered). Because of these features, it could provide a good opportunity to assess the changes that occur in a specific area subjected to a hazard event [22–24].

To meet this purpose, a change detection analysis should be performed by selecting a proper algorithm. These methods are commonly grouped into two main categories: i) bi-temporal change detection and ii) temporal trajectory analysis [25]. The former is based on the direct comparison between the information extracted from multi-source data, bringing them into a uniform model. Conversely, the latter processes a large amount of long-time series of remotely sensed images. A bi-temporal change detection approach is preferred when only two images gathered before and after the event are needed [26–28].

However, to monitor the status of an event, a huge amount of geospatial data should be handled. As a result, standalone software is no longer convenient to speed up data acquisition and processing phases. To overcome such a limitation, the cloud-based platform, Google Earth Engine (GEE), developed by Google in 2017 to store and manage geospatial big data, could be adopted. Indeed, it is characterized by an integrated catalogue, updated daily with free and open-source data provided by different sources, and hundreds of processors running customized scripts in parallel [29, 30]. Through an Application Programming Interface (API), any IT-skilled user can consult the integrated data, both in raw and pre-processed formats, as well as program a proper JavaScript or Python code defined to meet specific requirements [31].

As a result, this research aims to investigate the changes in Bitonto and Vico del Gargano (Puglia region) in 2021 following two small wildfire events. To achieve this goal, the potential of processing medium-resolution Sentinel-2 images pre and post-event in the Google Earth Engine (GEE) environment were explored. This involved implementing a proprietary JavaScript code to compute the dNBR and RBR indices. The accuracy of the resulting thematic maps was statistically analyzed by comparing them with both the ground truth provided by the European Forest Fire Information System (EFFIS) and the results obtained through photointerpretation techniques.

2 Material and Methods

This section outlines the methodology adopted to achieve the research objectives. As depicted in Fig. 1, the approach can be broken down into six main steps:

i) analysis of wildfire events to delineate test areas physical boundaries and determine dates;
ii) selection of Sentinel-2 satellite images and creation of a geodatabase;
iii) pre-processing analysis of the selected images to correct atmospheric interference and remove clouds, when necessary;
iv) application of an index-based classification method by computing the NBR index;

v) change detection analysis using a bi-temporal approach (dNBR); and,
vi) validation of resulting thematic maps through statistical assessment of their accuracy.

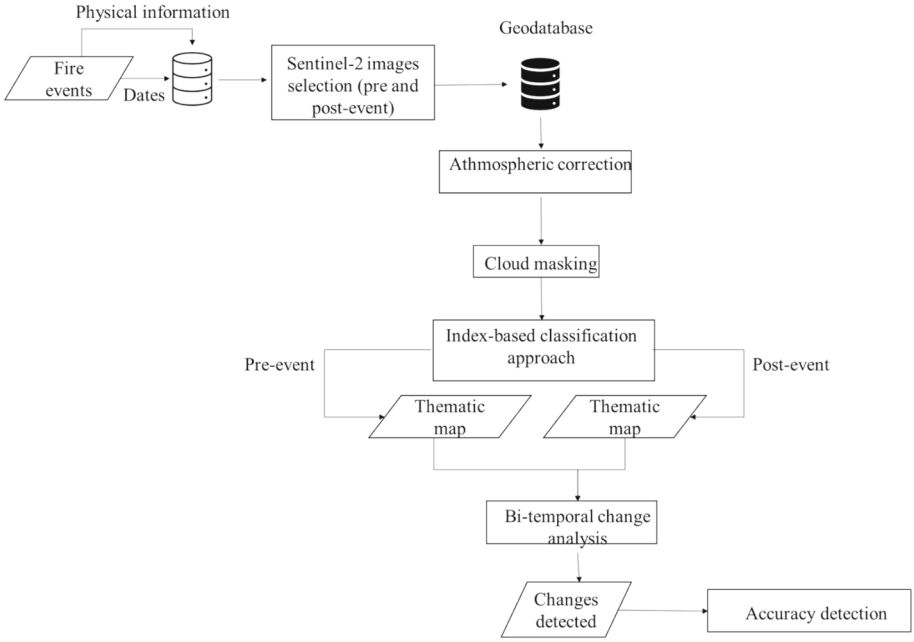

Fig. 1. Operative workflow to investigate the damages caused by a wildfire event from the medium-resolution Sentinel-2 images.

After investigating the major wildfire events in the Puglia region, Bitonto and Vico del Gargano were chosen as pilot sites to test the entire analysis. Accordingly, Sentinel-2 data corresponding to these areas were selected from the data catalogue integrated into the GEE environment and pre-processed to eliminate atmospheric influences and cloud cover. The resultant images were then processed in GEE using a custom JavaScript code, and the index-based method was applied, specifically estimating NBR and dNBR. Finally, the damages sustained by the pilot sites were examined through bi-temporal change detection analysis. The accuracy of the final outcomes was statistically evaluated by comparing them with both EFFIS data and ground truth obtained through photointerpretation. The procedure was performed on the two pilot sites separately. Each phase of the procedure is detailed in the following paragraphs.

2.1 Study Area and Input Data

The operational workflow outlined above was tested on two study areas, Vico del Gargano and Bitonto, located in the Puglia region, as they experienced small wildfire events in 2021.

Vico del Gargano, situated in Foggia province, is a municipality within the Gargano National Park and the Gargano Mountain Community. Covering 110.4 km2 in the north-eastern part of the Gargano promontory, it is a key area within the Gargano National Park, hosting a significant portion of the Umbra Forest. Its terrain varies from sea level to 782 m, encompassing sub-mountainous forests, coastal beaches, and Aleppo pine forests. The coastline is adorned with olive groves, citrus orchards, and terraced landscapes. The region features karstic geology, with numerous caves, including marine ones.

Bitonto, located in the metropolitan city of Bari in Puglia, spans over 170 km2, stretching from the Murgia highlands to within 2 km of the Adriatic Sea. The town is situated on the first step of the Murgia plateau at 118 m a.s.l., with its lowest point at 102 m a.s.l. The municipal terrain ranges from a minimum elevation of 39 m a.s.l. in the northern coastal area to a maximum of 491 m a.s.l. in the hilly southern region, resulting in an altimetric range of 452 m. Bitonto's municipal territory includes the Alta Murgia National Park and the Lama Balice, established in 2007 as a regional park on the outskirts of the historic city center. The terrain is characterized by Bari limestone and bitontina dolomite, used extensively in local construction.

The fire events in these pilot sites were identified by examining the EFFIS database (https://effis.jrc.ec.europa.eu/). EFFIS, developed in collaboration with the European Commission (EC) services (Directorate General Environment and the Joint Research Centre) and the relevant fire services in the countries (forest fires and civil protection services), provides both real-time and time series information on forest fires at the European level [32]. It encompasses the entire fire cycle, from pre-fire conditions to post-fire damage analysis (Fig. 2) [33]. Specifically, the system identifies vulnerable areas and elements at risk prior to a fire event, gathers data on burn areas such as perimeters during the event, and ultimately evaluates the damages, erosion, and emissions following a wildfire. It makes available all data about wildfires that happened after 2000.

EFFIS fire danger products are generated by computing the Canadian Fire Weather Index (FWI) based on data provided by two meteorological forecast models, conducted by Météo-France and the Deutsche Wetter Dienst (DWD) [32]. Conversely, near-real-time applications such as active fire detection and rapid damage assessment are derived from the daily processing of MODIS satellite images at a spatial resolution of 250 m, aboard the NASA TERRA and AQUA satellites, for detecting hot spots (active fires) and mapping burnt areas. In 2019, thanks to the introduction of Sentinel-2 outcomes, EFFIS resolution was significantly improved in terms of spatial accuracy. Now, it can indeed capture and describe burnt areas with a minimum size of 5 hectares, whereas previously it could only detect areas as small as 40 hectares [34]. More information about EFFI system and products are in [32–34].

Table 1 reports the EFFIS data events occurring at the test locations and the area of the regions burned by these fires. Date events were then utilized to identify Sentinel-2 images suitable for examining the observed phenomenon in more detail, while the shapefiles of the burnt areas, illustrated in Fig. 3, were subsequently employed to validate the methodology developed in this research. Since the accuracy of this database was unknown, the accuracy of the implemented methodology was also evaluated by selecting appropriate samples through the interpretation of Sentinel-2 images (Fig. 3). The validation procedure is explained in further detail in Sect. 2.4.

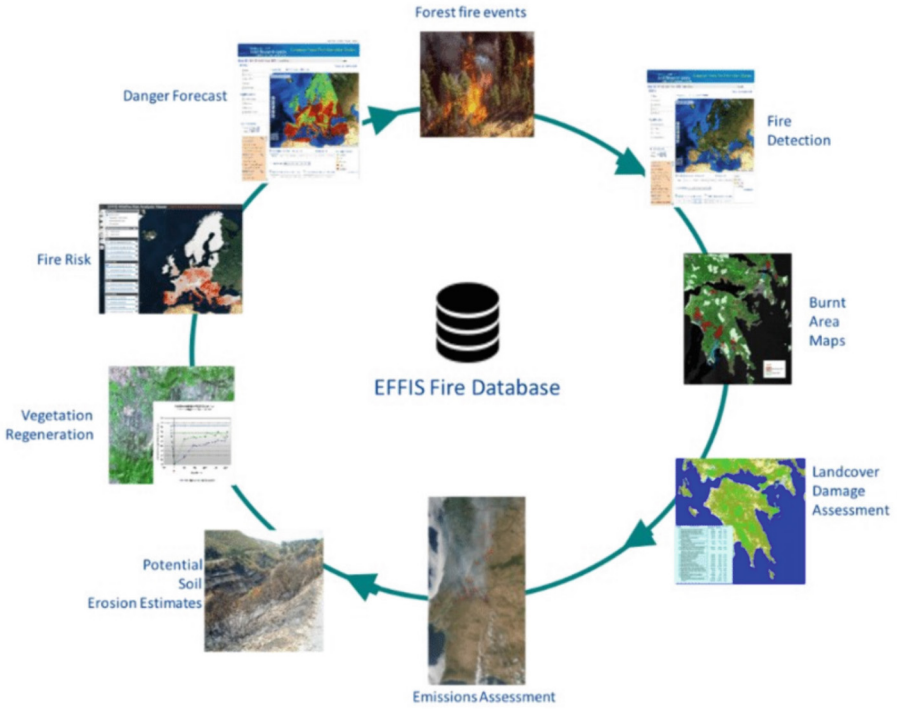

Fig. 2. Description of EFFIS products (source: [33])

Table 1. Wildfires events parameters provided by EFFIS dataset.

City	Municipality	Burned area (ha)	Date (dd/mm/yyyy)
Foggia	Vico del Gargano	116	13/07/2021
Bari	Bitonto	154	05/08/2021

Four Sentinel-2 images were selected for each study area: two acquired before the fire event and the remain two after it. It was decided to pick up four images to minimize the potential errors due to the clouds and their shadows. These images were retrieved directly from the GEE data catalogue by defining the boundaries of the test sites and setting temporal range and cloud cover percentage thresholds lower than 5. Table 2 provides further details on the temporal range used to identify the images before and after wildfire events addressing the requirements above-mentioned. Potential useful data were subsequently visually investigated to clean out those ones characterized by a low sun angle and a mismatched phenology between pre- and post-fire conditions, as suggested by [35–37].

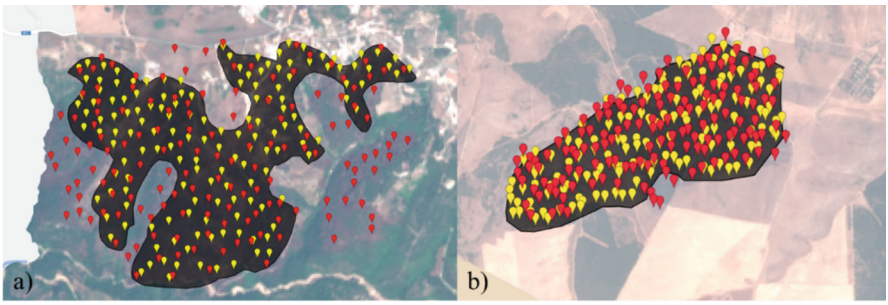

Fig. 3. EFFIS perimeters of the burned areas of Vico del Gargano (a) and Bitonto (b), respectively. Yellow and red points are the samples extracted from EFFIS data and Sentinel 2 images using photointerpretation, respectively. (Color figure online)

Table 2. Temporal range set in GEE data catalogue to select Sentinel-2 images with a cloud cover percentage lower than 5.

Municipality	Pre-fire range (dd/mm/yyyy)	Post-fire range (dd/mm/yyyy)
Vico del Gargano	06/07/2021–11/07/2021	21/07/2021–23/07/2021
Bitonto	28/07/2021–02/08/2021	10/08/2021–11/08/2021

As a result, the resultant radiometrically and atmospherically corrected images provided in the Universal Transverse Mercator (UTM) projection and the World Geodetic System (WGS84) datum, were imported in the GEE API.

2.2 Preprocessing Analysis

The collected images underwent preprocessing. Given their satisfactory geometric accuracy, further orthorectification was deemed unnecessary. However, clouds and their corresponding shadows were masked using the Sentinel-2 Correction (Sen2Cor) algorithm [38] where needed.

Sen2Cor produces an internal map characterized by 12 classes, including thin cirrus, cloud shadows, defective pixels, no data and clouds. This map helps differentiate cloudy pixels from clear ones, enabling the removal of the former to ensure clean processing in subsequent phases.

2.3 Severity Metrics

The resulting pre-processed images were subsequently handled to compute the NBR burn severity metrics, developed by Key and Benson within the Joint NPS-USGS National Burn Severity Mapping Project in 2005, for extracting fire information from Landsat satellite images [39]. This index relies on the combination of NearInfraRed (NIR) and Short Wavelength InfraRed (SWIR) bands (Eq. 1) and, recently, has been adapted for

use with Sentinel-2 data [40]. By differencing its pre and post-fire values pixel by pixel, the dNBR was obtained (Eq. 2) enabling the rapid estimation of fire damage over large areas.

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{1}$$

$$dNBR = (NBR_{pre-fire} - NBR_{post-fire}) \text{ x } 1000 \tag{2}$$

A dNBR value approaching zero indicates minimal changes in the surveyed area, whereas values further from zero suggest more significant changes. Following the recommendations of the Fire Effects Inventory and Monitoring Protocol [26], dNBR values were categorized into seven groups: High Severity, Moderate-high Severity, Moderate-low Severity, Low Severity, Unburned, Enhanced Regrowth – Low, Enhanced Regrowth – High. High severity areas are those that underwent substantial alterations post-fire, such as extensive tree mortality, significant consumption of ground fuels, and limited post-fire regeneration. Low-severity areas experienced lower mortality rates, minimal fuel consumption, and higher levels of regeneration.

Lastly, the RBR index, introduced by [19], was estimated using Eq. 3:

$$RBR = \frac{(dNBR)}{(NBR_{pre-fire} + 0.01)} \tag{3}$$

RBR is calculated by dividing the dNBR index by the NBR calculated from the images captured before the fire events, plus 0.01. This coefficient ensures that the index will never reach zero or infinity, thereby preventing failure. Also in this case, RBR values were discriminated into seven levels of severity: High Severity, Moderate-high Severity, Moderate-low Severity, Low Severity, Unburned, Enhanced Regrowth – Low, Enhanced Regrowth – High.

2.4 Validation

The samples identified using EFFIS data and Sentinel-2 images through photointerpretation were utilized to statistically estimate the accuracy of NBR and DNBR. Specifically, Overall Accuracy (OA) and Kappa coefficient (K) were calculated. OA measures the accuracy of the entire resulting burn severity maps without specifying the different classes related to the level of damage. However, it assigns greater weight to the class with a larger number of samples [41]. In contrast, K assesses the performance of each classification individually, making it preferable for comparing different classification maps [42].

2.5 GEE Code

The GEE data catalogue was consulted to select the optimal Sentinel-2 images required to fulfill the research objectives. As mentioned earlier, the catalogue contains both raw and pre-processed data; however, in this instance, raw format was preferred. The process was designed to merge the information provided by one image acquired before the fire

event and one after it, with specific parameters and temporal range set to select the images to be processed, as previously specified. These variables can be easily modified in the code to accommodate user requirements.

Subsequently, the selected images were imported into the API, and a custom JavaScript code was implemented to pre-process them, as detailed in Sect. 2.2, and then to estimate the NBR, dNBR and RBR indices, as described in paragraph 2.3. Finally, the resulting thematic maps underwent statistical validation through the development of a specific code aimed at evaluating the overall accuracy and K coefficient, as outlined in Sect. 2.4. This code was designed for easy application to various geographical locations, wildfire extents, and timeframes.

3 Results and Discussion

This research aims to assess the damages caused by wildfire events in Bitonto and Vico del Gargano, two municipalities located in the Puglia region, in 2021, by leveraging the potential of Sentinel-2 medium-resolution satellite images and GEE. To achieve this, a custom JavaScript code was developed and implemented in the GEE API to collect the necessary data for storage and analysis in subsequent steps, eliminating the need for additional platforms or standalone software. Indeed, as demonstrated by [29, 31], GEE proves to be an optimal tool for expediting procedures by saving both data collection and processing time. Indeed, it features an integrated data catalogue that consolidates all open-source and freely available data, eliminating the need to consult other platforms or download these layers separately. The data catalogue communicates directly with the API, allowing each layer to be imported into the script editor seamlessly without additional steps. Furthermore, it takes advantage of hundreds of processors that work in parallel, significantly reducing processing time. However, it is not a user-friendly platform, and as a result, only IT-skilled operators are able to implement correct and customized scripts tailored to meet users' needs [43]. Nevertheless, following the programming phase, the developed scripts can be easily adapted to process multi-source data and layers covering different geographical areas. This allows for minimizing the time required to extend the analysis to larger and diverse regions in order to monitor the damages triggered by a significant number of wildfire events. This feature is particularly compelling as it enables the monitoring of fire severity in regions lacking a dedicated program for mapping fire damages, similar to EFFIS, which provides information concerning the entire fire cycle, from pre-fire conditions to post-fire damage analysis (Fig. 2) [33], since 2000. However, EFFIS data resolution was not sufficient to discriminate elements smaller than 40 hectares until 2019, when a resolution of 5 hectares was achieved.

Such a dataset was used to list events that occurred recently in Bitonto and Vico del Gargano [32–34]. Consequently, it was employed to identify the timeframe under investigation (Table 1) and to provide ground truths (Fig. 3), although the accuracy of the data is not known beforehand. For that reason, the implemented GEE-based approach was validated using the Ground Control Points (GCPs) provided by EFFIS and those ones extracted manually by photointerpretation (Fig. 3).

For what above, GEE was selected to compute NBR, dNBR and RBR indices which are commonly defined as the gold standard to produce a BARC map and classify the

burn severity [12, 18]. The NBR index was estimated using Eq. 1, as suggested by [39, 40], on Sentinel-2 images captured both before and after the fire events. Subsequently, the dNBR index was calculated using Eq. 2 [18], while the RBR was derived from Eq. 3 [19].

dNBR and RBR resulting maps, reported in Fig. 4 and Fig. 5, delineate the varying levels of fire severity for both pilot sites. Specifically, RBR and dNBR values were grouped into seven classes in accordance with the recommendations of the Fire Effects Inventory and Monitoring Protocol [26]: High Severity, Moderate-high Severity, Moderate-low Severity, Low Severity, Unburned, Enhanced Regrowth – Low, Enhanced Regrowth – High. Both maps utilized a graduated color-scale, ranging from dark green to violet, to illustrate these classes. Dark green indicates areas experiencing highly enhanced regrowth, while violet signifies regions affected by high fire severity. Halfway colors were employed for the intermediate severity groups.

Figure 4 reveals that both dNBR and RBR maps, derived from the satellite images covering Vico del Gargano, extract the same number of pixels related to burnt areas. While most classes show comparable outcomes, there is a discrepancy in the high severity group. Indeed, RBR underestimates the pixels associated with this group, as evidenced by the absence of violet pixels in this map. Similarly, the yellow pixels representing areas characterized by "low severity" damages are fewer in the RBR map, as they are commonly classified as "unburned zones".

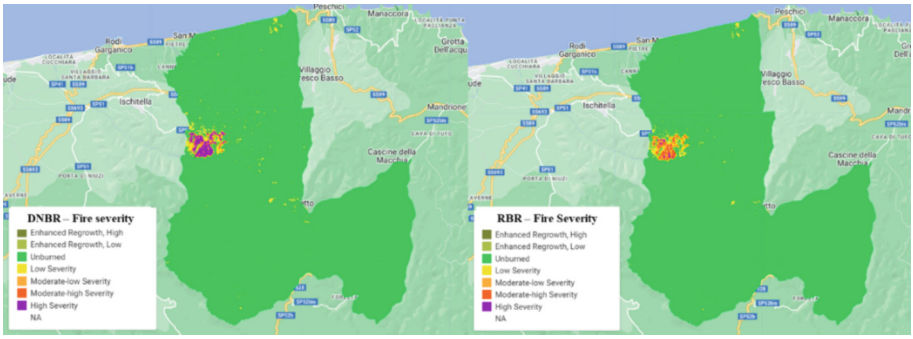

Fig. 4. Fire severity maps of Vico del Gargano. Such maps were produced from dNBR (on the left) and RBR (on the right) values.

While the thematic maps highlight these spatial variances among the maps derived from the two applied classification indices, they do not allow for a quantitative appreciation of such differences. Therefore, to quantify the differences for each specific class obtained by dNBR and RBR maps, the area expressed in hectares, corresponding percentage value, and the number of pixels involved are reported in Table 3. This table converts the spatial differences highlighted in Fig. 4 into numerical values.

By comparing such values, it is evident that both maps' outcomes are comparable albeit RBR underestimated fire severity, indeed, any pixels have been classified as high severity level (0 versus 871). Similarly, the pixels associated with the unburned zones are higher than those ones identified by dNBR (161069 versus 160011).

Table 3. Burnt area information related to the study area of Vico del Gargano extracted from dNBR and RBR maps.

Severity level	DNBR			RBR		
	Area (ha)	%	Pixel	Area (ha)	%	Pixel
High Severity	34.84	0.53	871	0	0	0
Moderate-high Severity	25.24	0.38	631	32.32	0.49	808
Moderate-low Severity	37.24	0.56	931	48.96	0.74	1224
Low Severity	106.52	1.61	2663	81.2	1.23	2030
Unburned	6400.44	96.89	160011	6442.76	97.54	161069
Enhanced Regrowth, Low	1.28	0.02	32	0.32	0	8
Enhanced Regrowth, High	0	0	0	0	0	0

Table 4. Burnt area information related to the study area of Bitonto extracted from dNBR and RBR maps.

Severity level	DNBR			RBR		
	Area (ha)	%	Pixel	Area (ha)	%	Pixel
High Severity	0.24	0	6	0	0	0
Moderate-high Severity	4.64	0.05	116	1.56	0.02	39
Moderate-low Severity	30.56	0.3	764	30.16	0.3	754
Low Severity	170.72	1.67	4268	126.76	1.24	3169
Unburned	9936.32	97.47	248408	9959.2	97.69	248980
Enhanced Regrowth, Low	51.24	0.5	1281	75.52	0.74	1888
Enhanced Regrowth, High	1	0.01	25	1.52	0.01	38

Figure 5 reports dNBR and RBR maps covering Bitonto. Similar to the previous case, the RBR map shows lower values than dNBR map. Upon comparison of the two maps, it's evident that the pixels associated with the moderate-high severity level class are fewer in the RBR map, and the unburned region appears to be larger.

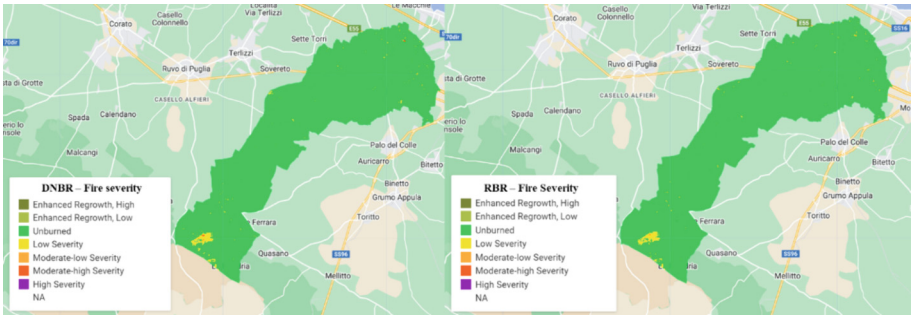

Fig. 5. Fire severity maps of Bitonto. Such maps were produced from dNBR (on the left) and RBR (on the right) values.

The area, the corresponding percentage value and the number of pixels involved are detailed in Table 4. Despite the fire severity level in Bitonto being lower than that in Vico del Gargano, the trends of dNBR and RBR are similar in both cases. Specifically, RBR consistently shows lower values than dNBR. For example, the high severity group is represented by 6 and 0 pixels in dNBR and RBR maps, respectively, while the unburned zones encompass 248408 and 248980 pixels in dNBR and RBR maps, respectively. This performance is in line with what detected by previous researchers [19] since RBR was developed to investigate the changes due Indeed, dNBR is better suited to explore regions covered by dense vegetation, whereas RBR is suitable for extracting information even in areas where pre-fire vegetation cover is low or discontinuous. This versatility is interesting since it allows for exploring urban areas too. Moreover, although Parks et al., (2014) [19] demonstrate that RBR has better correspondence to field-based burn severity measurements and a higher classification accuracy compared to dNBR, there is no universally optimal index for detecting fire severity levels. The choice depends on the specific areas of application and the objectives being measured.

To determine which fire severity metric is best suited for the specific features of the geographical area under investigation, the resulting classification maps were validated using GCPs extracted from both EFFIS data and those identified through photointerpretation. Since the samples' accuracy is unknown their OA and K coefficients were estimated. The outcomes of this analysis for the two pilot sites are detailed in Table 5. Both ground-truth datasets seem to be robust since their OA and K are higher than 0.90 and 0.80, respectively, for the study areas. Furthermore, their performance is similar in both cases, indicating that the samples' accuracy is independent of geographical conditions. As a result, estimating classification maps accuracy based on EFFIS or photointerpreted data yields similar outputs. The OA of dNBR and RBR derived maps are 0.91 and 0.93 for Vico del Gargano and 0.93 and 0.95 for Bitonto, respectively. Hence, both classification charts are consistent with fire severity damages and suitable for investigating the damages due to wildfire events. Nevertheless, in this case study, RBR performed better than dNBR even though their outcomes are pretty similar.

Table 5. Validation parameters (OA: Overall accuracy, K: Kappa coefficient)

	Vico del Gargano		Bitonto	
	OA	K	OA	K
Photointerpretation	0.98	0.96	0.99	0.98
EFFIS	0.91	0.81	0.92	0.83

4 Conclusion

The primary objective of this research is to assess the damages incurred by Vico del Gargano and Bitonto in the Puglia region following two wildfire events, utilizing medium-resolution satellite images provided by ESA's Sentinel-2 and Google Earth

Engine (GEE), a cloud-based platform developed by Google in 2017 for managing geospatial big data. To achieve this objective, the index-based classification method was employed by calculating the dNBR and RBR indices, recognized as the standard for estimating fire severity levels from satellite imagery. Consequently, seven classes were utilized to categorize the fire severity levels in line with the Fire Effects Inventory and Monitoring Protocol, and the quantity of pixels and the area involved were assessed and quantified for each class.

Through comparison of the classification results, it was observed that dNBR and RBR exhibit similar trends, which are consistent with the ground truth dataset. As such, both indices can be considered robust for fulfilling the research objectives, although RBR demonstrates superior performance in both cases. This discrepancy is primarily attributed to the geographical conditions of the pilot sites, as mentioned earlier, emphasizing that there is no universally applicable index due to variations in vegetation type and density.

Furthermore, Google Earth Engine emerges as the optimal tool for implementing custom scripts tailored to address users' specific requirements, offering a versatile platform that can be easily adapted to process multi-source data spanning various timeframes and geographical regions.

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Advancing Sustainable Water Management in Southern Italy Through Integrated Hydrological Modeling and Earth Observation

Vito Iacobellis[1(✉)], Andrea Gioia[1], Vincenzo Totaro[1], Margherita Lombardo[1], Aras Botan Izzaddin[1], Salvatore Manfreda[2], Ruodan Zhuang[2], Giuseppe Satalino[3], Anna Balenzano[3], Cinzia Albertini[3], Francesco Mattia[3], Francesco Lovergine[3], Davide Palmisano[3], Michele Rinaldi[4], Sergio Ruggieri[5], Pasquale Garofalo[5], Donato Impedovo[6], Nicoletta Noviello[7], Luigi Nardella[7], Michele Di Cataldo[7], Rocchina Guarini[8], Maria Virelli[8], Patrizia Sacco[8], and Deodato Tapete[8]

[1] Politecnico di Bari, Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica (DICATECh), Bari, Italy
vito.iacobellis@poliba.it
[2] Università degli Studi di Napoli Federico II, Dipartimento di Ingegneria Civile, Edile e Ambientale (DICEA), Napoli, Italy
[3] Consiglio Nazionale Delle Ricerche (CNR), Istituto per il Rilevamento Elettromagnetico dell'Ambiente (IREA), Bari, Italy
[4] Consiglio per la Ricerca in Agricoltura e l'analisi dell'Economia Agraria (CREA), Cerealicoltura e Colture Industriali (CREA-CI), Foggia, Italy
[5] Consiglio per la Ricerca in Agricoltura e l'analisi dell'Economia Agraria (CREA), Agricoltura e Ambiente (CREA-AA), Bari, Italy
[6] Università degli Studi di Bari Aldo Moro, Dipartimento di Informatica, Bari, Italy
[7] Consorzio per la Bonifica della Capitanata, Foggia, Italy
[8] Agenzia Spaziale Italiana (ASI), Rome, Italy

Abstract. In water-scarce regions, effective water resource management is crucial for performing sustainable agriculture. Scientists and decision-makers increasingly exploit the coupled use of hydrological and crop models to address resource conservation and productivity challenges. While emphasizing crop system performance and environmental impact assessment, equal attention is needed for ensuring sustainable crop production and effective water management.

In response to these needs, the Italian Space Agency (ASI), within the framework of the I4DP-SCIENCE programme, supports the collaborative THETIS project (EarTH Observation for the Early forecasT of Irrigation needS; Agreement n. 2023-52-HH.0).

THETIS aims at developing a spatial decision support system that integrates hydrologic and crop growth models with advanced Earth observation (EO) products, Artificial Intelligence, and a WEBGIS interface. Starting activities focus on processing tomatoes, which are highly water-demanding. A synergic data exchange between models is established to provide estimates of water needs before, at the beginning, and during the irrigation season with periodic updates.

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An essential component of the project entails producing estimated time series of root zone soil moisture, crucial for initializing the AquaCrop model and evaluating the water balance within the designated fields. To accomplish this task, in the THETIS project a joint use of the daily basin-scale hydrological model DREAM and the physically based Soil Moisture Analytical Relationship (SMAR) model forming a Soil Water Balance (SWB) module is proposed.

This paper provides a brief contextualization of the THETIS project focusing on the need for reliable estimations of soil moisture dynamics. To this end a review of the existing application of SMAR model is presented. It helped to draw remarks about the main challenges and perspectives of use of the model within a context where soil moisture may be strongly influenced by irrigation volumes and agricultural practices.

Keywords: Water needs · Soil moisture · Hydrological model · Satellite retrieval

1 Introduction

Root-zone soil moisture (RZSM) dynamics are pivotal in numerous research fields including numerical weather prediction, rainfall–runoff processes, agricultural applications, drought risk assessment, and eco-hydrological studies. In the past decade, many satellite missions have been dedicated for accurate spatiotemporal measurements/estimations of soil moisture, including Soil Moisture Ocean Salinity (SMOS) (Kerr et al., 2001), Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010) and Advanced Scatterometer (ASCAT) (Wagner et al., 2013). However, these satellite measurements are limited to the top few centimeters of the soil profile and many efforts have been made to extend satellite retrievals of surface soil moisture (SSM) data into the root zone (Li et al., 2023). Initial challenges involved identifying or creating models optimized for soil moisture data assimilation. The numerical weather prediction community, recognizing soil moisture's significance in land-atmosphere interactions, was the first to develop physically based Land Surface Models (LSMs) exploiting satellite soil moisture observations to accurately simulate profile soil moisture dynamics (De Santis, 2018). The European Centre for Medium Range Weather Forecasting (ECMWF) and the UK Met Office (UKMO) started operational assimilation of ASCAT SSM data, gaining improvement in soil moisture representation (de Rosnay et al., 2013; Dharssi et al., 2010).

Satellite SSM data assimilation efforts yielded root-zone soil moisture estimates. For instance, products like H14/SM-DAS-2 and H27/SM-DAS-3 were developed through the ECMWF Land Data Assimilation System (de Rosnay et al., 2013). Another reference product is the SMAP Level 4 Surface and Root-Zone Soil Moisture assimilating SMAP brightness temperature into the NASA Catchment land surface model using an Ensemble Kalman Filter (EnKF). The SMAP Level 4 product provides estimates of surface (0–5 cm) and root-zone (0–100 cm) soil moisture.

Various methods, such as the exponential filter (see, e.g., Wagner et al., 1999, Albergel et al., 2008; Brocca et al., 2012), regressions (see, e.g., Zhang et al., 2017), and artificial neural networks (Souissi et al., 2022) are employed to propagate SSM information to model depths of interest. The exponential filter typically leads to soil water index

estimates involving remotely-sensed surface measurements. The method is widespread for its simplicity as it involves using only one parameter, and has been extensively used to evaluate satellite-based RZSM estimates by comparison with in situ and modelled data (see, e.g., Paulik et al., 2014; Tobin et al. 2017).

The Copernicus Global Land Service provides a Soil Water Index (SWI) product from ASCAT SSM datasets (Paulik et al., 2014) and ASCAT-Sentinel-1 SSM (Bauer-Marschallinger et al., 2018) according to different exponential filter parameter values in order to represent soil moisture at various depths. SWI found application in a wide range of studies including drought and crop production forecastings (see, e.g. Qiu et al., 2014; González-Zamora et al., 2016).

Finally, physically based models such as SMAR (Manfreda et al., 2014) and SMAR-EnKF (Baldwin et al., 2017) show promise in predicting RZSM, being successfully applied to improve streamflow simulations (Patil & Ramsankaran, 2018).

In its original version, the SMAR model did not account for the high non-linearity of water loss function that may characterizes humid environments, making the model more suitable for arid zones and semi-arid basins, mainly characterized by flat areas and negligible baseflow (Baldwin et al., 2017). Faridani et al. (2017) and Rasche et al. (2024) have proposed modifications to the original version of SMAR. In particular, Faridani et al. (2017) included a non-linear soil water loss function explicitly describing deep percolation and evapotranspiration dynamics. Rasche et al. (2024) added three more parameters to the model along with the distinction between evapotranspiration and percolation terms. One of the main concerns for the application of SMAR consists of the calibration of its parameters, although they are somehow dependent on the physical soil properties and may be easily estimated based on the characteristics of the site under investigation (Manfreda et al., 2013).

This represent a key task for reliable RZSM estimates which are of concern for the collaborative THETIS project (EarTH Observation for the Early forecasT of Irrigation needS; Agreement n. 2023–52-HH.0). Based on the collaboration among different partner, the project aims at developing a spatial decision support system for the early assessment and forecasting of irrigation needs in the “Fortore” irrigation district located in the Apulian Tavoliere (Southern Italy). SMAR is expected to allow comparisons between soil moisture maps from Earth Observations (i.e., Sentinel-1 or other sensors) and the output of a basin-scale hydrological model, in order to provide reliable inputs of RZSM for AquaCrop.

As a part of the ongoing researches for supporting the project, this paper explores the main potential and challenges related to the use of the SMAR model for the research needs.

This paper is organized as follows: Sect. 2 provides a brief contextualization of the THETIS project and the research goals. Section 3 describes the area under investigation. Section 4 summarizes the main features of the SMAR model and presents an overview of studies which make use of SMAR for RZSM estimates. Finally, based on this review, a summary of the expected challenges to be addressed when applying the model in the context and for the needs of THETIS are reported in Sect. 5.

2 Research Context

In water-scarce regions, effective water resource management is crucial for performing sustainable agriculture. Scientists and decision-makers increasingly exploit the coupled use of hydrological and crop models to address resource conservation and productivity challenges. While emphasizing crop system performance and environmental impact assessment, equal attention is needed for ensuring sustainable crop production and effective water management.

In response to these needs, the Italian Space Agency (ASI), within the framework of the I4DP-SCIENCE programme, supports the collaborative THETIS project. The project involves the National Research Council – Institute for Electromagnetic Sensing of the Environment (CNR-IREA), the Council for Agricultural Research and Economics (CREA), the Polytechnic University of Bari, the University of Bari, and the Bonifica Capitanata Consortium (Foggia). THETIS focuses on the early assessment and forecasting of irrigation needs in the "Fortore" irrigation district located in the Apulian Tavoliere (Southern Italy).

The heart of THETIS lies in the development of a spatial decision support system that integrates hydrologic and crop growth models with advanced Earth observation (EO) products, Artificial Intelligence, and a WEBGIS interface. Starting activities focus on tomatoes which are highly water-demanding. A synergic data exchange between models is established to provide estimates of water needs before, at the beginning, and during the irrigation season with regular updates. Figure 1 illustrates the functional scheme of the preliminary THETIS architecture, identifying with different colors the input and output data, processing and models.

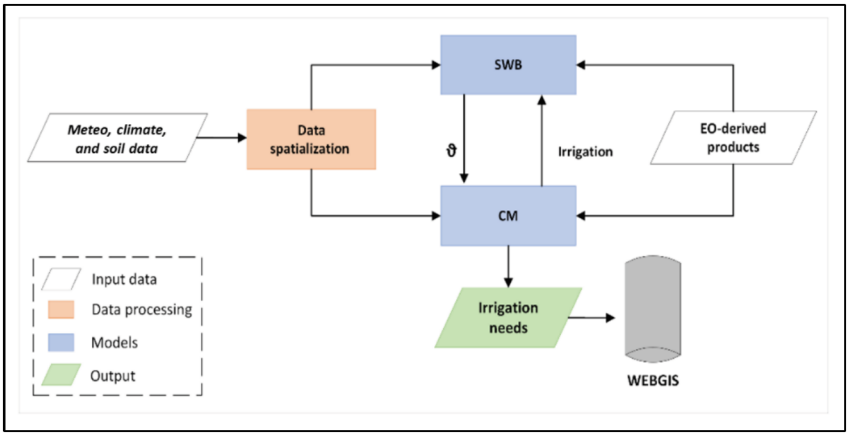

Fig. 1. Functional diagram on the integration of data and models in THETIS. ϑ: soil water content (depth of interest).

The scheme identifies the main relationships between the daily soil water balance (SWB) and crop (CM) models and highlights the role of data and information retrieved from Earth Observation (EO), including SSM maps, the leaf area index (LAI) and maps of

irrigated surfaces. Information such as LAI and irrigated areas, whose variability depends on the season and irrigation practices and may influence the predictive capabilities of the water balance model, can be directly or indirectly assimilated into the SWB module. Specifically, as a part of the SWB module, the SMAR model allows to relate the SSM maps from SAR data (i.e., Sentinel-1 or other sensors) and the output of the daily-hydrological model, within the irrigation district areas. This comparison could also serve as a local forcing for the semi-distributed hydrological model, based on the DREAM model (Manfreda et al., 2005), which operates over the whole watershed exploiting spatialized climatic data and transfers soil moisture information for the initialization of the crop model. The latter, in addition to high-resolution information related to vegetation indices and irrigated areas, will exploit observations related to EO-derived maps of tilled areas. CM periodically updates SWB with information regarding irrigated surfaces.

3 Pilot Case Study

The pilot case study is located within the plain of Tavoliere (Apulia Region, Southern Italy), which is the second largest plain in peninsular Italy after the Po Valley. It extends between the Daunian Mountains to the west, the promontory of Gargano and the Adriatic Sea to the east, the Fortore River to the north, and the Ofanto River to the south (Fig. 2a). The wide flat surfaces, predominantly cultivated with crops, extend up to the base of the Daunian Pre-Apennine. Specifically, the application area of the basin-scale hydrological model (based on the DREAM model) covers an area of approximately 2000 square kilometers, encompassing almost the entire basin of the Candelaro River (with its tributaries Triolo, Salsola, and Celone creeks), excluding the area near the mouth, in the Adriatic Sea (Fig. 2b). The plain and hilly areas are mainly used for the cultivation of wheat, durum wheat, and processing tomatoes, while pastures and forests prevail in the mountainous areas. Rainfall gauges, climate monitoring stations (at least thermometric) and hydrometric gauges are present within the basin and in the neighboring areas. They belong to two autonomous networks: Civil Protection Network (CP) and Land Reclamation Consortium (CBC, standing for "Consorzio di Bonifica della Capitanata"). The "Fortore" Irrigation District, which is crossed by many artificialized watercourses (Fig. 2c), represents the area of interest for the estimation of water consumptions by the AcquaCrop model, which needs to be initialized based on the soil moisture maps provided by the daily-SWB model.

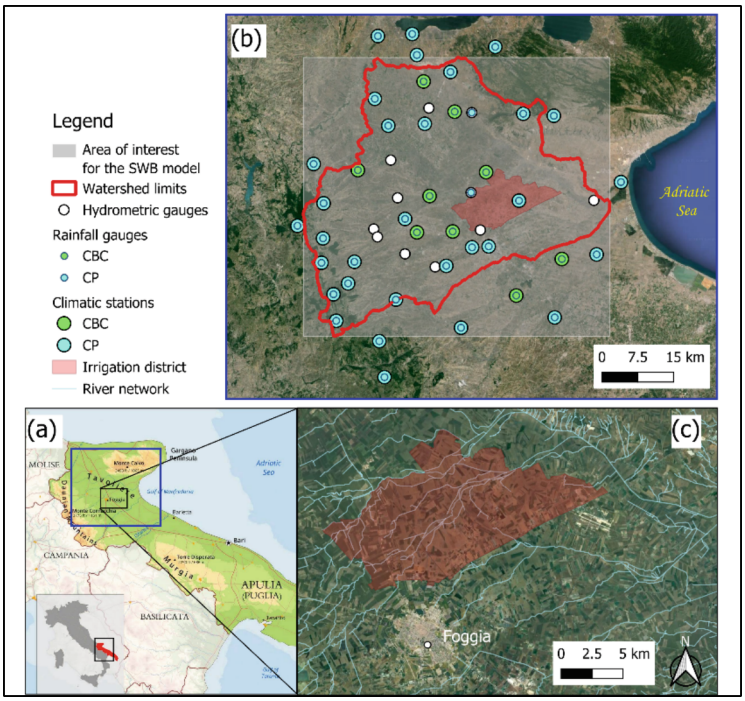

Fig. 2. Location of the areas of interest for the THETIS project (a). Area of application of the SWB model and active meteo-hydrological stations (b). Location of the "Fortore" Irrigation District (c).

4 SMAR Features and Use in the Literature

4.1 Description of the Model

The SMAR model (Manfreda et al., 2014) uses a physically based approach to estimate soil moisture in the reference soil thickness (i.e. the root zone) starting from SSM information. The model requires the estimation of some parameters, dependent on the physical characteristics of the soil as well as the availability of soil moisture satellite maps.

SMAR relies on the following hypotheses:

- Soil is schematized based on two layers of different depths (Fig. 3)
- Soil moisture movement from the upper to the lower layer according to Green & Ampt (1911);
- All water in the first layer above the field capacity moves into the lower layer within one day (Laio, 2006);
- Infinite permeability of the soil when the relative saturation reaches any value above the field capacity;
- Non-linearity of losses for high values of soil moisture is not accounted for.

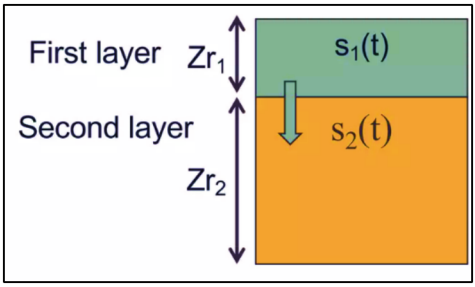

Fig. 3. Soil schematisation according to SMAR (adapted from Manfreda et al., 2014). s_1 and s_2 are the relative soil saturations of the first layer and the second layer, respectively.

Infiltration flux from layer 1 to layer 2 is modelled by Eq. 1

$$n_1 Z_{r1} y = n_1 Z_{r1} y[s_1(t), t] = n_1 Z_{r1} \begin{cases} s_1(t) - s_{c1}, s_1(t) \geq s_{c1} \\ 0, \quad s_1(t) < s_{c1} \end{cases} \tag{1}$$

where, n [-] is the soil porosity, Z_r [L] represents soil depth, V_2 [LT^{-1}] is the soil water loss coefficient accounting for both evapotranspiration and percolation, s_{c1} [-] is the relative soil saturation at the field capacity of the first layer.

By introducing $x_2 = \frac{s_2 - s_{w2}}{1 - s_{w2}}$ [-] as the "effective" relative soil saturation of the second soil layer and following the model hypotheses, a simplified soil water balance model is provided based on Eq. 2

$$(1 - s_{w2}) n_2 Z_{r2} \frac{dx_2(t)}{dt} = n_1 Z_{r1} y(t) - V_2 x_2(t) \tag{2}$$

The first product that appears in the second member of Eq. 2 represents infiltration, while the second describes losses.

By introducing the two normalized parameters a and b, defined as follows

$$a = \frac{V_2}{(1 - s_{w2}) n_2 Z_{r2}} \tag{3}$$

$$b = \frac{n_1 Z_{r1}}{(1 - s_{w2}) n_2 Z_{r2}} \tag{4}$$

after some analytical steps (see, Manfreda et al., 2014 for further details), Eq. 5 is derived allowing description of soil moisture in the root-zone, $s_2\ (t)$ at depth Zr_2 and at day t_j, based on the time series of surface soil relative saturation:

$$s_2(t_j) = s_{w2} + \left[s_2(t_{j-1}) - s_{w2}\right] e^{-a(t_j - t_{j-1})} + (1 - s_{w2}) b y(t_j) \left(t_j - t_{j-1}\right) \tag{5}$$

In the absence of reliable information for parameters estimation, a, b, s_{c1}, and s_{w2} (depending on physical properties of both the surface layer and the root zone layer) need to be calibrated, based on a comparison between daily field measurements of the relative saturation on the lower layer.

In the original version of the model a quite simple parameters calibration is proposed based on the minimization of the Root Mean Square Error (RMSE) between observed (field measurement) and simulated s_2.

It should be noted that SMAR may produce values higher than 1 and in consequence, these are automatically set equal to 1.

Following the calibration step, the SMAR model will be employed in THETIS to facilitate a comparison between the soil moisture maps calculated by the daily hydrological model and EO-derived SSM maps, when they are available.

4.2 Review of Applications

SMAR was originally applied in the arid and semi-arid environment of Africa (Benin, Mali, and Niger) and U.S. (New Mexico). The availability of climate and soil information about the study sites made possible the estimation of all model parameters. Moreover, consistent series of SSM and RZSM field measurements provided by the African Monsoon Multidisciplinary Analysis (AMMA) and the Soil Climate Analysis Network (SCAN) supported the comparison to the well-known exponential filter provided by Wagner et al. (1999) based on the T-parameter. This comparison helped to highlight the potential of SMAR for semi-arid environments. The application exploiting AMMA 25 × 25 Km^2 with calibrated parameters produced values very close to those estimated based on the physical information available for the sites confirming the physical consistency of the methodology. The dataset used in the original study has been used to support following applications of the model, with focus on (i) the use of satellite retrievals of SSM to support parameters calibration and (ii) improvement in the structure of the model to explicitly accounting for non-linearity of soil losses. In particular, Faridani et al. (2016) assessed the possibility to implement the TRMM/TMI (25 km resolution) dataset for parameters calibration. The Authors compared three different calibration strategies. The first one strategy exploited the time series of in situ SSM data and in situ observations of RZSM (i.e., point scale application). The second one used time series of satellite SSM data and in situ observations of RZSM (i.e., pixel scale application). The third one used a series of satellite SSM data and parameters values obtained from the point scale application. The Authors observed that in the transition from field to pixel of satellite data, parameters related only to soil texture are quite stable, while parameters linked to local soil properties, such as soil depth and water losses, show wider ranges of variation with respect to the input time series of SSM. Then, Faridani et al. (2017) suggested modification in the model structure to account for the non-linearity of soil losses explicitly accounting for percolation and evapotranspiration. An ensemble Kalman filter was used in Baldwin et al. (2017) to support SMAR by estimating a regional-scale satellite bias parameter using reference in situ data. The bias parameter is added to input AMSRE – 25 km SSM retrievals before their use in SMAR. The application concerned 43 sites located in the Eastern U.S. encompassing both wet and dry climates. SCAN/SNOTEL Soil Moisture Network (Schaefer et al., 2007) supported the calibration of three parameters over four, being the relative surface field capacity estimated through a Bayesian-MCMC method. The optimized SMAR-EnKF models RZSM with a lower degree of error with respect to previous SMAR calibration efforts. The new SMAR-EnKF found application in rainfall-runoff simulations over Krishna River basin, India. The study was conducted

by Patil & Ramsankaran (2018) who exploited SMOS L3 (0.25°) and ASCAT v. H113 (0.125°) products to overcome the absence of SSM field measurements. Model calibration was performed by using Particle Swarm Optimization (PSO) approach to match long-term subsurface soil moisture simulated through the Soil and Water Assessment Tool (SWAT) and using the Nash Sutcliffe Efficiency (NSE) in the objective function for optimisation. SMOS (25 km), AMSR2 (0.25°) and SMAP (36 km) products were used by Gheybi et al. (2019) for RZSM estimation in Iran. The INSAM (International Society for Agricultural Meteorology) supported parameters calibration over a period of about two years. Baldwin et al. (2019) extensively applied SMAR over 68 sites in the Eastern U.S., including a variety of climate conditions and exploiting information retrieved from series of 2 years with gaps less than 2 months of AMSRE (25 km), SMOS level 2, and SMAP level 3 (9 km), then validating results on the experimental Shale Hills catchment (U.S.). Both the SCAN/SNOTEL and the AMERIFLUX Monitoring Network (Baldocchi et al., 2024) supported calibration of the model parameters on regional scale, while the Shale Hills Automatic Sensors (Liu and Lin, 2015) and Shale Hills Manual TDR (Lin et al., 2006) supported site scale application. Zhuang et al. (2020) selected six satellite products for SSM retrievals, including AMSRE (25 km), SMOS (30 km), AMSR2 (25 km), SMAP (36 km), the European Space Agency Climate Change Initiative (ESA-CCI) Passive (25 km) and ESA-CCI Active (25 km). The study also assessed the potential use of blended ESA-CCI Soil Moisture (25 km) for SSM retrievals. The analysis concerned the application of the SMAR model over the Tibetan Plateau being available four in-situ measurement networks including arid, semi-arid and sub-humid environments. The analysis shed new light on the perspective of using blended products for SSM retrievals and confirmed poor model performances for humid environments compared to that of arid and semi-arid regions. Application of SMAR for the assessment of AMSR2 products and downscaled AMSR2 with MODIS parameters over the arid Rafsanjan Plain in Iran was found in Farokhi et al. (2021), who exploited the dataset provided by Ansari et al. (2015) to estimate three of the model parameters leaving only the loss term to be calibrated. Liu et al. (2023) proposed an application of SMAR on the Luan River in China, encompassing various climate zones. The Global Daily Surface Soil Moisture Dataset at 1-km resolution (2000–2020) provided by Zheng et al. (2023) was used for SSM retrievals. A selection of 34 stations of the field monitoring network described by Zhao et al. (2020), provided field measurement at different scales (large, 100 km; medium, 50 km; and small, 10 km). The Authors compared the RZSM series estimated by SMAR at different depths using covariates from different sources (China Soil Hydraulic Parameters dataset for SMAR-P1 configuration and literature references for SMAR-P2 configuration). Only SMAR-P1 successfully passed the significance test ($p < 0.05$) and finished the parameter regionalization process, highlighting the importance of the availability of local datasets for the description of soil properties. In a very recent study, Rasche et al. (2024) tested SMAR over the forested site of Serrahn (Germany) trying to extrapolate RZSM up to a depth of 450 cm. The analysis was supported by 1 year of 59 in-situ soil moisture measurements. The original SMAR could not capture the soil moisture dynamics well. Only with effective parameters in a non-physical range better model performances have been achieved. However, the inclusion of three more parameters in the model, specifically, the relative saturation at field capacity in the

second layer sc_2 (-), the cumulative root fraction to the maximum depth of the first and second layer R1 (-) and R2 (-) along with the explicit distinction between evapotranspiration and percolation terms leads to improve results. In general, a RMSE of 0.06 cm^3cm^{-3} was considered as a benchmark for performance assessment. Figure 4 shows applications of the original model and its modified versions worldwide.

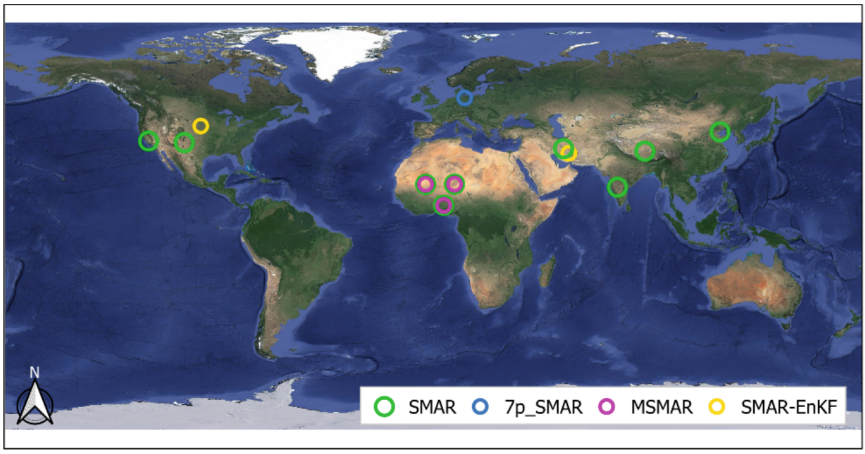

Fig. 4. Map of the applications of the model SMAR (original version and modifications) worldwide. "7p" stands for "seven parameters"

In summary, the SMAR model is a reliable tool for estimating root-zone soil moisture, especially in arid and semi-arid regions. While adaptable to satellite data, its accuracy decreases in humid environments. Past applications have shown the model's heavy reliance on local data for calibration and the frequent need for additional parameters or modifications to achieve optimal performance. Therefore, local climate or specific hydrological processes (like soil freezing or a water table) may significantly deviate from the model's simplified scheme, necessitating further parametrization or additional modules.

5 Conclusion and Research Directions

A reliable description of soil moisture dynamics is of paramount importance for applications concerning water management for sustainable agriculture. This represents one of the main goals of the THETIS project which aims at the early assessment and forecasting of irrigation needs in the "Fortore" irrigation district (Apulian Tavoliere, Southern Italy). Based on the review of works using SMAR, presented in Sect. 4, several challenges emerge that could be encountered in applying the model for the needs of THETIS and, more generally, in similar research context. They are mainly linked to the land use of the study area where soil moisture is strongly influenced by agricultural practices, water management and irrigation volumes. Such challenges can be summarized as follows:

- variability of soil properties: differences between soil properties among soil layers can significantly influence the parameters of the SMAR model. This introduces uncertainties when trying to estimate parameters based on coarse information;
- availability of local measurement on soil properties and climates: it seems to be essential for accurate calibration of the SMAR model. Studies using local data have demonstrated improved model performances compared to those using literature-based values;
- transition from local-scale to satellite-scale data: the use of satellite data for calibrating the model parameters may pose challenges in transitioning from local-scale to pixel-scale. This can lead to greater variability in parameters specifically related to local soil properties and processes;
- non-linearity of soil losses: structural modifications of the model to explicitly account for the non-linearity of soil losses might be necessary to improve the accuracy of the results, especially in contexts where irrigation and agricultural practices have a significant impact on soil moisture.

In conclusion, the application of SMAR in regions where agricultural practices and irrigation may have a significant impact on soil moisture dynamics, such as for the area of interest for the development of the THETIS spatial decision support system may present challenges related to the variability of soil properties, inhomogeneity in the resolution of input information, and the need to quantify irrigation contributions. Limitations may exist in the use of satellite-derived SSM data as reference observations for model input, mainly due to the inclusion of bias effect. However, potential benefits may be expected following the exploitation of high-resolution satellite retrievals about irrigated areas, detailed information on irrigation practices, and the available sparse measurements of surface and root zone soil moisture which remain essential for model calibration. Following calibration, as a part of model chain of the THETIS architecture, SMAR can be used jointly with the daily basin scale hydrological model, allowing for comparisons between satellite observations of soil moisture, soil moisture maps computed through basin-scale continuous simulations and crop-growth model outputs. This comparison is expected to ease and strengthen the coupled use of the hydrological and the crop-growth models in view of forecasting applications.

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Silting Effect on Tidal Basin Circulation: A Case Study

Daniela Malcangio, Vincenzo Totaro(✉), and Alberto Ferruccio Piccinni

DICATECh, Politecnico di Bari, 70125 Bari, Italy
{daniela.malcangio,vincenzo.totaro,
albertoferruccio.piccinni}@poliba.it

Abstract. Management of coastal lagoons is of paramount importance for ensuring the safeguarding of ecosystems and human activities. The growing threats due to climate change and anthropogenic pressure require specific measures to be addressed in these areas. Thus, a detailed knowledge about the dynamics of these coastal systems is needed for planning and designing strategies aimed at preserving their integrity. This study is focused on the investigation, monitoring and analysis of the environmental integration framework of the complex drainage system located in the wetland areas of the municipality of Porto Cesareo (southern Italy). In particular, the study area is characterized by the hydraulic system of Bacino Fede, a coastal lagoon designed in the wider framework of the land reclamation activities carried out during the twentieth century. This research was carried out in relation to the morphological, hydrological and hydraulic characteristics of the study area, with the purpose of identifying and investigating any induced critical states, both general and specific, related to the hydraulic functionality of the system. Relevant insights on the hydraulic behavior of the Bacino Fede basin were obtained through mathematical modeling, thus leading to an improved knowledge of the dynamics of the area. The technical and scientific contribution thus acquired could represent an important resource for the stakeholders and decision-makers that play an active role in management of this area.

Keywords: Coastal lagoon · Tidal basin · Land reclamation · Hydrodynamic and environmental modeling

1 Introduction

Coastal lagoons are very important and unique ecosystems. They are usually connected to the sea through channels (inlets) whose presence plays a crucial role as – among others - it helps in maintaining a good water quality inside the lagoon. These inlets are very often intermittent, as they can open or close as a consequence of both natural and artificial phenomena, and this can in turn impact the salinity and trophic status of these water bodies. Without the effective operation of these openings, the tidal exchange can be negatively impacted, causing a degradation in tidal exchange and, in turn, in water quality.

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Coastal lagoons are the habitat for numerous species at least for part of their life cycle, and the flux of water between each lagoon and the open sea results in the lagoon being primarily marine or freshwater. They are characterized by high biodiversity levels [1, 2], as they represent the point where marine and continental flora and fauna come into contact and they are populated by ecosystems engineers, like seagrasses, that can create specific habitats [3]. Moreover, these inner basins are highly productive systems, thanks to organisms, such as green algae and phytoplankton, that absorb inorganic substances such as carbon dioxide and water to produce at a high-rate organic compounds that can be used as a source of energy for other living organisms.

Coastal lagoons are relevant also from an environmental and economic perspective: in fact, due to their characteristics, they often host extremely productive fisheries and various kinds of aquaculture [4], and they can be also used as a resource for salt mining [5]. Due to their exploitation for economic profit, inland basins are heavily impacted by anthropogenic activities, and this makes them vulnerable to an increased risk of environmental degradation, especially with respect to water quality issues. This can cause eutrophication, which represents a threat for the health of these ecosystems. In order to be able to plan interventions that can help maintain a sufficient water quality and, more generally, a satisfactory health level for the whole ecosystem, it is first necessary to assess the quality of water in lagoons, which makes it important to carry out studies on their circulation.

Many studies have been carried out on transitional water bodies [6–8] as they are the basis for planning interventions and maintenance. Coastal lagoons are very common in Italy, the most famous one being the Venice Lagoon, which is also the largest wetland in the Mediterranean Basin, but many smaller lagoons are located all along the Italian coastline. In particular, some of these systems were artificially built during the land reclamation works that took place in Italy during the twentieth century [e.g., see [9]. In this paper, we focus on one of these operas, the *Bacino Fede* basin, located in the municipality of Porto Cesareo (Salento peninsula, southern Italy). This area is geographically framed in the wider portion of territory known with the toponym of *Arneo*, as area historically subject to marshes that made this territory inhospitable and without significant human settlements until nineteenth century [10]. After 1920, this area was interested by a relevant activity of land reclamation, which can be testified in the municipality of Porto Cesareo by the presence of six hydraulic systems nowadays classified as coastal lagoons. These operas allowed a restoration of the whole area, who was progressively interested by an intense urbanization, often devoted to tourist accommodation. With the aim of safeguarding the ecosystems, a number of protected areas were established. Among the most important, there is the Porto Cesareo Marine Protected Area, established by a decree from the Ministry of Environment in 1997 as a National Marine Reserve. Since these areas are very significant from an environmental standpoint, effective management is required, thus they require regular monitoring, in order to plan adequate maintenance and guaranteeing their hydraulic effectiveness. For performing the required interventions, it is important to monitor and study the environmental status of the lagoons.

The goal of this paper is to study the water circulation inside a coastal lagoon, Bacino Fede (located in Porto Cesareo, southern Italy), and how it is affected by silting

in different scenarios. The paper is organized as follows: in Sect. 2, the case study and the numerical methods employed for the study of water circulation are illustrated. In Sect. 3, results from the various simulated cases are presented and discussed. Finally, in Sect. 4 the main conclusions are reported.

2 Study Area and Methodology

2.1 The Case Study: Bacino Fede

This study is focused on the Bacino Fede, a coastal lagoon near the site of Torre Castiglione, in the municipality of Porto Cesareo, a city located in the northern part of the Salento peninsula, southern Italy (Fig. 1). As reported in the Introduction section, a significant activity of land reclamation was carried out during the twentieth century, thus restoring lands who were later urbanized and cultivated [11]. In this context, the design and the building of coastal lagoons played a key role in the renewed hydraulic asset of the site.

For the reclamation of the Fede marsh, a connection to the sea through lakes was considered, which had to be created and could also be used by the inhabitants for fishing. In fact, the purpose of these reclamation works was nothing but to improve the quality of life in these areas and exploit the territory, encouraging the inhabitants to cultivate even those agricultural lands. Therefore, Bacino Fede behaves as an autonomous lagoon and it is connected to the sea through two tidal inlets. For the purpose of this analysis and consistently with data availability, we modelled the system only considering the aforementioned elements. The water exchange between the basin and the sea ensures a gradual variation in salinity, with higher values during the summer months and lower values in the winter. In summer days, when the freshwater table decreases and flow rates are lower, the salinity in the basin increases due to the inflow of seawater, resulting in higher oxygen levels and higher temperatures. The obstruction of channels disrupts the gradual salinity transition and mixing processes and has severe repercussions on the ecosystem of the area. Additionally, the closure of channels during specific periods of the year, when there is fish migration between breeding and growth areas, would impede this natural process.

To safeguard this artificial environment, regular maintenance measures should be implemented, including periodic cleaning of channel mouths to maintain the overall quality of the ecosystem. Furthermore, interventions should be carried out in compliance with vital periods of the valuable animal species in that area, such as the nesting seasons for species like the Kentish plover or marine turtles.

2.2 Numerical Model

Hydraulic simulations of the coastal lagoon investigated in this paper were carried out by means of the 2D hydrodynamic model (HD) MIKE 21, a modeling tool for oceanographic, coastal and estuarine numerical studies distributed by the Danish Hydraulic Institute. The software is able to simulate two-dimensional free-surface flows, and it is designed to be modular, which makes it applicable to simulations of hydraulics, water



Fig. 1. Photogrammetric capture of the study area (adapted from Google).

quality and sediment transport in water bodies [12, 13]. The model has been applied in numerous previous studies and tested by means of field measurements [14–19]. A review of MIKE 21 studies carried out in several fields concerning the flow modeling, with the objective of developing an understanding of how and where it can be applied, can be found in Warren and Bach [20].

MIKE 3 is composed of three fundamental modules, i.e. the hydrodynamic (HD) module, the advection-dispersion (AD) module and the turbulence module.

The HD module solves the time-dependent three-dimensional conservation equations of mass and momentum, the Reynolds-Averaged Navier-Stokes (RANS) equations in a Cartesian coordinate system, in order to predict water level changes, circulation and transport driven by winds, waves, tides, river discharge or density forcing. The closure problem is solved in the turbulence module by relating turbulent fluctuations, i.e., the Reynolds stresses, to the mean velocity field, according to the Boussinesq eddy viscosity concept.

The flow field and pressure variation are computed by the mathematical model in response to a variety of forcing functions. In the present study, forcing considered were the wind and the tide. The intensity values for these forcings have been obtained from the tide gauge station in Porto Cesareo, at 15 min intervals. The historical time series obtained from the present study covers the period from 2007 to 2015, with the exception of 2010, when no tide data is available. The performance of the data acquired over the years is shown in Fig. 2. Three years relatively close to each other (2011, 2014, and 2015) were analyzed, given their high performance compared to other years, with the aim of observing the evolution of water circulation over the years, as well as the variations that could occur for different years. In particular, the year 2011 was taken as a reference for the period of analysis, as it has a high data yield. Thus, the 2011 solar year was differed into wind rose seasons to verify which season has the most frequent winds

(Fig. 3 and 4). The season that agrees the most with the annual wind rose and with the most frequent wind direction is from January to March, therefore the whole numerical model was implemented relative to this period.

Along with the HD module, the Ecological module (ECO Lab) was used, in order to estimate the quality of the waters within the basin through the analysis of the transport of state variables by advection-dispersion processes based on hydrodynamics. The reference analysis parameters considered for the ecological study of the basin are the BOD5 and dissolved oxygen (DO). Deoxygenation is caused by the oxygen consumption carried out by bacterial flora. An increase in bacterial activity results in a higher consumption of dissolved oxygen in the water. Depending on the BOD values, the level of water contamination can be determined, with values below 1 mg/l considered as non-contaminated. DO is also a chemical parameter used to characterize the pollution level of a water system and, consequently, the survival of the complex organisms living in that system. Eutrophication and the generation of redox equilibria are among the main causes of a reduction in DO, which can lead to critical situations with typical values of hypoxia (between 3 and 1 mg/l) or anoxia (less than 1 mg/l), preventing aquatic life.



Fig. 2. Performance of the wind and tide data acquired from the tide gauge station in Porto Cesareo.

Regarding bathymetry, as a first approximation data obtained with LiDAR and converted to ASCII with a resolution of 2 m has been considered. For the study of the potential impact of obstructing the two connecting channels between the Bacino Fede and the open sea, a comparison was made between simulations without obstruction, where the channels had a depth of -0.3 m, and simulations with an obstruction of 50 m length, resulting in a 30% and subsequently 50% reduction in the initial depth.

The goal was to compare the circulation of currents within the basin with and without obstruction, a circulation that undoubtedly affects water quality.

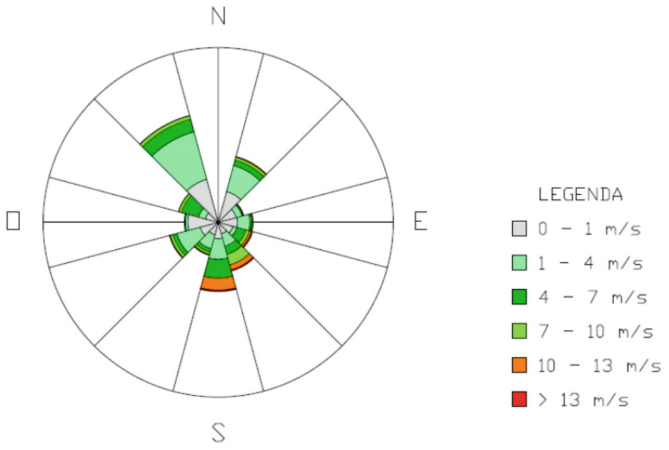

Fig. 3. Annual wind rose for 2011.

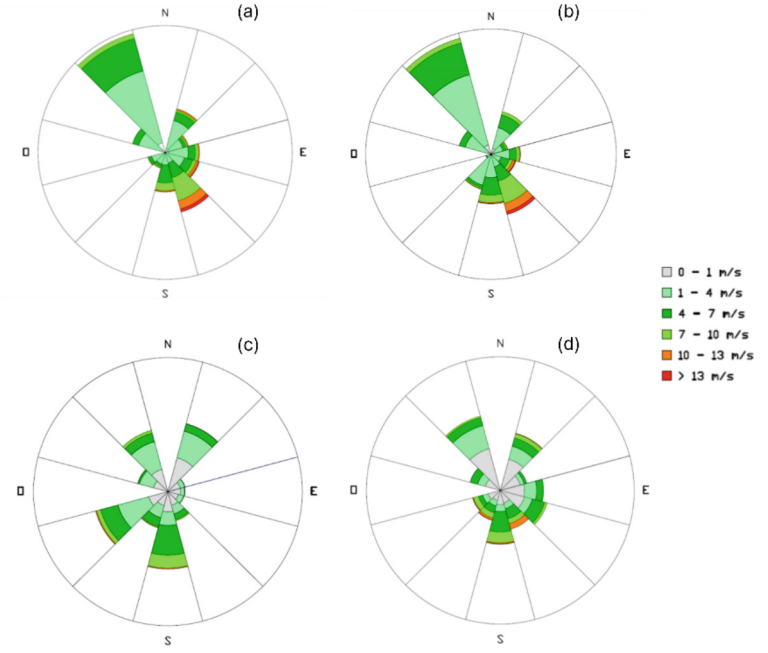

Fig. 4. Seasonal wind roses for 2011 (a) January-March, (b) April–June, (c) July-September, (d) October-December.

3 Results and Discussion

The results of the simulations carried out following the procedure outlined in the previous paragraph are shown below. In particular, simulations were conducted for three months (from January to March) over three different years (2011, 2014, and 2015) and considering three different configurations:

(i) no channel silting;
(ii) silting of the channel for a length of 100 m (starting from the sea and moving inland) and reduction of the water depth by 30% compared to the case without silting;
(iii) silting of the channel for a length of 100 m (starting from the sea and moving inland) and reduction of the water depth by 50% compared to the case without silting.

The last two configurations refer to a situation of silting, which could occur due to poor maintenance. For each simulation, the hydrodynamics, i.e., flow elevations and velocities, were examined. Moreover, the water quality was investigated by analyzing the concentrations of BOD and OD, taking into account the potential discharge of pollutants from the open boundary into the basin through the western open boundary.

The objective of the analyses, that is of the whole study, is to demonstrate that silting and obstruction of the channels have an impact on the water quality within the basin and consequently on all the surrounding ecosystems.

3.1 Hydrodynamic Simulations

Hydraulic simulations of Bacino Fede have been carried out through the use of a numerical code that simulates water bodies for which the plane bidimensional hydrodynamic approximation for vertically homogeneous fluids can be used. A hydrodynamical module (HD) simulating variations in the level of currents as a response to different types of forcings considered has been employed, and this allows the simulation of a large range of hydraulic phenomena even in the presence of complex structures.

Analyses have been carried out simulating different scenarios, with the aim of comparing the current circulation in the basin and taking into account the problems that emerge linked to channel silting. In order to analyze the elevation and velocity values within the Bacino Fede accurately, as the extent of silting of the channels varied, five points were taken into account (Fig. 5). The results reported in Table 1 confirm how in the five points analyzed, the estimated elevation values undergo a reduction in depth by increasing the value of the silting of the channels. This result is not particularly expected for points 2, 3, and 4, which are distant from the mouths of the two channels. Furthermore, for the year 2015, data are missing in points 1 and 5 under the condition of 50% channel obstruction compared to the initial depth. The year 2015 proved to be the most critical, with the disappearance of water in the initial part of both channels considering a 50% silting. This result is evident in Fig. 6, which depicts the distribution of elevation changes relative to the free surface at the end of the three-month simulation period. From the water depth results, it is evident that the obstruction leads to a reduction in elevation variations and, consequently, to minor fluctuations in the free surface.

Vector field analysis confirmed the results obtained by analyzing the water elevations. From Table 2, it is noticeable that, in general, the velocities are sufficiently small to be

Table 1. Punctual elevation values (see Fig. 5 for point location).

Point	Year	Silting (%)	H_{min} (m)	Date	H_{max} (m)	Date
1	2011	0	-0.1273	18/02	-0.1266	04/02
	2011	30	-0.0484	25/02	-0.0471	07/01
	2011	50	-0.0154	25/02	-0.0132	04/03
	2014	0	-0.0966	11/02	-0.0857	25/03
	2014	30	-0.0394	11/02	-0.0255	25/03
	2014	50	-0.0134	11/02	0.0011	25/03
	2015	0	-0.1300	21/01	-0.1277	25/03
	2015	30	-0.1099	04/02	-0.0906	28/01
	2015	50	N.A	N.A	N.A	N.A
2	2011	0	−0.1276	25/02	−0.1268	25/03
	2011	30	−0.0483	25/02	−0.0474	25/03
	2011	50	−0.0153	25/02	−0.0138	25/03
	2014	0	−0.0886	11/03	−0.0816	11/02
	2014	30	−0.0288	11/03	−0.0214	11/02
	2014	50	−0.0021	11/03	0.0052	11/02
	2015	0	−0.1296	28/01	−0.1255	04/03
	2015	30	−0.0917	14/01	−0.0875	04/03
	2015	50	−0.0902	28/01	−0.0864	04/03
3	2011	0	−0.1273	25/02	−0.1271	25/03
	2011	30	−0.0480	25/02	−0.0477	25/03
	2011	50	−0.0150	25/02	−0.0141	25/03
	2014	0	−0.0886	21/01	−0.0871	11/02
	2014	30	−0.0287	11/03	−0.0268	11/02
	2014	50	−0.0020	11/03	$2.45 \cdot 10^{-5}$	11/02
	2015	0	−0.1294	28/01	−0.1286	25/03
	2015	30	−0.0916	14/01	−0.0905	25/03
	2015	50	−0.0900	28/01	−0.0894	18/03
4	2011	0	−0.1274	25/03	−0.1270	25/02
	2011	30	−0.0480	07/01	−0.0477	25/02
	2011	50	−0.0150	07/01	−0.0141	11/03
	2014	0	−0.0889	25/03	−0.0881	14/01
	2014	30	−0.0290	25/03	−0.0280	14/01

(*continued*)

Table 1. (*continued*)

Point	Year	Silting (%)	H_{min} (m)	Date	H_{max} (m)	Date
	2014	50	−0.0023	25/03	−0.0013	14/01
	2015	0	−0.1305	04/03	−0.1291	11/03
	2015	30	−0.0923	04/03	−0.0908	11/03
	2015	50	−0.0913	04/03	−0.0898	11/03
5	2011	0	−0.1290	25/03	−0.1254	25/02
	2011	30	−0.0497	25/03	−0.0446	25/02
	2011	50	−0.0155	07/01	−0.0113	25/02
	2014	0	−0.1141	11/02	−0.0873	21/01
	2014	30	−0.0586	11/02	−0.0267	11/03
	2014	50	−0.0332	11/02	−0.0002	11/03
	2015	0	−0.1442	25/03	−0.1279	28/01
	2015	30	−0.0917	07/01	−0.0908	14/01
	2015	50	N.A	N.A	N.A	N.A

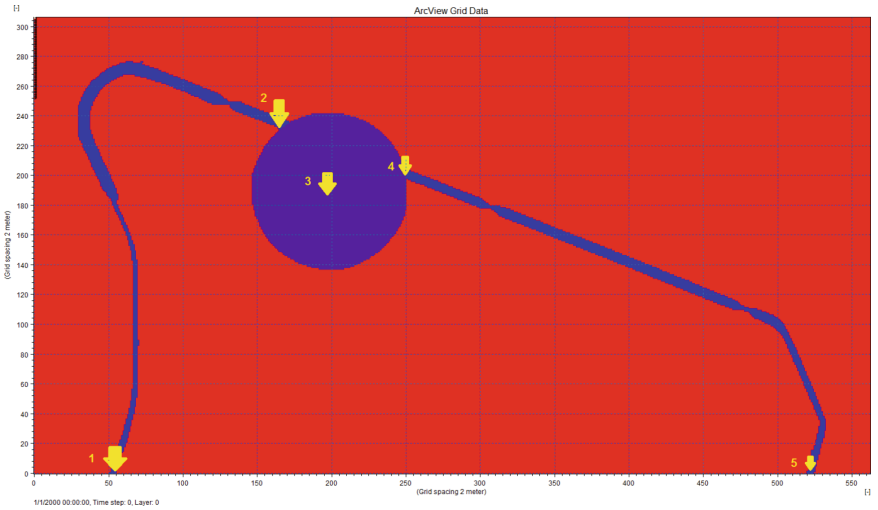

Fig. 5. Position of the numerical monitoring points in the Bacino Fede.

regarded as nearly negligible. As observed, the reduction in depths in the channels leads to a progressive decrease in velocities, although the reduction is of modest magnitude. Consequently, this decrease dampens the velocities within the basin, resulting in a poor water circulation in the Bacino Fede, compromising the beneficial effect of mixing on oxygenation and, thus, water quality.

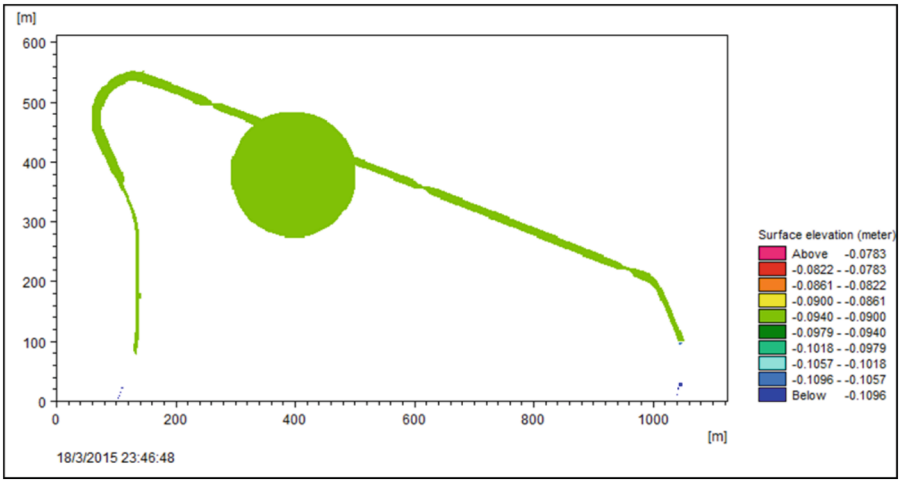

Fig. 6. Value of the elevation for configuration with 50% silting of canals, year 2015.

3.2 Water Quality Simulations

The analysis of water quality in the Bacino Fede was conducted examining the parameters BOD and OD through simulations carried out by ECO Lab module that considered two distinct scenarios, differentiated by boundary conditions. The first scenario simulates a situation where the basin is only fed from the sea with a defined BOD of 0.5 mg/l. The second scenario represents a situation in which the basin receives input from both the sea and external agents, such as anthropogenic discharges, the latter characterized by a BOD value of 11.36 mg/l at the western open boundary.

The input values considered for BOD, OD, temperature, and salinity at the two boundaries were provided by the Regional Agency of Environment Protection (ARPA PUGLIA), while within the basin, due to the absence of field measurements, a reliable set of values were used (see Table 3). Parameters implemented for simulating the two scenarios are reported in Table 4 and Table 5.

The simulation period considered is the first week of January 2011, and the results of the BOD and OD fields to be presented refer to the final step of the simulations, in the three cases analyzed, i.e. without silting, silting of 30%, and silting of 50%.

The results of the simulations within scenario 1 and considering the real and current situation, show BOD values that reduce both in the channels and within the basin, with the final result of BOD between 0–1 mg/l in the basin and values lower than 0.5 mg/l in the channels. With a 30% silting of the canals, a homogeneous variation of BOD is noted within the basin, to final values of 0.6–0.7 mg/l and 0.2 mg/l at the entrance of the basin and in the channels, respectively. Finally, in the configuration with a 50% silting, at the end of the simulation, the BOD presents values of 0.7–0.75 mg/l in the basin, while in the channels they tend to be zero. Overall, the analysis of the BOD data in scenario 1 does not show large differences within the basin in the configuration with 50% silting compared to 30%, while compared to the condition without silting the reduction in BOD over time occurs more slowly.

Table 2. Punctual time-average velocity values (see Fig. 5 for point location).

Point	Year	Silting (%)	Vel_{min} (m/s)	Date	Vel_{max} (m/s)	Date
1	2011	0	$2.99 \cdot 10^{-6}$	11/02	$5.46 \cdot 10^{-6}$	21/01
	2011	30	$1.55 \cdot 10^{-6}$	18/03	$4.07 \cdot 10^{-5}$	25/02
	2011	50	$8.25 \cdot 10^{-6}$	25/03	$7.12 \cdot 10^{-5}$	14/01
	2014	0	$6.37 \cdot 10^{-6}$	18/03	$5.58 \cdot 10^{-5}$	04/02
	2014	30	$1.75 \cdot 10^{-6}$	18/03	0.0001	18/02
	2014	50	$3.89 \cdot 10^{-6}$	07/01	0.0002	18/02
	2015	0	$4.27 \cdot 10^{-6}$	18/03	0.0001	04/03
	2015	30	$1.41 \cdot 10^{-1}$	28/01	$3.50 \cdot 10^{-5}$	14/01
	2015	50	0.0000	N.A	0.0000	N.A
2	2011	0	0.0003	28/01	0.0078	21/01
	2011	30	0.0001	18/03	0.0049	21/01
	2011	50	$5.80 \cdot 10^{-5}$	11/03	0.0050	25/02
	2014	0	0.0003	07/01	0.0082	25/03
	2014	30	0.0001	28/01	0.0051	18/02
	2014	50	0.0007	18/03	0.0059	14/01
	2015	0	0.0003	18/03	0.0105	25/03
	2015	30	0.0005	18/03	0.0109	25/03
	2015	50	0.0003	18/03	0.0109	25/03
3	2011	0	$6.78 \cdot 10^{-5}$	04/03	0.0006	18/03
	2011	30	$5.25 \cdot 10^{-5}$	14/01	0.0005	18/03
	2011	50	$3.89 \cdot 10^{-5}$	25/02	0.0004	18/03
	2014	0	$9{,}44 \cdot 10^{-5}$	18/03	0.0016	21/01
	2014	30	0.00004	14/01	0.0008	21/01
	2014	50	$4.76 \cdot 10^{-5}$	11/03	0.0003	11/02
	2015	0	$6.07 \cdot 10^{-5}$	18/03	0.0010	04/02
	2015	30	$6.95 \cdot 10^{-5}$	18/03	0.0008	04/02
	2015	50	$7.13 \cdot 10^{-5}$	18/03	0.0008	04/02
4	2011	0	0.0002	28/01	0.0097	25/03
	2011	30	0.0001	11/03	0.0039	25/03
	2011	50	0.0001	11/03	0.0037	25/02
	2014	0	$7.51 \cdot 10^{-5}$	28/01	0.0287	11/02
	2014	30	0.0001	07/01	0.0065	04/02

(*continued*)

Table 2. (*continued*)

Point	Year	Silting (%)	Vel_{min} (m/s)	Date	Vel_{max} (m/s)	Date
	2014	50	0.0001	25/02	0.0245	11/02
	2015	0	0.0002	07/01	0.0295	25/03
	2015	30	0.0001	14/01	0.0241	25/03
	2015	50	0.0001	18/03	0.0240	25/03
5	2011	0	$4.91 \cdot 10^{-6}$	14/01	$4.58 \cdot 10^{-5}$	18/02
	2011	30	$5.64 \cdot 10^{-6}$	11/03	$6.27 \cdot 10^{-5}$	18/02
	2011	50	$2.74 \cdot 10^{-6}$	07/01	$9.60 \cdot 10^{-5}$	21/01
	2014	0	$8.10 \cdot 10^{-6}$	18/03	$7.11 \cdot 10^{-5}$	18/02
	2014	30	$2.69 \cdot 10^{-6}$	25/02	0.0001	04/02
	2014	50	$2.52 \cdot 10^{-6}$	18/03	0.0002	04/02
	2015	0	$6.54 \cdot 10^{-6}$	14/01	0.0001	25/03
	2015	30	12.3	14/01	$2.18 \cdot 10^{-5}$	07/01
	2015	50	0	N.A	0	N.A

Table 3. Parameters set in the inlet waters of the Bacino Fede.

Parameters	Values
BOD (mg/l)	12
OD (mg/l)	7.69
Temperature (°C)	26.41
Salinity (psu)	8.2

Table 4. Parameters set at the open boundaries of the Bacino Fede. Scenario 1.

Parameters	Western open boundary	Eastern open boundary
BOD (mg/l)	0.5	0.5
OD (mg/l)	7.28	7.28
Temperature (°C)	19.7	19.7
Salinity (psu)	38.7	38.7

The analysis of the results of the second configuration (scenario 2) simulations highlights that not the entire basin appears to have BOD values lower than 1 mg/l as in scenario 1, but a part of the western canal assumes BOD values greater and around 2 mg/l, the one on the east 0.2–0.4 mg/l and the internal waters 0.6–0.8 mg/l. The BOD values,

Table 5. Parameters set at the open boundaries of the Bacino Fede. Scenario 2.

Parameters	Western open boundary	Eastern open boundary
BOD (mg/l)	13.36	0.5
OD (mg/l)	7.28	7.28
Temperature (°C)	19.7	19.7
Salinity (psu)	38.7	38.7

for the configuration with a 30% obstruction, vary almost equally for both the channels and the basin, with a continuous reduction of BOD reaching values at the last step of 0.6–0.8 mg/l within the basin. Compared to the scenario without channel interruption, with a 50% silting there is a slightly slower reduction in BOD. The BOD values for the channel to the west decrease more rapidly, while inside the basin they remain almost constant. Between scenario 1 and scenario 2, a faster reduction in BOD is observed in the former, although not significantly notable, whereas configurations of silting lead to similar results.

The results of simulations for scenarios 1 and 2 are further discussed in relation to the scalar fields of OD concentration. In the real configuration and considering scenario 1, there is an observed increase in OD over the simulation time, reaching values of 7.3–7.5 mg/l within the basin and in the channels near the basin with values even reaching 8.25–8.4 mg/l, leading to an equilibrium within the basin. With 30% silting, the OD reaches final values of 6.7–6.9 mg/l and 8.4–8.55 mg/l respectively in the basin and in the channels. Similar OD values are achieved by assuming a 50% silting along the channels. Comparing all three cases within scenario 1, it is observed that between the configuration without interruption and with interruption, in the latter, there is a slight reduction in the accumulation of oxygen, leading to a slower oxygen uptake. The higher oxygen content in the channels is found in the part closest to the internal basin.

If we analyze scenario 2, for the condition of uninterrupted channels, OD values within the basin are around 7–7.15 mg/l, and in the channels, they range from 7–8.35 mg/l, with values of 8.35 mg/l located in the upper part of the channels near the basin. Assuming a 30% obstruction, OD values of 6.45–6.75 mg/l are observed within the basin, and 8.35–8.45 mg/l values are noted in the channels, similarly to configuration with 30% silting and to scenario 1. In general, compared to scenario 1, slightly higher OD values are obtained considering different boundary conditions and pollution source at the inlet.

4 Conclusions

The present study describes the analysis of water dynamics in the Bacino Fede within the protected area of Porto Cesareo in southern Italy. The goal is to demonstrate the necessity of maintenance interventions on the channels connecting the internal waters of the basin with the open sea. Numerical hydrodynamic and ecological simulations were conducted to demonstrate that the low depth of the channels and their silting, by

the currents that transport solid material and sediments from the open sea into the same basin, lead to a low circulation in the coastal lagoon.

From the results of the simulations, it emerges that the reduction in depth leads to a decrease in elevation variations, consequently resulting in greater water steadiness within the basin and channels. There is even an observation of the absence of water in certain stretches of the channels during specific periods of the year. As for velocities, they appear lower when depth is reduced, exerting an impact on the circulation within the basin, which becomes weaker.

The BOD and OD are inversely correlated; to decrease BOD, oxygen is required. Therefore, a low BOD value and a high OD value are indicative of good water quality. In the absence of channel interruption, BOD has slightly lower values at the end of the simulation compared to cases with interruption, and it decreases more rapidly. On the other hand, OD exhibits higher values and increases more rapidly in scenarios without interruption. Assuming open boundary conditions on both sides, specifically at the two channels connecting to the open sea, with BOD values set at 0.5 mg/l, results in slightly higher OD values and slightly lower BOD values compared to cases with different boundary conditions. Furthermore, the study analyzed the impact of potential external factors that could alter the balance and water quality in that area, by introducing BOD values of 12 mg/l in one of the two channels, i.e. the western open boundary. The goal was to determine whether the mixing generated from internal currents is sufficient for the dilution of such discharges. Further investigation is needed to assess the actual possibility of discharges from external sources that could alter the balance and water quality in the area under study.

The results achieved highlight the negative effect of the silting of the canals on the exchange of the internal waters in question, with serious repercussions on the ecosystem of the area. It should also be noted that channel interruption, as observed in simulations, particularly at the mouth, would hinder the migration of fish fauna between reproduction and growth areas during specific periods of the year. Our study could useful insights for supporting current management techniques of such areas. In particular, further research could be dedicated to the ecological implications of potential climatic scenarios and could be supported by specific monitoring actions.

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Using the Intensity Values Obtained from Terrestrial Laser Scanner for Monitoring the Effects of Plant Disease: The Case Study of Gorgognolo (Italy)

Noemi Pagano, Eufemia Tarantino(✉), and Alberico Sonnessa

Department of Civil, Environmental, Land, Construction and Chemistry (DICATECh), Politecnico di Bari, Via Orabona 4, 70125 Bari, Italy
n.pagano@phd.poliba.it, {eufemia.tarantino, alberico.sonnessa}@poliba.it

Abstract. The continuous growth of agricultural production requires efficient strategies to manage the cultivation activities and ensure a high-quality standard for the food products. In this regard, the increased circulation of pathogens, also exacerbated by the consequences of climate change, represents a threat for environmental and agricultural assets. By the way of example, in recent years, the Xylella fastidiosa (Xf) bacterium has caused significant damage to the olive growing in the Apulia region, located in the south of Italy, with a consequent relevant economic impact. Geomatic methodologies for the acquisition and processing of ground spatial data can play a crucial role in the prompt identification of the effects of potentially harmful phenomena, such as Xf is, thus helping to develop effective countermeasures. This work presents the results of the analysis of a high-resolution three-dimensional dataset acquired with a Terrestrial Laser Scanner, which is generally used to reconstruct the shape of objects and structures. In this work, the intensity parameter associated to the point cloud has been investigated to infer information on the progression of the plant disease on a set of olive trees located in the Salento peninsula (Italy). These preliminary results could constitute the basis to design a strategy useful to monitor the effects of the spreading of Xf on medium-scale areas.

Keywords: Terrestrial Laser Scanner · Xylella fastidiosa · Intensity parameter · Olive groves monitoring

1 Introduction

The Apulia region, located in Southern Italy, is known worldwide for having an extensive heritage of monumental, centuries-old olive groves, symbolically and culturally relevant, so much so that they are included in the UNESCO patrimony for their landscape value [1]. The area devoted to olive production extends to 350000 hectares (about 79% of the area dedicated to this crop), accounting for 26% of national production until 2012 [2]. This percentage has decreased significantly in the last period (www.istat.it, 2012/22).

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The preservation of plant species diversity is compromised by the increasing emergence of new pathogens, and the persistent presence of already known threats. The Apulian rich olive-growing has not been spared from these problems since, over the past ten years, the Xylella fastidiosa (Xf) bacterium has begun to proliferate in the Salento area, placed in the southern part of the region, and circulate progressively throughout its whole territory. Recently, the presence of another Xf variant has also been observed in the Bari area, namely Xf subsp. Fastidiosa. The spread of this disease, which causes a rapid desiccation of the olive trees and lead to their progressive death, through a process referred to as olive tree rapid desiccation complex (CoDiRO - Complesso del Disseccamento Rapido dell'Olivo) [3], has directly damaged the economy and the environmental and tourist asset related to this specific crop.

This issue has risen to territorial and national relevance, triggering the adoption of several ministerial decrees, implemented by the regional phytosanitary service, which identifies areas affected by the Xf bacterium through a constant screening, in order to try to curb its spread and related symptoms.

In pursuit of monitoring the evolution of the phenomenon and providing a constantly updated overview of the situation, the Apulia Region has made available a web map service (wms), within the SIT Puglia portal (http://www.sit.puglia.it/), purposely developed for the specific case of Xf. The service maps the territory by subdividing it into infected, containment and buffer zones. Ministerial Decrees prescribe that plants harboring the Xf must be monitored also considering the stages of the disease evolution, different techniques have been used over time to better understand how the disease develops and put potential preventative measures into place. Among these, geomatics methodologies, which hold a considerable role in several scientific research contexts, have gained relevance in the field of precision agriculture [4]. The capability to support remote and proximity monitoring has boosted the use of these techniques in the control of different environmental factors.

Nevertheless, the gathering of in-depth information on the presence and evolution of a specific phenomenon sometimes requires the use of impactful and invasive processes.

Light Detection and Ranging (LiDAR) technology, implemented on ground-based sensors as Terrestrial Laser Scanners (TLS), has been tagged as a fundamental tool for the extraction of accurate dimensional information of various types of arboreal species in forestry, due to its non-invasive nature, high geometrical accuracy, and fast and flexible data acquisition mode [5, 6].

The work presented herein describes the results of the analysis of a high-resolution three-dimensional point cloud acquired by means of a TLS, describing a set of olive trees. The analysis reported in this work focuses on the intensity parameter, initially attempting to define the peculiar parameters of the two macro categories of the tree, i.e. trunk and leaves, and then proceeding with an analysis aimed at observing the state of the plant and the progression of the infection it is affected by.

2 The Study Area

The investigated area is located in Gorgognolo, an agricultural area about 10 km away from the city of Ostuni (BR) in the Salento peninsula, on the southern side of the Apulian territory.

Following the Ministerial Decree indications, the study area has been observed in two different periods of the year. The first measurement took place in August 2023 (T_0), while the next one has been carried out in January 2024 (T_1). The area under examination belongs to the buffer zone, where the presence of the disease has already been detected, as it can be inferred from the reports (http://sit.puglia.it/portal/portale_gestione_agricoltura/Elenchi/risultati). The surveyed land area has an extent of approximately 8250 m^2. However, the severity and stages of the disease are not uniform throughout the area. The zone of interest is shown in Fig. 1.

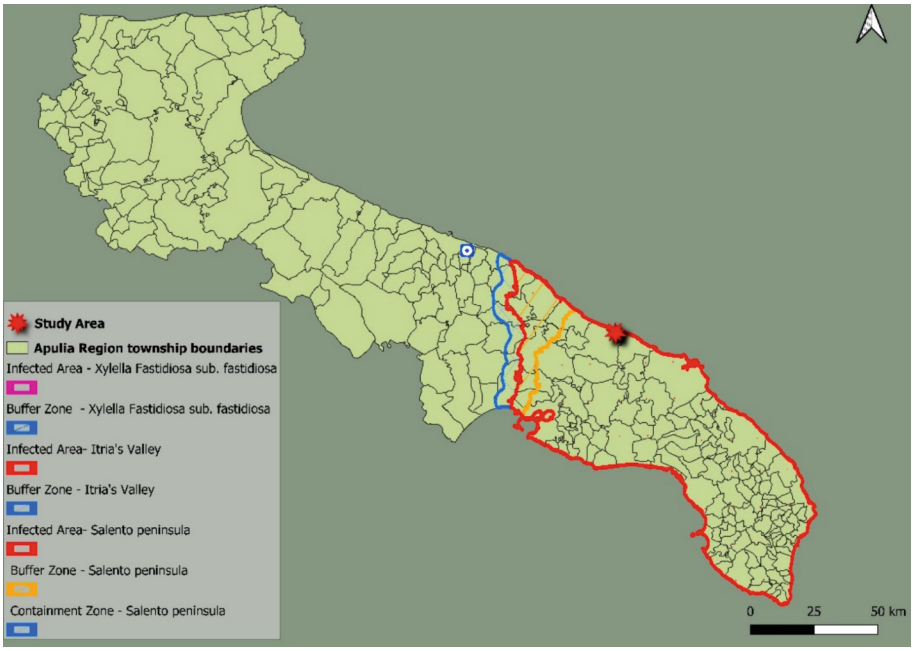

Fig. 1. Limits of the areas affected by the Xylella fastidiosa (Apulia Region wms). The study area is highlighted with the red star. (Color figure online)

3 Methodology Employed

TLS makes it possible to reconstruct the three-dimensional model of an object or a territory without invasive and/or destructive actions, providing with precision and quickness a considerable density of spatial information [7]. TLS is widespread used in forestry for determining the geometrical properties of plants [8]. The laser scanner functioning is based on the time-of-flight principle to deliver highly accurate point clouds that create a three-dimensional representation of the surrounding environment.

The technology is based on the emission of a laser pulse that, by the estimation of the elapsed time to hit the target, identifies its distance once the pulse is reflected to the

scanner. The coordinates, computed in a local reference frame integral with the instrument, are derived to create the three-dimensional point cloud, which density depends on the acquisition mode and the characteristics of the scanning device. In the present work, a class 1 Trimble TX8 Laser Scanner has been used. The sensor is characterized by a beam diameter of 34 mm at 100 m. The vertical Field of View (FOV) is 317°, with limited view below the laser scanner, while the horizontal FOV is equal to 360°. The scanner operates with a pulse frequency of 1 MHz and can acquire up to 300 m. According to its manufacturer, the instrument has different acquisition modes, shown in Table 1.

Table 1. Trimble Laser Scanner acquisition modes

Acquisition mode	Spacing (mm)	At a Distance of (m)	Number of points (millions of points)	Duration (min)
1	22.6	30	34	2
2	11.3	30	139	3
3	5.7	30	555	10
Extended	75.4	300	312	14

The point cloud is linked to color information (RGB - Red, Green and Blue) via the embedded digital camera, which is characterized by a resolution 12 Megapixels.

In addition to precise 3D coordinates, LiDAR systems also record the intensity parameter, broadly defined as the backscattered echo intensity for each measured point [9].

In a remarkable variety of applications, the effectiveness of LiDAR data is augmented by the availability of the aforementioned parameter. To date, LiDAR intensity data have proven to be extremely useful in data registration, feature extraction, classification, surface analysis, segmentation and object detection and recognition.

Furthermore, LiDAR intensity has proved beneficial in a wide range of applications because it can be related with specific attributes of the surface [10]. Unfortunately, there are also several variables to which the intensity is correlated, including the acquisition geometry, the scanning environment, and the sensors themselves [11]. The intensity value, fundamentally connected to the amplitude value recorded by the laser impulse, contained in the LAS format of the point cloud, comes from a scaling to a 16-bit dynamic level [12]. However, the scaling processes remains a prerogative of each manufacturer. In addition to the conversion mode of beam amplitude to retrieve the intensity, there are further parameters that exert a noteworthy influence, including power, range, angle of incidence, atmospheric transmittance, beam divergence and detector reactivity. Although numerous procedures have been introduced in the scientific field, and even commercially available software, to improve the usefulness of intensity data through a variety of normalization, correction or calibration techniques, this data remains still not easy to be used. The lack of standardization suggests that a different strategy should be adopted and pursued in each individual case [8].

In this study, a possible use of the intensity parameter in the evaluation of the effects of the Xf on olive trees is proposed.

4 Data Acquisition and Processing

As regards the study area, olive plantations are characterized by a low density and a rather irregular distribution; here, intensive plantations (i.e. grids with an average spacing of about 5 × 5) occupy less than 10% of the olive groves [13]. Therefore, during the acquisition phase, it has not been possible to maintain a fixed and distance between the device and each tree [14].

In the planning stage, the field activity has been designed to minimize the number of scans by optimizing the acquisition positions.

The sensor was mounted on a surveying tripod and multiple scans have been acquired to reconstruct a complete three-dimensional (3D) model of the investigated objects.

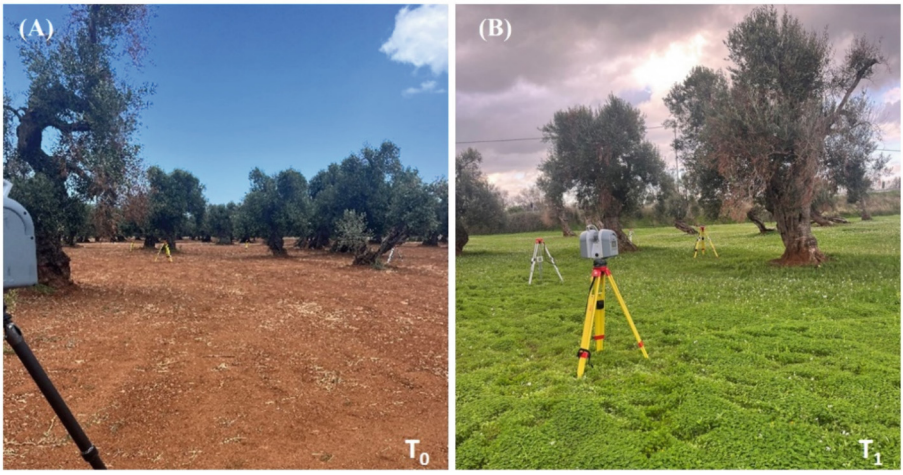

Fig. 2. Surveys (A) and (B) carried out in August 2023 January 2024 (T_1) respectively.

Therefore, each olive tree has been scanned from, at least three distinct positions [15]. In both surveys, (T_0 and T_1), a few tripods were set up, which location has been measured using a geodetic GNSS receiver, as a support for the flat targets used to facilitate the co-registration steps. The scan positions and the monitored area are shown in Fig. 2. Detailed scans of specific surfaces and targets have been carried out.

Following a visual assessment of the degree of crown desiccation, the analysis has been focused on four trees within the surveyed area. Scans were performed by keeping the device in high-definition mode for scanning relative to the preview- level 1 mode, while acquisitions relative to the specific targets or trees chosen were obtained in standard mode. The accuracy relative to the standard mode, as reported by the instrument certificate, ranges from ±2.8 mm with 68.3% confidence to ±8.5 mm considering 99.7%

confidence. As for the High-definition mode, the values range between ±2.2 mm (68.3% degree of confidence) and ±6.7 mm (99.7% degree of confidence) [16].

Point clouds were pre-processed by means of the Trimble RealWorks software (Trimble Navigation Limited, USA). The adjustment process was previously carried out by examining the position of the targets, while the quality of the model was gradually refined by pairwise registration of the scans, resulting in an accuracy of 2/3 mm for both surveys (Fig. 3).

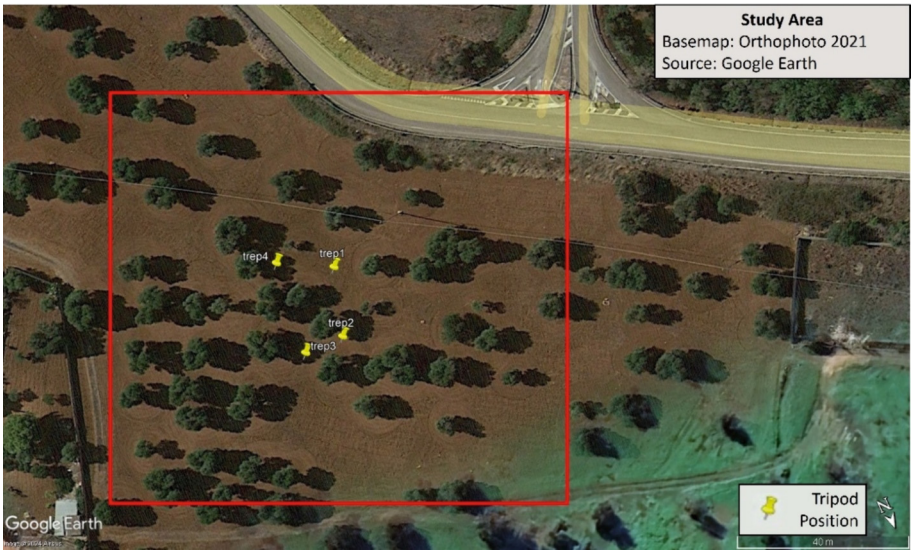

Fig. 3. Basemap of the study area- Source: Google Earth

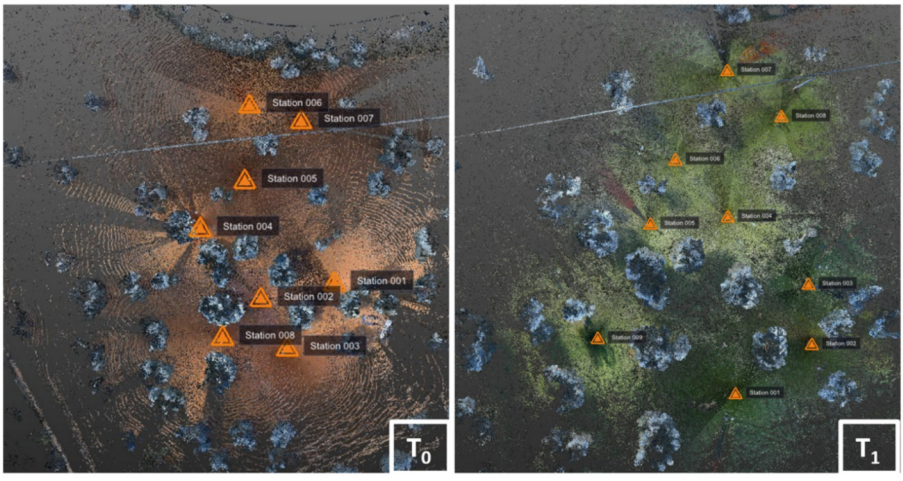

Fig. 4. Pre-processing operation in RealWorks Software - point cloud displayed in RGB values.

After the pre-processing step, the point clouds were analyzed in an open environment through Cloud Compare, a completely free and powerful 3D processing software (https://www.danielgm.net/cc/). The point clouds resulting from the two different acquisitions were aligned using T_0 as reference in order to make data spatially comparable. Before proceeding to any further analysis, the target trees were extracted with a clipping box whose dimensions remained unchanged. In addition, with the aim of ensuring more reliable results, appropriate filters were adopted make point clouds comparable in terms of informative content (i.e. number of points) [17] (Fig. 4).

5 Intensity Parameter Analysis

The intensity value recorded by a TLS is a radiometric measurement that allows to distinguish the different parts of a tree: leaves and wood [9, 18, 19]. Nevertheless, as underlined, this observation is influenced by several factors, including the beam incidence angle and the atmospheric conditions. That being so, the intensity values associated to points describing the same surface may differ when the environmental conditions change. As regards the two acquisitions, a temperature of about 36 °C has been recorded during the first survey, while an average temperature of 10 °C has been measured during the second survey. Pressure and humidity also were not the same [20].

An attempt to take account of these variations has been carried out by setting a steel pole, visible in both surveys and unchanged during the considered time span, as reference (Fig. 5). The related point clouds highlighted a change in the mean value of the intensity equal to 2303, on a 16-bit scale. The graphs in Fig. 6 show the range of intensity associated to the reference object in T_0 and T_1 respectively. The two curves evidence a similar distribution and comparable standard deviations, as displayed in Table 2. Therefore, the found mean intensity delta has been added to the intensity values recorded at T_1 on the whole scan.

Table 2. Steel pole intensity value for T_0 and T_1 surveys

	Steel Pole (T_0)	Steel Pole (T_1)
Average Intensity	16586	14283
Std. Dev.	2621	2565
M.A.D.	2092	2078

The intensity values have been then normalised on a scale ranging from 0 to 10.

A characterization of leaves and wood in terms of recorded signal intensity has been conducted on a sub-dataset created by extracting two trees from the T_0 survey (Fig. 7) and examining the intensity parameter of the point belonging to the trunk and the crown respectively (Fig. 8). The related values are shown in Table 3.

As expected, it could be noticed that the leaves and the woody part of the tree fall in different ranges. The values Table 3 in led to the definition of two classes, including all the measurements characterized by the identified average intensity value ±2 sigma,

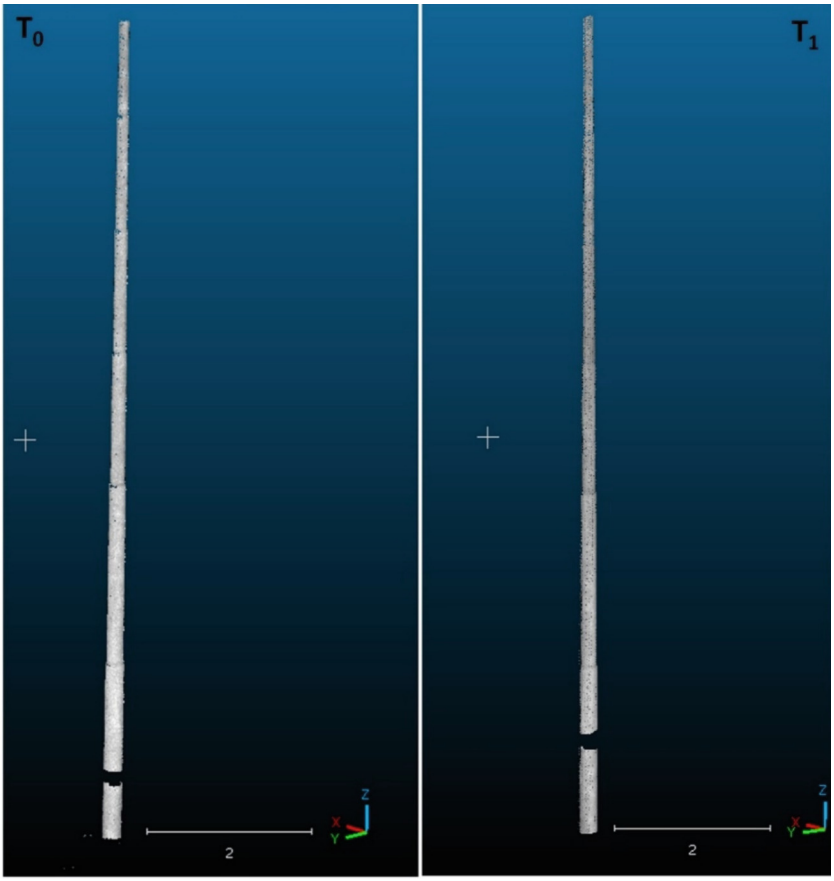

Fig. 5. Steel pole raw data in T_0 and T_1

Table 3. Intensity value related to Id F and 23 trees.

	F		23	
	Leaves	Wood	Leaves	Wood
Number of point	216179	12173	179665	19257
Average Intensity	4	9	4	9
Std. Dev.	1	1	1	1
M.A.D.	1	1	1	1

which robustness has been validated using such bounds as filter on the remaining trees and checking the relation with the corresponding part of the plant (Table 4).

Table 4. Statistical data analysis of the Id F and 23 trees at the T_1

	F		23	
	Leaves	Wood	Leaves	Wood
Number of point	212782	30812	179665	19257
Average Intensity	4	8	4	9
Std. Dev.	1	1	1	1
N.M.A. D.	1	1	1	1

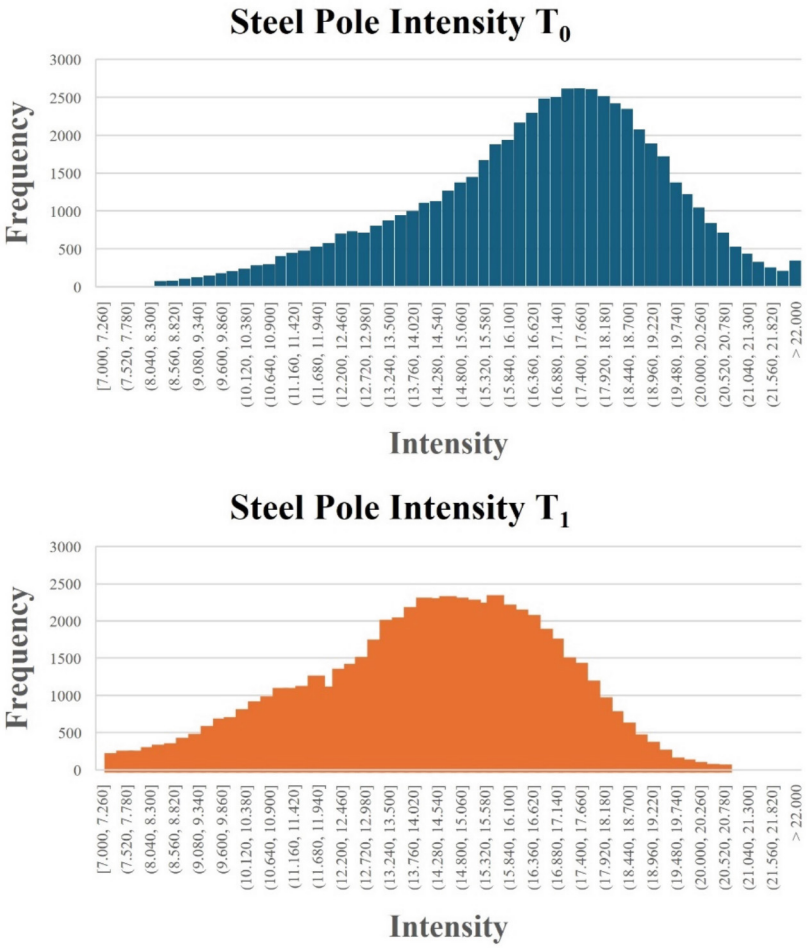

Fig. 6. Intensity distribution of Steel pole at the first (T_0) and second (T_1) survey

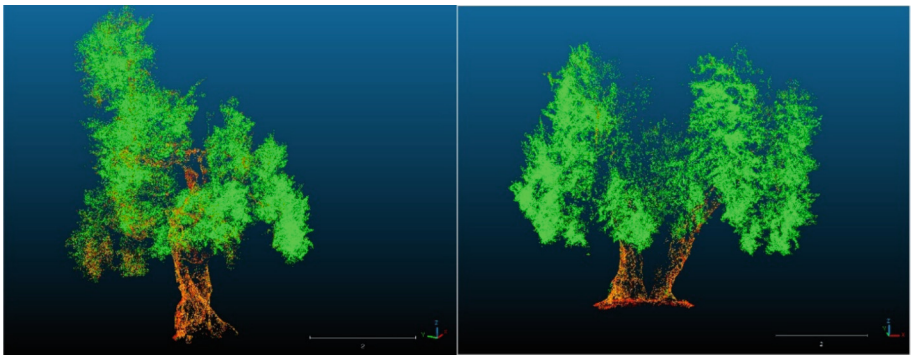

Fig. 7. Leaves and wood clustered with intensity value for the trees F and 23 at T_0

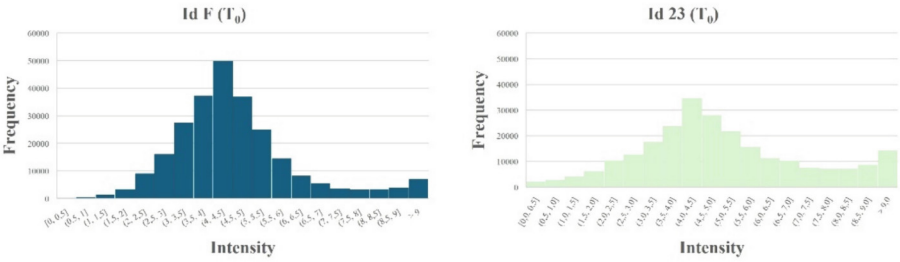

Fig. 8. Intensity value frequency of trees F and 23

Since the progress of the desiccation can be detected over a period of six months (i.e. the interval between the two surveys), as stated in [21], the intensity parameter has been used to quantify the evolution of the disease effects on a group of four olive trees (identified as 23, 24, F and 25 in Fig. 11 and Fig. 12).

The selected trees exhibit different levels of illness, as reported through the photographic documentation collected in both surveys; a qualitative visual analysis immediately evidences that the disease and its symptomatology have progressed between the two measurements (Fig. 9).

As, under the Xf action, the leaves gradually desiccate turning their pigmentation from light green to brown, estimating in a reliable manner the percentage increase of brown leaves can help in better understanding the evolution of the infection.

Assuming that dry leaves could behave like wood, in terms of radiometric response, the previously identified intensity ranges have been applied to the chosen samples. It should be noted that only the points belonging to the previously defined categories were considered in the reported evaluations, as shown in the Fig. 10; points falling outside these classes (between 6 and 10% of the whole point cloud) were not considered because spatially sparse and not clearly identifiable as wood or leaves.

The analysis of the point clouds selected following this criterion brought out the desiccation trend shown in Table 5.

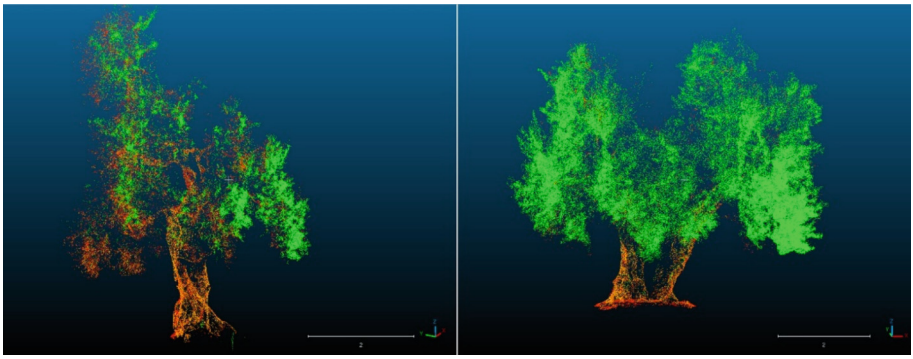

Fig. 9. Leaves and wood clustered with intensity value for the trees F and 23 at T_1

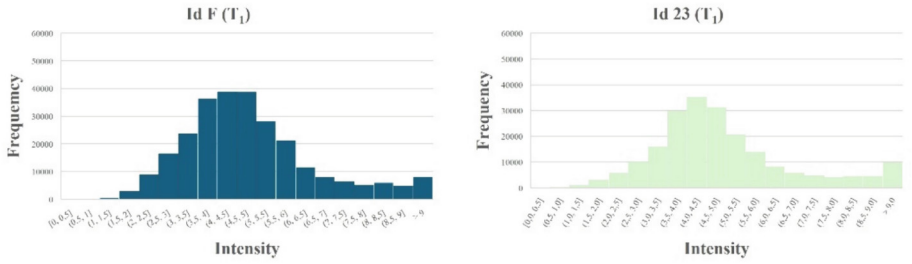

Fig. 10. Intensity value frequency of trees F and 23 at T_1



Fig. 11. Photographic documentation of the first survey.



Fig. 12. Photographic documentation of the second survey.

Table 5. Analysis of the leaves (A) and wood (B) classes.

T0	23		24		F		25	
	points	%	points	%	points	%	points	%
A-Leaves I (2–6)	165226	79	340947	90	216513	91	156049	89
B-Wood I (7–10)	44494	21	37934	10	21636	9	18900	11
T1	23		24		F		25	
	points	%	points	%	points	%	points	%
A-Leaves I (2–6)	163073	85	330857	87	212782	87	154463	86
B-Wood I (7–10)	28320	15	48679	13	30812	13	24353	14

Table 5 shows that, at T_0 the percentage points within the B interval associated with the olive tree 23 (corresponding to an intensity range 7–10) is greater than in the other samples, which is in accordance with the degree of damage visually detected (Fig. 12-23). In $T_{1,}$ the same class evidences a decrease, imputable to a loss of dry leaves. Again, this result is confirmed by the visual analysis (Fig. 11 and Fig. 12). Conversely. Trees 23, F, and 25 highlight an increase of the points behaving like wood. The different progression could imply that the trees, although all affected by Xf, were detected at different times in the evolution of the disease. In fact, the literature shows how the beginning of the disease generally occurs in the upper canopy level and then continues. It is necessary to point out that within the study area, no mechanical treatment, such as pruning, was executed between the first and second survey.

The approach adopted and data processing was wrapped up in the workflow presented below Fig. 13, which resumes the main steps of the presented analysis:

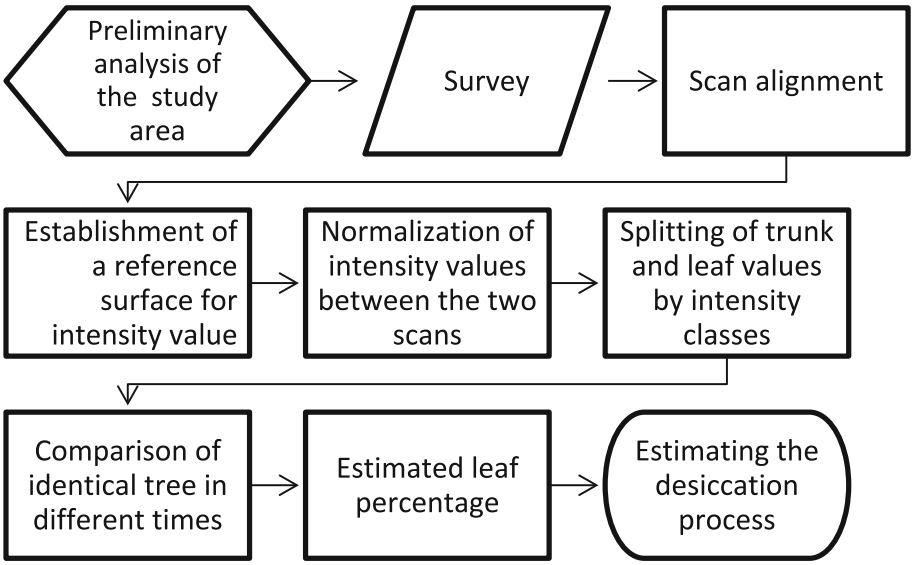

Fig. 13. Workflow.

6 Conclusions, Remarks and Further Developments

In order to improve and integrate analyses of the damages induced by pathogens on the arboreal species, and evaluate their increase over time, the discussed work has intended to provide an insight on the monitoring of a number of olive trees located in the Salento area, where the presence of the Xf bacterium has been widely documented.

The TLS technology, already in use in the forestry industry, has been employed in this investigation, with a focus on the intensity parameter collected with the three-dimensional dataset.

Four sample olive trees were selected and scanned in two monitoring campaigns con ducted in August 2023 and January 2024, to detect the development of the infection at different stages through the evaluation of the damages on the foliage. A comparison between the surveys evidenced that, in percentage terms, within the considered time interval, the progression of the desiccation process triggered by the Xf shows a similar trend, with an increase of about 3% (trees 24, F and 25) related to the class B. Where the disease is already in an advanced stage (tree 23), a loss of leaves can be observed.

Following these results, the use of the intensity parameter in the quantification of the effect of this bacterium on the olive trees seems to be very promising. It must be emphasized that these preliminary outcomes should need for further observations to be validated. As the presented study is in its infancy, the developments encompass further measurements and the integration with other methodologies, such as spectro-radiometry, to better understand the correspondence between desiccation and intensity levels.

Since the examined datasets have been collected by static scans acquired from positions that differed in the two surveys, for any future development a standardization in

the observation procedures should include a permanent materialisation of the scan stations. Nevertheless, due to the time-consuming measuring operations (i.e. about 1000 m^2 /hour) static TLS is not suitable when the crop exceeds one hectare. This issue might be overcome by using laser sensors placed on aerial vehicles, such as drones, which can cover wide areas in relatively short time, with low operating costs. On the other hand, the accuracy parameter associated to datasets acquired with this technique is worse than the analogue characterizing data collected by a static TLS [22], so additional tests should be conducted to verify its effectiveness.

Once validated, aerial measurements could be used to define threshold values of dry leaves percentage that would allow the identification of the occurrence of Xf bacterium.

In the light of the above, geomatic techniques could therefore play a key role in the countering of the Xf threat and help to implement strategies for controlling the effects of the spreading of this infection on medium-scale areas.

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The Influence of Sea Level and Wave Storms on Beach Erosion Along Apulian Coastline

Maria Francesca Bruno(✉), Matteo Gianluca Molfetta, and Umberto Fratino

Department of Civil, Environmental, Land, Construction and Chemistry Engineering, Polytechnic of Bari, Bari, Italy
{mariafrancesca.bruno,matteogianluca.molfetta,umberto.fratino}@poliba.it
http://www.poliba.it

Abstract. The coastline of Apulia extends for approximately 1000 km, of which about 29% consists of sandy beaches. It represents one of the main factors of socio-economic development in the region, but, at the same time, it has been subject over the years to progressive coastal erosion. Studies conducted, indeed, show a clear retreat of the coast, with non-negligible consequences on economically relevant sectors, such as tourism and land use planning.

In this study, the evolution of the coastline in the medium and short term has been analyzed, revealing a significant exacerbation of the phenomenon in the last decade. In an attempt to shed light on the intensification of these phenomena, an analysis of meteomarine events that occurred in those years and the variation of mean sea level has been carried out using data collected in situ or sourced from datasets made available by the Copernicus portal. The analysis of sea levels and sea storms has highlighted the occurrence of particularly stormy years and a significant sea level rise.

Keywords: Shoreline evolution · Sea storms · Sea Level

1 Introduction

Coastal areas are heavily exposed to several hazards weakening their environmental quality and sustainability and observations and forecasts of ongoing climate change (e.g. sea level rise, frequency of intense storm surges, etc.) also show an increasing exposure of coastal zones [1,2] erosion and flooding risk. In the long term, pressures cause a considerable deterioration in the quality of the coastal environment, causing important social changes in the development of economic activities and in the lifestyle of the coastal populations [3]. The great extension of the coastal territories threatened by climate change must also deal with the great extension of those at risk and the availability of economic resources for the protection and for the need to safeguard the natural environment. At the same

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time with the prediction of the impact on the coast of medium-long term events, it is also necessary to analyze the impacts of events that have already occurred [4] and which have led to a substantial change to the coastal environment, affecting the resilience of coastal regions with respect to future events.

In the last two centuries, starting from historical data series of continuous and reliable sea level data are available, the mean sea level of the Mediterranean Sea has risen and, more than in others, a significant rising trend has been found in the Adriatic Sea [5]. Hence, over the last century, the Relative Sea Level Rise (RSLR) of the Adriatic Sea has increased between 0.5 ± 0.2 mm/year and 1.2 ± 0.1 mm/year [6,7]. Even higher values have been observed in Venice (in the Northern Adriatic) where the tide gauge has recorded a variation of 2.5 ± 0.1 mm/year also due to anthropogenic subsidence, too. In the last years, this trend considerably increased; SLA dataset reported an average sea level increase over Mediterranean Sea equal to 2.5 mm/yr in the period 1993–2019 with an average local sea level trend uncertainty equal to 0.83 mm/yr [8]. An abrupt increase in sea level has been recorded throughout the Mediterranean during the period 2007–2009, when tide gauges in the northern Adriatic have recorded a rise of about 15 cm [9,10].

In the last decade a widespread coastal erosion has aroused a strong warning in the Mediterranean countries [11] and mostly in Puglia region (Southern Italy) [12], where the number of eroding sandy beaches has greatly increased. To deeply investigate the recrudescence of the erosive phenomena available sea level and wave datasets have been analyzed to find a relation between shoreline degradation and weather and climatic events.

2 Materials and Methods

2.1 Case Study

The coastal region of Apulia, which is bordered by both the Adriatic and Ionian Seas, spans a distance of 1034 km, including the Tremiti Islands. The coastline is divided into 6 provinces and covers the territory of 69 municipalities where approximately 43% of the total regional population lives.

Seven primary littoral cells (Physiographic Units - PUs) are identified along the coastline [12], with each capable of further division into sub-units, the boundaries of which are reported in Fig. 1.

The coastline in Puglia adheres to a microtidal regime, with a tidal range less than 0.5 m [13]. Analysis of observed wave data reveals that the wave conditions present a moderate climate, characterized by sea states with low to medium energy levels [14].

Upon classification according to shoreline typology, it is observed that cliffs cover approximately 33% of the total, sandy beaches account for 29%, rocky coast constitutes 22%, and anthropogenic structures are present in about 10%. Each Physiographic Unit (PU) encompasses a diverse coastal landscape, featuring several types of shoreline: (i) extensive sandy beaches flanked by coastal dunes (PU1, PU4, PU7), (ii) beach barriers dividing coastal lagoons from the open

sea (PU1, PU5), (iii) flat areas with lengthy sandy beaches (PU2), (iv) pocket beaches (present in nearly all PUs), and (v) rocky coastlines and cliffs, with or without accompanying protective beaches (PU1, PU3, PU5, PU6) [12].

As emphasized by numerous recent studies, the Apulian coastline has been experiencing long-term erosion since the latter half of the 20th century [12,15,16]. Due to the erosion process, numerous coastal protection structures have been constructed along the coast, particularly in PU2 [17]. Coastal regions are pivotal to the local economy, with coastal tourism alone contributing over 8% to the regional GDP in 2022. Over the past two decades, the influx of tourists to these areas has seen significant growth [18].

2.2 Data Sources and Methods

The position of the current coastline has been digitized based on orthophotos acquired in 2017 with a spatial resolution of 0.2 m. In the calculation of the regional coastal perimeter, the littoral zone within the inner basin of the Mar Piccolo in Taranto, which extends for approximately 30 km, has also been taken into account, while the perimeter of protruding coastal structures (e.g., external docks, breakwaters and piers) along the coastline has not been included.

The evolutionary trend in the medium and short term has been assessed by leveraging the available cartography (IGMI map dated 1960 and orthophotos acquired in 1992, 2005, 2008, 2010, 2011). Shorelines have been digitized and overlaid and the evolutionary trend was assessed through a polygon overlay analysis, evaluating erosion and deposit areas.

The analysis of sea level changes has been carried out by exploiting the daily global observations of the Sea Level Anomalies (SLA) on a regular grid (0.25° resolution) based on satellite altimetric measurements covering the period from 1993 to 2020 distributed by Copernicus Climate Change Service (C3S) [19]. The sea level anomaly is defined as the Sea Surface Height (SSH) with respect to the Mean Sea Surface (MSS) estimated for a 20-year reference period (1993–2012). Moreover, hourly sea level data recorded by tidal gauges belonging to Italian National Tide Gauge Network (RMN) [13] positioned along the Apulian coastline (Fig. 1) have been analyzed.

The existence of a monotonic trend in the period 1993–2020 was assessed using the non-parametric Mann-Kendall test [20–22]. Being non-parametric, the test is independent of the population distribution and is less influenced by the presence of any outliers in the time series. In this study, P-values <0.05 were considered significant.

The analysis of storm events has been carried out using the ERA5 wave dataset produced by the Copernicus Climate Change Service (C3S) at ECMWF [23]. ERA5 is the latest generation ECMWF atmospheric reanalysis of the global climate and it provides 0.5° gridded resolution wave data with a hourly sampling [24,25]. Figure 1 illustrates the geographic coordinates of the data extracted from the ECMWF dataset. With respect to the former ERA-Interim wave dataset [26], ERA 5 wave data have been improved in spatial and temporal resolution

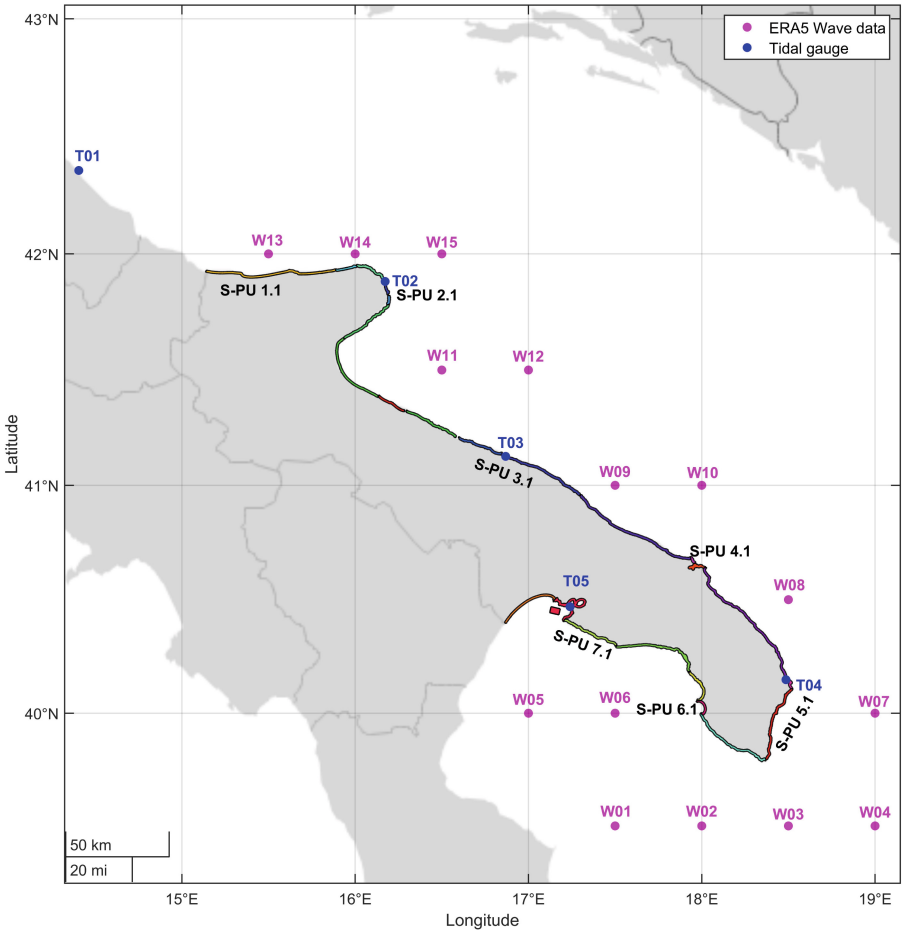

Fig. 1. Coastal physiographic sub-units (S-PU) are marked along the Apulian coastline. Position of examined RMN tidal stations (blue points) and wave data extracted from the ERA5 dataset (represented as magenta points) along the Apulian coastline are also reported. (Color figure online)

of ERA5 wave data have been significantly enhanced and tropical cyclones and troposphere have been also improved [25].

Significant wave height (H_s), peak wave period (T_p) and mean wave direction have been extracted at 15 grid points offshore the area of interest. The wave energy flux has been estimated as:

$$P_0 = \frac{\rho g^2}{64\pi} T_e H_s^2 (W/m) \tag{1}$$

where P_0 is the energy flux per unit of wave crest (W/m), ρ is the water density, and T_e is the energy mean period, estimated as $T_e = 0.9T_p$.

Storm events have been selected from the wave time series following the storm definition proposed by Boccotti [27] and for each storm the total wave energy flux of each storm has been obtained by applying a time-integration along every single event. In this phase, particular attention has been reserved to the identification of independent events, assuming that the independence of the storms is verified when the interval between two consecutive events is at least 48 h [28]. Storm events have then been classified using the Fisher-Jenks optimization algorithm [29,30] for splitting the storm dataset into five classes based on total wave energy flux spanning from Weak (Class I) to Extreme (Class IV) [31].

3 Results

The digitization based on high-resolution orthophotos has allowed for a more detailed and accurate description of the coast compared to previous studies, particularly regarding rocky shorelines, where greater lengths are observed compared to what was mapped based on orthophotos with lower spatial resolution [12].

For each S-PU, beaches were identified and mapped, including in the analysis sandy or pebbly sandstone beaches, as well as those along the rocky coast, both high and low, with sandy or gravel beaches found at their foot. The analyses thus encompassed a total beach length of 366 km. Geometric attributes, such as surface area, length, and width, have been defined for each beach (Table 1).

The analysis of the evolution trend of the Apulian coast, carried out by overlapping the shorelines extracted from several maps available, had shown that in the period 1960–1992 more than one third of the mapped beaches experienced erosion, while the shoreline degradation seemed to be halved in 1992–2005 [12,17]. In the subsequent period the erosion processes greatly increased affecting again more than one third of sandy beaches in 2005–2017. The analysis has disclosed that erosion has impacted the 34% of the coastlines, and also segments previously deemed relatively stable (Table 1).

To identify exactly the period when the erosive phenomena got worse, the evolution trends were also examined between 2005 and 2017. To do this, aerial photos acquired in 2008, 2010 and 2011 have also been analyzed. It should be noted that, unfortunately, maps related to 2009 are not available.

Table 2 reports the ratio of shoreline classified as eroded along the Apulian coast as carried out by the aforementioned analysis (percentages are calculated respect to the sandy coastline length). From 2010, a sudden increase of the erosive phenomena can be easily recognized from Table 2.

The substantial coastline stability observed during the period from 1992 to 2005 persisted over the subsequent three years, as evidenced by the 2005–2008 analysis. However, a notable increase in erosion rates was observed in the post-2008 period, coinciding with significant setbacks and damage to the dune belt on certain beaches of higher environmental and tourist significance. The significant increase in erosion has been observed along the Apulian Ionian side during the

Table 1. Geometric attributes (beach length and width) and shoreline change rates in the periods 1960–1992, 1992–2005 and 2005–2017.

S-PU	Beach length in 2017 (km)	Average Beach Width in 2017 (m)	Erosion 1960–1992 (%)	Erosion 1992–2005 (%)	Erosion 2005–2017 (%)
1.1	58.65	26.30	24.39	24.15	43.87
1.2	9.39	24.83	28.23	17.64	46.86
1.3	9.24	43.95	0.00	14.71	30.62
1.4	4.64	65.18	5.30	24.45	36.09
2.1	0.96	18.63	0.00	0.00	0.00
2.2	8.90	14.37	0.00	6.60	19.02
2.3	37.47	25.30	42.85	32.15	37.80
2.4	14.30	71.97	42.76	47.80	36.51
2.5	12.23	16.95	25.45	21.03	26.56
2.6	4.04	17.56	0.00	1.19	17.94
3.1	4.88	17.90	0.00	7.05	0.82
3.2	31.43	18.58	63.26	3.45	56.59
4.1	0.69	13.72	33.20	0.00	0.00
4.2	2.30	15.28	0.00	0.00	66.21
4.3	59.77	20.04	68.22	30.32	30.78
4.4	0.03	0.00	0.00	0.00	0.00
5.1	0.12	30.31	0.00	0.00	0.00
5.2	18.55	23.22	19.30	14.32	36.61
6.1	5.50	24.47	69.58	0.00	0.00
6.2	3.30	22.94	11.90	18.91	0.00
6.3	33.31	19.44	19.93	5.61	32.31
7.1	12.49	20.31	61.02	5.90	22.04
7.2	4.74	14.31	10.22	20.03	3.72
7.3	29.27	37.40	14.42	1.09	31.77
Total	366.18	25.50	35.54	18.33	34.74

period 2005–2010. Conversely, erosion on the Adriatic side has manifested with particular severity after 2011.

In order to investigate the shoreline variations that occurred in the recent period along the Adriatic and Ionian coasts, sea level data from the SLA dataset and tidal gauges have been examined. The Mann-Kendall test applied to the SLA dataset revealed the presence of significant trends at all collected points around the Apulian coastline. Consequently, a spatial trend map of SLAs was estimated (Fig. 2). The Adriatic Apulian coastline has experienced a notable rising trend in SLA, ranging from 2 mm/year to 3 mm/year. Conversely, along the Ionian coast, the increase in SLA appears to be comparatively lower, except for the southernmost part of the region, where the trend is almost similar to that observed in the case of the Adriatic side (Fig. 2).

Table 2. Eroded shoreline rates in the periods 2005–2008, 2005–2010, 2005–2011 and 2005–2017 in each Physiographic Unit (PU)

PU	Erosion 2005–2008 (%)	Erosion 2005–2010 (%)	Erosion 2005–2011 (%)	Erosion 2005–2017 (%)
1	18.03	30.57	37.15	42.27
2	15.96	20.59	22.52	32.16
3	29.24	25.8	34.64	49.09
4	20.71	18.25	15.18	31.72
5	28.05	51.22	44.51	36.38
6	19.96	40.92	29.34	25.56
7	8.20	47.24	22.46	26.30
Total	18.47	30.65	27.45	34.74

An even higher rising trend was identified when analyzing tidal data recorded across the Adriatic and the Ionian seas. The annual mean level has been computed with reference to the meteorological year spanning from September 1st to August 31st, so mitigating the effects related to the splitting of the winter season.

An analysis of the tidal data, extended to all the stations present in the lower and middle Adriatic, both of the RMN (Ortona - T01, Vieste - T02, Bari - T03, Otranto - T04), highlighted a generalized increase in the mean sea level starting from 2008, with a variation between 2007 and 2009 exceeding 10 cm, with a maximum recorded at T01 (13.5 cm) and a minimum at T04 (9.9 cm). After a sudden decrease in 2011, the MSL has again risen reaching the maximum value in 2012 at the Southern Adriatic stations (Ortona, Vieste, Bari) (Fig. 3).

Tidal data recorded in the Ionian sea - Taranto (T05) - exhibit a similar trend, differently to the SLA data (Fig. 3). The MSL recorded at T05 has risen by approximately 13 cm in the period 2007–2009.

The analysis of the total wave energy recorded during the period 1950–2019 has revealed significant variability over time across all examined points in the Ionian and Adriatic Seas (Fig. 4). The Ionian Sea appears to have an higher wave energy if compared to the Adriatic Sea, except for points located in the Gulf of Taranto (WG05, WG06).

When the analysis is focused on the most recent period, it can be observed as in the Ionian Sea, in the 2005–2007 period, was characterized by wave energy significantly lower than in previous periods, while a sharp increase was observed during 2008–2009 winter, in which the maximum value of the wave energy during the period 1950–2019 was recorded. The analysis of data from the Adriatic Sea, on the other hand, shows that the peak of energy occurred from the winter of 2011–2012 onwards. Similar trends was observed at all examined points in both Ionian and Adriatic Sea.

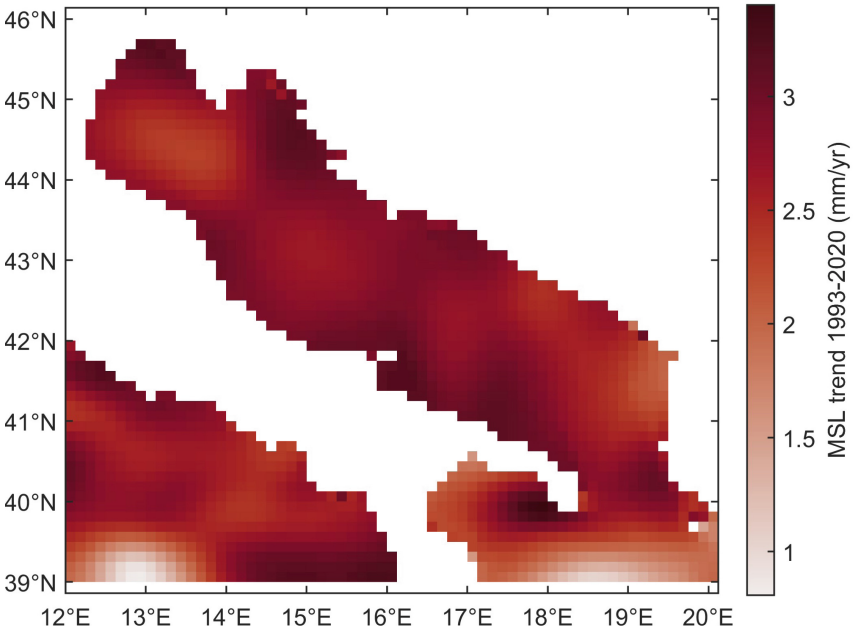

Fig. 2. Spatial trend map of SLAs in the period 1993–2020 based on satellite altimetric measurements [19].

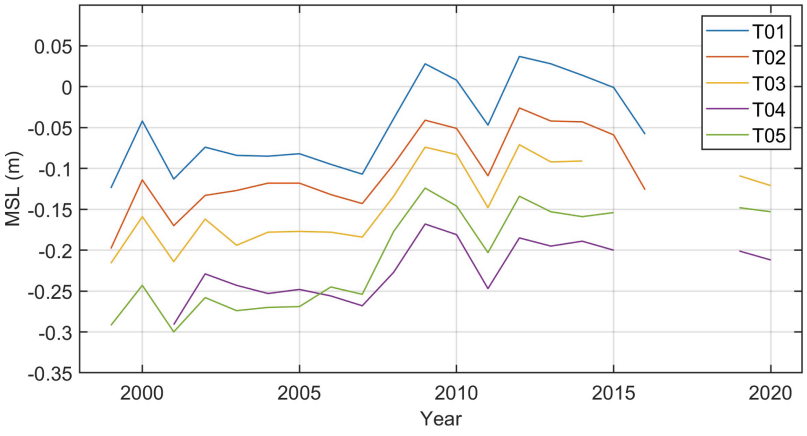

Fig. 3. MSL variation in the examined RMN tidal stations in 1999–2020.

The effect of the sea storm on the coast depends on various factors such as wave height at the peak of the storm, duration, wave periods and the direction of incidence. Moreover, in case of closer storm events, or when a series of years characterized by particularly intense events occurs, the effects on the coastline can be destructive [32,33]. The intensity and occurrence of sea storm during

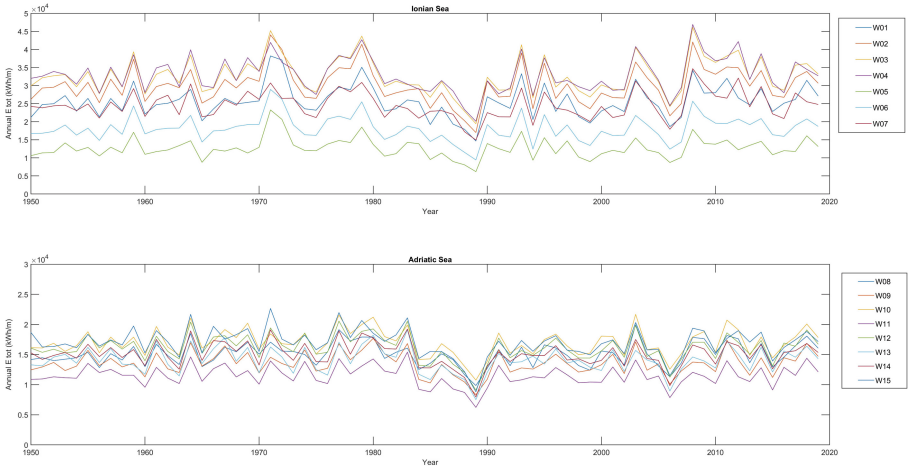

Fig. 4. Annual energy flux in the Ionian Sea (top panel) and in the Adriatic Sea (bottom panel).

the examined period have been therefore investigated. For each storm the total energy has been calculated and the storms classified using their total wave energy flux values.

Considering that sandy coastlines are more severely impacted by storms falling within classes III, IV, and V [31], a more comprehensive analysis has been conducted on such storm events. By employing a threshold value of the total energy of storms equal to the mean of total energy (μ) plus the standard deviation of the total energy (σ) calculated within the whole period of 70 years for the identification of the most severe years, the stormy years have been selected. For WG01 in the Ionian Sea 2008, 2011 and 2014 have been selected, while for WG09 in the Adriatic Sea, 2011 and 2018 have been identified (Fig. 5). In any case, it is noteworthy that, with reference to the average energy values, the data points within the Ionian Sea region consistently show values exceeding the mean throughout the years spanning from 2008 to 2014.

Exclusively focusing on storms falling within classes III, IV, and V, an analysis has been conducted on the number of events, their duration, and the interval between the occurrences of two events. Figure 6 reports that at WG01 in the period 2008–2011 the number of storm events has consistently increased, with very short intervals between them. In 2008, specifically, there were 10 storm events with an average interval of 12 days between each occurrence and a long duration (with an average value of about 100 h). Examining instead what occurred at point WG09, it can be observed that 2011 emerged as the worst year concerning the combination of the number of storm surges, their intervals, and duration.

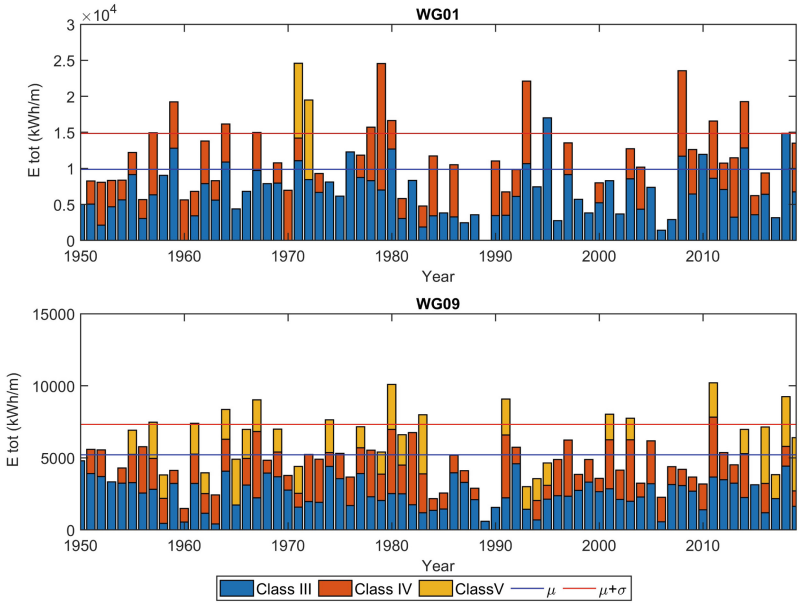

Fig. 5. Total energy of storms per year for Classes III, IV, and V at WG01 (Ionian Sea) and WG09 (Adriatic Sea). Blue and red lines respectively represent the average value (μ) and the average plus one standard deviation ($\mu + \sigma$). (Color figure online)

4 Discussion

An analysis of the sea level variation and higher storms that occurred during the last decades has been carried out in order to relate these variables and the erosive trend observed in 2005–2017 period. In the recent period, erosion has affected 34.7% of the regional sandy beaches, as opposed to the 18.5% observed in 1992–2005. These phenomena do not spare any of the physiographic units under analysis. However, it is noteworthy that PU3 (along the Adriatic coastline) and PU5 (Ionian coastline) have exhibited the most adverse trends, with respective transitions from 3.2% to 49% and from 16.1% to 36.4% of sandy coastline undergoing erosion.

The analysis of sea levels has shown a widespread increase along the Adriatic and Ionian coasts, with a remarkably large increment exceeding 10 cm occurred starting from 2007 to 2009. The rising MSL recorded in that period seems to be closely related to the large-scale forcing of the North Atlantic Oscillation (NAO), resulting in the ingress of substantial water masses into the Mediterranean Sea [9,10]. As reported in [34], the storminess in the Mediterranean region is also influenced by NAO values: winter average H_s results anti-correlated with the NAO index so that lower values of the NAO index corresponds to the increase of H_s.

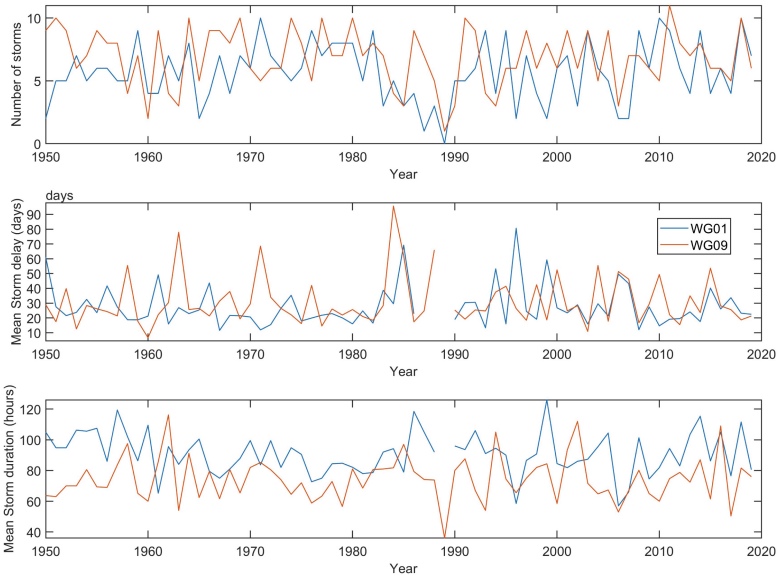

Fig. 6. Characteristics of the higher sea storms observed at WG01 (Ionian Sea) and WG09 (Adriatic Sea) during the period 1950–2019: number of storms, mean storm delay and mean storm duration.

The analysis of wave energy has revealed that in the Ionian Sea, the total energy of the extreme storms often exceeded the average value for the period 2008–2014, with the presence of very short intervals between successive storm events. Considering that the physiographic units along the Ionian Sea (PU5, PU6 and PU7) recorded the highest erosion rates after 2008, and that clusters of exceptional storm events occurred precisely from the winter of 2008, it can be inferred that this remarkable combination of high mean sea levels and sea storms characterized by high energy content and short intervals between them has certainly contributed to enhance the observed erosive phenomena.

Similarly, it can be noticed as the coastal erosion in the Adriatic side (PU2, PU3 and PU4) has significantly worsened after 2011, when the most intense storm events occurred. Indeed, in the Adriatic Sea the most severe sea storms occurred in the period 2011–2014.

On the Adriatic side, only the PU1 area exhibited a pronounced increase in erosive phenomena shortly after 2008. This situation may have been influenced by the significant rise in sea level, as made clear by the data of the nearest station (T01), which recorded a peak (+13.5 cm) during the winter of 2008–2009 winter, in addition to other local phenomena due to both the reduction of river solid discharge and to the effect related to the presence of coastal infrastructure. Indeed, it is emphasized that the coastlines within the PU1 areas (see areas close to the Lake Lesina and Lake Varano) are characterized by very flat beaches.

5 Conclusions

Analyses of the ongoing evolutionary dynamics along the Apulian regional coastline have highlighted the presence of numerous segments of sandy beaches undergoing erosion, with future projections indicating scenarios of widespread coastal retreat and a progressive reduction in beach width [35], already characterized by limited expanses.

To better understand the intensification of these occurrences, an analysis of meteomarine events during those years and the fluctuation of mean sea level has been conducted, utilizing data collected on-site or sourced from datasets provided by the Copernicus portal.

A comprehensive analysis of sea storms characteristics and the sea level variations report that in the Ionian Sea in the period 2008–2011 the number of storm events has consistently increased, with very short intervals between them and in the period post-2008 the worst cases of beach recession occurred along the Ionian coasts (PU5, PU6, and PU7).

At the same time, the Adriatic PUs (PU2, PU3, and PU4) have also suffered substantial impacts from erosive phenomena starting from 2011, a year marked by very severe storm events very closely spaced in time.

In the near future, the aim is to investigate the analyzed evolutionary processes using morphodynamic models as well.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Optimize the Estimation of Maize Height Using Sentinel-1: A Case Study in Umbria, Italy

Iva Hrelja[1], Andrea Soccolini[2(✉)], Sara Antognelli[1], and Francesco Saverio Santaga[1]

[1] Agricolus s.r.l., 06129 Perugia, PG, Italy
{i.hrelja,s.antognelli,fs.santaga}@agricolus.com
[2] Department of Civil, Construction and Environmental Engineering, University of Rome, 00185 Rome, Italy
andrea.soccolini@uniroma1.it

Abstract. Height is an important parameter to evaluate the crops growing state, being strongly correlated to plant other biophysical features. An accurate of this variable can allow farmers to carry out interventions aimed at optimizing crop development, which can be translated into an economic profit at the end of the cycle. The aim of the research is to explore key factors affecting the accuracy of remote sensing models in determining summer maize (*Zea mays* L.) height using Sentinel-1 SAR data. The study was conducted in 2023 on four fields in Umbria, Italy. The chosen approach is based on the construction of eight random forest (RF) models using different combinations of predictor variables, number of satellite images and speckle filters. In-situ maize height data and corresponding satellite images were acquired between 14th July and 4th September 2023. The results show that models constructed using four pre-full canopy coverage satellite image data (~150 cm) exhibited results with error ranging from 33.9 to 39.2 cm, while those built using all images yielded an error of 75.4 to 89.6 cm, thus demonstrating that maize height could be monitored effectively until to the point of complete canopy cover using SAR data. Future investigations are necessary could focus on refining model parameters further and exploring additional factors to enhance the robustness of the models.

Keywords: remote sensing · sentinel-1 · maize height · random forest

1 Introduction

The information obtained from biophysical parameters is fundamental for appropriate agronomic, ecological and economic management [1]. Periodic monitoring of plant height, biomass and Leaf Area Index (LAI) has a significant impact on company practices, considering the easy susceptibility of these variables to environmental conditions. Plants height, in particular, can represent a key factor in the growth state of crops, especially if associated with the phenological phase and biomass [2].

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Space-born images represent an opportunity to monitor spatial and temporal changes in crop growth. Tools such as UAV, Lidar and multispectral imaging have been widely employed to study and model plant height (see, e.g., [3–5]).

Active sensors such as SAR (Synthetic Aperture Radar), operating at microwave wavelengths and therefore not being influenced by the presence of cloud cover, allow images to be acquired both day and night and regardless of weather conditions [6, 7]. The capability of the SAR backscatter signal to penetrate not only the atmospheric components, but also the vegetation canopy, makes these types of sensors more suitable, compared to optical ones, for investigating biophysical properties of crops, such as the plant height [8].

Since the relation between plant height and SAR data is not linear [9] and is affected by a number of variables, prediction of plant height can benefit from machine learning (ML) techniques, a branch of Artificial Intelligence (AI) where algorithms are trained to emerge patterns and correlations from large data sets and make the best decisions and predictions based on those analyses. Among the numerous algorithms used, Random Forest (RF) is one of those that showed the best results for the estimation of plant biophysical parameters (see, e.g., [10, 11]).

The work aimed to assess whether satellite images obtained by Sentinel-1 were able to monitor the growth cycle of maize through the analysis of the height-backscatter signal relationship. Afterwards, the study focused onwhich RF predictor exerted the most significant impact of model accuracy, while keeping the model parameters constant. Much importance was given to the type of speckle filter used, because it represents a factor impacting the quality of speckle noise reduction in SAR images [12, 13]. In particular, the Lee Speckle Filter (LF, [14]) is effective at reducing speckle noise, it can also blur image details, especially in areas with high levels of speckle while Refined Lee Filter (RLF), thanks to additional steps tends to produce better results in terms of conservation and sharpness of image detail, simultaneously reducing speckled noise [15, 16].

In the bibliography, various approaches use data from multiple sensors as variables [see, e.g. [10, 11]. However, to maintain focus, we prioritize only the most common variables obtained from Sentinel-1, and the inclusion of additional SAR parameters, such as polarization intensity ratio and difference, as well as Radar Vegetation Index (RVI), would further improve accuracy, as noted in previous studies [see, e.g., [17–19]. Furthermore, we hypothesized that employing RLF-processed images and focusing solely on data from earlier maize growth stages could enhance model accuracy, leveraging the strong SAR-height correlations reported in prior research [9].

The detailed comparison of predictor selection and its impact on model accuracy represents a novel aspect of this study, not extensively explored in prior literature.

2 Materials and Methods

2.1 Study Area and Field Data

The experimentation was conducted in summer 2023 on four adjacent fields belonging to the “Foundation for Agricultural Education in Perugia” (FIA). All plots are located in the Tiber Valley, near Deruta, Umbria, Italy, and their total area amounts to approximately 60

hectares. The proximity with the Tiber River influences the soil component of the study area, thus characterized by a textural gradient from east to west. The experimental crop was biomass summer corn (Zea mays L.), sown at the end of the June. Previously, the pea (Pisum sativum Asch and Gr.) had been sown on the same fields. All the fields were managed with the same cultivation technique, respecting the principles of conservative agriculture.

Maize is a crop characterized by high water requirements, and in this area, the expected irrigation practice consists of complete irrigation from sowing to harvesting, using sprinkler irrigation in one-week shifts.

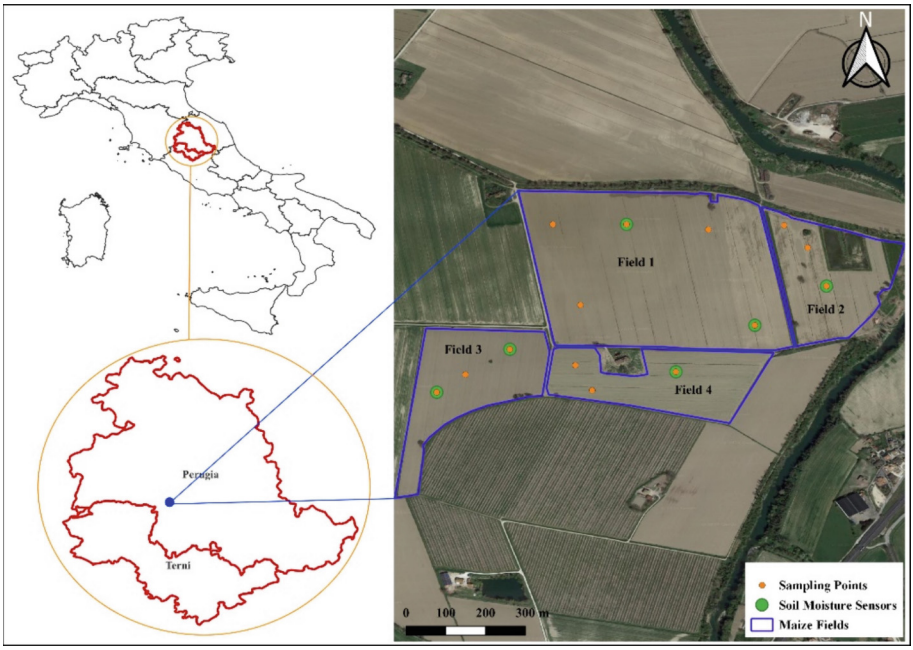

Fig. 1. The geographical location of the experimental plots.

Field data collection included measuring maize height in weekly intervals at 14 georeferenced locations (Fig. 1), photographing the growth process (Fig. 2), and recording field characteristics such as soil condition and crop health status. The field data was collected from 14th July to 4th September 2023. "Biologische Bundesanstalt, Bundessortenamt, and CHemische" (BBCH) [20] classification was applied to define the single development's stages of maize, while in-situ height measurements were obtained by the mean of three plant's heights for each sampling point.

Six soil moisture sensors were installed on the fields at a depth ~20 cm to acquire soil moisture data during the entire maize crop cycle. Data measurements occurred at 15 min intervals.



Fig. 2. Different growth stages of maize in the study area: **a)** Leaf development; **b)** Stem elongation; **c)** Flowering; **d)** Development of fruit.

2.2 Sentinel-1 Data

Seven Sentinel-1 Level 1 GRD images interferometric wide swath (IW) in descending pass direction were obtained from Copernicus Data Space Ecosystem [21]. The Sentinel-1 SAR data includes dual-polarization images in VV (Vertical-Vertical) and VH (Vertical-Horizontal) polarizations. We selected images based on their proximity to field measurement dates for optimal temporal alignment between satellite observations and ground truth data (Fig. 3). Probable irrigation dates, inferred from average soil humidity trends, also influenced our selection. In summer, with scarce precipitation, sudden humidity increases can likely be attributed to irrigation in irrigated crop areas (Fig. 4). Acquiring SAR images between irrigation periods helps mitigate the influence of water droplets and humidity on the typically stronger backscatter signal [22]. The acquired satellite data were subjected to preprocessing steps to prepare them for subsequent analysis and feature extraction. All preprocessing and feature extraction actions were done in Sentinel Application Platform (SNAP) software (version 9.0.8) [23]. The first step was to subset the images to a smaller area of interest (AOI). This was done to make the subsequent pre-processing steps more computationally feasible (larger images typically require more processing time). To convert the pixel values from integer digital numbers (DN) to backscatter coefficient or sigma-nought (σ°), radiometric calibration was performed. Next steps included terrain correction to project the pixels from the satellite reference system onto a geographic reference system and creation of a multitemporal stack to collocate the spatially overlapping products. The collocated images were then filtered using two speckle filters to reduce the effects of speckle noise: Lee filter with a window size of 7×7 (LF), and Refined Lee filter (RFL). Because SAR intensity can vary many orders of magnitude, the final preprocessing step was linear to dB conversion that compensates for very high dynamic range and expresses backscatter values in dB.

After preprocessing, five parameters were extracted from the SAR images to be used in modelling process: σ°VH, σ°VV, polarization intensity ratio and difference (σ°VH / σ°VV, σ°VH - σ°VV), and radar vegetation index (RVI), modified for dual-pol SAR data [24], as shown in Eq. (1). The workflow used in the study is shown in Fig. 5.

$$RVI = \frac{4\sigma^0 VH}{\left(\sigma^0 VH + \sigma^0 VV\right)} \tag{1}$$

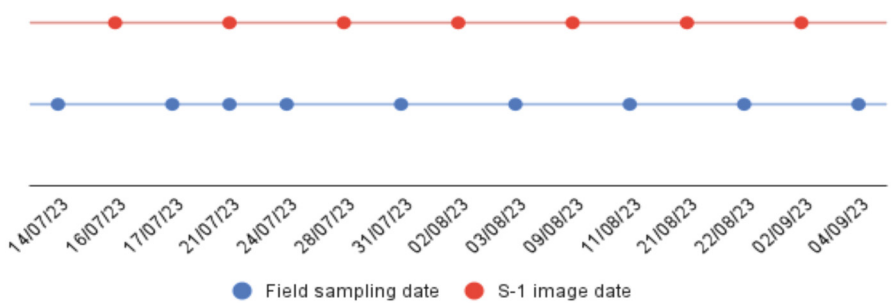

Fig. 3. Timeline of the field data collection and corresponding Sentinel-1 image acquisitions.

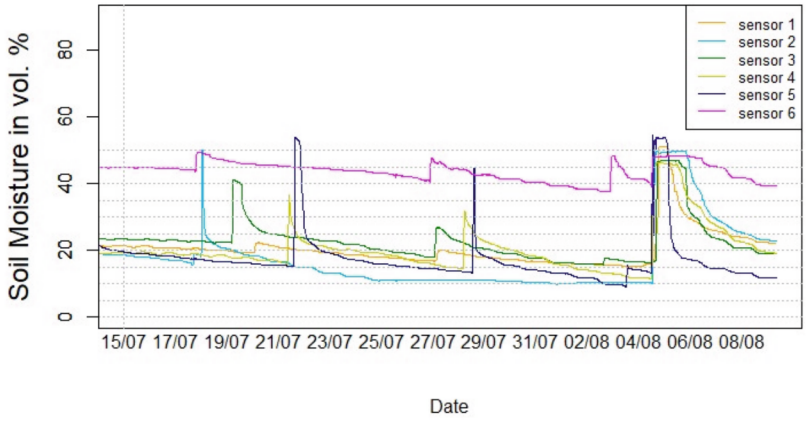

Fig. 4. Daily average soil moisture trend of six sensors.

2.3 Random Forest Modeling and Statistical Analysis

To assess the impact of key factors affecting model accuracy, eight Random Forest (RF) models were trained. Two sets of predictor variables were used: (1) σ°VH, σ°VV; (2) σ°VH, σ°VV, σ°VH / σ°VV, σ°VH - σ°VV, RVI. Moreover, two combinations of satellite image counts were used: (1) Data from all 7 images; (2) Data from the first four images,

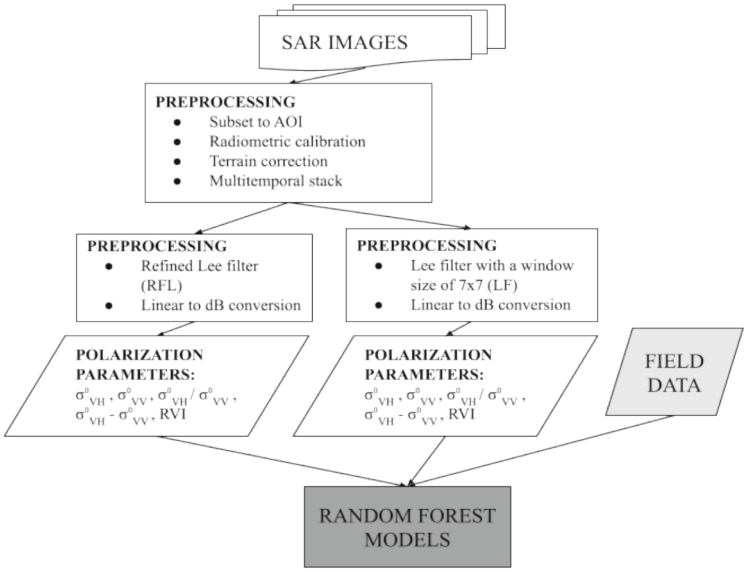

Fig. 5. Workflow for maize height estimation from Sentinel-1 images.

Table 1. Random forest models used in the study. Different sets of predictor variables were used while model parameters were constant.

Models	Predictors	Images (N)	Speckle Filter
RF1	σ°_{VH}, σ°_{VV}	7	RLF
RF2	σ°_{VH}, σ°_{VV}, $\sigma^{\circ}_{VH}/\sigma^{\circ}_{VV}$, σ°_{VH}-σ°_{VV}, RVI	7	RLF
RF3	σ°_{VH}, σ°_{VV}	4	RLF
RF4	σ°_{VH}, σ°_{VV}, $\sigma^{\circ}_{VH}/\sigma^{\circ}_{VV}$, σ°_{VH}-σ°_{VV}, RVI	4	RLF
RF5	σ°_{VH}, σ°_{VV}	7	LF
RF6	σ°_{VH}, σ°_{VV}, $\sigma^{\circ}_{VH}/\sigma^{\circ}_{VV}$, σ°_{VH}-σ°_{VV}, RVI	7	LF
RF7	σ°_{VH}, σ°_{VV}	4	LF
RF8	σ°_{VH}, σ°_{VV}, $\sigma^{\circ}_{VH}/\sigma^{\circ}_{VV}$, σ°_{VH}-σ°_{VV}, RVI	4	LF

and also two speckle filters: (1) RLF; (2) LF, while keeping model parameters constant, as shown in Table 1. The dependent variable was maize height measured in cm.

Random Forest is a type of ensemble learning method that can handle small datasets and help reduce overfitting by combining multiple decision trees into one model [25]. The advantage of using Random Forest lies in its ability to handle missing data and noisy predictors [26]. Modeling for each dataset was conducted in R 4.3.1 software [27] using Random Forest ('rf') method available within the caret (v6.0–94) [28] package. The number of variables used to construct each tree (mtry) was set to a range 1:4. Additionally, before building the RF model, data centering and scaling were used as pre-processing

steps. The effectiveness of the models was assessed through a 10-fold cross-validation process that compared the predicted and observed values of SOC in 70%–30% dataset splits. The following validation metrics were calculated to evaluate the performance of the models: root mean square error (RMSE) and coefficient of determination (R^2). Additionally, prior to modeling, Pearson correlation coefficients (r) and scatterplots were produced to display and measure the strength, direction and form of the relationship between backscatter coefficients and maize height. This was also conducted in the R environment using ggplot2 (v3.4.2) [29], and corrplot (v0.92) [30] packages.

3 Results and Discussion

3.1 SAR Parameters and Their Relationship with Maize Height

Higher sensitivity of both σ°VH and σ°VV was observed at the beginning of maize growth, which started to decrease once the crop reached ~150 cm in height (Fig. 6a and Fig. 6b). As the maize plants matured beyond the critical height of ~150 cm, the density of the canopy increased covering the soil and causing the dominance of volume scattering in SAR signal returns [31]. These results are consistent with what has been observed in the literature on maize [24, 32–34]. Moreover, σ°VH ($r = 0.53$) was found to be more strongly correlated to maize height than σ°VV ($r = 0.18$). These results could be explained by the fact that the development of large and randomly oriented maize leaves leads to a greater increase of the cross-polarized SAR backscattering [35]. Additionally, it has been found that σ°VV is sensitive to soil moisture levels even at high NDVI values (>0.7) [36], therefore it can be assumed that when maize canopy is well developed this sensitivity could affect the radar signal.

Contrary to the observed positive correlations with σ°VH and σ°VV, the σ°VH/σ°VV, as well as RVI (Fig. 6c and 6e) showed a negative correlation ($r = -0.3$) with maize height [37]. The backscatter difference (σ°VH - σ°VV) (Fig. 6d) was also positively correlated with maize height throughout the study period, and was not affected by the maize phenological stages, a phenomenon also observed in wheat fields [38]. This observation indicates the potential of σ°VH - σ°VV as a suitable predictor variable in modeling crop growth, but further research is needed to explore the underlying mechanisms driving these relationships and to refine the use of radar data for maize monitoring applications.

3.2 Random Forest Models

As can be seen in Table 2, the quality of speckle filtering has an impact on model accuracy. Contrary to our primary hypothesis, models using LF (RF 5-RF 8) showed improvement of RMSE from 10 to 15% when compared to models using a RLF dataset (RF 1-RF 4). For example, RF 6 showed a RMSE of 75.84 cm and a R^2 of 0.38, while RF 2 with the same model parameters, number of SAR images, and response variables showed a RMSE of 89.59 cm and a R^2 of 0.22. This result is probably caused by the nature of RLF that preserves image sharpness and detail near strong edges [14], which was not useful in a more homogenous, agricultural area studied here. LF with a 7×7 window size resulted in a smoother output image, and consequently created a dataset

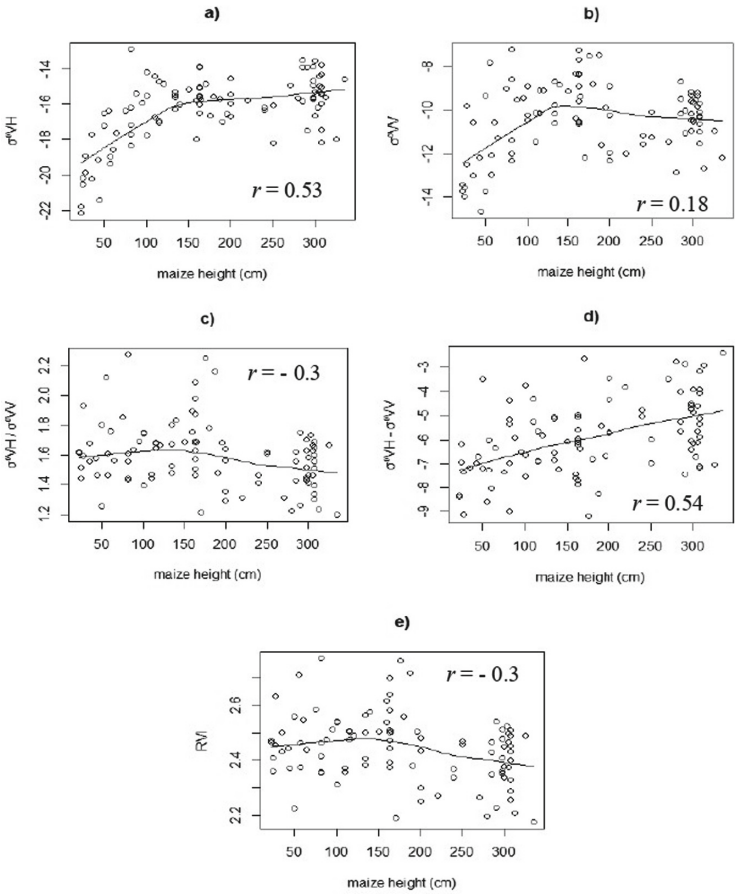

Fig. 6. Scatterplots and Pearson correlation coefficients (r) displaying the relationship between SAR parameters and maize height: **a)** σ°VH, **b)** σ°VV, **c)** σ°VH / σ°VV (ratio), **d)** σ°VH - σ°VV (difference), and **e)** Radar Vegetation Index (RVI). The images were produced using all satellite images (N = 7) and LF speckle filter with a window size 7×7.

of improved quality used in maize height modeling. More information on the effects of speckle filters on SAR image quality can be found in literature (see, e.g., [39]).

Furthermore, models constructed using four pre-full canopy coverage SAR data (RF 3, RF 4, RF 7 and RF 8) exhibited promising results, with RMSE ranging from 33.9 to 39.2 cm, while the models built using all SAR images (RF 1, RF 2, RF 5, RF 6) yielded an RMSE of 75.4 to 89.6 cm (Table 2). This is an improvement of 55 to 56% in model accuracy that strongly indicates that maize height could be monitored effectively until the point of complete canopy cover using SAR data, as previously observed [9, 10, 24, 32].

Finally, the performance of the RF models revealed a preference for fewer predictor variables as model inputs. Namely, RF 1, RF 3, RF 5, and RF 7 (RMSE = 86.53, 37.8, 75.43, and 33.88, respectively) performed better than RF 2, RF 4, RF 6 and RF

8 (RMSE = 89.59, 39.2, 75.84, and 34.26). Overall, the study observed an increase of model accuracy when using exclusively σ°VH and σ°VV as predictor variables by 0.5 to 4%. Compared to other factors that impact model accuracy considered in this study, this could be characterized as a minor improvement, indicating the primary focus should remain on refining preprocessing techniques and selecting appropriate SAR data, which have demonstrated more substantial impacts on model outcomes.

Table 2. Results of Random Forest (RF) and improvement (%) of the models with varying input used: different speckle filters, number of images and response variables. $\uparrow_{\text{filt. (\%)}}$ means RMSE improvement (%) of the model when using LF, $\uparrow_{\text{im. (\%)}}$ means RMSE improvement (%) of the model when using first 4 SAR images, $\uparrow_{\text{var. (\%)}}$ means RMSE improvement (%) of the model when using exclusively σ^0VH and σ^0VV as input variables.

Models	RMSE	R^2	$\uparrow_{\text{filt. (\%)}}$	$\uparrow_{\text{im. (\%)}}$	$\uparrow_{\text{var. (\%)}}$
RF1	86.53	0.23	–	–	+3.5
RF2	89.59	0.22	–	–	–
RF3	37.80	0.47	–	+56.3	+3.7
RF4	39.20	0.47	–	+56.2	–
RF5	75.43	0.42	+12.8	–	+0.5
RF6	75.84	0.38	+15.3	–	–
RF7	33.88	0.69	+10.4	+55.1	+1.1
RF8	34.26	0.60	+12.6	+54.8	–

4 Conclusions

The results of this study indicate that in the process of vegetation height modeling, several features should be considered to improve the accuracy of the models. Pre-full canopy coverage SAR data was a key contributor that enhanced model accuracy. This demonstrated that the temporal dimension is crucial for monitoring vegetation growth dynamics effectively. Moreover, the unexpected but significant improvements in model accuracy associated with LF filtering, particularly in the context of homogeneous agricultural landscapes, emphasize the importance of tailoring SAR preprocessing techniques to specific study areas.

Furthermore, the preference for fewer predictor variables as model inputs, namely σ°VH and σ°VV, emphasizes the importance of thoughtful feature selection in model construction, yielding enhancements in accuracy.

These findings not only advance our understanding of SAR-based vegetation height modeling but also offer practical insights for optimizing model performance in agricultural monitoring applications. The findings corroborate with previous studies on maize vegetation dynamics, underscoring the importance of considering crop growth stages in interpreting radar backscatter data.

Understanding the temporal dynamics of radar signatures in relation to crop height offers valuable insights into agricultural monitoring and management practices. These observations contribute to the refinement of remote sensing methodologies for assessing crop development estimation, thereby supporting informed decision-making in agricultural resource management.

This study assessed the RF machine learning technique for estimating maize height using Sentinel-1 data. However, the method has limitations, including the need for high-quality and sufficient ground truth data. Fluctuations in soil moisture due to irrigation practices could affect maize height estimation outcomes. Therefore, gathering data from additional seasons is recommended to enhance the robustness and generalizability of the findings.

It is also recommended to apply other types of ML algorithms for comparison with the employed model, in order to allow for a broader analysis.

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Optimizing Feature Selection for Solar Park Classification: Approaches with OBIA and Machine Learning

Claudio Ladisa(✉), Alessandra Capolupo, and Eufemia Tarantino

Department of Civil, Environmental, Land, Construction and Chemistry (DICATECh), Politecnico di Bari, via Orabona n. 4, 70125 Bari, Italy
{claudio.ladisa,alessandra.capolupo,eufemia.tarantino}@poliba.it

Abstract. In the context of climate change mitigation, the crucial role of solar energy as an inexhaustible and renewable source is underlined by the widespread integration of photovoltaic (PV) panels. To keep track of the rapid expansion of extensive PV systems (such as solar parks), it is important to keep monitoring their quantity, distribution, and impact. Despite the many complications involved in mapping PV systems, stemming from the diversity of materials and field layouts, many researchers have focused on ways to improve this process through Remote Sensing techniques aided by Machine Learning and Deep Learning. In this study, multiple object-based image (OBIA) classification models were created for mapping large solar parks, using open-source data (Sentinel-2) and computational tools such as Google Earth Engine (GEE) and RStudio. The case study was conducted in Pavagada Solar Park, India, which is the third largest solar park in the world spanning over 153 km^2. For training, validation, and testing purposes two zones within the park were identified. Data were collected for four seasonal periods; a classification model was developed for each season while validating them. The most accurate model was then implemented in the test area. The selection of features for the Random Forest (RF) classifier was done using the Recursive Feature Elimination (RFE) method, with the main objective of eliminating non-relevant features while preserving only the significant ones. This analysis showed a substantial improvement in accuracy, thereby validating the effectiveness of the RFE algorithm in feature selection. This is particularly true in the autumn when a maximum Overall Accuracy (OA) of 88.72% was achieved.

Keywords: Object-Based Image Analysis · Sentinel 2 · medium-resolution satellite images · photovoltaic panels

1 Introduction

Rising public consciousness about environmental problems as well as technological progress resulted from the increase of installed renewable energy sources

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in energy production [1]. To enumerate these, solar energy is among the most potential ones abounding in nature and has little negative impact on nature [2]. Countries and international organizations, like the European Union, China, India, the United States, and Japan, have provided huge funding for the design and implementation of PV systems [3]. Indisputably, India has made good use of its energy opportunities, sprawling across wide regions, and exploiting the many areas with more than 300 sunny days a year. It is not only that green energy is brought to rural areas, but by the same token, it keeps the environment clean and safe from the pollution of fossil fuel production [4]. The development of solar energy has been increasing strongly since 2009, with a compound annual growth rate of 41%, which will lead to an almost tenfold expansion by 2040 [5]. Nevertheless, concerns about the loss of territorial resource surface, reducing the size of arable farmlands, and alterations to the surrounding environment are also raised with the widespread installation of solar PV panels [6]. Consequently, more and more attention is being paid nowadays to the possibility of a process being established that will, as a result, fundamentally affect the animal and plant world and the overall functioning of the natural system [7]. Therefore, there is an urgent need for detailed monitoring and mapping of large solar parks. However, access to detailed national data on the location of PV solar panels is often limited and solar databases based on voluntary contributions may lack completeness [8]. Therefore, refining the update of spatial distribution data and generating dynamic information on PV systems plays a fundamental role in research, encompassing the analysis of impacts resulting from changes in land use in local climates [9]. Regarding the example of industrial solar parks, the usual mapping strategies, i.e. direct ground surveys, are too time-consuming. Therefore, the development of a comprehensive, fast, and non-invasive data collection method is of great importance [10]. The strong development of space programs such as Copernicus and Landsat have produced a significant amount of data on the Earth's surface. This phenomenon has enabled remote sensing to be a key subject and to be used in a wide range of environmental applications [11–13]. Several studies have shown excellent results for mapping PV parks utilizing open-source optical data such as Sentinel-2 (S2) or Landsat 8, rather than high-resolution commercial data, which need significant processing resources and limit its applicability across wide geographical expansions [10,14,15]. In some recent studies, remote sensing techniques have been combined with supervised Machine Learning algorithms or convolutional neural networks (CNN) for PV panel extraction [16,17]. However, from the latest research results, it was noted that CNN requires large training sets in contrast to supervised classification algorithms such as RF, which require less training data but still achieve excellent accuracy values [18]. This research aims to develop and validate an RF-supervised classification model to identify PV systems within the Pavaganda solar panel complex developed in Pavagada, Tumkur district, which is located approximately 180 km north of Bangalore in India. To address one of the recognized "salt and pepper" effects in image classification, the research opts for OBIA rather than pixel-based approaches and seeks to utilize the geometrical information in the range of segments [19]. Data

collection was done individually across four different seasons, which are February, April, August, and November 2022. The multi-temporal approach for this study was used to fully investigate the impact of seasonal changes on the efficiency of different RF classification models. During this study, only open-source platforms and tools, such as GEE and RStudio, were used together with S2 multispectral optical data to develop an easily reproducible methodology. This research differs from others in the choice of variables to be input into classification models. Various spectral indices, already used in previous studies, were collected and through the RFE algorithm within the RStudio environment, only the best were chosen. The algorithm is performed by cumulatively removing weak features, which leads the model to eliminate dependencies and collinearities, thus improving the accuracy of the classification process [20].

2 Study Area

The study area is located in Pavagada taluk, Tumkur district, Karnataka, India. Within this region lies the Pavagada Solar Park, a solar park spanning a total area of 153 km^2, making it the third-largest solar power plant in the world. Known as Shakti Sthala, the park is situated approximately 180 km from Bengaluru. The land on which the park is built was acquired from 2,300 farmers through a 25-year lease agreement [4]. In this work, two distinct areas within the Pavaganda Park extension were utilized. As depicted in Fig. 1, one area was designated as the training and validation zone, while another area was exclusively utilized as the test zone (ground truth).

3 Data Set

3.1 S2 Imagery

S2 satellite images were preferred over Landsat 9 images due to their better geometric resolution. The experience in the past with the use of S2 evidence confirms the good results for both PV panel mapping and other monitoring of land uses, among others [21–24]. The S2 multi-spectral sensor has 13 spectral bands from wavelengths of 0.44–2.2 μ m, including visible, NIR, and shortwave IR regions of the spectrum [25]. The spatial resolution varied from 10 to 60 m across different bands [26]. The S2 Level 2A product, which was already atmospherically corrected, was selected from the GEE platform. Image selection was carried out for February, April, August, and November, to conduct a multi-temporal analysis to identify the most suitable season for developing high-performance classification models. For each month, preference was given to images with minimal cloud coverage, particularly for those with a coverage percentage below 1%. Among the identified images, high-resolution bands of 10 m were used, including blue (band 2, 490 nm), green (band 3, 560 nm), red (band 4, 665 nm), and NIR1 (band 8, 842 nm). Additionally, 20-meter resolution bands were considered, such as red edge 1 (RE1) (band 5, 704 nm), red edge 2 (RE2) (band 6, 740 nm), red edge

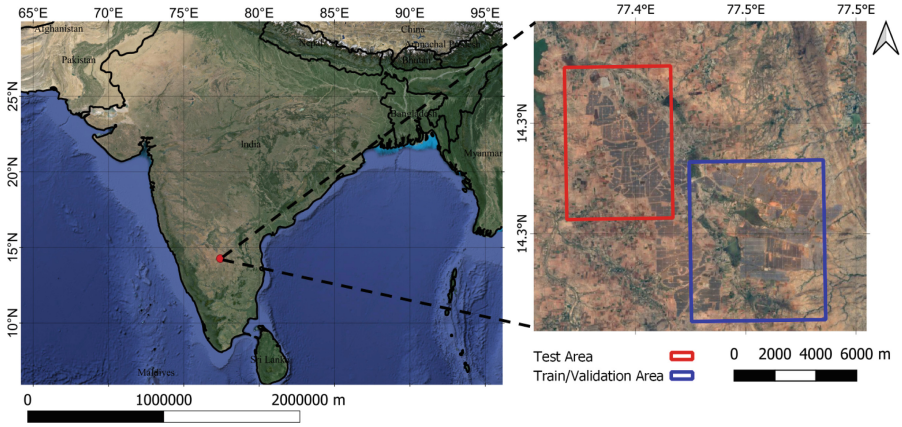

Fig. 1. Train/Validation and Test Area in the Pavaganda Solar Park.

3 (RE3) (band 7, 783 nm), narrow NIR2 (band 8a, 865 nm), SWIR 1 (band 11, 1614 nm), and SWIR 2 (band 12, 2202 nm). Red edge bands, narrow NIR, and SWIR were included, as they are crucial for distinguishing vegetated areas from non-vegetated areas and identifying bare soil from other land cover types [27]. The images were cropped within the designated study areas for training, validation, and testing.

3.2 Methodology

The study's classification model for the solar park was created mostly using OBIA and RF approaches. The initial stage of the work, shown in Fig. 2, was the data pre-processing after S2, as described previously in this paragraph. The next step occurred in segmentation, which is the preliminary phase of the OBIA approach [9]. This was a process that used a Simple Non-Iterative Clustering (SNIC) segmentation method accessible within GEE. The segmentation phase was applied to prepare the data both in the training/validation and test areas. Various features were computed for each object, focusing on the spectral indices previously employed in other studies for PV mapping [15,28,29]. These indices were calculated for each of the four considered months. Then, objects that had been separated were subsequently labeled using Quantum GIS (QGIS) software. Following segmentation, feature extraction, and object labeling, the workflow was continued in the RStudio environment. Before proceeding to the classification phase, feature selection was performed using RFE. This algorithm was applied each month separately. Because the objects classified as PV are much fewer than those assigned as NO-PV, the dataset was rebalanced after selecting the features for each month. The imbalance in the number of class objects, as in this scenario, may produce misleading results by effectively supplying the majority class while failing to identify the minority class [30]. Oversampling was used over subsampling since earlier studies showed that subsampling resulted in

information loss during the training phase [10]. After balancing the objects from the study area designated for training and validation, they were randomly split as follows: 70% of the dataset was set as the training dataset, and the rest of the 30% was used for validating the RF model. For this purpose, a unique RF model was generated for each month. Then plate metrics such OA, Cohen's Kappa (K), Producer's Accuracy (PA), User's Accuracy (UA), and F1 were calculated using different algorithms. Eventually, the model with the best accuracy was applied to the Test area, and the metrics were computed.

3.3 SNIC Algorithm Segmentation

The SNIC algorithm is made available by the GEE platform. The decision to use this segmentation technique was driven by the successful outcomes of previous studies employing S2 multispectral images, in the fields of PV plant mapping and other applications [10,30]. Assigning some pixels to centroids on a regular grid within the image serves as the algorithm's initial step. Following that, the distances between each pixel and its centroid in terms of color and spatial coordinates within a 5-dimensional space were computed [10,30,31]. It is a distance measurement that combines normalized spectral and spatial information leading to the generation of visually homogeneous, compact superpixels [32]. For expanding the superpixel cluster, SNIC chooses four or eight immediately connected candidate pixels from the priority queue without considering them. These candidate pixels are selected based on their minimum distance from the centroid [33]. Hence both memory use and processing time are better than in similar clustering methods like Simple Linear Iterative Clustering. The reason behind this outcome can be attributed to the implementation of connectivity (four or

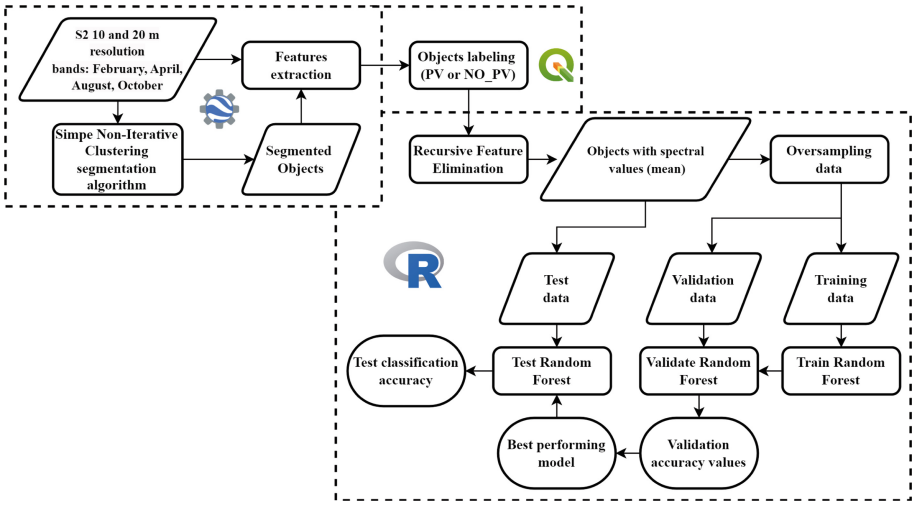

Fig. 2. Operative pipeline of the applied methodology.

eight connected pixels), which led to a reduction in the number of distance calculations during centroid evolution [34]. In the GEE platform, the segmentation parameters used were based on the configurations employed in previous studies [10]. These parameters consisted of (1) compactness, set to 1; (2) connectivity, set to 4; (3) neighborhood size, fixed at 64; (4) size, set to 10; (5) seeds, set to 15; (6) kernel, set to 3; and (7) scale, set to 10. For both the training/validation area and the test area, the multispectral image chosen for segmentation was the one captured in February, as, through visual interpretation, it was the one in which the PV plants were visually most separated from the adjacent land covers.

3.4 Features Extraction

Following the segmentation of elements, computations were done using GEE for intensities of specific S2 bands for each item, as well as many spectral indices. The indices described in Table 1 have shown useful in previous studies, playing an important role in the detection of solar systems.

3.5 Objects Labeling

After calculating all the indices listed in Table 1, the segmented objects from both the training, validation, and test areas were exported as shapefiles from GEE. These items were then separated into two classes in QGIS: PV and NO-PV. The classification technique was based on visual interpretation. Objects with more than half of the pixels associated with PV systems were classified as PV. Notably, this study focused just on PV panels produced from specialist PV systems, eliminating smaller panels attached to buildings, which were absent from both the test, validation, and test regions.

3.6 RFE

This study employed a feature selection method known as RFE. The widely adopted RFE algorithm was utilized to identify the most relevant features in predicting the target variable, whether in regression or classification-oriented models [35]. The RFE technique uses an iterative backward selection process to find the best feature combination by starting with all of the variables and progressively eliminating those that are incorrect for classification accuracy [36]. In this analysis, the implementation of RFE was conducted through the "rfFuncs" function within the R caret framework. With this specific function, the algorithm relies on assigning importance to variables and is internally evaluated using RF classifiers [37]. This process involves multiple rounds of classification, in which a new RF classification model is trained. Its accuracy is evaluated through cross-validation and the importance of parameters for each feature are analyzed. The feature set is updated for the next iteration [38]. Cross-validation was performed for ten cycles in this case. The feature-selection algorithm was repeated for the four seasonal training datasets. The best features obtained from the RFE algorithm were used as input variables successively for the various RF classification models.

Table 1. Spectral indices used in literature.

Index Name	Index Formula	Previous Studies
Normalized Difference Vegetation Index (NDVI)	NDVI = (NIR1 − Red)/(NIR+ Red)	[10,18,28,29]
Normalized Difference Water Index (NDWI)	NDWI = (Green − NIR1)/(Green + NIR1)	[10,18,28,29]
Normalized Difference Built-up Index (NDBI)	NDBI = (SWIR1 − NIR1)/(SWIR1 + NIR1)	[15,18,28,29]
Normalized Difference Tillage Index (NDTI)	NDTI = (SWIR1 − SWIR2)/(SWIR1 + SWIR2)	[15,18,28,29]
Enhanced Vegetation Index (EVI)	EVI = [2.5 × (NIR1 × Red)]/(NIR1 + SWIR1 × 4–7.5 × Blue + 1)	[15,18,28,29]
Modified NDWI (MNDWI)	MNDWI = (Green − SWIR1)/(Green + SWIR1)	[15,18,28,29]
Bare Soil Index (BI)	BI = (SWIR1 + Red − NIR1 − Blue)/(SWIR1 + Red + NIR1 + Blue)	[15,18,28,29]

3.7 Oversampling Data

Classification models can drastically change their performance if the learning dataset has unbalanced classes. This happens because models have difficulty effectively learning minority class characteristics. After all, they will receive fewer examples of that class than the majority class [39]. To solve this problem, an oversampling method was adopted aimed at balancing the number of objects in the two classes in question. Using the "upsample" functionality from the "caret" package in R, it was possible to equalize the number of objects for training the PV and NO-PV classes by generating synthetic objects of the PV class while preserving all the information of the objects of the NO-PV class [40].

3.8 RF Classification Models

There is a lot of interest in remote sensing and other machine-learning applications because of the RF technique for classification [41]. Its major feature is its ability to attain accuracy, even with poor training data [42]. RF is composed of a set of tree-based predictors, with each tree depending on the values of a randomly selected vector independently and with the same distribution as the other trees in the forest [43]. The RF model has two initialization parameters: (1) the number of classification trees or bootstrap iterations (ntree) and (2) the number of input variables picked at random at each node (mtry) [44]. Default settings were used for mtry and ntree, with mtry set to $\checkmark$p (where p denotes the number of predictive variables in a dataset) and ntree set to 500. Following RFE,

the polygons of the training and validation area were split. In this study case, the RF model was trained on 70% of the polygons, and the remaining 30% were utilized for validation. This technique was applied to all four seasonal datasets. The model with the highest accuracy was then applied to the test region data, which had already been categorized into two classes: PV and NO-PV.

3.9 Accuracy Analysis

The confusion matrix was used for model validation in the training and validation zone as well as evaluation in the test zone. The accuracy measures produced from the error matrix are OA, K, PA, UA, and F1. Table 2 shows the equations of the accuracy metrics used.

Table 2. Spectral indices used in literature.

Accuracy Metrics	Equations
Overall Accuracy	OA = (TP + TN)/(TP + TN+ FP+ FN)
Cohen's Kappa	K = (P(A) - P(E))/(1 - P(E))
Producer's Accuracy	PA = TP/(TP + FN)
User's Accuracy	UA = TP/(TP + FP)
F1 score	F1 = (2*TP)/(2*TP + FP +FN)

TP: True Positives, TN: True Negatives, FP: False Positives, FN: False Negatives, P(A): Concordance rate observed, P(E): Concordance rate expected

4 Results

4.1 Segmentation

The segmentation within GEE, using the SNIC algorithm, produced 2341 objects for the training/validation study area and 1599 objects for the test region. As illustrated in Fig. 3, the settings utilized for the SNIC algorithm resulted in objects with geometries that identify PV systems from other land coverings.

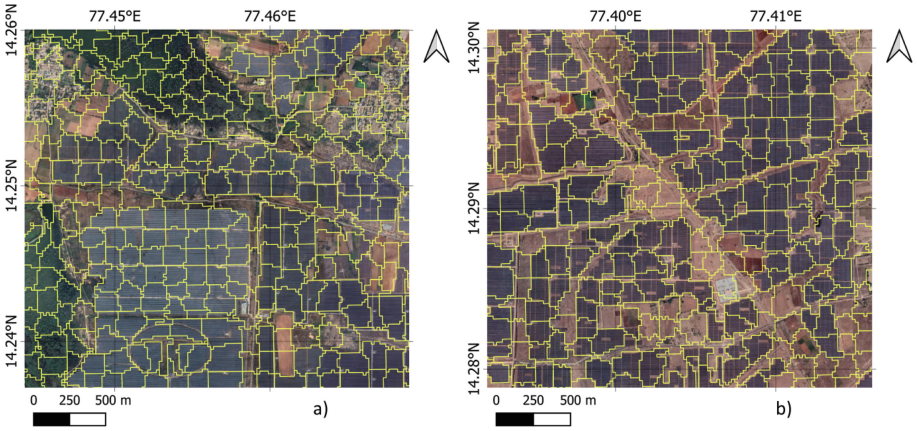

Fig. 3. Example of SNIC segmentation output obtained by processing the February image in the training and validation area (a) and test area (b).

4.2 Object Labeling

The QGIS software was used to carry out the labeling process. A total of 753 objects were identified and labeled as PV, while 1588 objects were categorized as NO-PV within the training and validation area. In the test area, 537 objects received the PV label, while 1062 objects were assigned the NO-PV classification.

4.3 RFE Results

Figure 4 shows the results obtained by the RFE algorithm for each season by month in the training and validation area. Table 3 shows the variables chosen by the RFE algorithm for each season, listed according to their predictive significance, from most to least important.

Table 3. Spectral indices used in literature.

Season	Features Selected	Accuracy values
Winter	Blue, BI, NDWI, NDTI, MNDWI, NDBI, EVI, NDVI	0.8729
Spring	NDTI, NDWI, EVI, NDBI, NIR2, NDVI, Blue, MNDWI, NIR1, Green, BI, RE3, RE2, Red	0.8738
Summer	NDTI, MNDWI, NDBI, Blue, SWIR1, BI, SWIR2, NIR1, NDWI, Green, NIR2, RE3, Red, RE2, NDVI	0.8781
Autumn	NDTI, Blue, SWIR1, MNDWI, SWIR2, BI, NDWI, NDBI	0.8742

4.4 RF Model Validation

Table 4 shows accuracy metrics results within the training and validation zone for every RF classification model generated for each season. The table represents

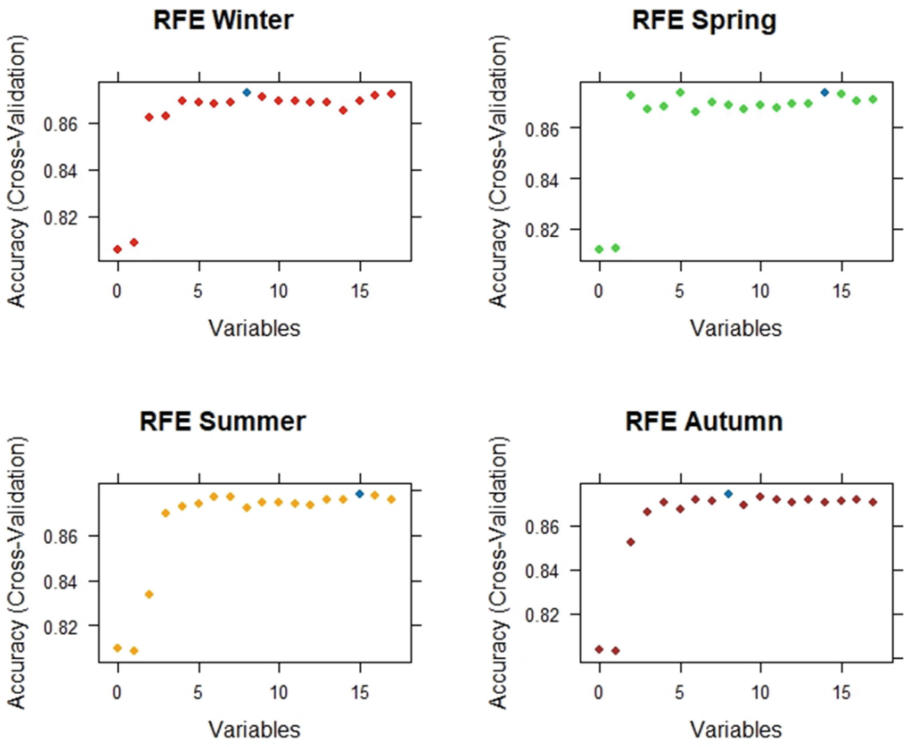

Fig. 4. The count of variables selected for each month using the RFE method, along with their corresponding accuracy values.

Table 4. Spectral indices used in literature.

RF model	OA (%)	K	PA (PV)	UA (PV)	F1 (PV)
Winter RFE	87.87	0.76	90.85	85.74	88.22
Winter	86.17	0.72	84.89	87.12	85.99
Spring RFE	86.89	0.74	85.32	88.52	86.89
Spring	86.49	0.73	86.38	86.57	86.47
Summer RFE	87.98	0.76	89.79	86.65	88.19
Summer	86.06	0.72	90	83.43	86.59
Autumn RFE	**88.72**	**0.78**	**89.57**	**88.08**	**88.82**
Autumn	85.96	0.72	83.62	87.72	85.62

accuracy values for both models using variables derived from RFE and those incorporating all variables, aiming to illustrate the disparities in the outcomes. The RF classification model, utilizing variables selected by the RFE algorithm during the autumn season, demonstrated superior accuracy metric values within

the training/validation domain. Consequently, this model was chosen for classification in the Test area.

4.5 Test Area Classification

Table 5 presents the accuracy metric results calculated using the Autumn RF model, with features selected by the RFE algorithm. Figure 5 visually displays the classification outcomes.

Table 5. Accuracy metrics of the "Autumn RFE" RF model in the Test area.

OA (%)	K	PA (PV)	UA (PV)	F1 (PV)
87.80	0.74	89.94	77.40	83.20

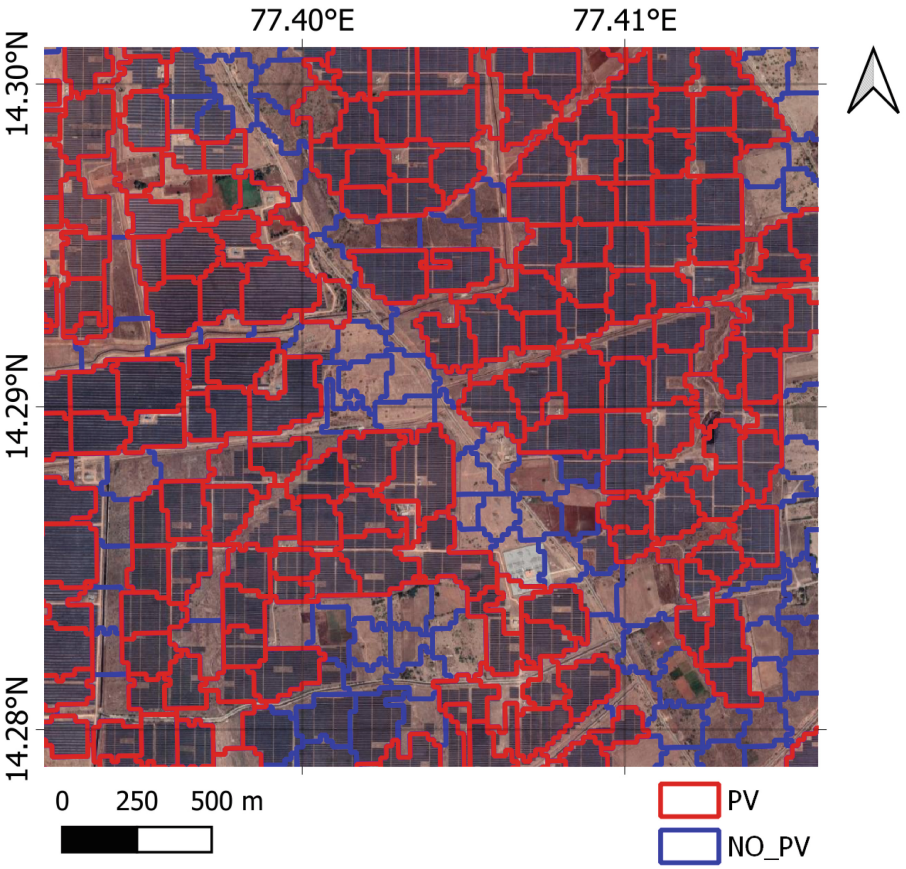

Fig. 5. Classification results obtained from the application of the RF model in the Test area.

5 Discussion and Conclusion

The goal of this study was to develop an RF classification model for mapping PV installations in Pavagada Solar Park in India using open-source data such as S2 and open-source software, including GEE and RStudio. The following conclusions were drawn from the results obtained. Starting with the OBIA approach, specifically from the segmentation phase, the SNIC algorithm within GEE produced geometrically consistent objects, aligning well with the actual geometries of PV installations. This facilitated the manual assignment of the PV and NO-PV classes in the subsequent object labeling phase. Consequently, the parameters of the SNIC algorithm proved effective, confirming the results of previous studies [10]. Some observations arise regarding the RFE algorithm step. First, the predictive ability of the indices chosen wherein from the literature is notable. Table 3 shows that the NDTI has great predictive power for PV objects, ranking first in all seasons except winter, where it remains fourth. This result confirms the exceptional predictive power of the NDTI index for mapping PV systems, as demonstrated by previous studies [15,18,29]. Figure 4 shows that the RFE algorithm selected a varying number of variables for each season while achieving similar accuracy values in predicting the PV class, as shown in Table 3. This is attributed to the seasonal variability of the spectral values corresponding to the PV installations. In any case, Table 4 shows that, as compared to utilizing all variables during all four times studied in the training and validation zone, using the variables chosen by the RFE algorithm produced greater accuracy results. The model developed in Autumn, with variables selected by the RFE algorithm, proved to be the best performant among the others, albeit with a slight difference. Finally, after validation, the same model was applied to the test zone, achieving accurate results, as shown in Table 5, confirming effective "knowledge transfer". This study introduces, for the first time, a methodology for selecting suitable variables for PV mapping. In previous studies, feature selection has relied on the analysis of the spectral signatures of PV installations, or the intrinsic meaning of the spectral indices used. However, the significant seasonal variation in spectral indices, primarily caused by the type of soil beneath the PV panels, did not provide certainty in using certain indices over others. Using the RFE algorithm allowed for the easy extraction of only the best features in terms of the predictive power for each period. This process optimized all classification models both computationally and in terms of accuracy. This work lays the basis for future studies, including the use of the created model in several test areas, the testing and comparison of other types of ML classifiers, and the study of optimizing hyperparameter choices for different classifiers.

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GIS, Remote Sensing, and Forecasting Systems for Precision Agriculture Development

Vincenzo Barrile(✉) and Emanuela Genovese

Department of Civil Engineering, Energy, Environment and Materials (DICEAM), Mediterranea University of Reggio Calabria, Via Zehender, 89124 Reggio Calabria, Italy
vincenzo.barrile@unirc.it

Abstract. Precision Agriculture (PA) primarily aims to maximize productivity while reducing impacts on the environment. This is made possible thanks to the implementation of advanced land monitoring technologies, such as GIS (Geographic Information Systems), together with other data generators in all phases of agricultural operations, from cultivation to storage. With the aim of contributing to the evolution of this field of research, this article describes an integrated system capable of managing information on climatic variables coming from an innovative and experimental atmospheric simulator and on parameters indicating the state of vegetation obtained through Remote Sensing and UAV techniques. All this to collect all the necessary information in a GIS implemented for the automation of an agricultural vehicle and a drone equipped for fertilization. The innovation of the present research consists precisely in the atmospheric simulator which, exploiting the SPH model (Smooth Particles Hydrodynamic) for the interaction of the atmosphere particles, taking as input the DEM (Digital Elevation Model) of the area under study and the historical data of meteorological stations contained in it, returns as output a punctual distribution of some atmospheric variables fundamental for precision agriculture, such as rain and wind from which the three-dimensional trend can be obtained. These parameters, together with in loco sensors' data, are therefore fundamental for planning the action of both agricultural vehicles and drones and for making the production process more efficient. The operation of this system was tested on an area in the province of Reggio Calabria.

Keywords: Precision Agriculture · Atmospheric Simulator · atmospheric Variables · Smooth Particles Hydrodynamic · Digital Elevation Model · Geographic Information Systems

1 Introduction

Precision agriculture uses sophisticated technologies through which it is possible to optimize available resources, reduce consumption and maximize production by analyzing the data and information acquired through advanced tools and technologies [1, 2].

In the field of precision agriculture, resource management and agricultural vehicles automation are certainly two key aspects to increase productivity, accelerate agricultural operations (from production to storage) and reduce waste. In this sense, GIS can

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constitute a fundamental tool in precision agriculture, acting as a container for all that information useful for the management of production processes and more. Within the GIS, in fact, it is possible to manage data of different nature and it is possible to implement appropriate specific algorithms depending on the desired objectives [3–6].

In this context, the present work exploits GIS technology with a dual purpose: to optimize agricultural operations through the management of heterogeneous data and to automate an agricultural vehicle and a drone appropriately equipped to support production processes. The particularly innovative aspect of this article is the inclusion in the GIS of data coming from an innovative and experimental simulator prototype, which, taking as input the DEM (Digital Elevation Model) of the study area and the historical data of meteorological stations, through an SPH model (Smoothed Particles Hydrodynamics) which governs the interaction of particles, manages to provide a precise distribution of atmospheric variables such as precipitations and wind. In essence, the simulator replicates the dynamics of the Earth's atmosphere concerning weather patterns. It models the changes in the state of discrete atmospheric particles and illustrates how these particles interact with one another.

The parameters of the atmospheric simulator together with those of in loco sensors, appropriately analyzed by an open-source GIS implemented by the authors, will then be used to plan, and to visualize the route of an agricultural vehicle used for irrigation and a drone equipped for fertilization.

These data together with a series of on-site sensors, such as soil moisture sensor, leaf wetness sensor, pH sensor and temperature and humidity sensor, were analyzed and evaluated together with vegetation indices including the NDVI (Normalized Difference Vegetation Index), the LST (Land Surface Temperature) and the NDMI (Normalized Difference Moisture Index) calculated using World-View 3 and drone images [7, 8]. From the analysis and evaluation of these parameters, using geoprocessing and analysis tools of the GIS, the areas that needed irrigation and fertilization were evaluated. Subsequently, using an appropriate plugin, the route of the tractor and drone was calculated and subsequently transmitted through the Cannelloni software, written in C++ and capable of transferring CAN frame between two machines using UDP (User Datagram Protocol) or SCTP (Stream Control Transmission Protocol). In particular, data flows transmitted by the GIS also included information in relation to the irrigation and fertilization needs of the area [9, 10]. The integrated system was tested in an area situated in the south of Calabria (Italy).

The main and specific objectives of this paper are to analyze GIS technology in the field of precision agriculture, optimize the efficiency and accuracy of agricultural operations through automated agricultural vehicles and drones, and implement a comprehensive workflow that integrates the planning of agricultural vehicles and drones based on the analysis results. The proposed system could be useful for farmers and agricultural companies to optimize resource usage, reduce costs, and maximize production by improving operational efficiency and promoting sustainable agricultural practices while reducing environmental impact.

2 Materials and Methods

During experiments, were employed various systems, algorithms, and structured and integrated techniques (cited in greater depth in Fig. 1) to determine locations that best fit the various conceivable typologies of cultivations and to plan the itineraries of both self-driving tractors and UAVs. Thoroughly, we used: QGIS software (an open-source GIS), an innovational and developmental atmospheric simulator, satellite images, UAV images, in loco sensors, specific algorithms and protocols for data transmission.

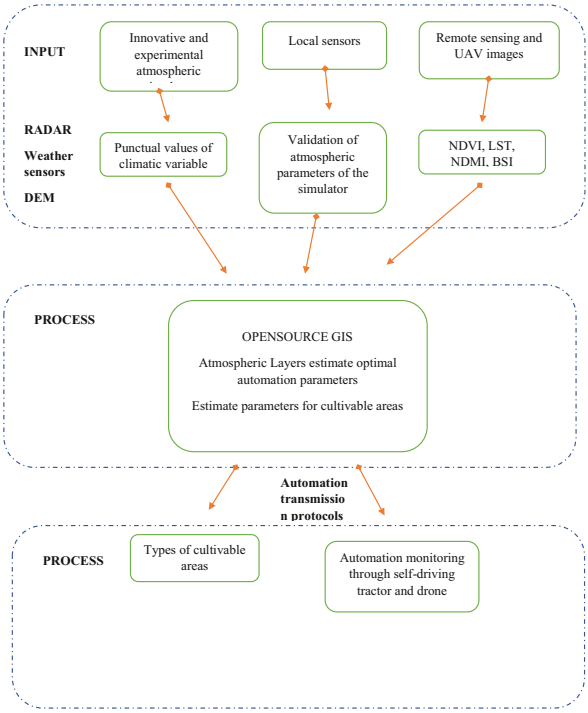

Fig. 1. A flowchart developed within the context of Precision Agriculture concept illustrates the methodological framework and the various integrated systems, algorithms, and methodologies designed to identify optimal areas for different types of crops and to strategize the most efficient routes for both autonomous tractors and UAVs.

First of all, the atmospheric simulator, which utilizes as input data the DEM (Digital elevation Model) territory, weather sensors data, radar data and large-scale weather models, is used for the production, as outputs, of the punctual measurements of typical meteorological variables such as: pressure, temperature, wind and precipitation; these values were then reprocessed to produce DEM layers of these variables. The previously meteorological variables are crucial for the so-called Precision Agriculture due to their direct influence on environmental conditions and consequently on crops. Precipitations are essential as they represent source of water for the plants; wind can influence plant development and can also spread diseases; information about imminent climatic changes

are supplied by atmospheric pressure, lastly, temperatures impact plant growth and maturation. The results confirmation was obtained combining different ground truth devices such as: local sensors (soil and leaf moisture sensors, pH sensors, wetness and temperature sensors, barometric pressure sensor) applying wireless sensor network nodes (WSNn). This network was assisted with the ZigBee protocol, an ATmega128L microcontroller, and a solar cell module with the purpose of transfer the collected sensor data to cloud server. With the application of data fusion methodology [11], was possible to combine satellite and UAV data and images obtaining significant indicators that can show the vegetation health and soil differences; these indices are:

- NDVI (Normalized Difference Vegetation Index).
- NDMI (Normalized Difference Moisture Index).
- LST (Land Surface Temperature).
- BSI (Bare Soil Index).

These indices have been chosen among the many available because they are the most significant, commonly used, and indicative for the analysis conducted. Through the combination and analysis of all this data in an open-source GIS, it was possible to evaluate the most suitable areas for cultivation and for the automation of tractors and drones.

In particular, the following materials and methods were used.

As regards satellite images, Sentinel-2, level 2A and WorldView-3 satellite images were used. From Sentinel-2 level 2A the processing involves a scenery classification and atmospheric correction related to a TOA (Top Of Atmosphere) level-1C orthophoto. The principal output from level 2A is an orthophoto BOA (Bottom Of atmosphere) corrected reflectance product.

WorldView-3 can acquire: panchromatic images at 31 cm, multispectral at 1.24 m, shortwave infrared images at 3,7 m and CAVIS (clouds, aerosols, vapors, ice and snow) at 30 m.

Concerning UAV images, a DJI Matrice 600 Pro was equipped with a Micasense Altum Camera to capture multispectral photos. This camera is suited to be used in agricultural environment because can collect crop's photos in visible and infrared wavelengths, simultaneously. The height of fly was about 30 m above the ground, obtaining so aerial GSD photo with a resolution of 5 cm.

Thanks to a range of sensors on board UAVs, real-time information may now be gathered in numerous application domains. Large volumes of data, including as photographs, are received by these flight objects; therefore, clever algorithms that can process and transform various data kinds into meaningful and succinct information must be introduced. The current approach to address this issue is the use of multiple sensor data fusions that can process data from high-resolution satellite imagery at frequent revisit times in addition to data from UAVs. So, UAVs are used to obtain periodic data, while the combination of satellites preserves a good spatial resolution in the observation area. UAVs and satellites data are not used in contemporary; the purpose is to merge these data through data fusion techniques, gathering so the images necessary to calculate the required agricultural indices, keeping in mind the pro and the cons deriving from UAVs and satellite data sources (cloud dependence, meteorological constraint, payload, data management).

This kind of data fusion strategy (spatial and spectral) wants to generate datasets with improved features, fusing one or more resolution from each source. This strategy, developed to tear out the characteristics of land and vegetation cover, at high resolution, is not often used in fields such as agriculture. This kind of data fusion offers several advantages such as: better spatial and temporal resolution, more customization possibility and more detailed and understandable information. Despite this, there are also some disadvantages: drone coverage is more limited compared to satellite, the costs are higher, the logistic is more complexed, and there are restrictions connected with the weather conditions. Specifically, the fusion spatial-spectral technique helps to increase the accuracy of land cover categorization and the spectral resolution of inexpensive UAV sensor data. When data are gathered over both space and time, they are analyzed using a spatiotemporal framework. It explains a phenomenon that occurred at a specific location and time. Some biophysical crop's indices, like leaf area index and chlorophyll content, can be obtained using the spatial-temporal fusion method, which also build a reliable prediction with fine spatial patterns. The image's spectral resolution consists in the frequency of the electromagnetic spectrum, observed by the satellite. Due to this spectral quality, is also possible to see various features as distinct entities. The temporal resolution of an image consists in the time required to return and to re-collect data for the same place. From the fusion spatial-temporal approach is possible to achieve information in multispectral satellite data with hyperspectral data from a UAV. The results acquired allow to obtain the required biophysical variables. Lastly, because of the structural features acquired from UAVs and the satellite-based spectrum characteristics gained from satellites, the satellite/UAV data fusion enhanced the model's performance when compared to data obtained separately from satellite or UAV.

Significant vegetation indices, derived through remote sensing techniques, serve as valuable tools for gathering information about vegetation characteristics. Optical sensors, including multispectral and hyperspectral systems, are utilized to collect this type of data. Key agricultural indices such as NDVI, NDMI, and BSI can be analyzed using this data. For this study, images were acquired from the Sentinel-2 satellite, which features a spatial resolution of around ten meters and revisits the same area every six days. Additionally, UAV images were captured concurrently, offering higher resolution and finer detail within canopy areas. Sentinel-2 Level 2A images were obtained on four different dates: June 16th, July 13th, August 17th, and September 14th. Furthermore, a WorldView-3 satellite image captured on November 17th, 2022, was included. WorldView-3 satellite images are recognized for their exceptional detail and precision, with a spatial resolution of approximately 30 cm per pixel. This allows for the identification of small objects on the Earth's surface.

The multispectral images were captured by DJI Matrice 600 Pro drone (SZ DJI Technology Co. Ltd., Shenzhen, China), equipped with a Micasense Altum Camera (AgEagle Aerial System Inc., Kansas, USA) which can capture images of crops in both visible and invisible spectra simultaneously, being so adapt for agricultural purpose. The drone's fly height was approximately 30 m above the ground, with an aerial GSD with a resolution of 5 cm.

The principal innovation of this study is the utilization of an atmospheric simulator [12] which, combining DEM, radar and sensor data, supplies climatic information related

to territory orography. This study describes the operation of an atmospheric simulator capable to produce high-detail weather fields outputs in a delimited area. The simulator can produce outputs for several atmospheric variables (i.e., wind, temperature, humidity, etc.) for a cubic cell of 50 m, even with few inputs. The microphysics of the simulator's atmosphere is regulated by laws governing the interaction of a number of particles with which the atmosphere has been discretized. The latter, indeed, comprises a collection of particles housed at the core of a cube (cells). Each particle encapsulates a distinct amount of gas, water, and humidity, determining its mass exchanges and interactions with other particles and the surrounding environment These particles experience a force derived from their energy state, interactions with other particles, or contact with surfaces. Basically, the simulator reproduces the conduct if Earth's atmosphere in relation to weather trends and describes the changes of the particles, whit which atmosphere was discretized, and the interaction whit each other. The simulator includes two solvers, called L1 and L2, which work simultaneously and face task at higher level. These solvers convert vertical exchange and troposphere processes into a particle model [13] of the atmosphere. Solver L1 performs several tasks, such as: attributing both physical and chemical properties to the particles, applying, in relation to their energy state, force to the particles, designing the particles and environmental objects initial condition, partitioning the 3D environment into macro-cluster, and offering individually identifiable forecast field for each. In Solver L1 we can also input real time data and hypothetical values. Solver L2, which is a Newtonian simulator utilizes the features of the SPH (smoothed particle hydrodynamic) software library (developed by Nvidia and technology is called "Nvidia PhysX"), which is developed to reliably simulate fluids or gasses down to a few hundred meters. This Solver, introduces the forces assigned to the particle by the previous solver and starts, using SPH fluid rules (based on PhysX) the dynamic development. For example, when cells locally overlap at time t, repulsive forces are activated based on specified parameters (viscosity, friction, mass, partial compressibility). In a 3D setting, this mechanism delineates wind patterns, encompassing intricate turbulence characterization and confined pressure fluctuations. This approach excels particularly in topographically intricate regions, such as the Apennines, where controlling sudden altitude changes using traditional Numerical Weather Prediction (NWP) methods proves challenging. The initialization process of SolverL2 entails assessing an ASCII DEM representing the orographic layout of the simulation area. Particles are uniformly distributed within the environment and evolve until they reach a state of stability. Following the processing of initial conditions derived from sensor or radar data, Solver L1 directs the allocation of forces, velocities, and positions within specific spatial volumes to Solver L2. Subsequently, after adhering to these directives for a predetermined duration, L2 progresses. Upon the completion of the evolution, Solver L1 is informed of the updated state of the particles, encompassing their position, velocity, density, and alterations from the initial state. Then, using the attributes provided by L2, Solver L1 correlates particle properties with atmospheric state-related attributes such as temperature and humidity. The pattern detector, a component of L1, forms groupings with consistent atmospheric features, including cloud cover, precipitation, humidity, mean temperature, and pressure, based on the information supplied by Solver L2. The results identified as clusters represent the output generated by the simulator.

The study used five types of sensors to assess key parameters: soil moisture sensor, leaf moisture sensors, pH sensor, humidity and temperature sensors, and a barometric sensor. In today's era of modern technology and the advent of precision agriculture, these advanced sensors enable farmers to optimize crop yields while minimizing the consumption of essential resources such as fertilizer, water, and agrochemicals. With the deployment of these new and more efficient sensors at ground level, farmers can obtain detailed insights into crop growth, leading to resource conservation and reduced environmental impact, [14–17]. The modern agricultural is based on several chemical and physical analysis and this is achievable considering sensors and IoT networks. According to this idea, the use of sensors in agriculture is mainly used to evaluate characteristics in soil, plants water and air. A sensor is a transducer developed to convert a physical quantity into another, often an electrical signal. This one must satisfy the requirements like operates at microscale. About the communication of the local sensors, WSNs [18–23] communicate through their radio modules. Two or more modules are directly connected if they can send and receive data from each other. The final outcome is a network that is capable of transmitting and receiving data, collecting a lot of data in the process. The advantage of WSNs is represented by the wireless connection. Nowadays, WSNs are a viable solution to improve quality and quantity in agricultural. The primary components of a sensor node are its sensing, storage, processing, and communication capabilities. A number of sensors that support this WSN are included, including an ATmega128L microcontroller, temperature, humidity, rain, leaf wetness, and ZigBee protocol [24, 25]. Intelligent IoT-based agriculture relies heavily on communication protocols that can be used over short or long distances for smart farming. For short-range applications, wireless technologies such as Wi-Fi and ZigBee are utilized in agriculture; for long-range applications, mobile communication networks, Bluetooth, long-range wireless area networks (LoRaWAN), and LPWAN protocols are employed. Regarding microcontrollers, the most used in agriculture, due to its ability to support multi-level data aggregation, low complexity, storage capabilities, energy management and flash memory, is ATmega128L nodes. Conventionally, batteries, which are limited in size and capacity, affect the lifespan of WSNs. Actual solutions consist in a combination of ultra-low-power nodes and energy harvesting techniques, making so a WSNs perpetually operative. Moreover, there are two special nodes-called sink-that will be added when there will be the necessity to communicate with an external network. This node transfers all information to the cloud platform. The low-power ZigBee wireless protocol is adopted from all sensors, sink and actuator nodes. Finally, the data gained from sensor and governed by actuators are subsequently sent by gateway to cloud computing and will be processed and stored. The aim of the gateway is to collect information and pass it to the cloud server [26–37].

The data collected by sensors and drones are subsequently processed, analyzed in a cloud data repository through a communication link. The real time data transferring to the cloud platform is achievable by the common communications protocols between sensors/UAVs and operators. Generally, drones for agricultural use have a flight height under 120 m and use a Wi-Fi with a range between 3 of 7 km, if drone is equipped with a large transmitting antenna. Instead, the use of 4G network link mitigate the distance related problem, so the drone is allowed to fly several kilometers away from the operator. The 5G mobile network is suited to support low-flying drone communications

and improve the safety and security of drone operations, hence extending the range of UAVs. Furthermore, the use of 5G networks allows the reception of several kinds of data in real time and in a faster and seamlessly way, compared to the previously mobile network. Drones do not need to have very powerful processors because 5G technology makes it possible to send all data to the cloud for quicker processing. The actual cellular technologies are essential in IoT devices development. The actual LTE (long-term evolution) capabilities have given rise to a new IoT system protocol the NB-IoT (narrow-band-IoT), which can use the same device, share the LTE frequency band without causing coexistence issues, and connect to the LTE main network with ease. NB-IoT characteristics are: large coverage area, longer battery life (up to almost 10 years), great network size (up to 52000 devices/channel/cell) and low-cost devices. Due to their low power consumption, NB-IoT technologies like LoRa (long-range radio) will soon be the dominant method of delivering agricultural data over vast distances. Using a point-to-point Zigbee network can extend the communication range up to 100 m in an outdoor environment; Zigbee's range could also been elongated using a specific distributed and mesh network typology. Furthermore, UAVs can also function as a mobile router node that can enlarge the communication range of the smart farm. Drones can transmit the acquired data from sensors to a master nodes, using a multi-hop [38–43]. The GIS processed all this data, estimating the ideal automation parameters and those associated with cultivable areas. In detail, the following algorithms were employed to determine the cultivable areas: Spatial data analysis algorithms (especially buffering, intersection, overlay, clustering analysis) are usable to recognize areas of interests, estimating the nearness of the different data sources (sensors, climatic and DEM) and performing comparative tests among distinct areas. Raster analysis algorithms to tear out information from raster data (i.e., DEM and NDVI) by calculating terrain data and distinguishing slope or elevated area that are more suitable for specific crops. Supervised classification algorithms, like Random Forest (RF), Support vector machine (SVM) and Neural network, to classify image, to find crop typology and to construct a forecast model. These algorithms can be installed and utilized within the QGIS environment as extra extensions or plugins. About the algorithms used suited for tractor automation, in QGIS are present several tools and algorithms able to perform tracking analysis and planning, the software also admits the exploit of additional plugins and the incorporation of other libraries and instruments which provides better features related to route optimization. In detail, the plugins used to achieve this advanced tracking analysis in QGIS were "NAI (Network Analysis Library)" and "PgRouting." These instrument offers, evaluating several variables such as: speed limits, obstacles, and particular option, to calculate the optimal itinerary. The output variables used to determine the cultivable fields are: crop classification map, crop suitability evaluation, evaluation of environmental characteristic, evaluation report and tabular output data. The map related to the cultures was obtained using supervised and unsupervised algorithms and allows to allocate the most suitable crop for each portion of the study area. Combining the various type of data [44–48] (Climatic, sensor, DEM and NDVI) was created a crop appropriateness evaluation and an analysis of the environmental characteristics of the study area [49–52]. In the evaluation report were presents several information such as: indices of crop fitness, characteristics of the prevailing crops and of the environment of the study area and other knowledge to

determine the cultivation of the area. Furthermore, in addition to maps and reports, data were also provided in tabular form, giving more detailed information.

For what concern the automation of the tractor, the output variables are:

- Real-time GPS coordinates,
- Operating routes: for increasing the efficiency of the operation,
- Speed regulation: to guarantee a safe and effective drive,
- Actuator control: to guarantee a smooth and accurate drive, in relation to the routes,
- Monitoring of ground state: to adjust the tractor's drive, take real-time choices and guarantee an optimal use of resources,
- Alert systems: to alarm operator/user in case of emergency,
- Performance monitoring.

3 Case Study

The research's study area is located in the municipality of Reggio Calabria (Calabria, South Italy), as shown in Fig. 2. The black circle shows the application area of the simulator, while the application of the entire methodology was focused in a zone near the Fiumara of Armo, always in Reggio Calabria, with an extent of 35 hectares. Several reasons lead to choose this area, in particular: it is a virgin area with no cultivation and little populated, so the GIS was allowed to detect the most indicated area for cultivation, the morphology is suitable for the simulator use, it is a small area and so it is possible to apply the entire proposed system.

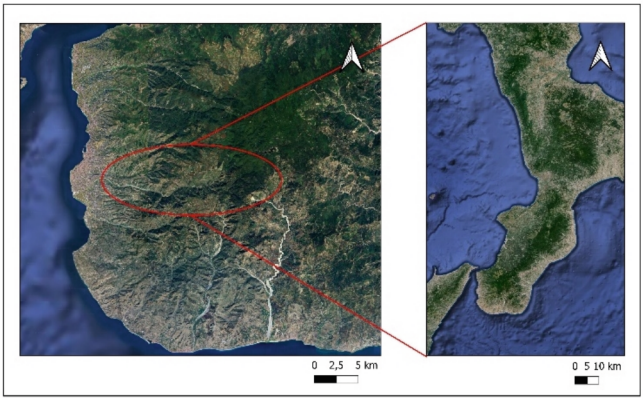

Fig. 2. Study area for the experimentation of the entire system. The area is located in the province of Reggio Calabria, south of Italy, is highlighted with a black line. The Image was extrapolated from QGIS, Google Satellite base map. (Color figure online)

4 Results

To pinpoint the regions more susceptible to adverse climatic events, we employed interpolation techniques to generate the three-dimensional map illustrated in Figs. 3 and 4. The occurrence of climatic events may vary depending on seasons and specific weather

conditions. Achieving precise predictions for adverse climatic events necessitates the utilization of local meteorological data. Consequently, we conducted an analysis of data obtained from local weather stations in Calabria, which were instrumental in the initialization phase of the simulator. The findings from this analysis indicate that, fundamentally, the most impacted areas in Calabria are those situated along the coast and in mountainous terrain.

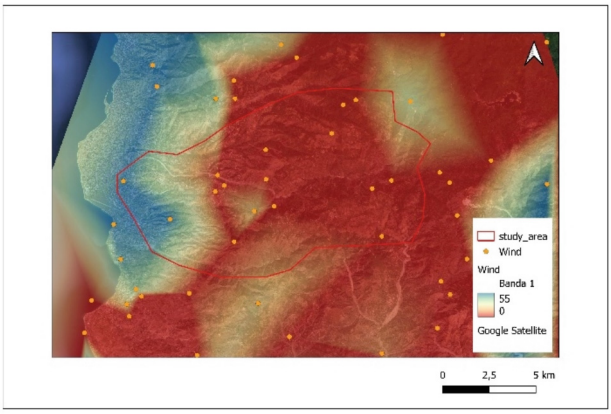

Fig. 3. GIS environment: three-dimensional distribution of wind values analyzed the Atmospheric Simulator values.

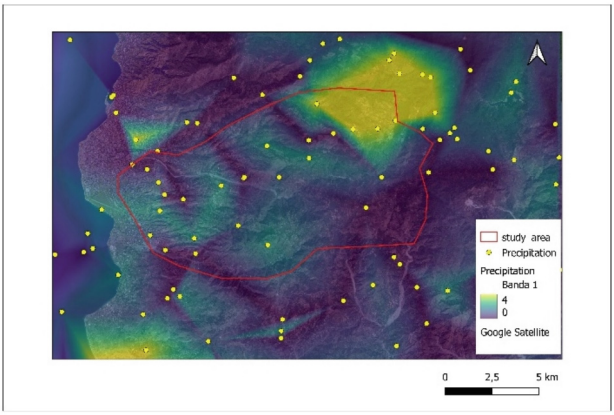

Fig. 4. GIS environment: three-dimensional distribution of precipitation values analyzed the Atmospheric Simulator values.

As regards the calculation of the different indices used, Fig. 5 shows an elaboration with "Raster Calculator" function in QGIS to obtain a crucial index, the NDVI (valuable for assessing vegetation richness) starting with multispectral images by drone. Figure 6 illustrates, instead, the application of a data fusion technique between UAV and satellite images, showcasing the calculation of NDVI using a Very High-Resolution (VHR)

image. Data fusion techniques allows for the integration of diverse data sources, such as satellite data and Unmanned Aerial Vehicle (UAV) images, to gather comprehensive information about an area and its cultivation needs.

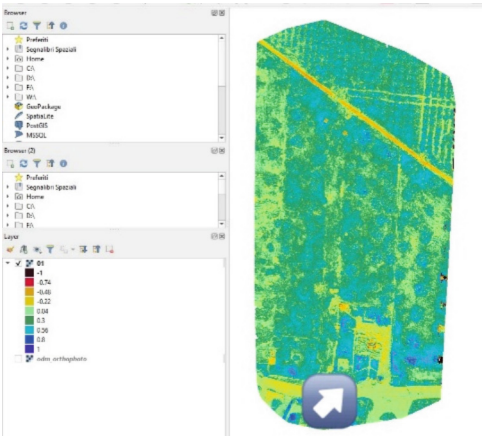

Fig. 5. GIS environment: NDVI calculation through "Raster Calculator" starting from multispectral images.

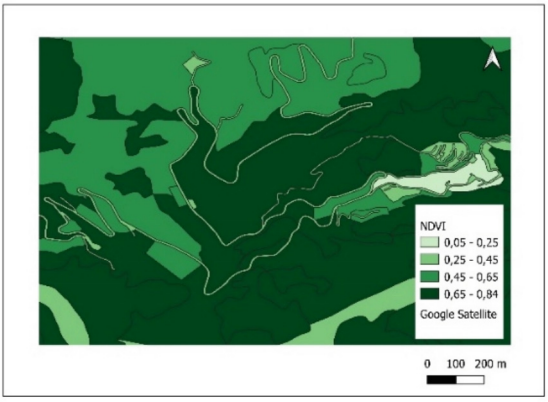

Fig. 6. GIS environment: application of data fusion technique between UAV and VHR image for the calculation of NDVI.

Upon aggregating data from various sources, open-source Geographic Information System (GIS) tools facilitated the identification of different cultivation areas based on climate parameters, sensor values, and indices derived from satellite and Unmanned Aerial Vehicle (UAV) images (including wind, soil type, soil moisture, NDVI, etc.). These areas, denoted by distinct capital letters (A, B, C, D, etc.), were categorized and grouped for ease of analysis according to parameters pertinent to specific crop types. In particular, the available dataset enabled the identification of three exclusive classes (A, B,

and C) in the study area, each represented by a distinct color. Class A (orange): designated for cultivation areas suitable for crops that do not require continuous irrigation. Class B (green): allocated for cultivation areas suitable for crops that necessitate continuous irrigation. Class C (yellow): earmarked for cultivation areas suitable for trees. Figure 7 visually depicts the distinct typologies of cultivation in these three categories.

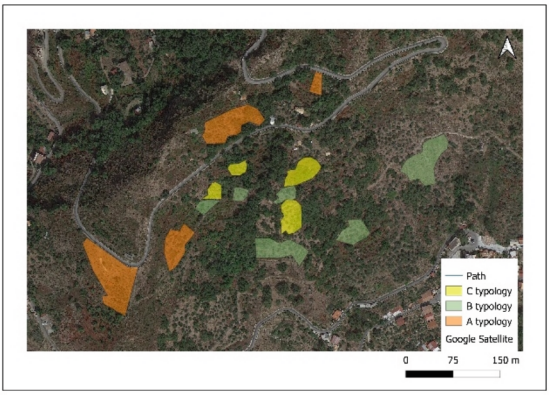

Fig. 7. GIS environment: representation of the three different typologies (A, B, C).

Ultimately, leveraging the methodology and algorithms detailed in paragraph 2, the Geographic Information System (GIS) facilitated the determination of routes for a drone tasked with monitoring existing crops and an automated tractor responsible for fertilization and irrigation. In Fig. 8, the drone's path within an existing crop is depicted by a blue line. It exemplifies the application of the methodology in selecting different cultivation typologies within a confined section of the study area.

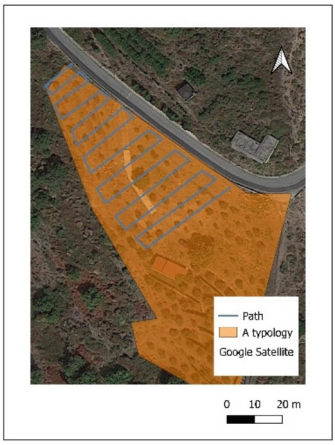

Fig. 8. GIS environment: drone's path highlighted with a blue line.

5 Discussion

The goal of this work's research was to test and experiment with an automated integration system for crop control and optimization. An experimental atmospheric simulator, UAV and satellite imagery, data from local sensors, data transmission methods, and an open-source GIS are all integrated into the process. The goal of the study was to categorize various farming practices and determine the best paths for a drone and an automated tractor to follow to track crop health and growth. A particular region in the province of Reggio Calabria was selected for the research because it was deemed suitable for the application of the many technologies discussed. In contrast to similar methodologies, this study presents various advantages and drawbacks. One significant strength is the comprehensive integration of multiple technologies, facilitating a holistic approach to Precision Agriculture. Our research enables precise optimization of fertilization and irrigation, offering deep insights into crop conditions. However, Precision Agriculture, encompassing our tested approach, also faces several challenges. The effectiveness of Precision Agriculture, including our proposed technique, depends on access to accurate and up-to-date data, as well as the necessary expertise for interpreting and effectively using the gathered data. Widespread adoption may also be hampered by the initial setup costs and the requirement for trained staff to run and maintain the system. Despite these inherent limitations of Precision Agriculture, this investigation provides insightful details about the sector's potential. To oversee crop well-being and refine irrigation techniques, it is exceedingly beneficial to amalgamate diverse technologies and data origins. It's evident that the authors prioritized the methodology over the results, retaining the option to scrutinize the data more deeply using various methods for the segmentation of the cultivable regions. Drones equipped with integrated technology hold promise for executing a range of functions, such as dispersing natural insecticides or fertilizers. These technologies encompass more intricate sensors. Indeed, industrial fertilizer manufacturing facilities still commonly employ evaporation and crystallization techniques.

This research progresses Precision Agriculture by showcasing the assimilation of various tools and approaches. The benefits of employing such integrated systems for precision agriculture outweigh the disadvantages, which necessitate attention. The findings underscore the significance of employing state-of-the-art technologies to streamline agricultural practices and pave the way for future advancements in more productive and environmentally sustainable farming techniques.

6 Conclusion

The advantages of the suggested and innovative system are obvious in terms of time savings, human resources, and productivity. Indeed, the automatization of some basic agricultural activities that are normally performed by people, saves time and money. Moreover, the possibility of evaluating different types of data on the condition of the soil and the health of the crops can increase productivity and quality and preserve a very precious resource, water, which is instead managed according to the weather variables provided by the simulator, which, with little input data, enables an evaluation of weather conditions. Furthermore, self-driving tractors already have a significant impact

on the agricultural industry, despite they are still recent technologies. With rapid improvements in technology, it seems probable that self-driving tractors will become increasingly common in the future, further changing the way farming is done.

This study applied different technologies to a particular region in the province of Reggio Calabria by taking advantage of the orographic and morphological features of the area. This illustrates how such approaches can be tailored to particular agricultural environments with the right planning and execution, optimizing the results. The primary goals of this research should be to expedite and optimize data processing and data transmission protocols; additionally, to validate and deploy these integrated systems on a large scale, as well as to potentially experiment with more productive and efficient algorithms. To facilitate the implementation of these innovative solutions that address the needs of various crops, environmental conditions, and farmer requirements, cooperation among research institutions, agricultural organizations, and farmers will be essential. The ultimate objective is to develop a sustainable farming strategy that benefits farmers, minimizes the impact on the environment, and makes effective use of the resources that are already available.

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Geographical Analysis, Urban Modeling, Spatial Statistics (Geog-And Mod 2024)

Emergency Communication Protocols for Pleasure Boats Using Eye-Tracker and EEG

Mattia Porta(✉), Patrizia Serra, and Gianfranco Fancello

DICAAR – Department of Civil and Environmental Engineering and Architecture, University of Cagliari, 09123 Cagliari, Italy
mattia.porta@unica.it

Abstract. This study proposes a multimodal approach to assess the prototype of an innovative maritime communication protocol, based on a web-app, by monitoring cognitive load and physiological responses. The experimental design involves a simulation of an emergency navigation scenario, requiring communication with maritime authorities. Tests have been conducted in a laboratory environment with a group of non-professional pleasure boat captains who have obtained the boat license. Human factor analysis devices include an eye-tracker device to observe first glance and focus areas, an electroencephalogram headset to gather scores of cognitive loads focusing on interest and mental stress, and a Smartwatch for assessing vital parameters, such as heart rate and heart frequency, blood pressure, and oxygen saturation.

The study's primary goal is to assess cognitive load in terms of stress and attention and evaluate the simplicity of the platform's usage. This experimental approach allows us to recognize difficulties in web-based communication protocol usage. Furthermore, to reduce the likelihood of making a mistake during maritime emergency communications, this study proposes some user interaction improvements, potentially enhancing response efficacy and maritime safety.

Keywords: Human Factor · Maritime Communication · Safety · stress · cognitive workload

1 Introduction

Human factors are a crucial aspect of maritime safety. According to Allianz Global Corporate and Specialty [1], human error is pointed out as a contributing factor in 75% of maritime casualties. McCallum et al. conducted an in-depth analysis of maritime casualties discovering that 18% of accidents are caused by communication problems. For this reason, maritime emergencies demand rapid, accurate, and stress-resistant communication protocols. Information and Communication technologies (ICT) and communication protocols play a fundamental role in emergency management by reducing human error likelihood and improving boat captains' safety perception. Lack of training, knowledge, and proper preparation for recreational boat captains, can be considered as fundamental elements in leading boating emergencies [2].

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Fadda et al. [3] highlights the importance of human factor-oriented measures that are being applied in the maritime sector and can further contribute to giving maritime operators and recreational boat captains a focus for maritime safety interventions (such as tailored training programs or improved communication tools and protocols based on human factor research) which can potentially enhance maritime safety.

In the context of ISIDE (Innovazioni per la SIcurezza DEi mari) [4], a project funded by the European Union, has been developed an innovative maritime communication protocol to improve maritime communication's efficacy. This protocol is a prototype designed and proposed during the above-mentioned project and this study aims to assess, through a multimodal approach, the ISIDE's ability to reduce the likelihood of human errors. This multimodal approach takes into consideration the following dimensions:

- Communication efficiency: evaluate the efficiency of pre-set messages in an emergency scenario for a target group of recreational boat captains.
- Cognitive load: explore how stress affects the choice of messages and the effectiveness of communication for non-professionals.
- Application Usability: evaluate whether the ISIDE application's Graphic User Interface (GUI) is intuitive for a non-professional target group and facilitates rapid communication in critical moments.

The paper is structured as follows: Section 2 presents a literature review on human factors analysis in the maritime sector; Sect. 3 describes the material and methods; Sect. 4 describes the results and Sect. 5 concludes.

2 Literature Review

Several authors dedicate their research to maritime safety and accident prevention, recognizing human factors as a fundamental aspect of avoiding critical navigational situations. Using hierarchical clustering methods [5] analyzes historical data relating to maritime accidents to highlight the potential causal relationships that can describe homogeneous groups of accidents. The results point out the role of the human factor as the prevalent (or contributing) cause of marine accidents related to work operations. Chauvin et al. [6] present key concepts for Human factor analysis from psychology, to understand the Human factors' role in complex situations like maritime accidents. The paper by Hetherington et al. [7] identifies several human factors influencing safety such as fatigue, automation, situation awareness, communication, decision-making, teamwork, and health and stress.

ICT (Information and Communication technologies) innovations provide a lot of opportunities for the maritime sector. Despite the great innovation in navigation and communication systems, the need to develop harmonized standards arises. IMO (International Maritime Organization) in 2014 developed a strategic implementation plan for e-navigation to improve safety and reduce human error [8]. In the context of the e-navigation strategic implementation plan, IMO dedicates an important space to Human-centered design. Guidelines on usability testing, evaluation, and assessment of e-navigation systems are actually under development [9].

Tanoubi et al. [10] and Arslan et al. [11], uses eye-tracking technology respectively to explore testers' visual perception during simulation scenarios and to assess the usability of electronic information systems. They find insights into how individuals process visual information during an emergency. Interesting research by Ronca et al. validates an innovative safety framework HURID (Human Risk-Informed Design), experimenting on 26 maritime operators within a simulated critical scenario through EEG (Electroencephalogram) [12]. Also, Liu et al. [13] use EEG technology to study stress among crew members during communication tasks on a ship's bridge virtual simulator.

This paper, compared with the state of the art, proposes a validation of an innovative communication protocol by experimenting on a target group of non-professional recreational boat captains. Some author dedicates their study to recreational boating. McKnight [14] investigates the role of human error in recreational boating, instead, Virk and Pikora [15] develop a tool to measure safety in recreational boating. Finally, Kwang An [16] defines necessary e-navigation services for non-SOLAS (International Convention for the Safety at Sea), in particular fishing and recreational boats.

3 Materials and Methods

This section is divided into paragraphs to describe in depth the ISIDE protocol and the experimental scenario, the biometric and behavior analysis devices, and the data collection procedures.

3.1 Communication Protocol ISIDE

The actual protocol, based on voice communications through VHF (Very High Frequency) radio technology, often reveals limits of recreational boat captains, due to lack of training and stress, in sending correct communication during navigation, particularly in emergency situations. The challenging purpose of ISIDE is to reduce human errors during ship-to-ship and ship-to-land communication, particularly in critical moments. It brings a radical innovation in maritime communication by introducing technologies that allow maritime operators and recreational boat captains to send the correct information to their interlocutors.

The prototype of ISIDE protocol is based on a web application that allows, through an interface, the exchange of information to the nearest vessels and port authorities. Indeed, through the application, maritime operators and recreational boat captains can exchange free text messages and pre-set phrases following SMCP (Standard Marine Communication Phrases) [17], the standard phraseology proposed by the International Maritime Organization as well as sharing one's geographical coordinates.

3.2 Technological Devices and Software

Three technological devices and two related software were used to run the experiment and study stress and fatigue during the tests: a smartwatch a mobile EEG device with related software and a portable screen eye-tracker with related software.

The smartwatch is equipped with complex components for measuring vital parameters. Through specific commands, it is possible to obtain, at a specific moment, the tester's vital parameters such as maximum/systolic (SYS) and minimum/diastolic (DIA) blood pressure (measured in mmHg) with a margin of error of ± 3 mmHg.

The mobile EEG device, specifically the Emotiv EPOC X, is a technological helmet that uses 16 high-resolution electroencephalogram sensors to monitor during the test, the operator's cognitive parameters through their brain activity. It captures electrical signals from the brain and, through the algorithm available in the related software Emotive PRO, allows researchers to deduce cognitive states, such as engagement, excitement, stress, and relaxation, during specific tasks. The analysis can be performed in real time or by evaluating recorded sessions. The device maps 16 neural markers to assess mental commands, performance metrics, and emotional indicators with an impressive 88% accuracy rate. The primary data extracted from the EEG provides insight into the cognitive stress score (SS) and attention score (AS) of the trainee throughout the experiment, measured in a ten-second frame on a scale ranging from 1 to 100. Lastly, Tobii Pro Nano is a portable eye-tracker positioned at the bottom edge of a screen that can recognize the operator's eye gaze within a limited framework. Gathering eye-gaze position during a given fraction of time, eye-tracker returns, through the related software Tobii Pro Lab a map of the gaze concentration areas (Heat map) and a sequence of the eye-gaze points that allow to identification of first-glance areas (Scan path). The experiment was designed, managed, and run within the software Tobii Pro Lab.

3.3 Scenario

The scenario designed for the experiment reproduces a simulated maritime emergency. It describes, in a screen, a typical critical navigation situation in which a recreational boat captain could occur. Furthermore, the scenario screen described the scenario's details, and instructions to perform the task. The entire text of the narrative's scenario is reported as Appendix 1.

3.4 Questionnaire

An anonym questionnaire is developed to collect the tester's demographic information and a first impression about the communication protocol. It is divided into three sections, the first one collects general information about the tester, in particular: the tester's age, gender, nationality, and year of navigation experience. The second section is composed of eight questions with a ten-point scale response option. Questions can be divided into three dimensions:

1. Simplicity of use: three questions to understand whether, from the tester's point of view, the web app is intuitive and easy to use when exchanging messages.
2. Safety perception: three questions to discover the tester's safety perception during the task performance.
3. Usability during an emergency: two questions whether the tester considers the communication protocol useful, or not, during ordinary or emergencies.

The latter section, asks the tester to leave some feedback to improve the web-app or the protocol in general. A copy of the questionnaire is available as Appendix 2.

3.5 Experimental Design

The experiment process includes four main points. The first stage is dedicated to calibrating the devices (EEG and Eye-tracker) and the first vital parameters measurement for the tester. The tester was seated at an office desk with a PC in front of them. Eventually, the laboratory operator started to calibrate the devices before starting the test and the initial data collection of the tester's pre-stimulus biometric parameters. After all the tools were correctly set up, the experiment could proceed to the next phase.

The second phase is further divided into three fractions as follows:

- Scenario's administration: To begin, the first screen had a narrative about the described scenario and the instructions to complete the task.
- Pre-test stimulus: Introduction of the ISIDE application.
- Test performance: The web app works and the tester can go ahead and carry out the task assigned. The tester's goal is to send a distress signal, trying to follow the documentation written for the scenario. At the end of sending the distress signal, the screen was closed. This stage takes between 5 and 10 min, depending on the tester's choices.

The optimum task result that a tester can reach is to send a distress signal using only pre-set phrases. Anyway, the task is considered accomplished even if the tester uses free test messages.

The last phase starts with the second tester's vital parameters gathering. Finally, the tester is going to submit his opinion about the usage of the platform by completing a questionnaire right after completing the task.

3.6 Participants

The participants' selection was oriented on the ISIDE protocol target of recreational boat captains. For this reason, the participants were selected with the requirement of the boating license' possession. The sample involved during the experimentation was composed of 13 testers. Some general information about testers was acquired for basic demographical statistics.

The sample has an average age of 42, 40 years and, again on average, 18,70 years of experience in recreational navigation. Table 1 reports demographic information for each participant.

3.7 KPIs

To align experimental data with research purposes, a set of KPIs (Key performance indicators) was identified. It can be divided into three groups: tester task performance (measured by observing the tester), tester cognitive and vital parameters (measured with EEG and Smartwatch), and tester eye gaze movement (measured with eye-tracker). Table 1 reports the list of task performance KPIs, where the first column reports the KPI name, the following description, and the last one is the result or unit (Table 2).

Instead, Table 3 is structured as follows: the first column provides the KPI name, the second one shows the unit of measurement and the third column describes the formula.

Table 1. Participant demographic information.

Participant N°	Gender	Age	Nationality	Years of experience in navigation
1	Male	48	Italian	30
2	Female	29	Italian	15
3	Male	31	Italian	1
4	Male	32	Italian	2
5	Male	49	Italian	25
6	Male	58	Italian	38
7	Male	25	Italian	6
8	Male	36	Italian	14
9	Female	29	Italian	5
10	Male	50	Italian	19
11	Female	58	Italian	12
12	Male	45	Italian	25
13	Male	61	Italian	50

Table 2. KPIs for task performance.

KPI name	Description	Result/Unit
Task time	Overall time to complete the task	Min
Optimum performance	Task completed by using only pre-set messages	Yes/No

The last column specified the equation symbols. The quantitative human factor KPIs are composed using the scores provided by the mobile EEG device (stress and attention) and from the smartwatch (heart rate, maximum and minimum blood pressure).

For the vital parameters KPIs, a percentage change from the initial collection to the final collection was calculated:

$$\Delta\% \text{ change} = \frac{(X2 - X1)}{X1} \cdot 100$$

where:

For the cognitive scores:

X_1: KPI value measured in the Scenario's Administration

X_2: KPI value measured in the Test performance

For the vital parameters:

X_1: KPI value measured in the first collection

X_2: KPI value measured in the second collection

The analysis of the percentage change of the KPI values could help to better understand the variability of the measures recorded during the tests.

Table 3. Quantitative human factor KPIs.

KPI name	Unit	Formula	Equation symbols
Average stress score	[-]	$\mathbf{ASS} = \frac{1}{6}\frac{\sum \mathbf{SS}}{\mathbf{ST}}$	SS: Stress score ST: Task time [min]
Average attention score	[-]	$\mathbf{AAS} = \frac{1}{6}\frac{\sum \mathbf{AS}}{\mathbf{ST}}$	AS: Attention score ST: Task time [min]
Hearth rate	[bpm]	–	–
Max blood pressure/ systolic pressure (SYS)	[mmHg]	SYS	–
Min blood pressure/diatolic pressure (DIA)	[mmHg] DIA		–

Finally, the KPIs gathered from the eye-tracker. Specifically, the analysis of eye-gaze movement provides data about the first-glance movement after a specific stimulus (scan path) and the eye-gaze concentration area in a specific time frame (heat map).

4 Result and Discussion

4.1 Test Performance

Table 4 reports the test performance results for each participant.

The average time spent by the tester to accomplish the task is 3 min and 26 s and about 85% of the testers achieve the task using exclusively pre-set messages. Testers that spend more than the average time, coincide in parts with testers that accomplish the task using free-text messages.

4.2 Cognitive and Vital Parameters

The analysis conducted through EEG gives an overview of the cognitive aspects of subjects during the experimental phases. It was particularly interesting to monitor the cognitive parameters during the experimentation, excluding the calibration phase, and to divide the entire collection into three main phases: the scenario administration phase, the pre-test stimulus, and the task performance phase. The average scores collected and reported in Table 5 and in the bar plot in Fig. 1, revealed two main phenomena. The first displays cognitive attention scores without significant variations, but with a slight increase in the more critical phases, the scenario administration and the test performance. However, the cognitive stress scores highlight a continuous increase during the three selected phases, displaying an increase in stress even during the central phase of the stimulus administration. This phenomenon suggests an engagement of the subjects in

Table 4. Test performance KPIs.

Participant N°	Task time	Optimum performance
1	4′13”	Yes
2	3′16”	Yes
3	3′01”	Yes
4	3′28”	Yes
5	4′26”	No
6	3′14”	Yes
7	2′21”	Yes
8	2′23”	Yes
9	2′30”	Yes
10	4′25”	No
11	2′41”	Yes
12	4′09”	No
13	4′37	Yes

Table 5. Cognitive stress and attention scores and variations.

KPI name	Scenario’s administration	Pre-test stimuli	Test Performance	Variation %
Average cognitive stress	34,45	39,73	44	27%
Average cognitive attention	48,42	46,86	50,28	3,9%

the experimental scenario and a cognitive sensitivity due to not knowing and managing the unfolding events.

The vital parameter data, obtained as an average of the values from all participants in the experiment, provide a consistent view of the phenomenon from the perspective of the testers’ vital parameters. Table 6 reported the average values which can be observed a slight variation between the initial recording and the second recording at the end of the experiment. The slight increase highlights a physiological variation due to concentration during the tasks and a potential adaptation of the subject to the environmental factors of the laboratory.

4.3 Eye-Gaze Movement

Some of the most interesting aspects of this experiment are revealed by the eye-tracking analysis tool. Regarding this tool, given the dynamic nature of the application and the

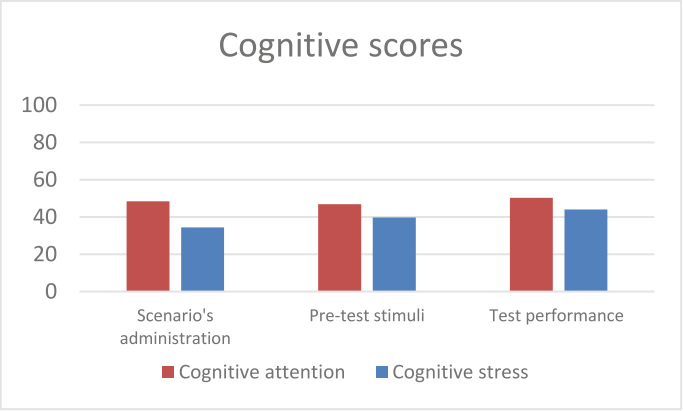

Fig. 1. Bar graph of the average cognitive scores (stress score and attention) divided for phase.

Table 6. Vital parameters scores and variations.

KPI name	First collection	Second collection	Variation
Average Hearth rate	71,92	76,46	7%
Average max blood pressure/ systolic pressure (SYS)	119	121,30	2%
Average min blood pressure/diatolic pressure (DIA)	77,92	82,23	6%

subsequent inability to have a holistic view of the phenomenon during experimentation, the focus has been on analyzing the most critical moments of the entire communication: the moment of sending the first distress call (MayDay) and the end of the conversation where feedback on the request for geographical coordinates and the arrival of rescue are received.

Initially, the inquiry was about the users' ability and speed in locating the GUI (Graphic User Interface) button to click to send the correct communication and, subsequently, the impact of other elements in terms of distraction from the focus of the moment. Figure 2 helps to track the first glance that the testers' gaze took during the presentation of the stimulus. In this figure is the reported gaze path for the whole sample. It is simple to recognize the different bubble colors. Each color represents a tester and the number inside the bubble is the sequence number recorded by the device. It emerged that the largest number of views and, consequently, attention focused on the correct button, the MayDay one.

Confirming the information gathered from the eye-tracking, Fig. 3 displays the eye-gaze heatmap. This figure, for readability reasons, reports the heatmap of one tester. The heatmap represents the intensity of viewing during the fraction of time in which the web app screen is shown for the first time. This insight makes it unequivocal that the

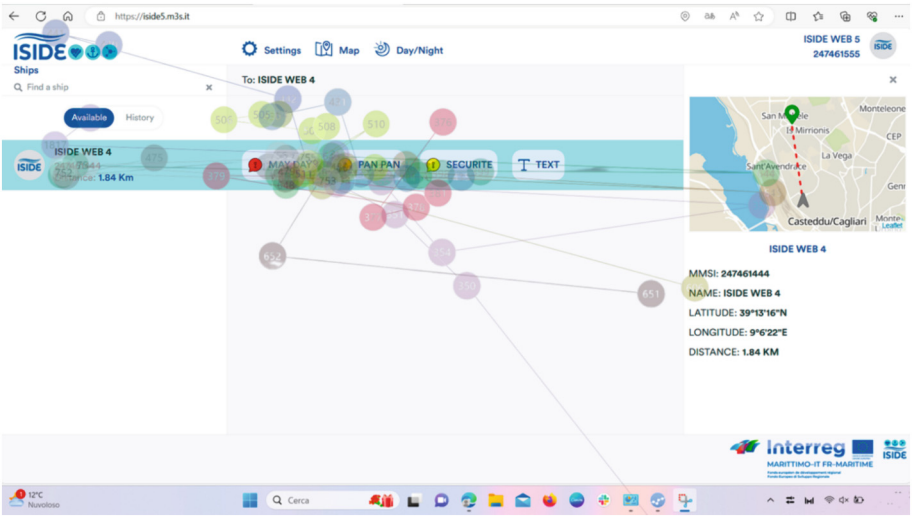

Fig. 2. Eye-gaze scan path recorded by the screen eye tracker.

subjects, despite some distractions to other areas of the screen, focused mainly on the correct point of the screen.

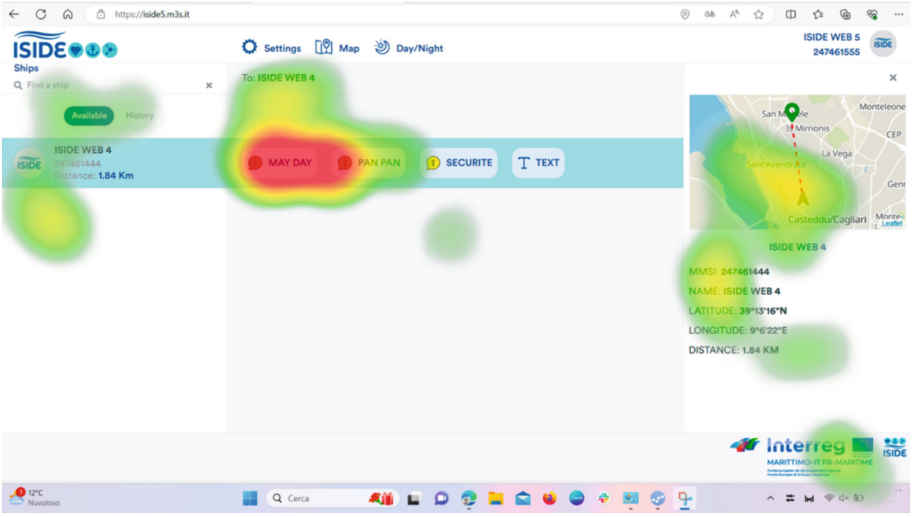

Fig. 3. Eye-gaze heatmap recorded by the screen eye tracker

4.4 Questionnaire

The questionnaire administered at the end of the experiment reports generally positive feedback. No tester offered suggestions for improving the application.

Despite all values being generally positive, the lowest score was observed in the section regarding the usability of the application during emergencies. Given the testers' proven navigation experience, this insight suggests a mistrust of using a technological/digital device during navigation. This phenomenon could arise from the actual lack of adoption of such systems as standard onboard communication equipment.

4.5 Limitations

Some limitations in this study are identified. The first important limitation of this study is the restricted sample size. The experiment was conducted on only 13 participants, consequently restricting the generalizability of the findings. Furthermore, the statistical power of the study is weak, which may lead to increased variance and potentially less reliable results. For this reason, this research could be considered a preliminary study for this experiment with the objective, for future research, to expand the size of the sample and allow more robust statistical analysis. On the other hand, is necessary to point out the real difficulties in gathering enough participants consistent with the target of the experiment.

Another important limitation could be identified in the simulated scenario. Even if the scenario could reproduce a real-life situation, it is not enough immersive to influence the human factor to predict with accuracy the behavioral variations caused by a real-life emergency. For further studies, could be interesting to replicate the experiment, always through a simulation, but in a real navigation situation at the sea taking into consideration the difficulties of catching target participants and the management of a real-life simulation experiment.

5 Conclusions

In conclusion, this experimentation, which focuses on a target group of pleasure boaters, suggests a further alignment of the application and, therefore, of the entire sea-to-land and sea-to-sea communication model proposed by the ISIDE project. This multimodal approach to user-focused experimentation validates the proposed communication protocol as suitable even for a less professionally trained public in navigation. The collected data suggest and confirm almost intuitive dynamics, in particular; the testers that use only the pre-set phrases spend less than the average time to send the distress message. The cognitive data provided by the EEG suggest that the uncertainty in the expectation of communication through an application has an impact on the subject's attention and stress levels, confirming the intuition to focus attention at that moment, and classifying it as more critical. The data provided by the eye-tracker entirely validate the simplicity and intuitiveness of the proposed model. The physiological parameters, acquired indicate an increasing concentration of the subject during the experiment and a physiological adaptation to the environment. The feedback provided by the testers at the end of the

experimentation validates the protocol but still hints at a slight mistrust regarding the use of innovative systems not yet familiar with the contexts of recreational navigation. On the other side, the restricted number of participants might not represent the population and, as a consequence, limit the ability to detect reliable variations that could be more apparent in a larger group. Future research with expanded sample sizes is recommended to validate and extend these preliminary findings.

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Appendix 1

Scenario

Welcome to the maritime emergency simulation experiment.

Today, you will find yourself at the heart of a critical situation at sea. Imagine you are the captain of the boat ISIDE5, sailing on the calm sea of the Mediterranean. The weather is clear, a gentle breeze accompanies the waves, and everything seems to be going well.

But in the meantime, something unexpected happens: your boat's engine went on fire. You find yourself in trouble, far from land, with a crew of 3 people relying on you. It's time to activate the emergency protocol.

Your first action is to use the ISIDE application to send a standardized distress message, following procedures, to the nearby ship ISIDE4. The series of messages you send must report crucial information: type of emergency, nature of the emergency, condition of the crew, and the request for immediate assistance.

No particular danger situations like explosions or injuries on board are detected.

But it doesn't end here. If necessary, you are allowed to use the free messaging feature to provide additional details.

Remember, your role is crucial: your actions and decisions can influence the outcome of this simulation. Ready to start? Face this challenge with calm and concentration. Your reactions and decisions will give us valuable information on how to improve maritime communication in emergencies.

Appendix 2

Questionnaire

General demographic information

- Years of experience in navigation: _____
- Gender: _____
- Age: _____
- Nationality: _____

Express your evaluation of the following aspects of the Application by marking the appropriate judgement (1 = Poor, 10 = Excellent):

Intuitiveness within the screens	1	2	3	4	5	6	7	8	9	10
Simplicity of use	1	2	3	4	5	6	7	8	9	10
Simplicity in sending communications	1	2	3	4	5	6	7	8	9	10
Perceived safeness during screens‘ surfing	1	2	3	4	5	6	7	8	9	10
Perceived safeness in sending communications	1	2	3	4	5	6	7	8	9	10
Perceived safeness in receiving communications	1	2	3	4	5	6	7	8	9	10
Usability in emergency situations	1	2	3	4	5	6	7	8	9	10
Usability in ordinary situations	1	2	3	4	5	6	7	8	9	10

Suggestions
Do you have any suggestions to improve the protocol?

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Spatial Multi-criteria Analysis for the Planning of Green Hydrogen Infrastructure: The Case Study of the Industrial Area of Viggiano

Rossella Scorzelli[1(✉)], Shiva Rahmani[1], Michela Delfino[1], Grazia Fattoruso[2], Alfonso Annunziata[1], and Beniamino Murgante[1]

[1] School of Engineering, University of Basilicata, Viale dell'Ateneo Lucano 10, 85100 Potenza, Italy
rossella.scorzelli@unibas.it

[2] Photovoltaic and Sensor Applications Laboratory, ENEA RC Portici, P.le E. Fermi 1, 80055 Naples, Italy

Abstract. The paper examines the criteria that help to identify the most suitable sites for the location of plants, structures, and networks needed to produce, store, and distribute green hydrogen produced through water electrolysis. To carry out this analysis, it was necessary to work through the integration of two tools: the Analytic Hierarchy Process (AHP) and the Geographic Information System (GIS). While AHP allows for the analytical analysis of criteria, GIS identifies the spatial relationships generated in identifying suitable sites for the Green Hydrogen Infrastructure (GHI) placement. The approach considers several criteria that fall into three main categories: technical, economic, and environmental. Developing the criteria results in a land suitability map as the final product. The process mentioned is evident in the case study, namely identifying suitable sites for the location of GHIs in the Viggiano industrial area in Basilicata (Italy). The paper reveals that the methodology supports urban planners, decision-makers, and stakeholders in developing and using green hydrogen as a sustainable energy source.

Keyword: Green Hydrogen Infrastructure (GHI) · Land Suitability Map · Spatial Multi-Criteria Analysis

1 Introduction

Today's society has numerous challenges and emergencies, and the climate crisis is one of them [1]. Data on environmental pollution are increasingly dramatic, and several studies [2–5] point to the well-known correlation between human health and environmental health. Greenhouse gas emissions due to the use of fossil fuels are among the main contributors to climate change [6], which is why the world's policies are moving towards clean energy sources that can overcome the limitations of fossil fuels [7]. In this scenario, green hydrogen plays a key role [8, 9]. Its versatility and diverse uses allow for easy deployment [10], although it is currently limited by investment costs in the infrastructure needed to produce, store, and distribute green hydrogen [11]. Presently, the prospects for

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the use of hydrogen are particularly favorable for the transport sector. This last is, in fact, responsible for about 65% of global Green House Gas (GHG) emissions [12]. Acting in this sector makes it possible to reduce pollution and the energy dependency of Nations [13]. Hydrogen can be used in vehicles in essentially two ways: a) in fuel cells (Fuel Cells) to produce electricity that then powers the vehicle's electric motor (FCEV - Fuel Cells Electric Vehicle) [14]; b) as fuel in an internal combustion engine (HICEV - Hydrogen Internal Combustion Engine Vehicle) [15]. Among the most promising methods for producing green hydrogen is the electrolysis of water [16]. Electrolysis is when water is split into oxygen and hydrogen gas using electricity from renewable energy sources [17]. This process makes it possible to produce hydrogen with zero carbon emissions [18]. The paper aims to investigate the criteria necessary for identifying GHIs to locate suitable sites. A spatially based analytical methodology was implemented to achieve this goal, integrating the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS). The adoption of this method is underscored in the scientific literature, highlighting its utilization in decision-making processes concerning the localization of Renewable Energy Sources [19–28]. The specificity of this approach is that it allows both qualitative and quantitative factors to be considered and their spatial dimensions to be visualized. The methodology was applied to a case study concerning the Viggiano industrial area in Basilicata, Italy, to verify its effectiveness. The final output is the land suitability map showing the suitability of the investigated study area for the placement of GHIs.

The paper is divided into three sections. The first concerns the method of analysis, in which the methodology steps are described. The second section contains the case study, and the last section regards concluding remarks.

2 Analysis Method

Assessing the sustainability of land transformation interventions is now a topic of central importance in cultural, scientific, and political debate. In this context, decision problems are typically characterized by involving a spatial component, requiring more than one evaluation criterion, and pursuing more than one objective [29]. Multicriteria assessments support decision-making processes [30, 31] that choose multiple alternative solutions. The last are analyzed against a set of criteria that can be either economic, and therefore monetizable [32], or qualitative. Multicriteria methods aim to identify the compromised solution [32–34]. The best alternative is not the one that optimizes each criterion but achieves the best compromise considering all the criteria selected for comparison. Among the most comprehensive multicriteria decision analysis methods is the Analytic Hierarchy Process (AHP) [35]. This method owes its considerable popularity in the international arena to its ease of application [36]. It also finds use in various fields [37] ranging from engineering to politics, from social issues to economics. Several simplifications have affected the AHP technique. These simplifications were introduced by its very creator, the mathematician Thomas Saaty [35, 38, 39]. The main steps are:

1) Recognize the main problem and decompose its complexity into simpler problems.
2) Identify the actors involved.
3) Represent the problem through a hierarchy consisting of the goal, criteria, sub-criteria, and alternatives.

4) Make comparisons of the elements of the same levels concerning over-ordered ones through a scale of judgments ranging from 1 to 9.
5) Identify local weights of criteria and global weights of alternatives.
6) Check the goodness-of-fit of the model by calculating the maximum eigenvalue, CI Consistency Index (CI), and Consistency Ratio (CR).

The functions of the Analytic Hierarchy Process (AHP) can be integrated [40] with the spatial functions of Geographic Information Systems (GIS). Criteria and attributes can be represented through geographic maps [41]. The hierarchy consists of levels but does not include the level of alternatives represented geographically by linear elements, polygons, or through a raster's cells if the maps' format is vector type [42]. The weights of the hierarchy elements and the spatial information of the problem under consideration can be processed in the same environment. Maps give a spatial distribution of criterion values in the study area [43–45].

The case study aims to create a land suitability map for placing GHIs (Green Hydrogen Infrastructure) in the Viggiano industrial area in Basilicata. Consequently, within the GIS environment, the following steps are followed:

1) Identifying constrained areas and making the study area map with free areas.
2) Represent the criteria and sub-criteria through maps.
3) Overlay of the maps through map-algebra tools and assignment of the weights obtained with AHP.
4) Elaborate the land suitability map.

This methodology greatly simplifies the decision-making process regarding a complex and multifaceted topic, such as choosing the most suitable site for the location of GHIs. As a result, greater stakeholder involvement promotes the development of a resilient and environmentally aware society [46–48].

3 Case Study

Hydrocarbon exploration and production in Italy using industrial techniques began in the second half of the 19th century and has developed considerably since World War II, following the discovery of significant quantities of natural gas, especially in Basilicata. In Val d'Agri, one of the most characteristic valleys in Basilicata, there is an important industrial area with the presence of the largest oil platform in continental Europe. At the Centro Oli Val d'Agri (COVA) plant, hydrocarbon processing is carried out. Crude oil fed to the plant undergoes all the treatments necessary for commercialization, which essentially consists of the separation and subsequent processing of the phases present in the extracted fluid: crude oil, gas, and water.

The water that emerges along with the crude oil and gas during extraction is called process water. These waters undergo treatment consisting of separating the associated gas, de-oiling, degassing, filtration, and storage. The treated waters can be used in electrolysis to produce green hydrogen.

3.1 Study Area

Centro Oli Val d'Agri (COVA) is located in the industrial area of Viggiano in Basilicata as show Fig. 1.

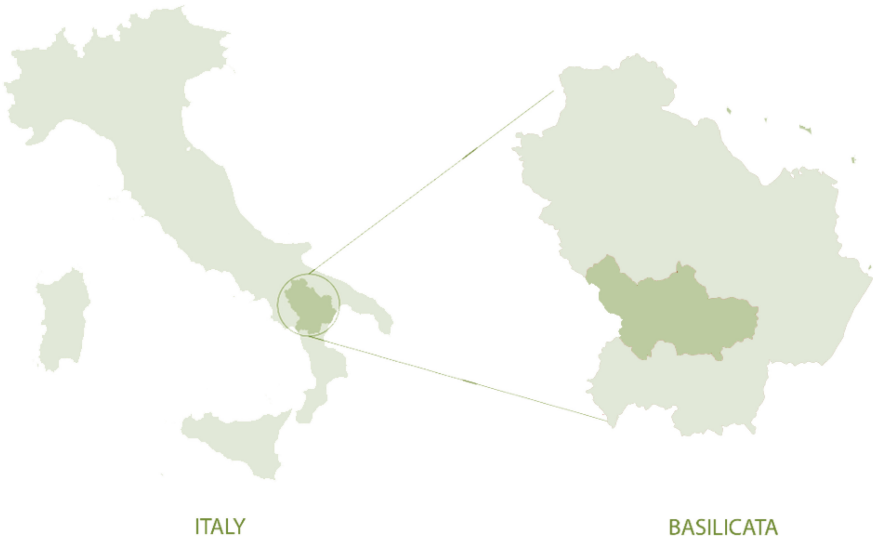

Fig. 1. Location of the study area in the Basilicata region.

The site covers an area of approximately 171,700 m^2. The southeastern perimeter of the complex runs parallel to the municipal boundary, while the surrounding areas, within a radius of 1 km, fall within the municipal territories of Viggiano and Grumento Nova. In order to carry out a more detailed analysis, for the identification of suitable sites for the installation of GHIs, it was also necessary to include neighboring municipalities, such as Armento, Aliano, Castronuovo di Sant'Andrea, Corleto Perticara, Gallicchio, Guardia Perticara, Marsico Nuovo, Marsicovetere, Missanello, Moliterno, Montemurro, Paterno, Roccanova, San Chirico Raparo, San Martino d'Agri, Sant'Arcangelo, Sarconi, Spinoso and Tramutola. The complete study area shown in Fig. 2 covers 1405 km^2.

The first operation carried out in the GIS environment involved identifying areas that are constrained and, therefore, not suitable for the installation of GHIs. The constrained areas include:

- the hazard areas of the Hydrogeological Structure Plan.
- The urban centers and rural areas are drawn from ISTAT data on national locations.
- areas protected by law concerning the regulatory framework for regional landscape planning, consisting of the European Landscape Convention (ECL).

Eliminating constrained areas resulted in the map of the vacant areas shown in Fig. 3.

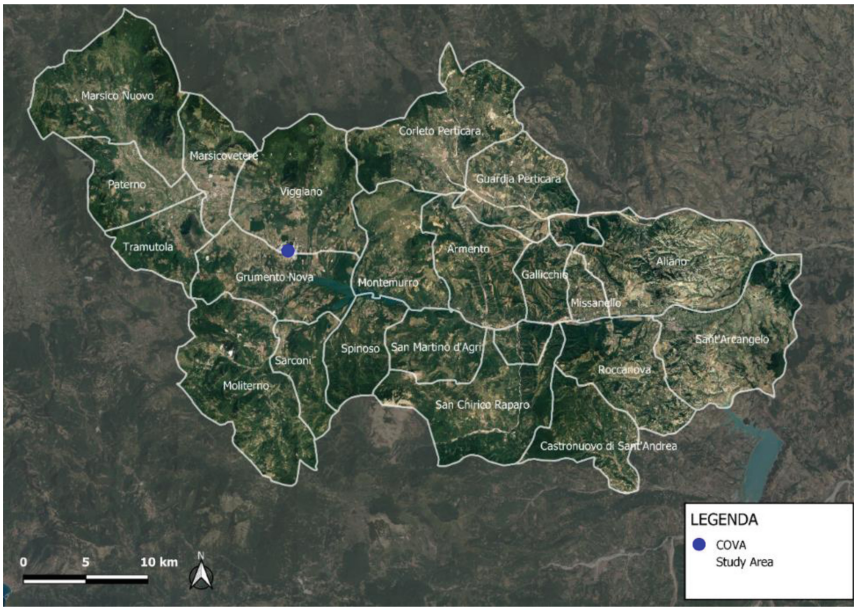

Fig. 2. Study area.

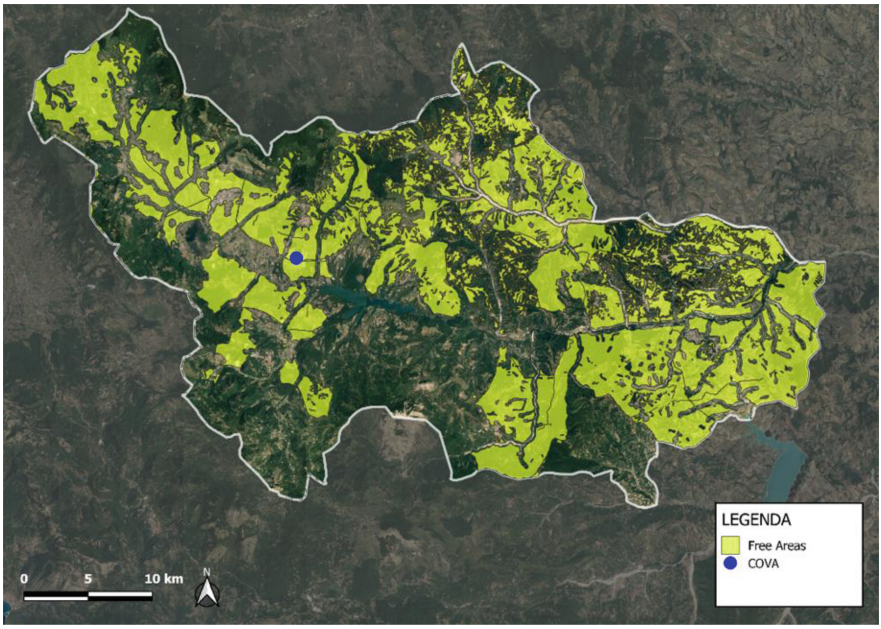

Fig. 3. Map of free areas.

3.2 Spatial Analysis of Criteria

The criteria and sub-criteria selected for the study area analysis were evaluated after careful analysis with experts in the field. The criteria pertain to three categories: technical, economic, and environmental. There are seven sub-criteria: slope, solar radiation, accessibility to roads, accessibility to the Val d'Agri Oil Center (COVA), distance to RES, and distance to the TERNA power grid. Finally, the environmental criterion has a sub-criterion as a summary indicator of three ecosystem services: habitat quality, carbon stock, and crop production. Criteria and their sub-criteria are summarized in Table 1.

Table 1. Identification of criteria and sub-criteria.

Main Criteria	Sub-Criteria
Technical	C_1: Slope
	C_2: Solar radiation
Economic	C_3: Distance of roads
	C_4: Distance of COVA
	C_5: Distance of RES
	C_6: Distance of TERNA power grid
Environmental	C_7: Ecosystem Services

Next, the steps of the AHP technique explained in Sect. 2 were applied. For each criteria, weights were calculated thanks to the pairwise comparison matrix shown in Table 2 using the semantic scale with values ranging from 1 to 9 proposed by Saaty [35]. The vector of weights is shown in the last column of the matrix.

Table 2. Pairwise comparison matrix and weights of sub-criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	w_i (%)
C_1	1,00	0,25	0,17	0,17	0,20	0,20	0,25	3
C_2	4,00	1,00	0,33	0,33	0,33	0,33	0,25	6
C_3	6,00	3,00	1,00	1,00	0,50	0,50	0,25	11
C_4	6,00	3,00	1,00	1,00	0,50	0,50	0,25	11
C_5	5,00	3,00	2,00	2,00	1,00	1,00	0,25	15
C_6	5,00	3,00	2,00	2,00	1,00	1,00	0,25	15
C_7	4,00	4,00	4,00	4,00	4,00	4,00	1,00	37

The judgments' consistency was checked by calculating the maximum eigenvalue and then the Consistency Index (CI) and Consistency Ratio (CR). The consistency index

is calculated through the formula shown in Eq. 1. The term "n" represents the number of items compared; in this case, there are seven criteria.

$$CI = \frac{\lambda max - n}{n - 1} \tag{1}$$

The CR is provided by the ratio of the consistency index to the Random Consistency Index (RCI). The latter is a tabulated value that depends on the number of elements considered, as shown in Table 3.

Table 3. RCI values.

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0,58	0,90	1,12	1,24	1,32	1,41	1,45

As shown in Table 4, the consistency ratio is less than 10%, and the upper limit when the elements considered (n) are greater than 4. The consistency check is therefore satisfied.

Table 4. Consistency Check

λ max	n	CI	RCI	CR	CR (%)
7,730711	7	0,12	1,32	0,092262	9,23

Each criterion was then spatially analyzed in a GIS environment. A reclassification in raster format is made through ArcGIS, compared to the free areas resulting from the previous analysis. Reclassification was done using a suitability scale of 1 to 5, where:

- 1 highly suitable areas.
- 2 medium-high suitability areas.
- 3 medium suitability areas.
- 4 areas with medium-low suitability.
- 5 areas with low suitability.

3.3 Land Suitability Map

After carefully analyzing all sub-criteria, the final result of the spatial multi-criteria analysis is a Land Suitability Map shown in Fig. 4.

Through Map Algebra operations, the weights assigned to each sub-criterion, derived from the pairwise comparison table (Table 2), were entered. From the resulting map, the best sites to locate GHIs are deduced. The high suitability level presents a fair extent throughout the study area. In particular, an area of high suitability with an extent of 184,6 hectares is close to COVA. This extension appears to be largely suitable for locating facilities for producing, storing, and distributing green hydrogen. COVA falls

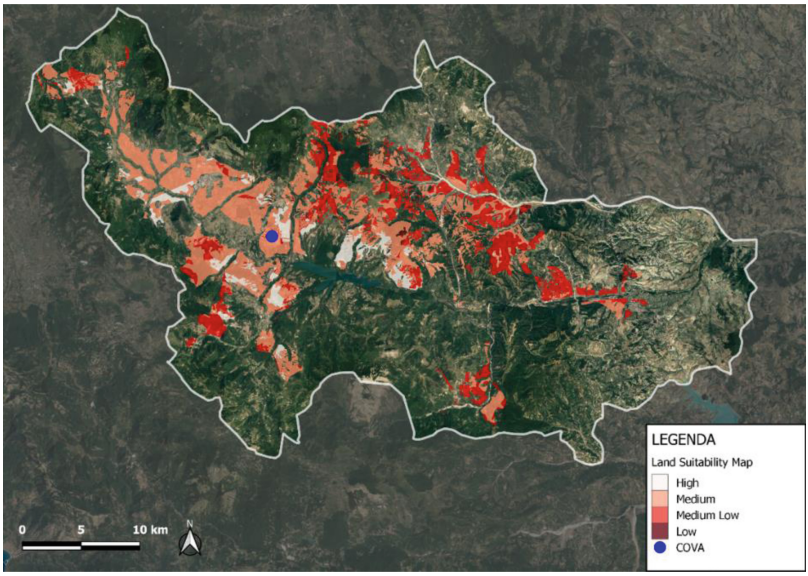

Fig. 4. Land Suitability Map.

within an area of medium suitability equal to 540 hectares. By expanding the range and considering COVA as the center of reference, the suitability decreases, with medium-low and low levels.

4 Conclusion

In conclusion, the paper's main objective is to identify the most suitable location to design and implement a green hydrogen production, storage, and distribution infrastructure to promote sustainability and low-carbon energy consumption.

The methodology used, characterized by the integration of AHP (Analytic Hierarchy Process) in a GIS (Geographic Information System) environment, sees its application to the selected case study: the identification of suitable sites for the location of Green Hydrogen Infrastructure (GHI) serving the Val d'Agri industrial area. AHP allows us to simplify a complex problem into simpler sub-problems by considering numerous quantitative and qualitative criteria. This methodology is an important support tool for planners, who play an important role in decision-making processes. Using this spatial analysis technique, stakeholders, policymakers, and companies can compare different sites and scenarios about criteria such as renewable energy, existing infrastructure, and transportation systems.

Ultimately, the elaborations show that green hydrogen represents a promising energy resource in the transition to a sustainable future, and its deployment could play a key role in powering those energy-intensive sectors.

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Complex Network Analysis of Imported and Exported Goods in the United States of America

Konstadinos G. Goulias(✉) and Hui Shi

University of California, Santa Barbara, CA 93106, USA
kgoulias@ucsb.edu

Abstract. In this paper the network structure of imported and exported freight flows in United States in 2022 is explored. The data used are from the Freight Analysis Framework (FAF) that represents freight movement among states and major metropolitan areas by all modes of transportation. Using tools from network science hubs and central nodes making the network of freight flow vulnerable are identified and communities of nodes based on shipments of goods in value of tonnage flows are extracted to distinguish different functional regions. Different network topology in 2022 is found analyzing imported goods and exported goods. The networks are graphs with 132 nodes that are spatial subdivisions based on major Metropolitan Statistical Areas (MSAs) and the non-MSA parts of their States. The links are the directional movement of freight flows among the nodes. The imports graph explored here has 10739 directional links among the 132 nodes. The graph of international exports is smaller with 9722 links among the 132 nodes and displays different freight flow behavior and community clustering than the much larger 2022 domestic freight flow network that has 17356 directional links. The analysis here finds some similarities in the location of vulnerable nodes. Similarities are found in functional regions formed by data-driven clusters of nodes dividing the US into Northeast, Southeast, Southcentral, West, and Midwest with differences among the domestic, import and export networks. The number of distinct clusters in the imports and exports networks is higher than the domestic network clusters and in a few clusters node membership violates regional contiguity and proximity. This is due to the infrastructure connectedness and economic complementarity (e.g., nodes that exchange goods for auto manufacturing with Detroit, Michigan, and Laredo in Texas that imports goods from Mexico).

Keywords: Network science · Functional region · Community · Freight flow · Freight value · Exports · Imports

1 Introduction

Regions around the world are interdependent and often form trade alliances with a high degree of international economic and political influence [1, 2]. The impact of these agreements and alliances is different among localities in a country for a variety of regional and historical development reasons but also local policies create spatially

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differentiated impacts such as found by Hayward when exploring the impact of the European Community formation and resulting trade with the US [3]. Local influence of international trade could be examined at the level of a State or Province as was done by [4, 5] for the United States and Canada but a more detailed geography may reveal key differences within states. This motivates our analysis here using a more fine-grained geographic subdivision in the Freight Analysis Framework (FAF) maintained by United States agencies. FAF combines data from the US Census Bureau Commodity Flow Survey (CFS) with a variety of other sources to develop trade flow data among 132 places (metropolitan areas and non-metropolitan areas in each of the 50 states and Washington DC). This captures goods movement in agriculture, resource extraction, utility, construction, retail, services, and other sectors. The data used here are presented in a later section and they are from FAF5 that has been recently completed [6]. This paper focus is on the international freight flows among the 132 FAF5 places in the US and the worldwide regions. Domestic monetarized flows are used as benchmark. Network science tools are used to detect and describe regions in the FAF5 data for 2022, which is the closest year to the writing of this paper and has been validated with observed data. FAF provides three metrics of freight flow that are tonnage of goods, value of this tonnage, and ton-miles. The focus here only on the value of tonnage flows in USD 2022.

Network science views origins, destinations, and the movement of goods between them as a graph of nodes (vertices) and links (edges). Importance of edges is based on the size of freight flows moving from one node to another, which are commonly called weights of the edges (links). Node importance is based on the number of connections with other nodes and the total amount of commodities moving into a node and/or moving out of a node. In this way one can identify nodes that function as major predominantly producers, major predominantly consumers and as hubs of freight flow movement. Network statistics also allow to identify node hierarchy within a network based on the node degree of influence exerted to the entire network. In this way vulnerability of a network can be studied in terms of loss when eliminating an influential node. Another outcome of network analysis is the identification of groups of nodes (in this paper they are metropolitan places or entire states) that have higher levels of freight flows within their group. These places create functional regions derived from relationships among nodes and may be a factor of resiliency for a group of places and for the entire freight network as a whole. Making these distinctions among nodes and groups of nodes requires a specialistic analysis that is network science and reviewed briefly later in the paper. The key research questions are:

1. Are there topological differences between import and export freight networks?
2. Are there critical nodes of production, consumption, and intermediaries that make the import and/or export networks vulnerable to threats?
3. Are there groups of nodes that belong together in a functional region and are they geographically clustered?
4. Does membership in these functional regions differ between imports and exports?

2 Data Used Here

The freight flow data analysis here is modeled using a multimodal and intermodal network of facilities that bring produced goods (e.g., goods by agricultural fields, extraction of crude oil in wells, mining of iron ore) to facilities that transform these goods (e.g., preparing food and packaging, refining crude oil to gasoline, manufacturing cars) that in turn are transported to the end consumer (e.g., grocery stores, retail gasoline pumps, car buyers at salons or residences). Many commodities have distinct infrastructure components underlining their movement geography such as petroleum crude. Its supply chain includes extraction technologies at the origins where production happens (e.g., oil wells), pipelines, railways, highways and trucks, barges, tanks for storage, refineries, and a distribution system to the ultimate customers (e.g., power generating plants, industrial complexes, businesses, and residential customers). All these form spatial networks that take a different form impacting the nature of node and links. In this paper no distinction among the different goods, or the infrastructure used to transport them are made. Instead, network science is used to identify clusters of nodes and links that represent groups of regions that participate in international trade of goods with higher "intensity" among them than with other regions in the U.S.

The core data and the spatial organization of origins and destinations are from the Commodity Flow Survey (CFS) conducted by the Bureau of Transportation Statistics (BTS), the US Department of Transportation, the US Census Bureau, and the US Department of Commerce to provide data on domestic freight shipments in a variety of industries with the latest version in 2017 (https://www.census.gov/programs-surveys/cfs/about.html). The nodes are metropolitan areas in the United States and places in a state that are not metropolitan areas. The data assembled and combined produce the Freight Analysis Framework (FAF) using the CFS regions as origins and destinations (see Appendix A). To distinguish among different states in a major metropolitan area CFS divides an area by state. For example, the area with code 408 is divided in a Connecticut part, a New Jersey part, a New York part, and a Pennsylvania part. These regional economic centers aim to balance geographic representation and good quality of data. This delineation includes Metropolitan Areas, state remainders that are not in the Metropolitan Areas, and entire states such as North Dakota. FAF in essence is a major fusion of data from different agencies and includes CFS to provide estimates of flow of goods in the form of a matrix of origins and destinations (the 132 zones that CFS is also using). Appendix A shows the map of the current (2017 and later) FAF zones and their list. The freight flow is classified into categories of the Standard Classification of Transported Goods (SCTG) and FAF uses the two-digit classification from SCTG to develop a 43 class list that spans from the commodities of agricultural products to the precisions machinery and fuels [6]. The value in dollars is based on shipments in CFS and other available data and it is the *net selling value* and excludes freight charges and excise taxes [6, 7]. The current version of FAF5 (FAF5.2) provides estimates for tonnage (unit: thousand tons), value (unit: million dollars), and a combined weight and distance (unit: million ton-miles) by origin-destination pair of FAF regions, commodity type, and mode for the base year (2017), predicted values and validated/verified with observed data for 2018, 2019, 2020, 2021, and 2022 and forecast year estimates for other years. The metrics provided differentiate among imports, exports, domestic, and total amounts.

3 Method

In the context of flows a network is composed of two major elements that are the places (nodes or vertices) where commodities are originating and/or destined and the relations between these places represented as nodes of a network called links or edges. A relation can be simply the connection between two nodes and in our analysis are directed indicating that the link from node A to B is different than from node B to A in terms of the amount of goods moved. This allows the possibility of asymmetry in the movement between origins and destinations (e.g., goods produced at one place are transported to another place without equal reciprocity). Goods are not only produced at nodes but they within but are also transshipments from international origins or to international destinations and other domestic nodes. Movement of goods happens only along the links. The combination of nodes and links form a network with a number of indicators (metrics) that are used to describe the properties of this network. Many of these indicators originated in graph theory and the terminology used in this analysis follows this formalization of a network as a graph. This section uses ideas and metrics based on methods developed first in social networks analysis [8, 9] and later developed further to explore other networks with complex structure by physics-oriented approaches [10–13].

A graph indicated as G = (V,E) is a combination of nodes/vertices (V) and links/edges (E). Let's assume the number of nodes is N and the number of links is L. The N nodes form an adjacency matrix A of dimensions N by N with elements a_{ij} (with i = 1, 2,…,N and j = 1,2,…,N) taking the value 1 if there is a link between the i node and the j node. To account for the size of commodities flowing from node i to node j we define a weights matrix W with elements w_{ij}. In the commodities flow this matrix is not symmetrical which means $w_{ij} \neq w_{ji}$. In commodities we also have material that originates in one place and is destined in the same place. The weights matrix in this case has non-zero diagonal elements. In networks language this creates a loop link (called loops herein). In one network here we study the tonnage network in which we can have tons of goods in a place in which local manufacturers transform raw material in other commodities that are also consumed within the node. This means that commodities (goods) produced in a node are transformed, stored, consumed or shipped to other nodes.

Average degree is the ratio between edges and nodes. The word *degree* is always used to describe the number of edges connected to a node. The *in-degree* is the number of edges pointing to a node (in terms of commodities this means the number of connections carrying commodities to a destination). The *out-degree* is the number of edges leaving a node representing the commodities transported to other nodes. Each link can have a *weight* that represents the physical weight or value of all commodities moved along the edge/link. In this way the *weighted degree* is the total sum of weights for all the edges in the in-degree and the opposite for the weighted out-degree.

In networks we look for *connectivity*, *centrality*, and *community*. Connectivity is represented by the weighted and unweighted *in-degree* and *out-degree*. The higher these are and the more connected the nodes are. A super-connected node would be the one that has the highest degree. This may also be a *weakness* of the network if there are no alternatives to bypass the highest degree node that functions as intermediary if commodities need to be rerouted around it.

Another metric of network connectivity is its *diameter*, which is the topological distance between the two furthest away nodes. We can also enumerate all the paths with topological distance lower than a threshold number. A network with better connectivity is the network that has more short topological paths and a smaller diameter. Often random graphs are better connected than real world networks. *Graph density* is the number of connected edges over the total number of possibly connected edges and it is between 0 and 1 with the value of 1 for the network with the highest connectivity with no holes in the graph. Graphs that have density much lower than 1 are sparse network types. *Average path length* is the number of intermediaries between any two nodes along the shortest paths between them and it is an indicator of network overall efficiency. Average path length together with the clustering coefficient are used to judge if a network is a small-world network (i.e., few degrees of separation among the nodes).

Of interest in analyzing networks is to find out if nodes form groups based on their characteristics and relationships. One way to examine if nodes belong to a close-knit community is to enumerate how many nodes of a node's connections are connected to each other in the network. When many of these nodes are connected to each other, the node belongs to a highly clustered network. The clustering coefficient is the number of neighbors that are connected to each other over the highest number of possible connections. The word clustering in this context has been challenged because in reality it indicates *transitivity* (i.e., "…this means the presence of heightened numbers of triangles in the graph" see Newman [9], page 183). The calculation counts the number of triangles (or triplets) over the potential number of triangles (triplets) that the neighbors of a node can have. In this case we account for the edge direction. The average clustering coefficient is the average of the clustering coefficients of the nodes in the network. A high average clustering coefficient for a network and a low average path length show that we have a tightly connected network in which we can reach from one node all the other nodes with a few steps. This is called a *small-world network* and often compared to a random graph that is usually having higher clustering coefficients all else equal. Small-world networks are more *robust* than random networks because removal of a node in a small-world will have much smaller repercussions for the rest of the nodes than the removal of a node in a random graph. However, it is also important to identify the relative location of a node within the structure of a network. For example, removal of a central node will divide the entire network in multiple independent structures making this network vulnerable in its functioning just by the removal of one node. This is where centrality indicators are important to identify hubs or super connected nodes. Related to this is also a scale-free network in which the degree distribution follows a power law, which means we have a few nodes with extremely high number of connections and then a very large number of nodes with an extremely low degree (few connections to other nodes). There are different centrality indicators for nodes. The betweenness centrality that measures how important a node is for other nodes moving commodities from one node to another is used here. This indicator shows how often a node lies on the shortest path between two other nodes.

From the social network analysis literature, a community is a subgraph of a network with nodes that are more connected with each other than with any other nodes outside the subgraph (e.g., also called a clique or cohesive group). Since randomly wired networks lack a community structure a metric that compares a random network's wiring with the same number of nodes to the wiring of an observed network can be used. This metric is called modularity (Q) because in essence divides the network graph into modules (subgraphs) with each module containing nodes that are more tightly connected than nodes belonging to other modules [14]. This was first developed for undirected and unweighted graphs and then extended to directed weighted graphs [15]. The computation and allocation of nodes is done by a series of steps that assign nodes to groups and computing the modularity until a maximum is found corresponding to an optimal separation of nodes into groups (see the method named the Louvain algorithm in [16] that is used in this paper as implemented in Gephi). Computation of the modularity metric becomes more complex when we have a large origin-destination directed network with weights (the freight amount and/or value moving from an origin node to a destination node as explored in this paper). In this sense the modularity metric is maximized like a fit metric. At the end of the process the modularity algorithm assigns nodes into an aggregated group or cluster based on shared characteristics. One interpretation of modularity is as the difference between the fraction of edges within an observed community and the number of edges of the same nodes that a random connectivity would produce. The higher the modularity then the more systematic the presence of edges in a group becomes.

Methods based on the network science techniques have been used in the analysis of aviation [17], in maritime transportation as in the review of more than 120 papers in [18], in high-speed rail [19], and urban travel demand verification and validation [20]. They have also been extended and used in emergencies and crises [21, 22], but also to develop a variety of methods improving community detection [23, 24, and 25].

4 Analysis and Results

There are two examples in this section to explore the role played by a few major hubs in the US and are based on international imports and international exports and a benchmark network of domestic flows. US is the largest goods importer in the world and its top 5 suppliers are China, Mexico, Canada, Japan, and Germany. US is also the second largest exporter of goods in the world with the top five countries receiving the US exports ranked as Canada, Mexico, China, Japan, and United Kingdom (www.ustr.gov). The ratio of imported goods in value over exported goods is approximately 1.6 (US Census, 2023). Our interest in this analysis is to first identify the hubs to which imports arrive in the US and then if there is a community that exchanges these imports with each of these major hubs with higher intensity than others. Identifying the hubs of exit of exported goods and their community of nodes that provide exported goods is also an interesting question in this paper. As shown later not all places in the US participate in imports and/or exports. Table 1 shows the statistics of these two networks and the domestic network that is by far the densest network and shows a clear propensity to have clusters heavily influenced by contiguity, adjacency, and closeness forming six

functional regions that are the NorthEast, SouthEast, SouthCentral, West, MidWest, and NorthCentral. Major hubs in this network are as expected major metropolitan areas in New York, Florida, Georgia, Texas, California, Illinois, and Michigan. Figure 1 shows a map of these functional regions together with the hubs in each region with the size of the circles proportional to the weighted degrees of the nodes.

Figure 2 shows international imported goods in USD by port of entry in the US. The communities shown by different colors are defined based on final destination of imported goods in USD 2022. The size of each node is proportional to weighted out-degree in USD 2022 to depict the role each node plays in distributing imported goods to the rest of the 131 places and to itself. For example, goods arriving in Los Angeles are valued in 2022 USD at approximately 370576 million and are destined to itself and other places (imported by Los Angeles and staying in Los Angeles are goods worth 114290 million 2022 USD) making this node the largest importing node in value in the United States. The lions share (approximately 62.8%) of these imported goods are from Eastern Asia and this includes China, Hong Kong, Japan, Macao, Mongolia, North Korea, South Korea, and Taiwan. This node receives most goods through its major ports of entry that are Port of Long Beach, Port of Los Angeles, and Los Angeles International Airport forming a major vulnerable location for the entire United States.

This node not only transfers to other nodes goods but also receives large value of goods from other places valued at approximately 82353 million USD of 2022 from within California such as San Francisco, San Diego, Sacramento, Fresno, and Rest of California (i.e., international goods imported at San Francisco or San Diego are transported to Los Angeles) but also other nodes further out forming a community (based on the modularity) shown with the same color in Fig. 1 and containing nodes that are far from California. This community contains Louisville, KY, that is transferring higher value of goods to Los Angeles than Los Angeles to Louisville while another node of the same community, Sacramento, does the opposite. This implies the international import communities in Fig. 2 sometimes violate the geographic contiguity and closeness relationships found in the domestic networks. However, as shown in Fig. 2 many nodes of this community are also from places contiguous to California (e.g., nodes in Arizona).

Figure 3 shows international export by port of exit and the communities displayed by different colors are defined based on origin of the exported goods and the point of departure to international destinations (i.e., the size of nodes is proportional to weighted in-degree in USD 2022). It should be noted the communities in Imports22 and Exports22 are different (see the bottom of Table 1 illustrating differences and commonalities between the two network community structures). Some nodes however play major roles in freight flow for imports and exports as explained below but also domestic goods flows. In fact, Los Angles is a hub for both Imports22 and Exports22 and dominates the community labeled here as West and SouthWest with 12.88% of nodes in Imports22 and 20.45% of nodes in Exports22.

Table 1 shows the network metrics of the domestic, import, and export networks and communities identified using modularity. Both international networks have lower connectivity than the domestic network. Domestic22 network has all its nodes connected to all other nodes with lower network diameter, highest node density, and an order of magnitude higher average weighted degree is a robust network with many options for

hubs and routes. Also shows the domestic production and associated consumption are by far higher than exports and imports. The international import and export networks also show more communities with hubs distributed throughout the US and communities with multiple hubs spatially distributed within the communities. They also show spatial interactions that can span the entire nation. For example, the community in Imports22 called SouthCentral-Texas includes major Texas hubs such as Laredo and Houston and Detroit in Michigan. Similar occurrence in Exports22 is for the community called NorthCentral-Detroit that includes a hub in Laredo, Texas. This example is a reflection of manufacturing corridors heavily influenced by the role Laredo plays as exporting and importing goods to and from Mexico and then used in manufacturing.

The presence of more communities is an indication that some hubs can function as a redundant system of US ports of entry or exit to other systems (e.g., one community of nodes supporting another community of nodes in emergencies). This is heavily dependent on the supporting infrastructure surrounding them (e.g., highways, pipelines, railways, and regional airports) that can function as alternate routes in emergencies and/or disasters at other hubs and communities. The eastern seaboard of the US has many nodes that are endowed places with ports that could function as substitutes for each other in emergencies. In contrast, the western seaboard of the US has Los Angeles dominating the entire region with supporting roles by San Francisco and Seattle.

Tables 2 and 3 illustrate the different roles played by the top 20 nodes in imports and exports. In Table 2 when the ratio of weighted out-degree over the weighted in-degree is greater than 1 we have a node that functions as a net distributor of goods to other nodes. In Table 3 the ratio of weighted in-degree to the weighted out-degree is an index of the net collector role each node plays. In essence, other nodes and itself provide goods to be exported by the collector node. However, the same node plays a different role in different communities depending on analysis of imports or exports. Notable in this role is Laredo in TX that has a ratio of 56 in Imports22 and 80.40 for Exports22. This makes Laredo the largest distributor and collector in the US. In fact, Laredo is a hub with major infrastructure components to transport goods from and to Mexico that includes major vehicle and rail bridges and an inland port. Goods moved to and from this node are automobiles, automobile parts, fuels, and electronics (www.laredoedc.org). Another node that emerges in this analysis is Savannah, GA, as both a distributor (ratio 15.02) and collector (ratio 11.07) and this is mainly due to its major international containers port. North Dakota is another node of importance for imports and exports from and to Canada for fossil fuel and agricultural machinery (https://www.usglc.org/state-facts/north-dakota/). The minimum weighted in-degree in Imports22 is 520 million for the node Rest of Hawaii and the minimum in Exports22 weighted out-degree is 96 million USD also for the Rest of Hawaii node.

Figure 4 illustrates the difference among zones that specialize in exports and zones that are specializing in imports using the total weighted degree of imports and exports for each node of the two networks Imorts22 and Exports22. The smooth line separating these is one way to draw a border in the two different data of imports and exports and captured the non-linear correlation between imports and exports. Notable is again the role of major metropolitan areas and the diversity among them (e.g. New York in the NY portion vs the NJ portion).

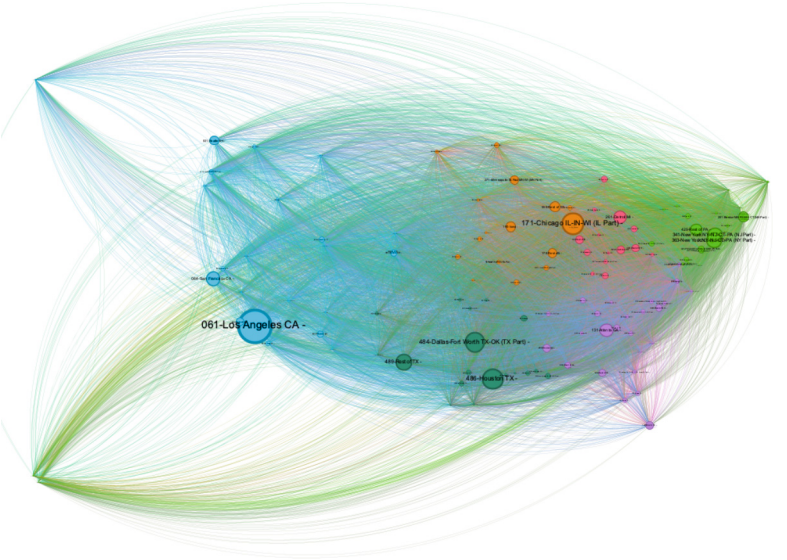

Fig. 1. Domestic network defined with size of nodes proportional to weighted degree in USD 2022 (Domestic22)

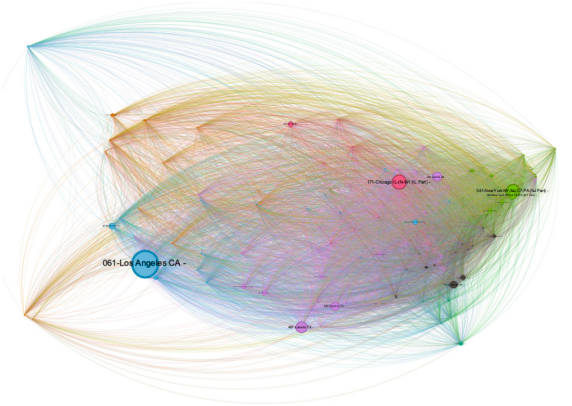

Fig. 2. International imports by port of entry and communities defined based on final destination (size of nodes is proportional to weighted in-degree in USD 2022) – Imports22

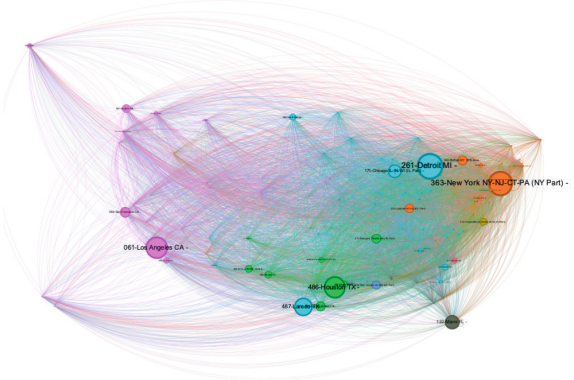

Fig. 3. International Export by Port of Exit and communities defined based on export origin (size of nodes is proportional to weighted in-degree in USD 2022) – Exports22

Table 1. Freight Flow US Network 2022 for Domestic and International Imports and Exports

	Imports22	Exports22	Domestic22
Average Degree	81.356	73.652	131.485
Number of Nodes	132	132	132
Number of Edges	10739	9722	17356
Average Weighted Degree	18477	11534	112408
Network Diameter	3	3	2
Graph Density	0.621	0.562	1.0
Average Path Length	1.3	1.4	1.0
Average Clustering Coefficient	0.722	0.692	0.996
Highest Betweenness Centrality	Many nodes	Many nodes	Many nodes
Community Detection			

(*continued*)

Table 1. (*continued*)

	Imports22		Exports22			Domestic22	
Modularity	0.396 (8 classes)		0.428 (8 classes)			0.35 (6 classes)	
	%nodes	Major Hubs	%nodes	Major Hubs		% nodes	Major Hubs
Northeast	22.73	New York NY & NJ parts	22.73	New York, NJ part		21.21	New York NY & NJ parts
MidAtlantic – Virginia	In NorthWest & SouthEast		3.03	Virginia Beach- Norfolk, VA		In SouthEast	
SouthEast	11.36	Savannah, GA and Charleston, NC	2.27	Charleston, NC		21.21	Atlanta, GA, Miami, FL
Southeast – Florida	3.79	Miami, FL	4.55	Miami, FL		In SouthEast	
SouthCentral -	27.27	Texas many hubs with Mexico	9.09	Houston, TX		13.64	Dallas-Ft Worth & Houston, TX
SouthCentral – Louisiana	3.03	New Orleans, LA	3.03	New Orleans, LA		In SouthCentral	
West and SouthWest	12.88	Los Angeles, CA	20.45		Los Angeles, CA	18.18	Los Angeles, CA
NorthWest	9.85	Seattle, WA & Portland, OR & high dispersion	In SouthWest			In SouthWest	
MidWest	9.09	Chicago, IL	In NorthCentral			14.39	Chicago, IL
NorthCentral – Detroit	In SouthCentral		34.85%	Detroit, Mi, Laredo, TX, & Chicago, IL		11.36	Detroit, MI

Table 2. Top 20 Distributing Nodes of International Imports in 2022 (Imports22)

Top 20 Distributors for Imports				
	Weighted in-degree (IN) in USD	Weighted out-degree (OUT) in USD	Ratio OUT/IN	Modularity Class
061-Los Angeles CA	196643	370576	1.88	SouthWest
171-Chicago IL-IN-WI (IL Part)	131724	193744	1.47	MidWest
341-New York NY-NJ-CT-PA (NJ Part)	97463	176604	1.81	NorthEast
487-Laredo TX	2631	147317	55.99	SouthCentral
261-Detroit MI	67678	118055	1.74	SouthCentral
486-Houston TX	78312	110624	1.41	SouthCentral
363-New York NY-NJ-CT-PA (NY Part)	92601	107306	1.16	NorthEast
132-Savannah GA	6231	93590	15.02	SouthEast
064-San Francisco CA	90893	71598	0.79	SouthWest
380-North Dakota	3132	66727	21.31	MidWest
451-Charleston SC	6723	58299	8.67	SouthEast
489-Rest of TX	64934	56383	0.87	SouthCentral
212-Louisville KY-IN (KY Part)	14675	51806	3.53	SouthWest
485-El Paso TX-NM (TX Part)	8086	50888	6.29	SouthCentral
063-San Diego CA	32641	49916	1.53	SouthWest
122-Miami FL	27665	46645	1.69	SouthEast-Florida
241-Baltimore MD	17504	45140	2.58	NorthEaest
531-Seattle WA	34357	44704	1.30	NorthWest

(*continued*)

Table 2. (*continued*)

Top 20 Distributors for Imports				
512-Virginia Beach-Norfolk VA-NC (VA Part)	6326	40440	6.39	SouthEast
421-Philadelphia PA-NJ-DE-MD (PA Part)	31876	36667	1.15	NorthEast

Table 3. Top 20 Collector Nodes of Exported Goods in 2022 (Exports22)

Top 20 Collectors for Exports	Weighted in-degree	Weighted out-Degree	Ratio In/out Collector if > 1	Modularity Class
261-Detroit MI	127842	39411	3.24	NorthCentral
363-New York NY-NJ-CT-PA (NY Part)	121573	54327	2.24	NorthEast
061-Los Angeles CA	107068	76493	1.40	SouthWest
486-Houston TX	106616	75833	1.41	SouthCentral
487-Laredo TX	88947	1106	80.40	NorthCentral
122-Miami FL	68857	21977	3.13	SouthEast - Florida
171-Chicago IL-IN-WI (IL Part)	64541	52719	1.22	NorthCentral
064-San Francisco CA	49736	51439	0.97	SouthWest
362-Buffalo NY CFS Area	45713	7756	5.89	NorthEast
483-Corpus Christi TX	44234	5051	8.76	SouthCentral
471-Memphis TN-MS-AR (TN Part)	42869	4891	8.77	SouthCentral
212-Louisville KY-IN (KY Part)	42047	9161	4.59	NorthEast
223-New Orleans LA-MS (LA Part)	39623	24456	1.62	SouthCentral

(*continued*)

Table 3. (*continued*)

Top 20 Collectors for Exports	Weighted in-degree	Weighted out-Degree	Ratio In/out Collector if > 1	Modularity Class
531-Seattle WA	36497	34052	1.07	SouthWest
485-El Paso TX-NM (TX Part)	33562	4200	7.99	SouthCentral
512-Virginia Beach-Norfolk VA-NC (VA Part)	33267	3922	8.48	MidAtlantic
489-Rest of TX	32397	104127	0.31	SouthCentral
482-Beaumont TX	30819	5864	5.26	SouthCentral
380-North Dakota	29652	4146	7.15	NorthCentral
132-Savannah GA	26323	2378	11.07	NorthCentral

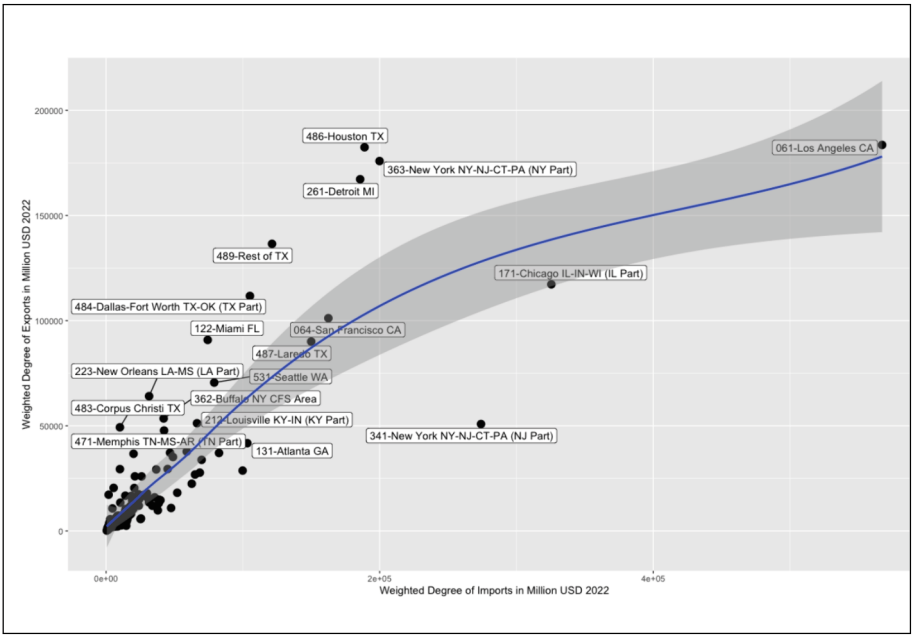

Fig. 4. Weighted degree in USD 2022 of international exports versus international imports

5 Summary and Conclusion

In this paper network science is used to explore freight flows among the 132 CFS and FAF areas used to collect and provide domestic and international freight origins and destinations as well as directional flows. The analysis is done with networks that are based on the value of freight flows. Freight flows are viewed as produced by a node, attracted to a node, and flowing onto directional links among all nodes considered here. Each link between two nodes is weighted by the metric used to quantify freight flow in US dollars of 2022. In this analysis network science statistics are computed that show formation of communities of nodes and their geographic location in the U.S., the importance of each of the 132 places (nodes) analyzed as hubs for the entire country and as hubs within their community of places, and the relationship of all these patterns with distance and contiguity. NAFTA and the border effect with Mexico and Canada are clearly exhibited by the patterns in the networks analyzed here. There are also internal to the U.S. borders among the communities identified here but these are different depending on domestic, import, and export goods.

With respect to the research questions in the introduction major topological differences are present among the three networks analyzed here and particularly between imports and exports. The topology of international imports and exports is not only different than the total freight flow networks but also shows the existence of trade corridors crossing the entire country with directional bias from North to South and the opposite.

We also find critical nodes making the networks here vulnerable and they are often major metropolises endowed with transportation infrastructure and large population centers. For international trade, hubs are the portals of imports or exports such as Laredo in Texas and Detroit in Michigan. The megaregion/community structure and membership of each node in a community has similarities to more traditional division of the US into functional regions but with key differences that network science tools enable us to identify. The modularity analysis for all the networks considered here identifies geographical subdivisions with strong relationships among places within a group (community or functional region). This multilateral analysis of freight flow reveals the formation of communities of freight flow that resemble in shape typical megaregions in the US (e.g., the Northwest, SouthEast, SouthCentral, MidWest, West). However, many places in the U.S. show marked differences in their membership to communities altering topological aspects of community formation and hub emergence depending on the role played by specific places explored in international import and export network topologies.

Throughout this analysis, however, the place endowment in major infrastructure investments in ports and airports and also border crossing portals such as Laredo, TX, and the role played by Los Angeles, New York (both portions of NY and NJ), Chicago, and Houston signify subregional economic roles that are different depending on the type of economic activity examined. The existence of communities that are different among domestic goods, imports and exports challenge the oversimplifying modeling approaches such as the shift-share type of models or new economic geography. However, alternative techniques are still to be developed using network science.

Network science is an efficient computational technique to identify through pattern recognition and visualization the topology of exchange networks and pinpoint many aspects of the movement of goods (major and minor hubs, different communities that depend on the type of metric and the type of freight transported). However, these tools are not designed to detect qualitative differences among nodes (e.g., Houston vs Rest of Texas). These are defined by CFS as origins and destinations and they can be very different geographies and regional subdivisions that are treated computationally as equivalent (i.e., computing in-degree and out-degree using the same definition). Similar issue is also the handling of some States as one node (e.g., Iowa, North Dakota, and so forth).

There are many additional next steps emerging from our experience with the network models here. *First*, an attempt could be made to increase the spatial resolution using the 3,244 counties and county equivalent subdivisions as nodes. For transportation planning applications the FAF origin and destinations have been disaggregated to a finer level of geographical subdivision in Florida to predict the impact of these flows on the transportation infrastructure [26]. Similar exercises are found in other geographies [27] and for emission modeling national level [28] and could be expanded and not only cover the entire country but possibly include Canadian and Mexican fine resolution subdivisions. *Second*, the node-to-node links do not distinguish the movements by different modes (e.g., air, rail, highway, pipeline) and this blurs the connectivity among nodes and the vulnerability of nodes and links. Developing methods to bring the physical aspects of mode -specific networks enhances our ability to view hubs as major intermodal facilities and assess their robustness using methods as in [29]. *Third*, the modularity method used here is found to be an effective way to group nodes together in communities based on the exchange of goods. There are competing approaches to detect communities that one could experiment with in future analyses as in city interaction [30].

Appendix A

See Figure A.1 and Table A.1.



Fig. A.1. Maps of the 2017 Commodity Flow Survey Zones

Table A.1 United States and their two-letter abbreviations

ALABAMA	AL	MONTANA	MT
ALASKA	AK	NEBRASKA	NE
ARIZONA	AZ	NEVADA	NV
ARKANSAS	AR	NEW HAMPSHIRE	NH
CALIFORNIA	CA	NEW JERSEY	NJ
COLORADO	CO	NEW MEXICO	NM
CONNECTICUT	CT	NEW YORK	NY
DELAWARE	DE	NORTH CAROLINA	NC
FLORIDA	FL	NORTH DAKOTA	ND
GEORGIA	GA	OHIO	OH
HAWAII	HI	OKLAHOMA	OK
IDAHO	ID	OREGON	OR
ILLINOIS	IL	PENNSYLVANIA	PA
INDIANA	IN	RHODE ISLAND	RI
IOWA	IA	SOUTH CAROLINA	SC
KANSAS	KS	SOUTH DAKOTA	SD
KENTUCKY	KY	TENNESSEE	TN
LOUISIANA	LA	TEXAS	TX
MAINE	ME	UTAH	UT
MARYLAND	MD	VERMONT	VT
MASSACHUSETTS	MA	VIRGINIA	VA
MICHIGAN	MI	WASHINGTON	WA
MINNESOTA	MN	WEST VIRGINIA	WV
MISSISSIPPI	MS	WISCONSIN	WI
MISSOURI	MO	WYOMING	WY
DISTRICT OF COLUMBIA	DC		

Porto Rico, Guam, Northern Mariana Island, and Virgin Islands are not included in the analysis here.\

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An Approach for Spatial Optimization on Positioning Surveillance Cameras

Rodrigo Tapia-McClung[1(✉)] and Rodrigo Lopez-Farias[2,3]

[1] Centro de Investigación en Ciencias de Información Geoespacial CDMX, Contoy 137, Lomas de Padierna, Tlalpan 14240, Mexico
rtapia@centrogeo.edu.mx

[2] Centro de Investigación en Ciencias de Información Geoespacial Querétaro, Pedro Escobedo, 76709 Querétaro, Mexico
rlopez@centrogeo.edu.mx

[3] Consejo Nacional de Humanidades, Ciencias y Tecnologías, Insurgentes Sur 1582, Crédito Constructor 03940, Mexico

Abstract. Strategic crime monitoring, surveillance, and prevision in public security is a fundamental topic in public administration to efficiently control certain types of criminal behavior that affect citizens' integrity and quality of life. Technological advances in computer networks and video surveillance cameras allow improving monitoring coverage by installing closed circuit television network systems comprising several high-resolution panoramic cameras in public roads and streets. This is specially useful in cities with high density of population where, naturally, crime density is high in specific zones. One of the main problems is to decide where to locate the surveillance video-cameras. To address this problem, we present an optimization-based methodology that suggests where the surveillance cameras are more likely to observe more crimes. In order to implement the optimization methodology, we propose the use of the Criminal Visibility Index that evaluates how optimal the position of a video-camera is, given the historical reported geo-referenced criminal incidence. The definition of this index is fundamental to pursue the cost function that can be solved by means of optimization algorithms for non-convex problems. Our proposal focuses on the spatial aspects of the optimization problem and relies on the implementation of a greedy algorithm that has the advantage to find a near-global optimal solution for any number of surveillance cameras limited by the available computing memory.

Keywords: Spatial optimization · Coverage · Crime monitoring · Surveillance

1 Introduction

Crime monitoring, surveillance, and prevention have become important topics in studying and modeling urban settings and behaviors therein. Closed circuit

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television (CCTV) has been adopted as a popular tool to incorporate the use of technology in urban surveillance tasks. While there has been debate on whether surveillance cameras are actually useful in reducing crime, catching offenders, or are indeed helpful in creating the sense and perception of a more secure environment [2], they have proved to be useful in certain cases [19].

Deploying surveillance systems plays a pivotal role in ensuring public safety, securing critical infrastructure, and preventing unlawful activities. The effectiveness of these types of surveillance systems heavily relies on the strategic placement of cameras to help maximize coverage and minimize blind spots. In this sense, spatial optimization have become indispensable tools in achieving optimal camera placement, thereby enhancing the overall surveillance capabilities.

With this in mind, it then becomes important to study crime incidence events and critically observe where these devices have actually been useful and where cities and governments can profit from certain adjustments, given the possible budgetary constrains that they are typically subject to, the high percentage of security budgets that are assigned to these types of projects, and, at the same time, the fact that surveillance cameras may be useful, but are far from being the solution societies need [11,15].

In this sense, the spatio-temporal nature of crime incidence gains more relevance, as certain events are likely to detonate criminal behaviors and incidence, or may show seasonal trends. But careful and timely monitoring could reveal interesting shifts and changes that could prove useful for the authorities.

Different studies have tackled the problem of covering a certain area with surveillance cameras, where coverage can focus on incidents, area or a decent trade-off with a combination of both [3,7,9,13]. On the one hand, because these approaches are typically developed in a static setting, cameras are previously placed in or around the area to be monitored and, thus, placement plays a fundamental role. On the other hand, a static setting makes it difficult for surveillance to be easily modified or adapted after possible interventions or other events that may change the currently observed patterns of incidence in the area.

The optimal surveillance camera positioning is related with the classical set-covering problem. This problem is one case of combinatorial optimization and it has been proved that, due to its computational complexity, there are no algorithms able to efficiently find the exact solution in polynomial time. Nevertheless, greedy approximation algorithms can achieve a near optimal solution in polynomial time [5]. Also, there are approaches that look into finding the exact solution to the problem, but are typically difficult to implement and sometimes are not a real-life option [17]. Other methods have looked into exhausting the possibilities and find and optimal solution, but usually take a very long time demonstrating the no polynomial time complexity nature of the problem. Another approach has been the use of heuristics, which do guarantee a sufficiently good solution in a reasonable amount of time, but cannot ensure it is the optimal one or that it can be replicated [1,8,18].

An alternative to combinatorial, heuristic or meta-heuristic methods, are greedy algorithms. The greedy algorithms construct a solution incrementally

searching for the immediate best solution. This strategy ensure that, given certain conditions and simplifications, to achieve near-optimal or optimal solutions in the best case. One advantage is that greedy algorithms are deterministic and results can be replicated [5].

Selecting the place, installing, and providing maintenance to CCTV systems can be costly and, therefore, it is advisable to study the selection of the optimal placement as an optimization problem to better spend the allotted resources. Our goal is to first analyze the spatial data in a central portion of a Mexican city and propose an optimal placement of cameras, subject to budgetary constrains. In terms of optimization, we develop an index to measure aerial and incidence coverage and test all possible solutions and select the most useful ones.

2 Background and Related Work

Surveillance can be easily associated with "Big Brother watching" scenarios where everything and everyone is being watched. While, under some circumstances, this could be desirable, in reality it is far from feasible and attainable. Typically, a reasonable trade-off between coverage and performance must be attained [7,20] so that surveillance tasks can be accomplished.

Surveillance applications usually look into solving the problem of locating cameras, understanding the area of study, and taking into account what is going to be monitored. In this step, it is usually considered whether it is an open or closed space, private or public. Additionally, it is also important to take into consideration specific characteristics of the devices that will be used [9,10,21].

Because we are interested in studying and analyzing coverage and visibility, the "Art Gallery" problem was a source of inspiration [16], given the idea it puts forward of triangulating space to calculate the least number of guards one would need to visually cover a specific region of space. Because we are interested in covering both area and incidence, a natural second step was to look into coverage models that aim at maximizing effectiveness in the sense of Church and Meadows' proposed "Location Set-Covering Problem" of identifying "how well a particular location configuration performs with respect to the overall purpose facilities are intended to serve" [4] and trying to identify the least number of facilities that satisfy a particular demand within a certain given distance.

There are, however, improvements to this proposal like the "Maximal Covering Location Problem" [6] that aims at maximizing coverage with a given number of facilities or covering the maximum proportion of space as possible with a limited number of objectives [14]. Another improvement is the "Backup Coverage Model" [6] which states that "providing secondary, or backup coverage, to as much of the population as possible is an appealing method by which to protect coverage from varying with time or with unit availability". A further refinement is the "Backup Coverage Model 2" [6] that looks into the need and usefulness of having backup coverage in regions where there is a high density of incidence or where it is likely for a large number of simultaneous events to occur. It is important to note that, even if one were to use the best technical

capable surveillance cameras, maximizing their coverage is secondary to said characteristics, but rather depend on where they are located.

By taking into consideration the stochastic nature of crime occurrence and displacement in coverage models, Hogan and ReVelle [6] conclude that they must be multi-objective. For the case at hand, we consider a limited number of surveillance cameras, and realize we will only be able to cover a certain amount of incidences with the available resources. Additionally, while suitable, at this stage we do not consider overlaps between sensors to support backup coverage, especially in dense areas. We recognize that overlaps could prove useful when trying to reconstruct or follow certain observed events that my be of interest, but is beyond the scope of this paper.

Spatial displacement of crime incidence is a very interesting subject that could greatly benefit from predicting the spatio-temporal behavior of crime but, as identified by Waples et al. [19], it is a complex topic to address, given there are no standardized method yet and is beyond the scope of this paper.

Even though there are exhaustive methods to solve the problem, our focus turns to proposing a greedy algorithm able to select the immediate top performing locations. Again, unlike meta-heuristic approaches, these results can be replicated and guarantee that the same solution can be obtained, while improved with additional field work. [8].

In this study, we propose to address the problem of positioning Surveillance Cameras as an optimization approach using the novel Criminal Visibility Index I. We also propose a greedy algorithm to effectively optimize the index I by positioning strategically the surveillance cameras. By adopting a greedy approach, the research aims to address the inherent challenges in surveillance camera positioning of limited camera surveillance resources.

By identifying suitable camera placements through the index I and application of the greedy algorithm, this study seeks to provide valuable insights for security professionals, urban planners, and decision-makers involved in the design and implementation of surveillance infrastructures in the public policy realm.

We first introduce the proposed Criminal Visibility Index, then we detail the implementation of the algorithm to optimize the objective function based on the Criminal Visibility Index to produce a near-optimal solution. We then present a discussion of the results and, lastly, the conclusions where we summarize key findings and suggest avenues for future research in the dynamic field of spatial optimization for surveillance systems.

3 Study Area and Data

To test the usefulness of the proposed index, we study the Mexican city of Aguascalientes in the state of Aguascalientes, located in the central-northern region of the country, about 480 km northwest of Mexico City. Covering an area of about 5,470 km^2 (roughly 0.03% of the country), it is a very small state that contains 11 municipalities. The central municipality of the state of Aguascalientes is also

called Aguascalientes and houses an estimate of 76% of the state population. Furthermore, 85% of the criminal incidence in the state occurs in this central municipality.

The city of Aguascalientes is located in this central municipality and is host to the annual San Marcos Fair, considered to be the most important one in the country [12]. The Fair attracts millions of visitors during its the three-week duration. Because of the large number of visitors the city welcomes during the Fair, it is of interest to study the behavior of criminal incidence during this time. Additionally, most of the activities occur in the central region for the city, inside the first ring. Thus, only consider this region to test our methodology in this paper. The ring-shaped road "Aguascalientes Convention of 1914" bounds the area of interest, distributes transportation both north-to-south and east-to-west, and the downtown area is contained inside it. Figure 1 depicts the locations of the state, city, and municipality of Aguascalientes, along with the border of the first ring considered for this study.

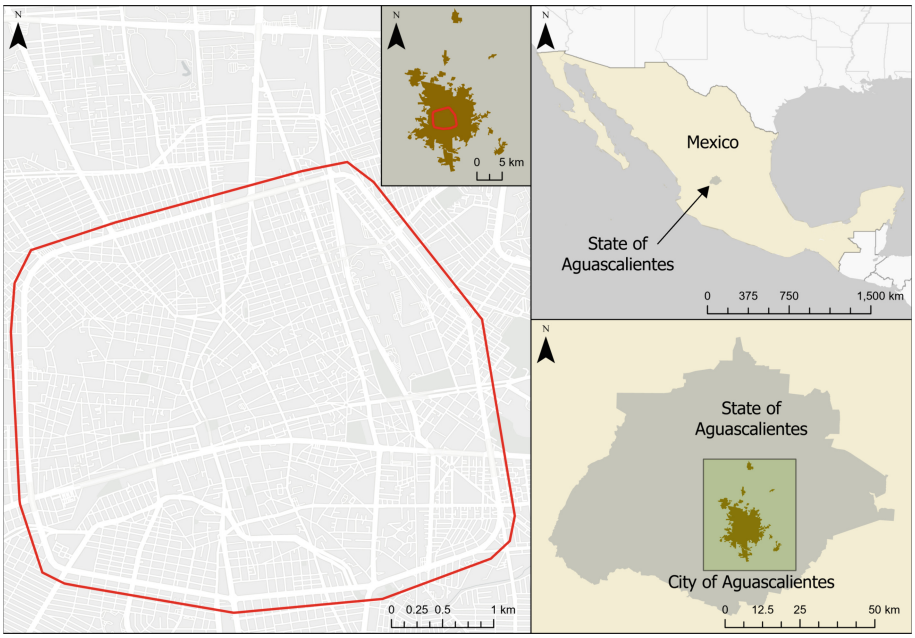


Fig. 1. Area of study: The location of the state, city, and municipality of Aguascalientes and the First Ring.

Data for this study is obtained from two official sources. On the one hand, city blocks and streets of the state and city of Aguascalientes are from the National Institute of Statistics and Geography (Instituto Nacional de Estadística

y Geografía - INEGI). On the other, geo-referenced criminal incidence records from the state's General Attorney's office for thefts that occurred in 2018 in the whole state. For the rest of the study, however, we only consider incidence that occurred in the public space, in particular on the streets inside the first ring of the city. Therefore, for those cases in which they are registered as occurring on parks or inside buildings, their original locations have been slightly modified so they can be accounted for in the visible surface of the space solution. Overall we have little over 1300 data points.

The first ring of the city, housing many of the Fair's activities, experiences an increase both in the number of visitors and the demand for services like lodging, food, transportation, and banking. The nature of the activities during the 3-week duration of the Fair makes it more likely for three main different types of theft to occur: pedestrian, vehicle, and auto parts, which are depicted in Fig. 2.

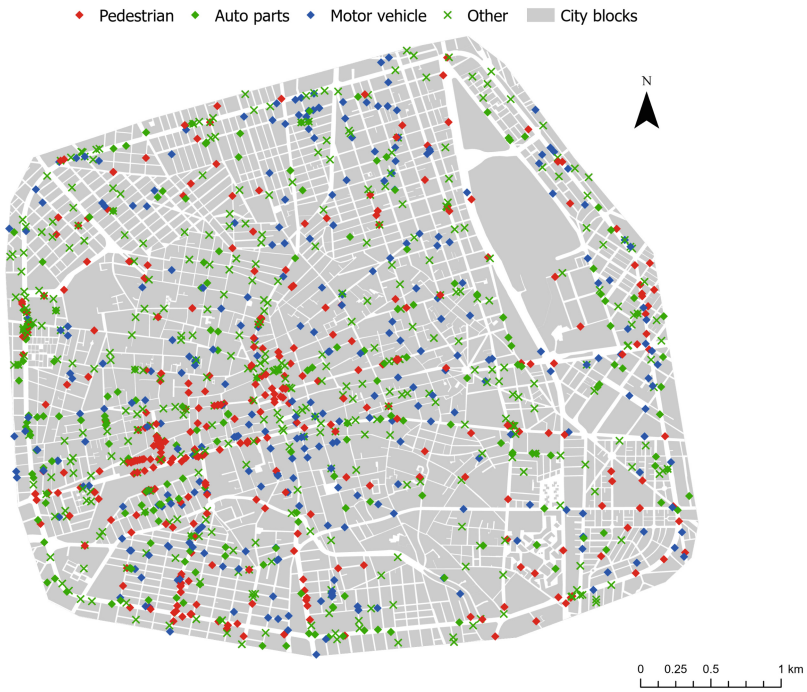


Fig. 2. Spatial distribution of different types of theft inside the first ring of the city of Aguascalientes.

4 The Criminal Visibility Index for Surveillance Cameras

This section describes the Criminal Visibility Index I. This is a measure to estimate the ability to detect criminal theft events given a set of cameras positioned in the region of interest. To use this index we make the assumption that the distribution of events remains roughly the same throughout the years. This assumption is adequate given the nature of the city and the Fair.

Formally speaking, the camera positions are represented by the set $\mathbf{p}$, where $\mathbf{p} = \{p_i | p_i = (x_i, y_i), \text{for } i \in \{0, 1, \ldots, n\}\}$ contains the positions (x_i, y_i) for each camera p_i.

We associate attributes of interest at each camera p_i. First, we associate the proposed Criminal Detection Sensitivity Map $R(p_i)$. This map describes the detectability of a crime at a certain distance from a camera positioned at coordinate p_i.

As an example, Fig. 3 shows the Criminal Detection Sensitivity Map $R(p_i)$ for a camera positioned at matrix coordinates $p_i = (2836, 1394)$, and the Local Criminal Detection Sensitivity Map $R_i^{\Omega}(p_i)$ enclosed by the red square.

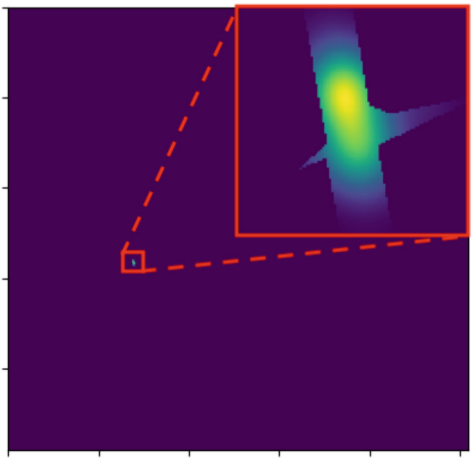


Fig. 3. Example of the Criminal Detection Sensitivity Map $R(p_i)$, for a given camera position in the Cartesian plane $p_i = (2836, 1394)$ and its Local Criminal Detection Sensitivity Map $R^{\Omega}(p_i)$.

Here, the Global Criminal Detection Sensitivity Map $R(p_i)$ represents the entire region for p_i, but only the neighborhood around p_i can have values if and only if the isovist detects criminal activity.

$R(p_i)$ is a sparse matrix where only the cells inside the area bounded by a radius r from the position (x_i, y_i) would present a level of Criminal Detection Sensitivity. The circular region is inside a square with side length of $M' = 2r + 1$ for matrix operation convenience.

The Crime Density Map D represents the criminal activity required to calculate the Criminal Visibility Index I for each position. The Criminal Visibility Index for each camera p_i depends on the following three spatial variables:

1. The closeness to the camera position described by a Gaussian kernel represented by the matrix $K \in \mathbb{R}^{M' \times M'}$.
2. The Criminal Theft Density map $D_i \in \mathbb{R}^{M \times N}$ that is the result of applying a Gaussian kernel to the raster image of geo-referenced crimes.
3. The visible range of camera p_i described by its isovist, $V_i \in \mathbb{R}^{M \times N}$, which is a binary map.

Therefore, $R(p_i)$ is a sparse matrix where only the cells inside the area bounded by a square of side M' with the camera in the center (x_i, y_i) would have a level of crime detectability, since the cameras have a limited range. An example of these variables is presented in Fig. 4. The map $R(p_i)$ only has values in its neighborhood $R^{\Omega}(p_i)$ and is the result of applying the element-wise matrix operation $R(p_i) = V(p_i) \circ D(p_i) \circ K$.

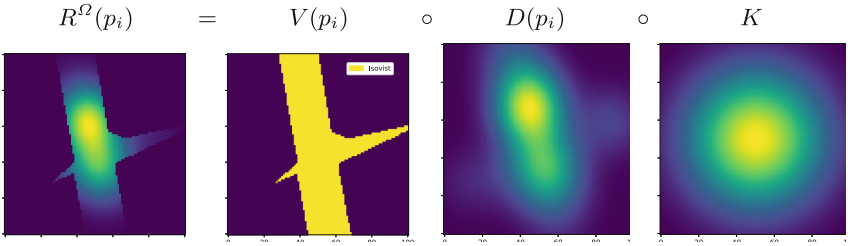


Fig. 4. Example of the three spatial variables at position $p_i = (2836, 1394)$ required to evaluate the surveillance camera suitability.

Formally, the Global Criminal Detection Sensitivity Map $R(p_i)$ is defined in Eq. 1 as follows:

$$R(p_i)[m,n] = \begin{cases} 0 \text{ if } \sqrt{(m-x_i)^2 + (n-y_i)^2} > r \\ V_i(x_i, y_i) \cdot D_i(x_i, y_i) \cdot K_i(x_i - m - r, y_i - n - r) \text{ otherwise} \end{cases}, \tag{1}$$

where (m, n) are the values of all the possible coordinates in the horizontal and vertical axes. The matrix has zero values in case (m, n) is out of range with respect to the position (x_i, y_i).

With the expression for $R(p_i)$ established, we now define the Criminal Visibility Index I for surveillance cameras in Eq. 2.

$$I(\mathbf{p}) = \sum_{x \in M} \sum_{y \in N} \max_i R(p_i)[x, y], \tag{2}$$

where $R(p_i)[x, y]$ is the value of a matrix coordinate (x, y) of the Global Criminal Detection Sensitivity Map of camera p_i. The max operator seeks the camera that produces the maximum value in a coordinate (x, y). Then, the maximum values are added-up to produce the Criminal Visibility Index I of solution $\mathbf{p}$.

Lastly, we define the cost function for I in Eq. 3 that indicates we want to find the set of positions $\mathbf{q}$ that maximizes the index I.

$$\begin{aligned} \mathbf{p}^* = & \arg\max_{\mathbf{p}} I(\mathbf{p}) \\ \text{subject to: } & \{(p_i, p_j) | \text{Distance}(p_i, p_j) \geq r, \forall (i, j) \in [0, \ldots, |\mathbf{p}| - 1]\} \\ & \text{and} \\ & |\mathbf{p}| = s\,, \end{aligned} \tag{3}$$

where all the possible pairs (p_i, p_j) must have an Euclidean distance of at least a radius of r, and s is the constraint for the number of sensors.

The cost function is useful to compare several different solutions and decide which one is the best. While this function can be solved in different ways, one of the most basic strategies is to test several random solutions and select the best one. Another one is to implement optimization algorithms, like evolutionary or gradient-based algorithms. Yet another one is to use greedy algorithms, which is the approach we follow.

5 A Greedy Algorithm to Approximate the Solution for Optimal Camera Placement

We propose the implementation of an easy but powerful algorithm to find the near-optimal solution to the camera placement problem.

A greedy algorithm is one that is used to approximate the global solution for a wide variety of problems in a reasonable amount of time. In some cases, it can lead to an exact global solution of an optimization problem [5]. One characteristic of a greedy algorithm is that the solution is constructed by selecting the best immediate solution without considering any consequences.

In this case, if we add the constraint that two or more cameras cannot be located inside a radius r of another, then the greedy algorithm produces a near-optimal global solution by positioning cameras in regions not already covered with the highest criminal density.

Algorithm 1 shows the proposal for finding a near-optimal global solution for locating cameras. The central component that allows to implement the greedy algorithm, is the sorted camera positions in decreasing order according to their individual Criminal Visibility Index, $I(p_i)$. These sorted positions are in the list $\mathbf{p}^{\text{sort}}$. The radius r is a constraint that allows finding a near-optimal solution restricting one camera inside a circle with respect to position p_i.

Algorithm 1 requires the sorted list of positions in $\mathbf{p}^{\text{sort}}$ and the desired number of cameras s to allocate. The algorithm returns the solution in $\mathbf{p}^*$.

Algorithm 1. Greedy algorithm for finding a near-optimal global solution for camera positioning

Require: $\mathbf{p}^{\text{sort}}$
Require: s ▷ Number of sensors
Ensure: $\mathbf{p}^{*}$ ▷ Solution
1: $\mathbf{p}^{*} \leftarrow \{p^{\text{sort}}_{\text{first}}\}$
2: $\mathbf{p}^{\text{candidate}} \leftarrow \{p^{\text{sort}}_{i} | \text{Distance}(p^{\text{sort}}_{\text{first}}, p^{\text{sort}}_{i}) > r, \forall i, (i \neq \text{first})\}$ ▷ Euclidean Distance
3: $\mathbf{p}^{\text{sort}} \leftarrow \mathbf{p}^{\text{candidate}}$
4: **while** $(\mathbf{p}^{\text{sort}} \neq \{\emptyset\})$ and $|\mathbf{p}^{*}| < s$ **do**
5: $\quad \mathbf{p}^{*} \leftarrow \{\mathbf{p}^{*} \cup \text{first}(\mathbf{p}^{\text{sort}})\}$
6: $\quad \mathbf{p}^{\text{candidate}} \leftarrow \{p^{\text{sort}}_{i} | \text{Distance}(p^{\text{sort}}_{\text{first}}, p^{\text{sort}}_{i}) > r, \forall i, (i \neq \text{first})\}$
7: $\quad \mathbf{p}^{\text{sort}} \leftarrow \mathbf{p}^{\text{candidate}}$
8: **end while**

In Line 1, we initialize the set $\mathbf{p}^{*}$ with the first position in the list $\mathbf{p}^{\text{sort}}$ that contains the position with the highest index I.

In Line 2, we retrieve only the position candidates that are outside the circular region of radius r with a center in the position with the highest Individual Criminality Index $p^{\text{sort}}_{\text{first}}$. We discard other positions inside the radius.

In Line 3 we update the $\mathbf{p}^{\text{sort}}$ list. In this step, we reduce the candidates by discarding the positions inside the circle of the currently best position.

We repeat the process inside the loop in lines 4–8 while there are still candidate positions to select and the number of sensors to position has not been satisfied. Inside this loop, in Line 5, we append the next best position to $\mathbf{p}^{*}$. In Line 6, the list of candidates outside the current best position in $\mathbf{p}^{\text{sort}}$ is updated. Line 7 deals with updating $\mathbf{p}^{\text{sort}}$ by reducing the possible number of candidates available for selection during the next iteration.

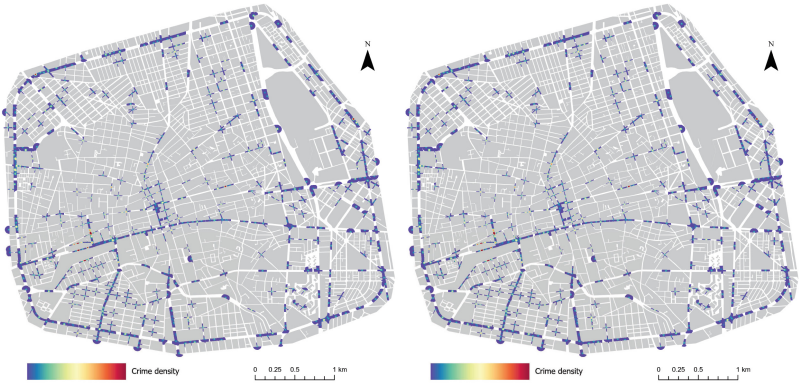
6 Experiments and Results

As mentioned before, we consider thefts occurring inside the first ring of the city of Aguascalientes for 2018. All maps have a 1 m pixel resolution. The Crime Density Map D, is produced in GRASS GIS using the `v.kernel` function with default parameters but with radius $r = 50$ and a Gaussian kernel window.

Our approach is to find a suitable solution that can leverage the cost associated with implementing a surveillance system considering the trade-offs between the cost and the benefit of increasing the Criminal Visibility Index while incrementing the number of cameras. Once we run the algorithm, we obtain a solution $\mathbf{p}^{*}$ with the list of coordinates sorted in descending order by their associated index I. One can decide on the particular number of cameras before running the algorithm.

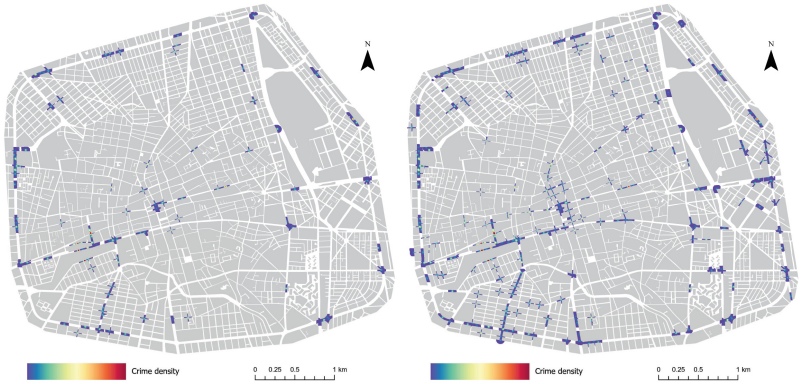
Figures 5a to 5f show the resulting optimal locations for 25, 50, 100, 250, 500, and 1000 cameras, respectively.

Our results indicate that including a larger number of cameras increases the value of the proposed index. This is expected since, intuitively, more cameras



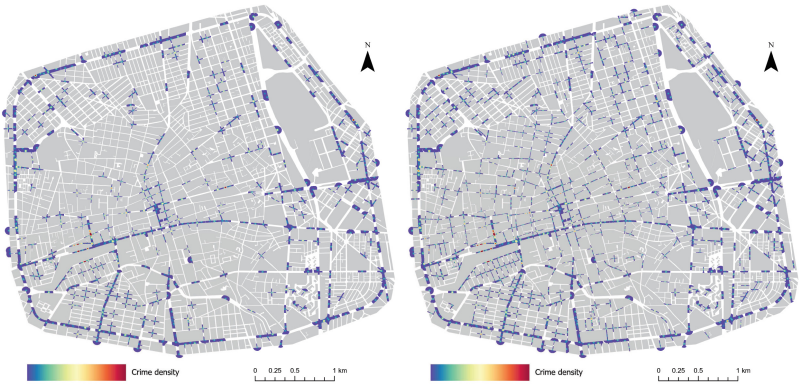
(a) 25 surveillance cameras; $I(\mathbf{p}^*) = 0.04153$.

(b) 50 surveillance cameras; $I(\mathbf{p}^*) = 0.06246$.



(c) 100 surveillance cameras; $I(\mathbf{p}^*) = 0.10188$.

(d) 250 surveillance cameras; $I(\mathbf{p}^*) = 0.17084$.



(e) 500 surveillance cameras; $I(\mathbf{p}^*) = 0.25129$.

(f) 1000 surveillance cameras; $I(\mathbf{p}^*) = 0.33097$.

Fig. 5. Solutions obtained with the proposed algorithm for different numbers of surveillance cameras and their associated Criminal Visibility Index values.

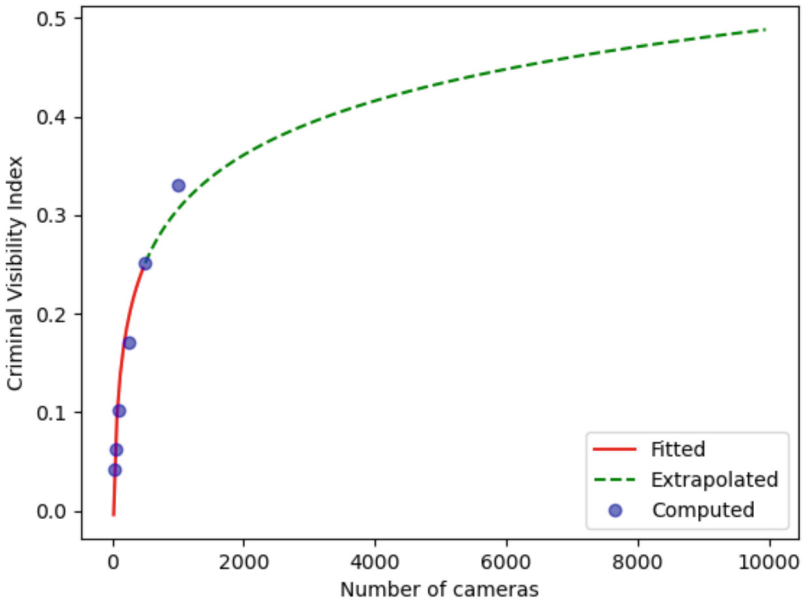


Fig. 6. Computed and expected values of the proposed index as a function of the desired number of cameras.

correspond to more locations on the streets and, thus, more possibilities to monitor. At the same time, more cameras mean more individual contributions to the overall value of the index.

Upon closer inspection, the corresponding values of the proposed index for the different number of cameras tested do not hold a linear relationship. A twofold increase in the number of cameras does not translate into a doubling of the obtained index, which is expected. By fitting a log-like function to the computed values and extrapolating their behavior for a large number of cameras (see Fig. 6), we can see that there seems to be an asymptotic behavior that tends to an index value of approximately 0.5. This means that, eventually, the cost of adding more cameras will not provide much value observing the space under scrutiny, hence using this plot as a tool would prevent the unnecessary use of public resources.

The experimental upper bound of the index is obtained by summing all the possible contributions of the pixels in the feasible geographic space. Each pixel contributes a very small amount, mainly given by $\max(K) \cdot D(x_i, y_i)$, where $\max(K)$ is the maximum value of the Gaussian kernel. In this case we use a Gaussian kernel with $\sigma = 4$. The maximum value for I is 0.62847 and we can thus measure the relative improvement of each of our experiments as a function of the number of cameras considered. Table 1 shows these results.

Table 1. Index values and percent of total for the different number of cameras considered.

Number of cameras	$I(\mathbf{p}^*)$	Percent of total
25	0.04153	7%
50	0.06246	10%
100	0.10188	16%
250	0.17084	27%
500	0.25129	40%
1000	0.33097	53%

7 Conclusions and Future Work

A methodology to define the best set of locations to obtain the optimal cover of criminal incidents, measured by the Criminal Visibility Index, was proposed. The greedy algorithm that was considered delivers good results in terms of finding optimal locations for surveillance cameras subject to the restriction of one surveillance camera in a fixed radius. In contrast to an exhaustive algorithm that searches for possible solutions, this approach explores the construction of the solution using a sorted list of positions in decreasing order by the index I of all the possible cameras and iterating to take the best immediate solution until the sorted list is empty.

Applying this methodology to the first ring of the city of Aguascalientes made it possible to test the suitability of using this approach with only considering geo-referenced theft incidence, the street network, and the geometry of city blocks. With this approach, it is possible to develop in-house solutions for city planners and decision-makers in terms of identifying the best locations to set up surveillance cameras. Of course, this approach does not replace field visits and confirmation of the suitable locations, but is certainly faster, more efficient, and provides a way to reduce costs.

It is, however, important to note that this is a data-driven solution. Perception or other subjective variables are not taken into account. As such, if citizens feel that placing a surveillance camera in a specific location would make them *feel safer*, it is not possible to refute or support that claim. Nevertheless, we propose an index that is useful for complementing other studies.

In terms of the solutions, we are, naturally, interested in those that perform better, and can easily select the best locations, map them, and compute the overall performance of the solution. Figure 5 shows the increase in area coverage together with a higher index value by considering more cameras.

It is important to note that Fig. 6 is obtained by using very few data points from our experiments. While it could be argued they are not enough to ensure a log-like fitting function is appropriate, we report our current findings and realize the need for more experiments and data points to compute a better fit.

Additionally, we realize it should be possible to execute parts of the algorithm in parallel and leverage the use of several cores to improve computation time.

We consider the results of the greedy algorithm to be the best solution, albeit expensive, that can be obtained. As such, it represents our benchmark or baseline for how solutions obtained using alternative methods and algorithms should perform. A natural next step is to compare these results with those obtained using other methods and spatial optimization strategies and test the efficiency of the proposed approach.

Additionally, while only considering incidents for 2018, we still need to test our approach with data from different cities, particularly ones that either have frequent crime incidence data updates or real-time data available. These tests could possibly expose some unidentified weaknesses of our approach and would provide grounds to develop a more robust one. Of course, it would be important to improve the current camera characterization and incorporate field of view or other more realistic coverage geometries.

Should we have better cadastral and urban data, like crowd-sourced building heights, tree locations, street stands, etc., it would be beneficial to incorporate them to better model and take into account elements that could hinder camera visibility. It would also be useful to consider parks and other potential surfaces as visible areas from the streets, so we could dispense with slightly adjusting the geometries of some data points to be located on the streets.

While the computed values of the proposed index seem relatively small, they are more easily understood when expressed as a percentage of the maximum value the index can have. This understanding could, however, be enhanced by comparing the performance of the existing cameras inside the first ring in 2018 to the experiments. Only after computing the value of the index for these cameras we will be able to better rank the solutions in these experiments and compare the spatial locations of both the existing and the proposed sets of cameras.

While the constraint regarding the number of camera inside a radius r simplifies the optimization problem, it would be interesting to explore other variations for solutions oriented to criminal traceability producing surveillance corridors in important or crowded streets.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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ClimaInfo: Information Visualization Dashboard for Climatological and Environmental Data

Camile Maria Cunha Aguiar[1(✉)], Roberto Yuri da Silva Franco[1], Divino Vicente Silvério[1], Tiago Davi Oliveira de Araújo[3], Eduardo Queiróz Marques[1], and Bianchi Serique Meiguins[2]

[1] Federal Rural University of the Amazon, Pará, Brazil
camilemaria55@gmail.com, eduardobio@gmail.com {roberto.franco, divino.silverio}@ufra.edu.br
[2] Federal University of Pará, Pará, Brazil
bianchi@ufpa.br
[3] University of Aveiro, Aveiro, Portugal
tiagodavi70@ua.pt

Abstract. Brazil is a continental country with great potential for agribu-siness according to the specificities of each region. Many of these agribusiness scenarios require climatological data to make more assertive decisions regarding business and public policies. However, the country's northern region, particularly the state of Pará, faces several challenges with the unavailability of climatological data, mainly due to insufficient weather stations. Furthermore, the download from the weather station is limited to a short period, and information is not ready to be used, given several gaps and other issues that require considerable technical knowledge to solve. On the other hand, remote sensing data, while providing a comprehensive dataset covering the entire globe, lacks the precision of station data and isn't easily accessible to the general public. Thus, this article aims to present a web information visualization application named ClimaInfo to present read to use historical climatological and environmental datasets derived from remote sensing products with global coverage, mainly for micro-regions or cities in Brazil that do not have the necessary infrastructure to collect these data. . The remote sensing data are gathered, processed, and presented in different scenarios of interactive dashboards to communicate and support the decision-making processes. Finally, a ClimaInfo communicability assessment was carried out to indicate whether the participant could understand all the elements in the interface. In conclusion, ClimaInfo bridges the gap in data accessibility and enhances the capabilities of stakeholders to make informed decisions through user-friendly web-based applications.

Keywords: Information visualization · Climatology · Environmental · Dashboard · Assessment

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1 Introduction

The state of Pará faces a significant challenge in obtaining climate and environmental data; this lack is evident in several available applications, making it challenging to conduct research more quickly [2] and make important decisions in agribusiness and public policies. This data is valuable, as it can help agricultural producers in a given micro-region or city make more assertive decisions based on the climate forecast and the farm calendar [13]. Consequently, the availability of these data and its dissemination practically and intuitively becomes an essential service for society.

For example, Capitão Poço, a city of Pará, has two meteorological stations, one from the National Institute of Meteorology (INMET) and the other from Purple Air, resulting from a research project. However, the data collected by these stations present problems, such as missing data, storage failure, sensor malfunction, equipment calibration problems, and other problems [1]. Therefore, the data is not entirely reliable for research and other applications.

An information visualization application was developed to assist in accessing, representing, and interpreting climatological and environmental data to mitigate this challenge. To overcome the issue of missing data, remote sensing data from ERA5, CHIRPS, and SRTM obtained through Google Earth Engine [6] were utilized, enabling the collection of a series of data at different time intervals. Among the variables that compose the proposed set of data, the following stand out: precipitation, temperature, slope, and elevation, focusing on historical data of minima, averages, and maxima for the cities of Pará.

The ClimaInfo web application's main interface is an interactive dashboard for data visualization. It uses intuitive visualization techniques that facilitate data understanding, even for users without a technical background. Furthermore, it allows data to be downloaded in CSV format and used freely without access restrictions.

Finally, a communicability assessment of the ClimaInfo application was carried out to determine the ease of understanding the proposed data visualizations, the application's functionality, and the available interactions.

Thus, this project offers three main contributions: the availability of a dataset of climatological and environmental data, the development of a web application, ClimaInfo, for disseminating data through interactive dashboards, and the dissemination of climatological and environmental data from cities in the state of Pará.

2 Background and Related Works

Information visualization involves representing complex data through visual elements and creating abstract representations that facilitate understanding of the data and associated information [15]. Such visual representations are remarkable in communicating denser information, as they allow large volumes of data to be condensed and interpreted more clearly and accessible in a simple visualization [9].

For instance, when analyzing the impact of climate change, the most common representation is a choropleth map, as in Fontana's work [3], because it aims to enable the user to understand the climatic conditions of a particular location quickly.

Commonly, information visualization tools use a dashboard because its use combines various visualization techniques, in addition to seeking to mitigate potential problems in data reading, and offers a simpler understanding of information to the user [10], given that each applied technique highlights the representation of a specific group of data.

Some fundamental steps compose the views of visualization techniques to make data into perceptible visual representations [7]. Data Transformation and Analysis, where data is structured and standardized, defining attributes such as name, type, range, and semantics. Selection and Filtering, where focus data is selected based on data modeling results. Mapping, where focus data is linked to visual representations, allows the perception of patterns and characteristics. Rendering, where data and its visual attributes are transformed into images, and additional information is added to assist in understanding the visualization. User Interface Control, where user interaction with the visualization occurs, exploring data from different perspectives.

Some ways to evaluate visualization tools are assessments that use the System Usability Scale (SUS) method or the Communicability Evaluation Method (CEM). SUS is a 10-question questionnaire that evaluates user effectiveness, efficiency, and satisfaction [12]. The test involves participant training, specific task performance, and questionnaire response. The test has these stages, which are qualitative and quantitative evaluations. Scores with different usability levels range from 0 to 100 [12].

CEM evaluates whether the system's functionalities and interface are understandable to the user [8]. The evaluator defines tasks for the participant and observes communication breakdowns. The SUS questionnaire was also applied, and the results analysis was similar to that of traditional SUS. Participant support is limited in CEM, with only initial training, but training also occurs before the test begins, based on a video recorded by the evaluator.

3 Methodology

The first step involved data collection. Due to the unavailability of weather station data for many municipalities and the gaps in the available datasets, we chose to use data obtained through remote sensing products. Thus, climatic and environmental data were extracted using the Google Earth Engine (GEE) [6], including temperature, precipitation, slope, and elevation. Precipitation and air temperature datasets were acquired from CHIRPS [5] and ERA5-Land [11]. The slope and elevation data were obtained from the Shuttle Radar Topography Mission (SRTM), which has a spatial resolution of 900 m per pixel and global coverage. Using the GEE platform, we calculated for each of the 144 municipalities in Pará state, Brazil, the monthly average, minimum, and maximum values

for temperature and precipitation from 1965 to 2022. We computed average, minimum, and maximum values for each municipality for slope and elevation that do not vary over time. Some information is presented in Table 1.

Table 1. Table with information on data extracted from GEE.

Variables	Source	Temporal Resolution	Spatial Resolution
Temperature	ERA5	1965–2022	0.5°
Precipitation	CHIRPS	1981–2022	0.1°
Slope	SRTM	N/A	30 m
Elevation	SRTM	N/A	30 m

Thus, the application's database consists of sensor-derived data, which may have less precision but provide a complete series with no gaps. Data obtained from weather station sensors will also be processed and organized to eventually complement the application's database, thus forming an accurate and complete dataset from multiple sources (Fig. 1).

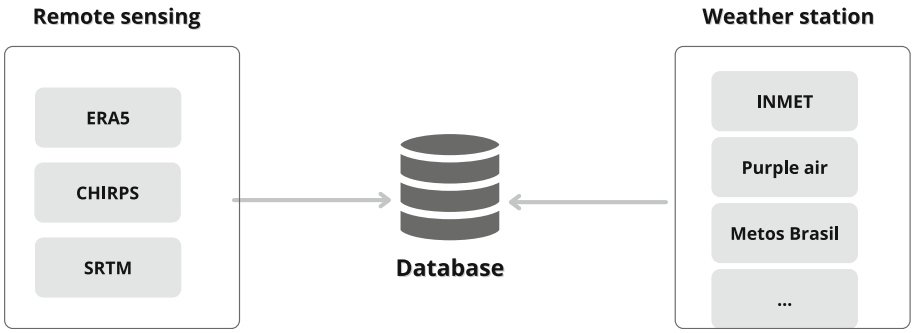

Fig. 1. Scheme of the application's database.

The requirements are divided into functional and non-functional requirements. Functional requirements (FR) outline the system's functionalities and determine user demands [14]. In contrast, non-functional requirements (NFR) specify the product's needs, such as security, which is crucial for software but addresses a software need rather than a user need [14].

Functional requirements include the monthly and annual availability of Pará state data, including precipitation, air temperature, elevation, terrain slope averages, minima, and maxima, represented by simple bars, stacked bars, and choropleth maps. They also include filters by municipality and time interval.

Non-functional requirements are essential elements for the success of the system, extending beyond specific functionalities. They address crucial aspects

such as security, ensuring data protection, and system integrity against potential threats. Additionally, they emphasize system responsiveness, ensuring it efficiently and promptly responds to user requests. A high level of usability is also a fundamental non-functional requirement, ensuring the system is intuitive and easy to use for a wide range of users. Effective communication with the user is another important aspect, ensuring the system provides clear and understandable feedback, and facilitating user interaction with the application.

The project's architecture aims to facilitate the creation and design of the web application. The architecture consists of three main modules. Preparation module: responsible for organizing and preprocessing all data to be used in the tool, whether from remote sensing or automatic sensors from weather stations, adapting them to a specific standard. Representation module: creates information visualizations with established visualization techniques. Interaction module: renders visualizations with data and allows different views and interactions, such as filtering by time and municipality (Fig. 2).

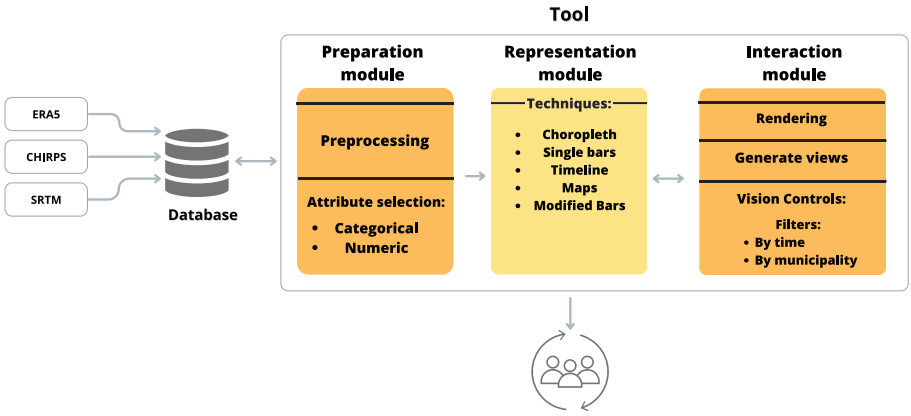

Fig. 2. The figure illustrates how the project's architecture works.

4 Prototype - ClimaInfo

Initially, the Django framework in Python was used to execute and develop the backend. Subsequently, the interface, the frontend, was developed using HTML, CSS, and JavaScript (JS) to create the menu with functionalities such as data entry and listing related to cities, temperature, precipitation, slope, and elevation. Additionally, each data entry and listing screen was created to allow users to perform CRUD (create, read, update, and delete) operations on the mentioned data. These functionalities were implemented so administrators can register and manipulate the data, but the general public will not have access; identification and validation are required to perform such actions. It's worth noting that users

can download all data on all listing screens by clicking a button. This functionality makes the data public and easily accessible to the entire community, enabling everyone to collaborate in filling the gaps in third-party databases.

Subsequently, visualization techniques were developed and manipulated using the D3.js library, as determined in the functional requirements survey. The mapping technique was developed to view the map of Pará and the choropleth map, as well as simple bars and stacked bars. Therefore, with the map, the user can filter which municipality they want to view and select it by clicking on the region, thus generating simple bars and stacked bar charts. There is also filtering by time, which is determined by a range that the user can control.

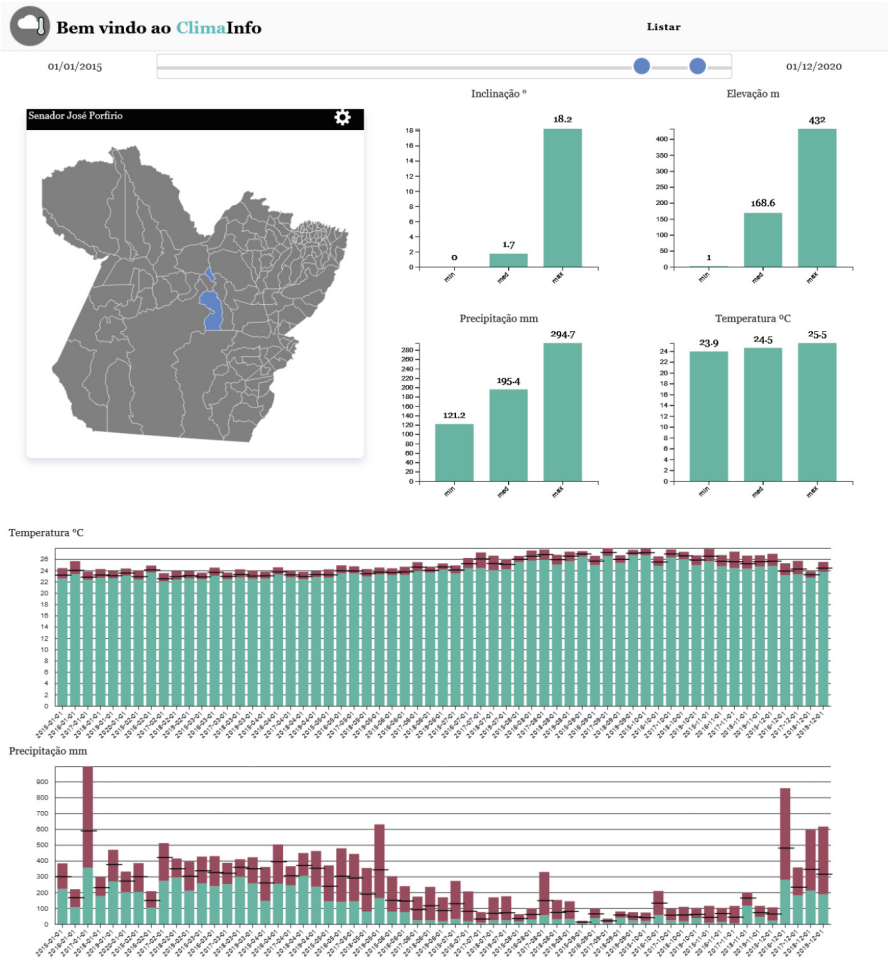

Fig. 3. The application's homepage features a map of Pará and simple and stacked bar visualizations. These elements appear upon interaction with the map, along with a time window for adjusting the months the data will be displayed.

Bar plots show the variables' average, minimum, and maximum data (Fig. 3), where environmental variables like slope and elevation do not vary over time, while precipitation and temperature do. From this, the historical average, minimum, and maximum for the period chosen by the user are presented for climatic variables. Stacked bars are used to visualize the entire chosen time series of environmental variables, with the maximum represented by the red color, the minimum by the blue color, and the average by the black color (Fig. 3).

The choropleth map technique was developed to assign colors to the map according to the data and user preferences. The user can select the desired variable, such as minimum, maximum, or average temperature, and define the initial and final colors, where the initial color represents the lowest recorded amount. In contrast, the final color represents the highest amount. In this sense, the colors vary according to the data of each municipality and the selected period (Fig. 4). All these functionalities can be tested by accessing the ClimaInfo application (http://apps.roberto.eti.br/climainfo/).

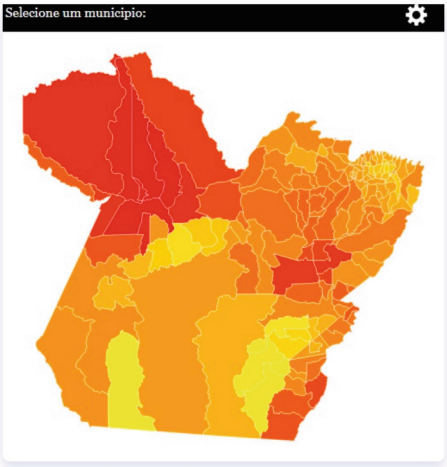

Fig. 4. The Choropleth technique was applied to the map for visualization of the maximum temperature over the selected period to display the municipalities with the highest temperature and make a comparison in the Pará region.

5 Evaluation Methodology

The ClimaInfo communicability evaluation aimed to verify if participants could comprehend the information presented in the dashboard. The process involved several steps, beginning with the application and Informed Consent Form (ICF) presentations. The ICF ensured participants that their data and identity would be protected, and they could withdraw from the evaluation if uncomfortable,

with their data not being stored. Subsequently, participants underwent training to understand the application, facilitated by an instructional video provided by the evaluator, given that the evaluation was conducted via an online questionnaire.

Furthermore, a participant identification stage was conducted to collect information about name, age, gender, education level, location, and whether they were experts in information visualization or climatology. This step was crucial for understanding user-profiles and determining whether they were part of the target audience, which includes students conducting climate-related research and experts in the two areas addressed in this project.

Participants were then asked to perform specific tasks akin to a qualitative test. Each task aimed to determine whether the participants easily understood the data presented in the visualizations. Static images accompanied the questions to assist the participants. Examples of questions include identifying periods with the lowest precipitation amount and selecting regions with the highest amount based on color shading.

1. What is the period with the lowest precipitation amount? (Considering that the options are cutouts from the image below).
2. Considering that lighter shades represent lower amounts and darker shades represent higher amounts, select the option that indicates the region with the highest precipitation amount.
3. What is the maximum temperature amount indicated in the visualization?
4. Which municipality do the presented visualizations refer to?
5. What period will be represented in the visualizations based on the image below?
6. Considering that precipitation and temperature vary depending on the selected time window, answer:
   (a) The minimum, average, and maximum values indicated in the visualization refer to the entire time series of data.
   (b) The minimum, average, and maximum values indicated in the visualization refer to the user-selected time window.
7. The image below represents the visualizations in the chosen time series from 01/01/2000 to 01/12/2015. If the user modifies the time window, will the slope and elevation amounts also be altered? Why?
8. Choose the option that shows the maximum temperature amount recorded in November 2012.

The first three questions aim to verify if the chosen visualization technique could convey the information to the participant, and the last question. All of them were built using a different data visualization technique to test all available ones in the application. The fourth and fifth questions are to analyze if the participant understood the filtering functionality existing in the application; both filters, by time and by municipality, were tested. The sixth and seventh questions are more related to the data; it was an attempt to verify if the participants could understand the data in the application just by visualizing its representation.

An adapted version of the System Usability Scale (SUS) questionnaire was also administered to assess application usability and obtain quantitative results. The SUS questions included inquiries about application usage frequency, perceived complexity, ease of use, need for technical assistance, integration of map functions, consistency in data representation, learning curve, confidence in application usage, and the need to acquire new skills.

1. I would like to use the ClimaInfo tool frequently.
2. I find the ClimaInfo tool unnecessarily complex.
3. I found the ClimaInfo tool easy to use.
4. I would need assistance from someone with technical knowledge to use the ClimaInfo.
5. The various map functions are well integrated into the ClimaInfo tool.
6. The ClimaInfo tool represents the data inconsistently.
7. People will learn how to use the visualizations quickly.
8. I found the ClimaInfo application complex to use.
9. I felt confident using the ClimaInfo.
10. I needed to learn several new things before being able to use the ClimaInfo.

Finally, participants were invited to highlight the positive and negative aspects of ClimaInfo in the feedback stage, providing insights for future improvements. Participants were also thanked for their contribution and participation in the evaluation.

6 Results and Discussion

In communicability evaluation, the target audience was established as individuals who already possess a minimum level of prior knowledge. Thus, participants include those understanding areas such as biology, forestry engineering, and agronomy, as well as experts in information visualization and climatology, to understand how these areas can be better addressed in the application. The goal was to ensure that the application was initially accessible to undergraduate students to make all necessary adjustments for the application to become practical for the entire community regardless of their technical knowledge level in areas such as climatology or information visualization.

As suggested by Forsell [4], it is ideal to have a group with a minimum of 12 people for information visualization evaluations. Based on this, there were a total of 35 participants, who were separated and reorganized into three groups: group 1 consisted of all participants, totaling 31, considering that the selected participants were only those with the desired profile, as four were from the healthcare field, thus not fitting the target audience; group 2 consisted of undergraduate students, with 14 participants; and group 3 consisted of experts, with 13 participants, who consider themselves experts in one of the two areas addressed in this project, information visualization and climatology. The other four participants who complete Group 1 do not belong to Group 2 or 3.

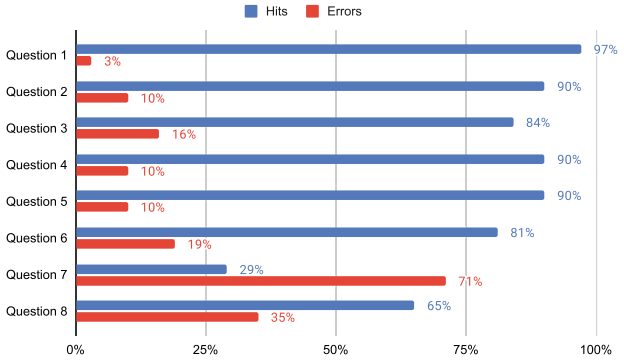

Fig. 5. The figure presents the percentage of errors and correct answers of the group with all participants, where the red bar represents the percentage of errors made by the participants in the applied tasks, and the blue bar represents the correct answers. (Color figure online)

In group 1, the age ranged from 21 to 35 years old, and regarding the educational level of the participants who took part in the evaluation, about 35% had incomplete undergraduate degrees, 29% had a doctorate, and the other levels had a low percentage. In carrying out the proposed tasks, the participants obtained a high correctness rate in seven questions; however, there was an error rate in the seventh question, and after a thorough analysis, it was found that interaction with the application was necessary. For this reason, this task was discarded (Fig. 5). The SUS result calculated for this group was 80.2, classified as "A−" on the scale, which means a good level of usability, but it indicates that there are measures to be improved.

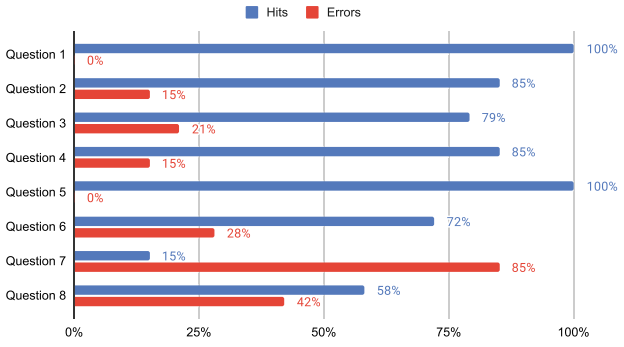

Fig. 6. The figure presents the percentage of errors and correct answers of group 2, where the red bar represents the percentage of errors made by the participants in the applied tasks, and the blue bar represents the correct answers. (Color figure online)

Group 2 gathered over 70% of participants between 21 to 30 years old, with the educational level divided between completed high school and incomplete undergraduate degrees; in other words, no participant in this group has a completed undergraduate degree. This group had the lowest correctness rate in the tasks compared to the other groups (Fig. 6), possibly because the training phase was ignored, as there was feedback that a video teaching how to use the application was necessary. Furthermore, the group with the lowest SUS result, with a value of 79.8, was classified as "A−".

Group 3, composed of people who qualified as experts in the areas addressed in the application, had an age range of 26 to 35 years old, with education corresponding to doctorates, masters, and completed undergraduate degrees. This group achieved the highest percentage of correct answers compared to the previous groups, even in the discarded seventh question(practically 60% got it right), demonstrating high performance in solving the proposed tasks (Fig. 7). Moreover, the method calculation pointed to a result of 87.5, classifying the application as "A+" on the SUS scale.

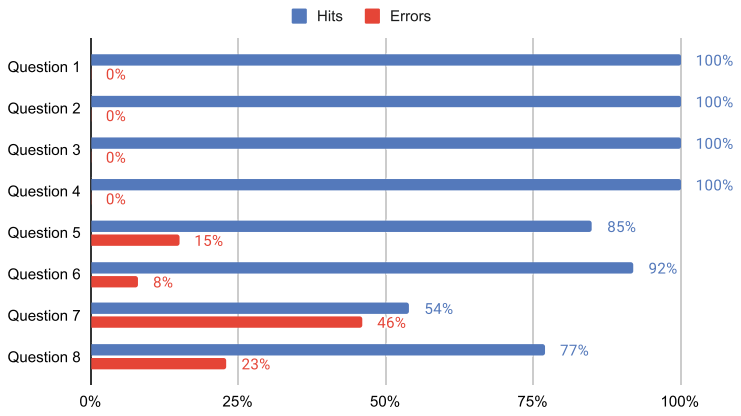

Fig. 7. The figure presents the percentage of errors and correct answers of group 3, where the red bar represents the percentage of errors made by the participants in the applied tasks, and the blue bar represents the correct answers. (Color figure online)

As mentioned earlier, the SUS calculation for the expert group yielded a score of 87.5, placing the application in the 'A+' category on the scale. In contrast, the student group obtained the lowest SUS score of 79.8, resulting in an 'A−' classification. The overall SUS score for all groups was 80.2, also falling within the 'A−' range. While this suggests a commendable level of usability, it also hints at areas where enhancements could be made. It's believed that the higher score attained by the expert group might be attributed to their familiarity with the dataset, thereby streamlining their use of the tool. This correlation is illustrated in Fig. 8.

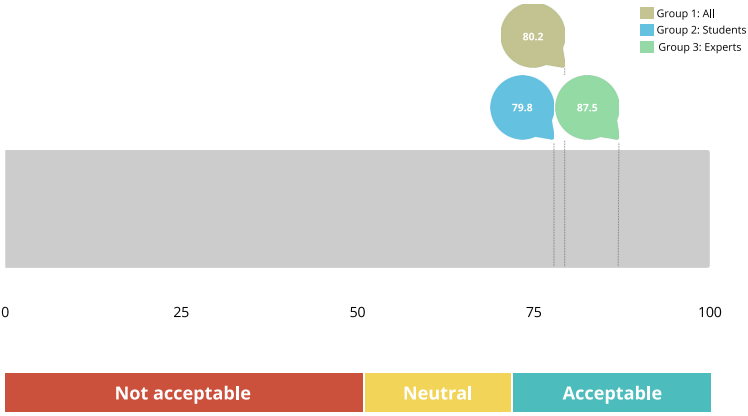

Fig. 8. The figure represents the system usability scale score for the three groups, the expert group achieved the highest score.

7 Final Remarks and Future Works

The ClimaInfo application was developed to address the problem of unavailable climatic data in municipalities in the state of Pará. Through visualization techniques, the application provides representations of minimum, average, and maximum historical temperature and precipitation series and slope and elevation, thus filling gaps in the database. Thus, providing the download of the data used in the application helps fill the existing gaps in the database.

The ClimaInfo communicability evaluation, conducted with different groups, demonstrated that the application is a communicative and user-friendly application. The SUS results indicated a usability level between A− and A+, confirming its usefulness for the target audience.

As future improvements, it would be interesting to display data series from across Brazil and implement new visualization techniques to present the data in different ways and increase interactivity. Additionally, introducing the functionality to compare data from different municipalities would provide users with a more simplified and comprehensive analysis.

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Enhancing Urban Walkability Assessment with Multimodal Large Language Models

Ivan Blečić[1(✉)], Valeria Saiu[1], and Giuseppe A. Trunfio[2]

[1] Department of Civil and Environmental Engineering and Architecture, University of Cagliari, Cagliari, Italy
{ivanblecic,v.saiu}@unica.it

[2] Department of Biomedical Sciences, University of Sassari, Sassari, Italy
trunfio@uniss.it

Abstract. Recent advances in computer vision and Convolutional Neural Networks (CNNs) have facilitated the use of street view imagery (SVI) for the automatic assessment of physical and perceived attributes of walkable areas. However, these methods still overlook the broader urban context and fail to capture and communicate to the user the qualitative factors influencing the assessed walkability score. This paper addresses these challenges by leveraging a Multimodal Large Language Model (MLLM) to provide a holistic assessment of walkability, consisting of both quantitative scores and linguistic qualitative insights. This approach offers a more comprehensive understanding of the factors contributing to the walkability score attributed to the image and enhances the interpretability and practical applicability of the assessments for urban planners and policymakers. Preliminary experiments demonstrate that a MLLM-based methodology can effectively capture a diverse range of factors of walkability, suggesting a promising direction for future developments of evaluation tools aimed at supporting the design of pedestrian-friendly environments.

Keywords: walkability assessment · machine learning · deep learning · multimodal large language model · street view

1 Introduction

Walkability, the measure of how conducive an environment is to pedestrian activity, has attracted significant attention in urban planning and public health research [1–4]. Numerous studies have investigated the impact on walking behaviour of the physical attributes of neighbourhoods, including factors such as residential density, land use mix, street connectivity, public transport accessibility, accessible amenities, highlighting a positive correlation between favourable neighbourhood design features and increased pedestrian activity [5,6]. Other key factors influencing pedestrian behaviour are those related to the physical walking environment, including the specific pedestrian-friendly infrastructures, which

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determine pedestrian comfort and safety and which, taken together, account for the so-called *perceived walkability* [7–9].

Traditionally, experts have relied on surveys or time-consuming on-site assessments to identify key factors influencing perceived walkability. However, recent advancements in software and hardware technologies enabled novel approaches, largely based on computer vision methodologies applied to street view imagery (SVI), which can be nowadays considered as an important data source for urban analytics [10]. The proprietary Google Street View (GSV) service is the most well-known and widespread service providing SVI. However, in some areas it is also available Baidu Maps (https://map.baidu.com/) and a notable trend is that of crowdsourced street view imagery, facilitated by services such as Mapillary [11], KartaView (https://kartaview.org), in some cases providing adequate geographical coverage and temporal granularity, at a permissive licence.

According to the recent literature, semantic segmentation based on Convolutional Neural Networks (CNN) is one of the techniques that has been applied to SVI and has emerged as a promising method for assessing the physical walking environment. For example, in [12], Baidu street view images were used to measure visual walkability in Shenzhen, creating indicators on "psychological greenery" and "visual crowdedness". In [13] the authors developed and index based on semantic segmentation incorporating factors like greenery and street width. Similarly, in [14] the authors analysed street view images observing variations in object importance at different spatial scales. While these approaches offer new insights into walkability assessment, challenges remain, particularly regarding the accuracy and analysis of semantic segmentation results from SVI and the difficulties in establishing an effective model connecting segmented entities and perceived walkability.

In addition to automatically detecting the specific physical attributes of walkable areas, researchers have also delved into direct modelling of people's perceptions of walkability based on SVI. Starting from the Place Pulse dataset [15–17], created by MIT's Media Lab, which was used as a valuable resource for understanding public perceptions of urban environments through street view images, several deep learning models based on CNNs, have been developed to predict perceptual properties based on training sets of rated SVIs [12,14,18]. For example, in [19] we have developed an approach based on transfer learning in order to build a CNN, pre-trained on the Places dataset with 365 scene categories, capable to classify an input image from GSV into one of the five ordinal categories of walking suitability ranging from 1 to 5, where 1 corresponds to low and 5 to high walkability. The resulting network was trained using a relatively small dataset composed of rated images, with the objective of predicting the score to be assigned to any other image [19,20].

While the CNN-based approaches have proven effective in identifying physical features such as green spaces, street widths, and pedestrian infrastructure, they face limitations. Specifically, approaches based on semantic segmentation often result in a narrow focus on detectable elements without capturing the broader, more synergistic and subjective aspects of walkability. These include overall aes-

thetic appeal of an area, perceived safety, and the ambiance that contributes significantly to pedestrian subjective perception. Furthermore, the CNN-based approaches that aim at modelling the overall perceived walkability lack the ability to provide contextual insights or explanations for their assessments, making it difficult for urban planners and policymakers to understand the underlying "reasoning" and factors that have contributed to or detracted from a machine assessment of walkability.

In recent years, the field of deep learning has seen significant advancements with the introduction of Large Language Models (LLMs) and their subsequent evolution into Multimodal Large Language Models (MLLMs). LLMs have demonstrated remarkable abilities in understanding and generating text, paving the way for applications that require nuanced interpretation of complex data. Building on this, MLLMs extend these capabilities to include the analysis of imagery alongside textual data, offering a more holistic approach to understanding and interacting with the world. These models can integrate and process information across different modalities, providing a richer, more comprehensive understanding of content.

Given these advancements, our study started investigating an application of MLLMs to the domain of urban walkability assessment. This approach aims to overcome the limitations of previous CNN-based methods by not only analysing physical features visible in street view images but also interpreting the broader urban context that influences pedestrian experiences. By leveraging the multimodal processing capabilities of MLLMs, we can extract deeper insights into the factors that contribute to walkability. This methodology could enable a more nuanced analysis that combines quantitative assessments with qualitative evaluations, providing urban planners and researchers with a comprehensive understanding of walkability that aligns more closely with human perceptions and experiences.

Furthermore, our approach emphasizes the importance of explainability in AI-driven assessments. By generating interpretations and explanations for the walkability scores, we aim to provide insights into the specific factors that influence these evaluations. This not only increases the transparency but also enhances the utility of the assessments for informing urban planning and policy decisions. Throu gh this innovative application of MLLMs, we seek to contribute to the development of urban spaces that are not only physically conducive to walking but also enrich the overall quality of life for their inhabitants.

The paper is organized as follows. Next section provides a short background on MLLMs. In Sect. 3, we provide relevant details of the experimental setup, including utilized models, datasets and processes. Section 4 illustrates and discusses the obtained preliminary results. Section 5 concludes the paper with some final considerations and hypotheses on future work.

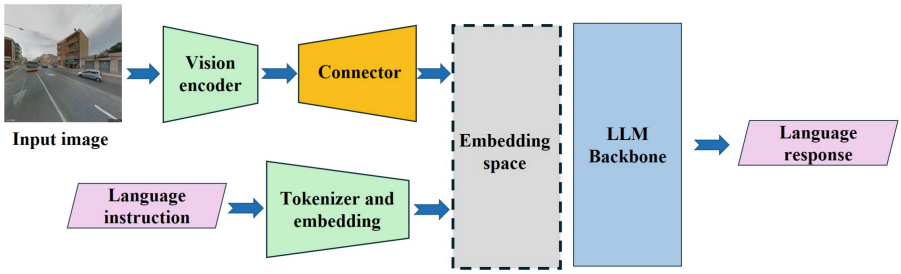


Fig. 1. An example of MLLM architecture.

2 Background

Recently, machine learning technologies featuring LLMs [21] have showcased superior performance in generating coherent and contextually appropriate text, advancing the field of natural language processing (NLP). However, a fundamental constraint of traditional LLMs is their unimodal nature, limiting them to text-based inputs and interactions. This is in contrast to the multimodal approach of human cognition that combines multiple sensory inputs for understanding the environment.

In response to the limitations of unimodal LLMs, recent research has focused on MLLMs, representing a significant enhancement. In general, MLLMs are able to integrate and process information across various data modalities, primarily text and images, expanding the advantages provided by LLMs to include understanding, interpretation, and generation of multimodal content. This advancement is indicative of progress towards artificial general intelligence, with the goal of mimicking the human capability to understand complex concepts through the integration of diverse sensory data.

Generally, MLLMs are characterized by quite complex architectures designed to manage multimodal data. These models include a reliable LLM, which is utilized for its deep linguistic comprehension and generative ability. An example is shown in Fig. 1 where an input image and a language instruction are processed by a vision encoder and a tokenizer respectively, which transform the raw data into a format the system can work with. These processed inputs converge in a connector that fuses the visual and textual information into a single embedding space. This combined data is then fed into the Large Language Model (LLM) backbone, where it is interpreted to generate a coherent language response, encapsulating the insights drawn from both the image and the accompanying text. This architecture permits MLLMs to comprehend multimodal content, namely images and text, producing textual output and represents a substantial step towards AI systems capable of understanding and communicating with the world in a way similar to human cognition [22].

Training approaches for MLLMs have evolved significantly and utilize a combination of techniques to effectively integrate information from various

modalities. These include Multimodal Pre-training (M-PT), Multimodal Instruction Tuning (M-IT), Multimodal In-Context Learning (M-ICL), Multimodal Chain of Thought (M-CoT), and LLM-Aided Visual Reasoning (LAVR) [22]. These methods enable the integration of visual elements with traditional text-based processing in LLMs. For example, M-IT involves fine-tuning pre-trained LLMs with datasets formatted with instructions that include both textual and visual inputs, allowing models to understand and execute tasks requiring information synthesis from multiple modalities. Techniques such as M-ICL and M-CoT further extend LLMs' in-context learning and reasoning capabilities to multimodal domains, facilitating complex reasoning over tasks involving visual components. M-PT utilizes extensive datasets with paired data from different modalities to teach the model the complex relationships between them [22].

The integration of multimodality in LLMs through MLLMs has vast implications across various applications. This includes improvements in content creation and media generation, as well as transforming interactions with digital assistants. In the study described in this paper, we present some results of applying a MLLM able to process images and text to the task of evaluating walkability in urban contexts.

3 Methodology

Using a pre-trained open-source MLLM, we investigated the evaluation of urban walkability from street-level images, aiming to develop an automated tool that can provide insights similar to those of human experts in urban design and walkability. This approach aims at exploiting effectively the new capabilities of machine learning to analyse visual data, potentially transforming how urban spaces are evaluated and improved for pedestrian friendliness. Our methodology encompassed prompt optimization, expert validation, and a scoring system to ensure both accuracy and relevance in our findings.

It is worth noting that one key difference between the approach discussed in this paper and the computer vision methods mentioned in Sect. 1, lies in its ability to provide both a quantitative score and a qualitative explanation for each urban walkability assessment. In fact, unlike standard computer vision techniques that typically output scores or classifications without context, the MLLM-based methodology under investigation generates linguistic explanations alongside scores. This dual output offers insights into the factors influencing each score, thereby enhancing interpretability and trust in the model's evaluations. This aspect is closely aligned with the principles of explainable artificial intelligence (XAI), which emphasizes the importance of making AI decisions transparent and understandable to humans.

In this preliminary study, we relied on prompt optimization without computationally expensive MLLM fine-tuning. This process inherently is based on the model's zero-shot learning capabilities, hypothesizing its potential to assess walkability despite not being explicitly trained on such evaluations. Zero-shot learning represents the model's ability to apply its generalized understanding to

novel tasks, offering a promising avenue for analysing complex urban environments through the lens of walkability without the need for task-specific training data.

Our evaluation of the approach initiated with experts reviewing the model-generated scores and comments for accuracy and relevance. This preliminary phase, involving experts of urban design and walkability, served to validate the model's assessments against professional standards, ensuring the reliability of subsequent automated evaluations.

A subsequent experiment consisted in attributing a walkability score to the streets of Cagliari, a city of about 150,000 inhabitants, and the capital of Sardinia island in Italy. For the automatic walkability assessment we had already collected a dataset of about 30,000 Google Street View photos relative to the city street network. For each edge of the city-wide street network graph we had a number of photos ranging from two to six, depending on the edge's length.

For streets represented by multiple images, we employed a two-stage scoring process. Initially, images from identical viewpoints were aggregated via majority voting, a method that ensured robustness against outliers but might reduce the diversity of perspectives considered. Subsequently, for a comprehensive street evaluation, scores related to different points of the same street were averaged, and a LLM was used to summarize the different comments earlier produced by the MLLM, providing a unified street-level insight. This method balanced detailed analysis and practical scalability.

3.1 The Adopted MLLM: LLaVA

The Language and Vision Assistant (LLaVA) model [23–25] represents a recent and significant advance in the field of MLLMs, primarily focused on visual instruction tuning. LLaVA stands out for its data efficiency and simplicity in architecture. Utilizing a fully-connected vision-language cross-modal connector LLaVA's code and model have been made publicly available, underscoring the team's commitment to open-source advancements in the field.

The LLaVA model's architecture is intuitively simple, consisting of a pre-trained visual backbone to encode visual features, a pre-trained large language model for understanding user instructions and generating responses, and a vision-language cross-modal connector to align the outputs of the vision encoder with the language model. Notably, LLaVA achieves this with minimal architectural complexity and training data, unlike other models that require extensive pretraining on large-scale datasets.

Our approach is based on the latest version named LLaVA-1.6 [25], which introduces enhancements in reasoning, OCR, and world knowledge over its predecessor, LLaVA-1.5. In particular, it features a 4x increase in input image resolution, supporting varied aspect ratios, and improvements in visual instruction tuning data mixture for better OCR and reasoning capabilities.

More in detail, for our experiments we used the available pre-trained LLaVA-1.6 with Mistral-7B LLM backbone [26]. All runs were executed on a consumer-level GPU card Nvidia GTX 4090.

Mistral-7B is a LLM developed by Mistral AI and is equipped with 7.3 billion parameters. According to [26], this model surpasses the performance of Llama 2 with 13 billion parameters, in all tests, and it even outperforms Llama 1 with 34 billion parameters in numerous benchmarks. The model employs techniques like Grouped-query attention (GQA) for quicker processing and Sliding Window Attention (SWA) for better handling of longer text passages.

According to [24], the LLaVA MLLM has been trained using a method that leverages ChatGPT/GPT-4 for multimodal instruction-following data collection from image-caption pairs. The study creates text-based instructions that allow GPT-4 to process visual content in text form. The training dataset, utilizing COCO images [23,24], includes 158K unique samples categorized into three distinct types of instruction-following data: *conversations* that delve into the visual content through a series of questions about objects, actions, and spatial relationships; *detailed descriptions* aimed at generating comprehensive depictions of images; and *complex reasoning tasks* that require in-depth logical analysis. This approach significantly enhances the model's capability in spatial reasoning and understanding visual content through textual descriptions, with GPT-4 consistently outperforming in generating high-quality instruction-following data across these categories. To give an idea of the training data, in Fig. 2 is represented an example of conversation concerning an image from the COCO dataset.

For the experiments we used the source code and pre-trained model provided by the developers of LLaVA 1.6 setting the parameters as in Table 1. In addition, after a few experiments we developed the prompt reported in Fig. 3 which proved effective for obtaining responses easy to process.

Table 1. Main parameters used in LLaVA and their values.

Parameter	Value/Description
temperature	0.0 (Deterministic output, aiming for the most likely outcome)
top_p	None (Default or deterministic behavior in text generation)
num_beams	1 (Beam search used with a single beam, i.e. greedy decoding)
max_new_tokens	1024 (Limits the length of the generated output)

4 Results and Discussion

In this section, we first present a preliminary semi-qualitative analysis of model-generated scores and comments based on a dataset of scored street-view images collected in a previous study [19]. Then, we present a practical experiment to assess the walkability of streets in a city, using a dataset of SVIs covering the city's street network.



Training dialog:
“from": “human", “value": “How many traffic signals are there in the image?"
“from": “gpt", “value": “There are two traffic signals in the image."
“from": “human", “value": "Is there a lot of traffic in the image?"
“from": “gpt", “value": “No, the image shows an empty street with no visible traffic."
“from": “human", “value": “Where are the traffic lights positioned in the image?"
“from": “gpt", “value": “The traffic lights are positioned near the street intersection on the sidewalk or a little island."
“from": “human", “value": “What is the perspective of the image?"
“from": “gpt", “value": “The perspective of the image is a topside view, likely taken from an elevated position."
“from": “human", “value": “What can you infer about the traffic in the area based on the image?"
“from": “gpt", “value": “While it’s not possible to draw definitive conclusions about traffic conditions in the area based on just this single image, a few inferences could be made. The fact that the intersection is empty at the time the photo was taken might suggest that the area experiences low to moderate traffic or that the image was captured during a non-peak traffic period. Having multiple traffic signals and a dedicated island for the signals could indicate that this intersection is usually busier during different times of the day. Increased traffic could be expected, for example, during morning and evening rush hours or on weekends, when more people are likely to be out driving. In summary, the image provides limited information about overall traffic conditions in the area, but the presence of traffic signals suggests that the intersection may experience higher traffic volumes at other times of the day or week."

Fig. 2. Figure 000000393242.jpg from the COCO dataset and the corresponding LLaVA training conversation [24].

4.1 Evaluations of LLaVA Responses

We leveraged the expertise of urban walkability assessments from a prior study [19], where experts were engaged solely to furnish walkability scores to facilitate the training of a CNN-based classifier. This phase had the only purpose to perform a preliminary evaluation of the degree to which LLaVA’s computational assessments align with or diverge from human expert evaluations. Such a com-

Analyze the provided street-level photo to assess the walkability of the urban environment. Focus on the urban context visible in the image.
Scoring Criteria: Assign a walkability score from 1 to 5. A score of 1 indicates extremely poor walkability, and a score of 5 indicates high walkability. Base your score on both visible elements and inferred aspects of the urban environment. Provide a score utilizing contextual clues and inferences as necessary.
Response Template: Adhere strictly to the template below for your analysis. Begin your response with the motivation and conclude with the score. Do not include any additional text outside of this template.
- Motivation: [Provide the reasoning behind your score in no more than 250 characters].
- Score: [Insert the walkability score from 1 to 5].

Fig. 3. Prompt used for the LLaVA-based assessment of urban walkability.

parison is instrumental in validating the efficacy of MLLMs in recognizing and interpreting the complexities inherent in urban walkability metrics. However, a certain level of disagreement was expected being the LLaVA model not explicitly trained on walkability evaluation.

In Figs. 4, 5, 6, 7 and 8 we provide some of the evaluations we performed in terms of comparison between the LLaVA scores with human experts' scores.

In the first example of Fig. 4 both LLaVA and the human expert recognize the high walkability of a residential area. LLaVA noted the mix of urban and natural elements, presence of parked cars indicating pedestrian activity, ample greenery, and well-maintained wide sidewalks. This instance demonstrates LLaVA's capability to accurately assess environments that exhibit clear and strong indicators of walkability, aligning closely with human perception. In the second example, LLaVA assigns a slightly higher score than the human expert to a street scene. While LLaVA acknowledge the presence of parked cars, pedestrians, greenery, perhaps it weighs the positives more heavily than the human expert. The discrepancy could indicate a variation in the prioritization of certain features or a difference in the perceived impact of these features on walkability. This is perfectly understandable in a zero-shot learning setting.

In the examples of Fig. 5, LLaVA rates narrow alleyways and streets higher than human experts do. As mentioned, the motivation of human experts are not available, as they were asked to provide only a score. However, the model recognizes clear paths for pedestrians and the potential for pedestrian-friendliness due to parked cars and a mix of residential or commercial buildings. The higher scores by LLaVA may reflect its valuation of unobstructed paths and mixed-use environments. However, human experts might have considered additional factors such as the narrowness of pathways and the lack of certain amenities, which slightly lower their assessments.

In Fig. 6, in which some intermediate-level walkability scenarios are depicted, both LLaVA and human experts agree on the scores. LLaVA noted the presence



Human expert score: 5; **LLaVA score**: 5
LLaVA comment: "The image depicts a street-level view of a residential area with a mix of urban and natural elements. The presence of parked cars along the sidewalk indicates that there is pedestrian activity in the area. The street is wide and appears to be designed for moderate traffic flow. There is ample greenery with trees lining the street, contributing to a pleasant and walkable environment. The sidewalk is wide and appears to be well-maintained".



Human expert score: 4; **LLaVA score**: 5
LLaVA comment: "The image depicts a street in a European city with a mix of residential and commercial buildings. There are parked cars on both sides of the street, and the presence of pedestrians suggests that the area is walkable. The buildings are close to the sidewalk, and there are trees and greenery, which contribute to a pleasant urban environment. The street appears to be designed for moderate traffic, and there are no highways or motorways visible".

Fig. 4. Two examples of street view images scored 5 by LLaVA.

of sidewalks and urban settings but also recognizing limitations like the primary design for vehicular traffic and lack of pedestrian-focused infrastructure. These examples show a good alignment between LLaVA's assessments and human judgment, suggesting that the model is capable of nuanced analysis where walkability indicators are mixed.

In Fig. 7, both assessments provide a score of 2. LLaVA points out the challenges to walkability posed by a wide street primarily designed for vehicular traffic, with parked cars on both sides and a lack of clear pedestrian infrastructure. This agreement indicates that LLaVA can effectively identify environments where the walkability is compromised by factors prioritizing vehicle movement over pedestrian access.

Finally, in Fig. 8 both LLaVA and the human expert assign the lowest score to an environment characterized by a highway with multiple lanes of traffic and an absence of pedestrian infrastructure. This consensus underscores the model's



Human expert score: 3; **LLaVA score**: 4
LLaVA comment: "The image depicts a narrow alleyway between two buildings, with a clear path for pedestrians. The buildings appear to be residential or commercial, and there are no visible obstructions or hazards. The presence of a mailbox suggests that this area is likely to be maintained and serviced. The alleyway is not wide, but it is clear and unobstructed, which could make it a pleasant and convenient route for walking".



Human expert score: 3; **LLaVA score**: 4
LLaVA comment: "Motivation: The image depicts a narrow street lined with parked cars on both sides. The presence of multiple parked cars suggests that the area is likely to be pedestrian-friendly, as it is designed to accommodate parked vehicles. The buildings appear to be residential or commercial, which could indicate a mix of activities and services available within walking distance. The street itself is not wide enough to accommodate high-speed traffic, and there are no visible signs of highways or motorways. The overall impression is that of a pleasant urban environment with a moderate level of walkability".

Fig. 5. Two examples of street view images scored 4 by LLaVA.

ability to recognize and evaluate scenarios where walkability is severely limited due to the dominance of vehicular traffic and industrial or commercial settings with no pedestrian access.

Overall, we mostly found instances where LLaVA's walkability scores align with those of human experts. This congruence demonstrates LLaVA's potential to accurately interpret and assess the walkability of urban environments. Such consistency is particularly notable in cases where the walkability determinants are visibly apparent, such as the presence of sidewalks, greenery, and pedestrian activity. These findings suggest that LLaVA can effectively identify and weigh these visible factors in its assessments.

However, the analysis also reveals discrepancies between LLaVA scores and those of human experts. These differences may arise from the model's interpretation of subtle urban design features or its valuation of certain walkability



Human expert score: 3; **LLaVA score**: 3
LLaVA comment: "The image depicts a street in a residential area with low-rise buildings, parked cars, and a few pedestrians. The presence of sidewalks and the absence of high-speed traffic suggest a relatively walkable environment. However, the lack of visible shops, cafes, or other amenities might limit the attractiveness of the area for pedestrians".



Human expert score: 3; **LLaVA score**: 3
LLaVA comment: "The image depicts a street scene with a mix of parked and moving vehicles, including cars and a motorcycle. There are pedestrians visible, and the presence of a sidewalk suggests a pedestrian-friendly environment. The street is lined with buildings, indicating an urban setting. However, the street appears to be primarily designed for vehicular traffic, with no clear pedestrian pathways or crossings. The presence of a bicycle lane suggests some consideration for alternative modes of transportation".

Fig. 6. Two examples of street view images scored 3 by LLaVA.

determinants over others. For instance, LLaVA may assign a higher score to a street with ample greenery and pedestrian infrastructure but overlook factors like street connectivity or the presence of amenities, which human experts might consider crucial for walkability. Such discrepancies highlight areas where LLaVA's assessment criteria could be refined to better align with human judgment.

These variations suggest areas for further refinement in LLaVA's evaluation process, particularly in fine-tuning its sensitivity to subtle urban design features and the relative importance of different walkability determinants. Training LLaVA with a dataset explicitly labeled with walkability scores and associated rationale could enhance the model's ability to evaluate complex urban environments similarly to human experts. This process could help the model better understand the nuances of what makes an area walkable, including less tangible aspects like safety perceptions or the social vibrancy of a street, which are often considered by human assessors.



Human expert score: 2; **LLaVA score**: 2
LLaVA comment: "The image shows a wide, tree-lined street with parked cars on both sides, indicating a residential area. There are no visible pedestrian crossings or sidewalks, and the street appears to be designed primarily for vehicular traffic. The presence of parked cars and the absence of clear pedestrian infrastructure suggest that this is not a highly walkable urban environment".

Fig. 7. An example of photo scored 2 by LLaVA.



Human expert score: 1; **LLaVA score**: 1
LLaVA comment: "The image shows a highway with multiple lanes of traffic, including cars and trucks. There is no visible pedestrian infrastructure, such as sidewalks or crosswalks, and the surrounding area appears to be industrial or commercial with no clear pedestrian access. The environment is not pedestrian-friendly, and the presence of high-speed traffic suggests a low walkability score".

Fig. 8. An example of photo scored 1 by LLaVA.

4.2 Example of Application to an Urban Area

To illustrate a practical application of the MLLM-based methodology for walkability assessment, we conducted an experiment focusing on the city of Cagliari, the capital of Sardinia Island, Italy. The urban area has a varied urban fabric, encompassing a mix of historical and modern elements, diverse street layouts, and different levels of pedestrian infrastructure. This provided a rich dataset for evaluating the MLLM's ability to assess urban walkability comprehensively. The experiment utilized a dataset of approximately 30,000 Google Street View images, covering a significant portion of Cagliari's street network. Each street segment in the network was represented by two to six images, depending on the segment's length, to ensure a robust spatial representation. The MLLM, specifically the LLaVA model, was then tasked with analyzing these images to assign walkability scores based on its training and zero-shot learning capabilities.

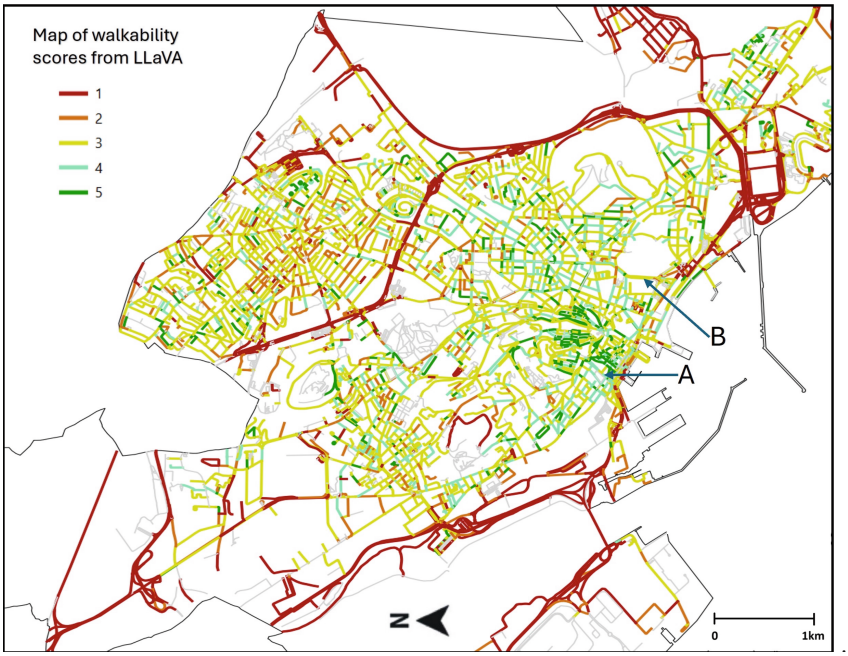
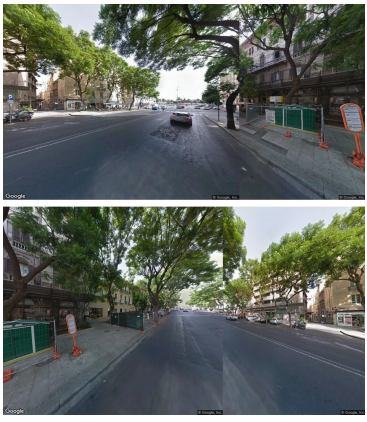


Fig. 9. The map of walkability scores obtained for Cagliari using LLaVA in a zero-shot learning setup. (Grey lines represent natural and administrative boundaries, or borders of areas non accessible to pedestrians.) Details of results obtained from streets labeled as A and B are shown in Figs. 10 and 11.



Overall generated comment: "The photographs capture a city street with a mix of pedestrian and vehicular activity. Lined with trees, the street offers shade, enhancing the walkability and creating a pleasant environment. The presence of parked cars, a motorcycle, and outdoor seating at a café indicates accessibility and use by people. Although designed for moderate traffic, the street is pedestrian-friendly with clear lanes for vehicles and sidewalks. Its location in a low-density urban area suggests a higher walkability score, making it an attractive and inviting space for both pedestrians and vehicles.".

Fig. 10. Details of case A in Fig 9. The overall generated score for the street is 5.



Overall generated comment: "The street in question is a mix of urban elements, with varying degrees of pedestrian-friendliness. The presence of trees and sidewalks in some areas suggests efforts to create a welcoming environment for pedestrians, while the visible vehicular traffic and wide roads in other sections may indicate a design prioritizing cars over pedestrians. The overall walkability of the street appears to be moderate, with potential for pedestrian activity in low-density urban areas, but concerns about pedestrian safety due to the lack of designated crossings or traffic calming measures. ".

Fig. 11. Details of case B in Fig 9. The overall generated score for the street is 3.

The application process involved three steps. First, each image was independently assessed by LLaVA, which provided a walkability score ranging from 1 (low walkability) to 5 (high walkability), accompanied by a qualitative explanation of the score. This step utilized the model's ability to generate insights based on both visible elements and inferred aspects of the urban environment. Subsequently, for streets represented by multiple images, scores were aggregated to derive an overall walkability assessment for each street segment. This aggregation considered the variability and diversity of perspectives within the same street, using majority voting for identical viewpoints and averaging for different viewpoints. Finally, the aggregation of all the available qualitative comments for each street segment was performed using the open source Mistral LLM developed by Mistral AI [26]. This advanced language processing step is necessary for integrating diverse observations and insights into a comprehensive summary that reflects the collective attributes of walkability as depicted across multiple images. This process goes beyond simple averaging or majority voting.

The final result of the process outlined above is a detailed walkability map of the city, with each street segment color-coded according to its overall walkability score and annotated with synthesized comments that highlight specific areas of

strength or needed improvements. The comprehensive street-level walkability map of Cagliari is shown in Fig. 9. This map serves as a practical tool for urban development, providing a clear visual and textual representation of walkability across different parts of the city.

The walkability map generated from LLaVA's assessments revealed reasonable patterns of walkability across the city, highlighting areas with high pedestrian friendliness as well as zones where improvements could enhance pedestrian experiences. Notably, historical centers and residential areas generally received higher walkability scores, attributed to their urban layouts, presence of greenery, and limited vehicle traffic. In contrast, more modern districts characterized by wider roads and vehicle-oriented design tended to receive lower scores.

To gain further insights we focused on two notable cases, labeled as A and B in the walkability map. In Case A (Fig. 10), the street, receiving a high walkability score of 5, was characterized by abundant greenery, pedestrian infrastructure, and a balanced mix of vehicular and pedestrian activity. LLaVA's overall comments underscored the area's pleasant and inviting environment for pedestrians. In Case B (Fig. 11): the street received a moderate walkability score of 3. The model's assessment pointed to the mixed urban elements, with some pedestrian-friendly features offset by areas prioritizing vehicular traffic, indicating room for pedestrian safety and amenity improvements. Overall the generated comments seem well justified by the street view images.

One of the distinctive characteristics of the MLLM-based walkability evaluation investigated in this study, lies in associating aggregated comments to the classical walkability scores. This provides urban planners and policymakers with an easily interpretable overview of the factors affecting walkability, enriched by the model's ability to detect and articulate complex patterns and insights.

5 Conclusions and Future Work

With its capability to produce qualitative comments along the walkability scores, the proposed method is significantly more powerful than conventional ones reliant on CNNs and SVI, which typically yield scores without explanations. This dual-output approach improves the interpretability of walkability data, aiding urban planners and policymakers in making informed decisions. Such transparency fosters trust in AI-driven assessments and encourages public participation by making urban walkability assessments more understandable.

Furthermore, the detailed comments allow for targeted urban development strategies, directly addressing specific walkability factors. This method facilitates a comparative analysis over time or between different areas, enabling a dynamic approach to urban improvement.

In this preliminary study, we relied on prompt optimization without computationally expensive MLLM fine-tuning. This process inherently is based on the model's zero-shot learning capabilities, hypothesizing its potential to assess walkability despite not being explicitly trained on such evaluations. Future work will explore enhancing this approach through specific fine-tuning of the MLLM. This

refinement could further align the model's assessments with expert evaluations and real-world urban walkability considerations, strengthening the methodology's application in creating pedestrian-friendly urban environments.

Another potential direction of improvement is represented by the integration with other data sources: combining SVI with other data types, such as pedestrian flow data or urban infrastructure databases, aerial images could provide LLaVA with a more comprehensive basis for its assessments, potentially reducing discrepancies with human expert scores.

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Past, Present and Climate Change Scenarios: Investigating Erosion Risk on Archaeological Heritage in the Sinni Valley (Basilicata, Italy)

Antonio Minervino Amodio, Maria Danese(✉), and Dario Gioia

ISPC-CNR, Tito Scalo 87050, Potenza, Italy
maria.danese@cnr.it

Abstract. Erosion is one of the main hazard factors for archaeological heritage; consequently, it is important to monitor it in the past and in its current distribution and to forecast its evolution in the future. Climate changes and its effects alter this last, in particular depending on rains. Consequently, in this paper, the USPED model is used to calculate erosion for different years; moreover, a simulation of future development is proposed. This in order to investigate the erosion risk on the archaeological heritage in the Sinni Valley, a place rich of sites and traces of the past.

Keywords: Erosion · climate changes · archaeological heritage · spatial analysis

1 Introduction

In the context of conservation of cultural heritage, a critical factor is the complex interaction between archaeological sites and environment. Consequently, implication for the territory deriving from climate changes and the increased vulnerability of archaeological heritage became a topic of primary importance [1–6].

Generally, a fragile territory, subject to natural hazard, is a threat also for cultural heritage [7, 8] because it favors:

- the destruction of the cultural identity represented by individual landscapes;
- the removal of archaeological traces and findings in areas not yet investigated;
- the damages to cultural heritage exposed to sources of risk.

In particular climate changes contribute to increase hazard by causing the following impacts [7]: sea level rise, flooding, erosion along the coast, temperature changes in the air and sea, variations in humidity, harsh weather, weathering, and modifications to the conditions of the soil and sediment.

Between all these, in this paper we focus on erosion and how climate changes can affect it and, consequently, cultural heritage.

Erosion is an element of danger for both the visible and the unexcavated archaeological heritage [9–12], so it is important to effectively model and map it, by simulating variable scenarios as weather conditions vary from a regular situation.

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Future climate change is expected to present significant difficulties for heritage management, particularly in landscape contexts such as river valleys. The magnitude, intensity, and character of geomorphological processes are likely to change in response to shifting threshold conditions. Landscapes with archaeological sites pose specific challenges to heritage professionals, not only because of the close association of historical remains with the physical environment, but also because in these landscapes erosion and soil denudation phenomena often affect the cultural heritage.

In recent years, advances in IT have led to the proliferation of physics-based predictive models aimed at quantitative investigation of soil erosion and sediment flux assessments in basins [13], which, however, have shown controversial results and poor reliability, due in part to the difficulty of parameter estimation and their local validity. Therefore, their application is limited to small areas where a large amount of data is available. Instead, the USPED (Unit Stream Power-based Erosion Deposition) model is semi-physical based on a more simplified and conceptual approach that focuses on water stream energy as the main driver of soil erosion that has returned good results in the literature [14].

The aim of this paper is, consequently, to study the evolution of erosion in the Sinni Valley in the last thirty years and to foresee how it will evolve in the future by considering the effects of climate changes according to the scenarios envisaged by IPCC (Intergovernmental Panel on Climate Change). This in order to highlight areas most subjected to erosion and archaeological heritage susceptible by it at the present and in the future and to contribute also to the management of archaeological heritage in the practice, for a planning and a programming aimed to their conservation or however for risk mitigation.

The paper is structured as follows: in Section 2 the methods used are introduced, in Section 3 the case study of the Sinni Valley and its archaeological heritage are presented; finally in Section 4 the vulnerability assessment and the application of USPED are showed, before the final discussion in Section 5.

2 Methods

2.1 Spatial Analysis: Nearest Neighbor Methods and Kernel Density Estimation

To determine vulnerability areas, in this paper two methods were used. For the practical description, see Sect. 4.

Nearest Neighbor (NN) methods are the most common distance-based methods (distance d between each couple of s_i and s_j elements) and provide information on the interaction between the n events at the local level.

By calculating the NN Observed Distance (NNOD, Eq. 1), the NN Expected Distance (NNES, Eq. 2), the NN Index (NNI, Eq. 3) and by comparing this last with the z-score and p-value of the distribution, it is possible to understand if events are distributed in a random or clustered way over the space. NNI shows positive spatial autocorrelation if it tends to 1, if the p-value (probability that a spatial process is created randomly) is very small and the z-score (number of standard deviations) is very high or very small. This, in the case of vulnerability, is useful to understand, in presence of clusters, if the area

between sites have a greater probability to be vulnerable from the archaeological point of view.

$$\text{NNOD} = \frac{\sum_{i=1}^{n} d_{min}}{n} \tag{1}$$

$$NNED = 0.5\sqrt{\frac{A}{n}} \tag{2}$$

$$\text{NNI} = \frac{\text{NNOD}}{\text{NNED}} \tag{3}$$

Kernel Density Estimation (KDE) uses a three-dimensional moving function to weight events by their distance from the point at which the intensity is estimated. KDE is commonly used in statistical contexts to obtain smooth estimates of univariate or multivariate probability densities. KDE (Eq. 4) is always nonnegative and depends on key parameters such as grid resolution, kernel function (k), the intensity (L) and especially bandwidth (τ). For a complete description of KDE see [15].

$$\lambda(L) = \sum_{i=1}^{n} \frac{1}{\tau^2} k\left(\frac{L - L_i}{\tau}\right) \tag{4}$$

2.2 USPED Method for Erosion Estimation

The USPED model was applied to simulate erosion scenarios in different years: in 1990, in 2000, in 2015, in 2023, in 2023 but considering a climate change scenario (ccs) with land use of 2023 and simulations of extreme events in the rainfall series as explained further.

USPED model uses the structure of the empirical Revised Universal Soil Loss Equation (RUSLE) to calculate the average soil loss (A). The 2-dimensional USPED model of erosion was created with an assumption that erosion and deposition are principally dependent from the sediment transport capacity of surface runoff.

In particular, the following equation (Eq. 5) was used [16]:

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{5}$$

where: A is the annual average soil loss, R is the rainfall intensity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the land cover factor, P is the soil conservation or prevention practice factors.

The formula is based on the upslope contributing area. It considers the tangential (perpendicular to the downhill direction) curvature as well as the profile (downhill direction) [17].

Net erosion or deposition (ED) within a grid cell is computed as the divergence of sediment flow (change in sediment transport capacity) using Eq. 6, where α is the terrain's aspect (in degrees).

$$ED = \partial[(A \cdot cos\alpha)/\partial x] + \partial[(A \cdot sin\alpha)/\partial y] \tag{6}$$

According to the physical basis of the model, net erosion pixels correlate with profile convexity and tangential concavity (flow acceleration and convergence), while net deposition pixels correlate with profile concavity (decreasing flow velocity).

The parameters of rainfall and runoff, which are influenced by height and location, define the R factor. This was determined by applying an empirical Eq. (7) [18] tested in [14, 19] where *EI30* is the rainfall erosivity (MJ mm h − 1 ha − 1 yr − 1) and P_{24} is the daily rainfall amount (mm).

$$EI30 = 0.1087(P_{24})^{1.36} \tag{7}$$

Equation 7 was calculated using daily precipitation data for the period from 2000 to 2020.

To simulate the effects of climate change on the rainfall series, some daily values were modified. In particular, for each month, a higher (one-day) rainfall event was introduced by summing the rainfall of a 3–4 or 5-day rainfall event. In this way, by condensing the rainfall amount of several days into one day, the final rainfall amount does not change, but the value of the R-factor changes, which follows the behavior of Eq. 7. In this way today's rainfall events are simulated, in which greater amounts of rain fall in a more closely spaced manner.

Using a standard Wischmeier erosion plot [20], the soil erodibility factor (K) was calculated as the rate of soil loss per rainfall erosion index unit (Mg h MJ^{-1} mm^{-1}).

Equation 8 determines the K factor, which shows how the soil profile responds to erosive force of rainfall events:

$$K = 0.001317\Big[2.1 \cdot 10^{-4}(12 - M)\Big[(Si + f_S)(100 - c)]1.14 + 3.25(a - 2) + 2.5(P - 3)] \tag{8}$$

In Eq. 8 M is the organic matter content (%), Si is the silt fraction in % (2 to 50 μm), f_S is the fine sand content in % (50 to 100 μm), c is the clay content in % (less than 2 μm), a is the structure, P is the permeability class (within the top 0.60–0.70 m); factor 0.001317 is derived via division by 100 of the conversion value (0.1317) to the SI.

Data on texture, structure, and permeability were taken from previous researches [21, 22] that examined the physical and chemical characteristics of deposit outcropping in the southern Apennine chain's foredeep area.

The topographic factor LS (dimensionless) was determined using Eq. 9, where Ac is the upslope contributing area per unit of width (m), α_0 is the length (72.6 ft, equal to 22.13 m) of the standard terrain, β_0 is the angle (9%, equal to a 5.16 slope degree) of the standard terrain, m and n (0.6 and 1) are empirical exponents [16].

$$LS = (m + 1) \cdot (A_c/\alpha_0)^m \cdot sin(\beta_0/0.0896)^n \tag{9}$$

The topographic parameters were calculated using a 5 m DEM collected from geoportals of the Basilicata and Calabria Regions.

The C factor, which indicates how crops and management practices affect soil erosion rates, was computed using values assigned based on vegetation cover, density and type of cover, according to literature data [23, 24]. Different C-factors were used for modelling scenarios in different annualities, in particular, land uses of 1990, 2000, 2015 and 2023

were used. The years 1990 and 2000 are derived from Corine Land Cover (CLC), while 2015 and 2023 are derived from Dynamic World (DW) data (satellite land-use data with a pixel resolution of 10 m. The P-factor does not vary in the study area; therefore, its value is assumed to be equal to one.

3 Study Area

3.1 The Sinni Valley

The Sinni Valley is a region located in the southern part of Basilicata, Italy (Fig. 1). The entire valley is crossed by the Sinni River, which finds in it the extension of almost its entire basin. The Sinni River largely traverses the Southern Apennines from west to east. In the lower section, after deeply incising a NNW-SSE-trending morphostructure of the Apennines (known as the Valsinni Ridge), the river flows with a wide deviation toward the southeast, passing through the internal sector of the Bradanic foredeep before emptying into the Ionian Sea near Policoro. In the intermediate section, the Sinni River and its major tributaries—the Sarmento River and the Serrapotamo Stream—cross the southern part of the Pliocene-Pleiscocene Sant'Arcangelo Basin [25]. This basin represents a tectonic depression bounded to the southwest by the Pollino Massif, Monte Alpi, and Monte Raparo, and to the northeast by the Valsinni Ridge, which separates the basin from the Bradanic Foredeep. The area occupied by the Sinni basin is 1343 km^2 and varies in elevation from 0 to 2247 m.

3.2 The Archaeological Map of the Sinni Valley and Vulnerability Criteria

The Sinni Valley is a region rich in history and archaeological sites that testify human occupation since ancient times. These sites include prehistoric settlements, necropolises, Roman settlements, medieval churches, castles, and many other archaeological features. Indigenous people have inhabited the area since prehistoric times, as evidenced by outcrops of lithic artifacts and the remains of dwellings. This study region is interesting because of the variety of archaeological sites in terms of both typology and chronological, being wide and favorable for population, both because of its landscape and the proximity to two large cities, Siris and Heraclea.

For this article, data from the Archaeological Map of the Middle and Upper Sinni Valley, entrusted in the years 1996–2003 to the Chair of Ancient Topography at the Second University of Naples and the Chair of Topography of Ancient Italy at the University of Bologna, were used [26–33]. Overall in the studied area we mapped 1014 sites.

For what concerns the vulnerability of the study area, different classes were identified according to criteria discussed by [34] (Fig. 1):

- Minimum protection priority classes: classes in which what found is unlikely to imply the possibility of having additional buried items. These are terracing, sporadic frequentation, spring, agricultural shelter, lookout, for a total of 14 sites.
- Classes with medium protection priority: classes in which it is not certain, but it may well be the case, that further investigation will lead to the presence of additional features beyond those known, thus not yet excavated or investigated by geophysics. These are materials, necropolis, kiln, tomb, for a total of 664 sites.

– Classes with high protection priority: classes in which elements of archaeological interest are actually already present or in which it is possible, through further investigation, to discover additional elements of interest. They are farm, habitation, settlement, castle, fortification, shrine, structure, monastery, rustic house, abbey, cave, mule track, villa, aggregate, church, castling, fortified town, monastic settlement, street, rustic settlement, cult building, for a total of 337 sites.

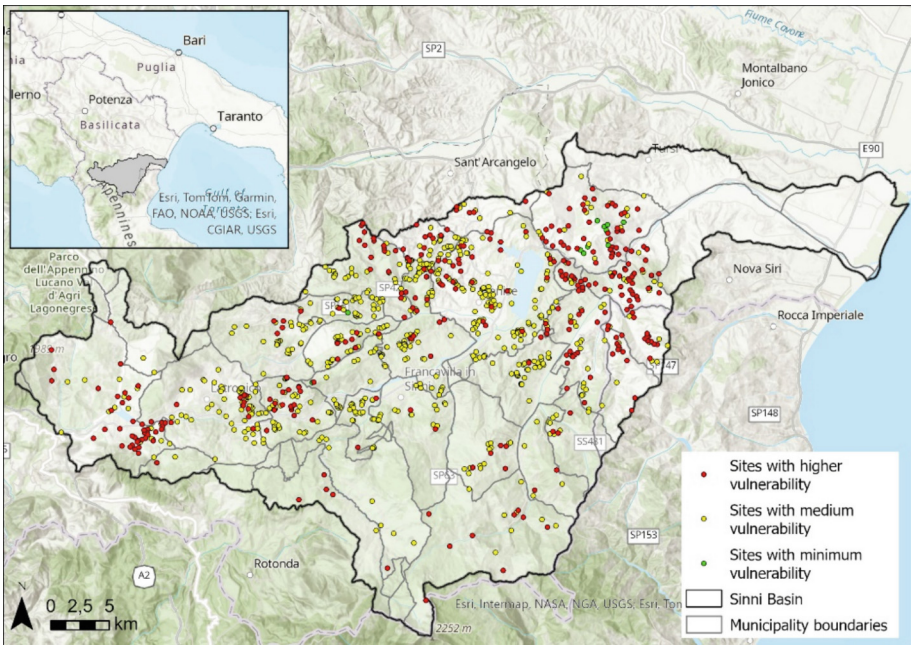

Fig. 1. The study area: the Sinni Valley sites and the catchment of the Sinni River.

4 Results

4.1 Vulnerability Assessment

With the purpose of estimating erosion in the past, at the present and under a future scenario modified by climate change, the first step consisted in computing at risk areas.

Consequently, the three classes of sites characterized by a different vulnerability level of vulnerability, as defined in the previous paragraph, were investigated with the NNIs and KDE, in order to obtain vulnerability areas. According to the NNI found, the z-score and the p-value (Table 1), it emerges that sites with minimum vulnerability have a random distribution, while sites with medium and maximum vulnerability have a clustered distribution.

Afterwards, the NNED were introduced as bandwidth for KDE, in order to find areas more vulnerable, from the archaeological point of view, by erosion (Fig. 2). For

what concerns the other KDE parameters: the sum of the occurrences of each site in the different epochs was used as the intensity; a cell size of five meters was set; the Epanechnikov's kernel was chosen, in order to consider a finite spatial relationship between the sites. The KDE results (Figs. 2, 3, 4) were classified in quantiles. For the sites with minimum vulnerability two classes were sufficient, instead for the medium and maximum vulnerability five classes were highlighted.

Table 1. NNIs found for the three classes of sites with different vulnerability level.

Index	Sites with minimum vulnerability	Sites with medium vulnerability	Sites with maximum vulnerability
NNOD (m)	1685,74	400,71	681,63
NNED (m)	2017,03	753,79	1106,61
NNI	0,84	0,53	0,62
z-score	-1,13	-23,09	-13,49
p-value	0,26	0	0

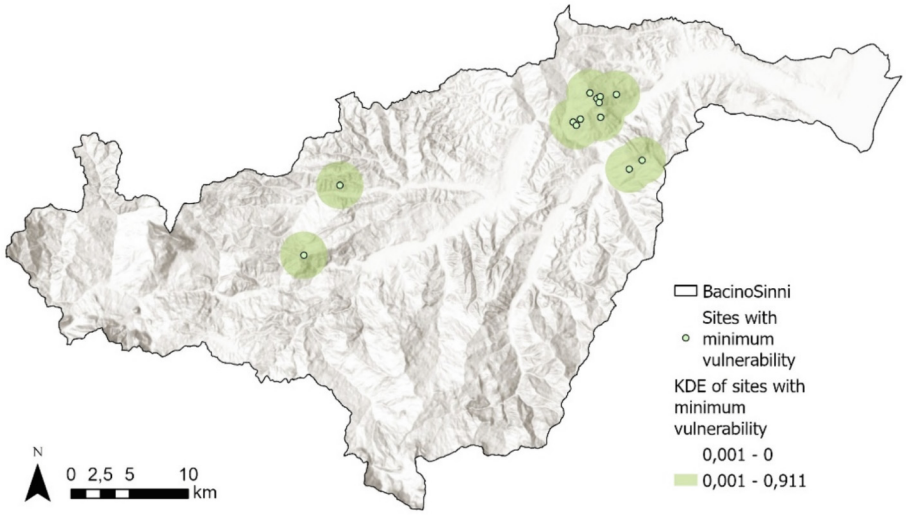

Fig. 2. KDE for sites with minimum vulnerability.

Here a limitation of this method appears, because a better way to proceed to find vulnerability areas would be to use, instead of a simple area of influence, predictive archaeological models [35, 36] calibrated for each historical era identified within the sites and taking into account the different environmental parameters present in the study area. However, the KDE is sufficient for a rough estimation of how much erosion affects the distribution of clustered sites such as these and their landscape context.

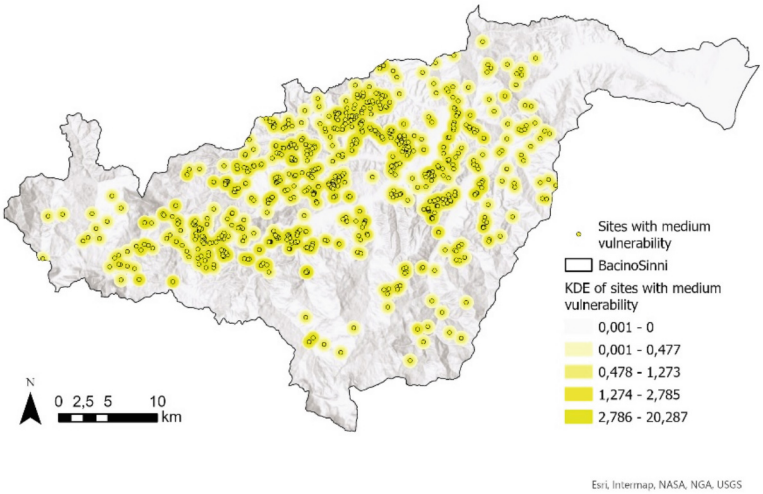

Fig. 3. KDE for sites with medium vulnerability.

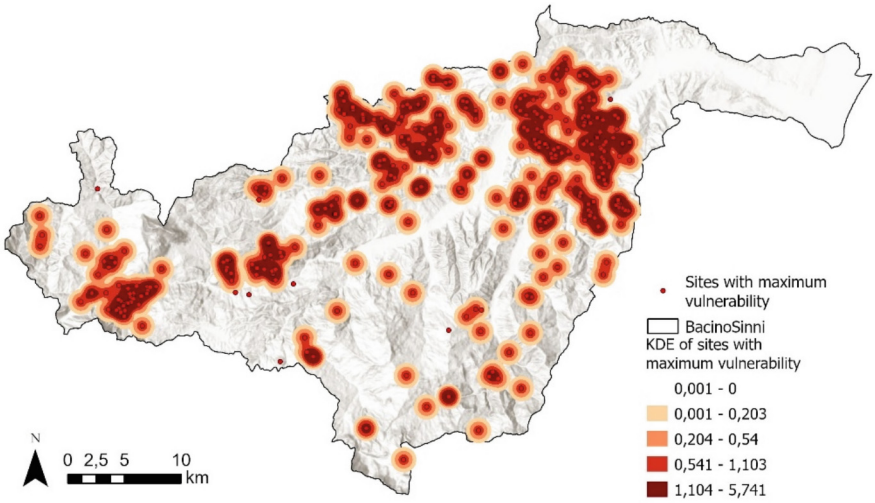

Fig. 4. KDE for sites with maximum vulnerability.

4.2 USPED Computation

For USPED computation, the following parameters were calculated:

1 The study area was classified, for each period, into eight land-use classes: (1) urban, industrial, and commercial area; (2) arable land; (3) fruit tree, vineyard, and olive groves; (4) pastures and natural grasslands; (5) forest area; (6) water. Values were assigned to these classes for the calculation of the c-factor for the different years with values used in the literature [14].

2 The rainfall intensity factor (*R* factor) was calculated taking into account a time range from 2000 to 2020 for 21 stations: Agromonte, Armento, Carbone, Castelluccio Inferiore, Castelsaraceno, Cersosimo, Cogliandrino, Lagonegro, Lauria, Missanello, Noepoli, Nova Siri, Nova Siri Scalo, San Giorgio Lucano, San Severino Lucano, Senise, Terranova del Pollino, Trecchina, Tursi, Valsinni and Viggianello.
3 The soil erodibility factor (K factor) was derived from lithological information [37] and shows a range between 0.15 and 0.35.

The slope length and steepness factor map (LS factor) shows a value between 0 and 1700.

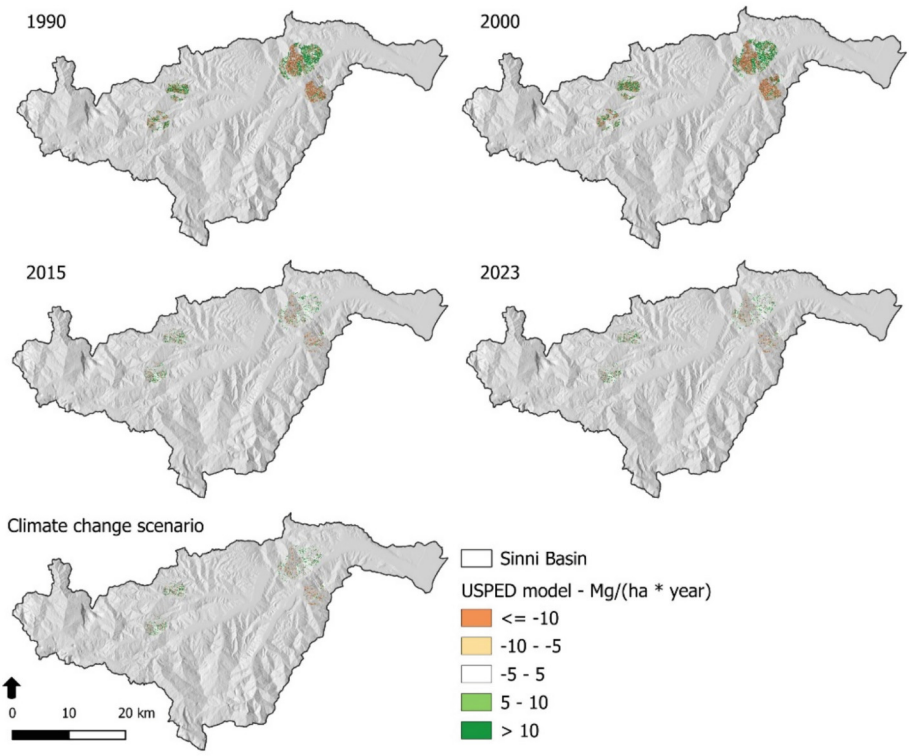

Fig. 5. USPED model for different year and scenarios inside areas with minimum level of vulnerability.

After the erosion simulation using the USPED model, the scenarios were derived from the different input data in the years 1990, 2000, 2015, 2023 and in case of climate changes (Ccs). The difference between the various scenarios depends on the land use at the reference year (c-factor), except for USPED Ccs, which compared to USPED 2023 changes the value of the R-factor taking into account more concentrated and intense rainfall than the current situation.

For all USPED map each pixel was categorized using the five erosion/deposition classes listed below:

- High erosion (<-10 Mg ha^{-1} yr^{-1});
- Low erosion ($-10/-5$ Mg ha^{-1} yr^{-1});
- Stable ($-5/5$ Mg ha^{-1} yr^{-1});
- Low deposition (5/10 Mg ha^{-1} yr^{-1});
- High deposition (>10 Mg ha^{-1} yr^{-1}).

The USPED maps from five distinct periods were overlaid onto maps depicting the vulnerability levels of archaeological sites. The three erosion scenarios for the three vulnerability classes were obtained in this way, resulting the maps in Figs. 5, 6 and 7.

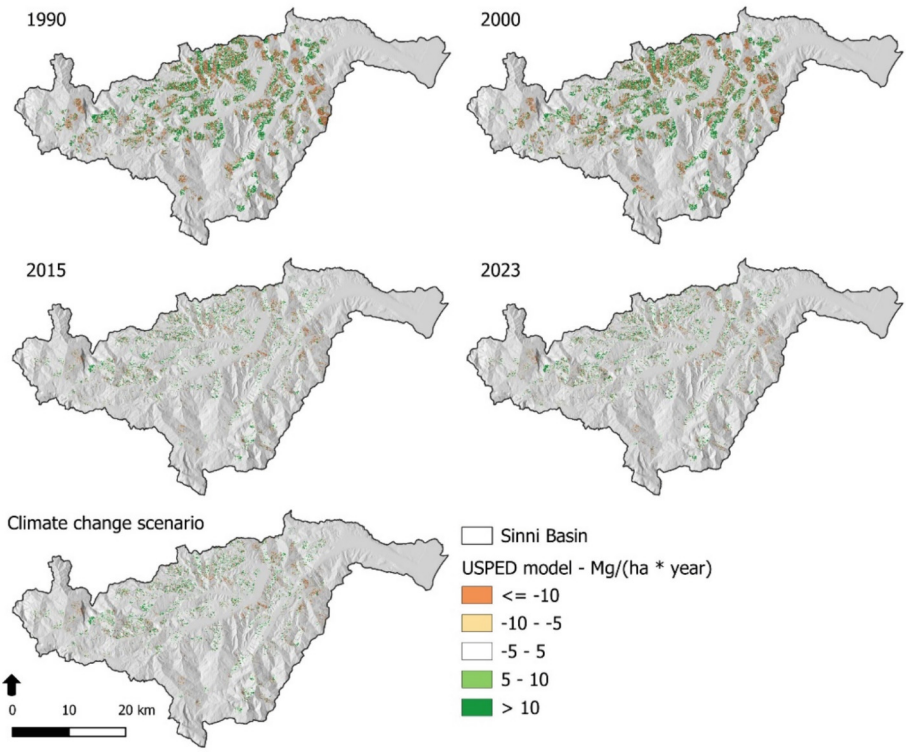

Fig. 6. USPED model for different year and scenarios inside areas with medium level of vulnerability.

The results obtained, depicted in Table 2, show two different behaviors. 1990 and 2000 show values for the stable class for sites with maximum vulnerability of about 28500 hectares, which are significantly lower than the values in 2015, 2023 and Ccs of about 41000 hectares. This trend is also similar for the other two vulnerability classes. The period 1990/2000, having a smaller amount of stable soil, have a larger amount of soil in erosion and deposition than the years 2015, 2023 and Ccs.

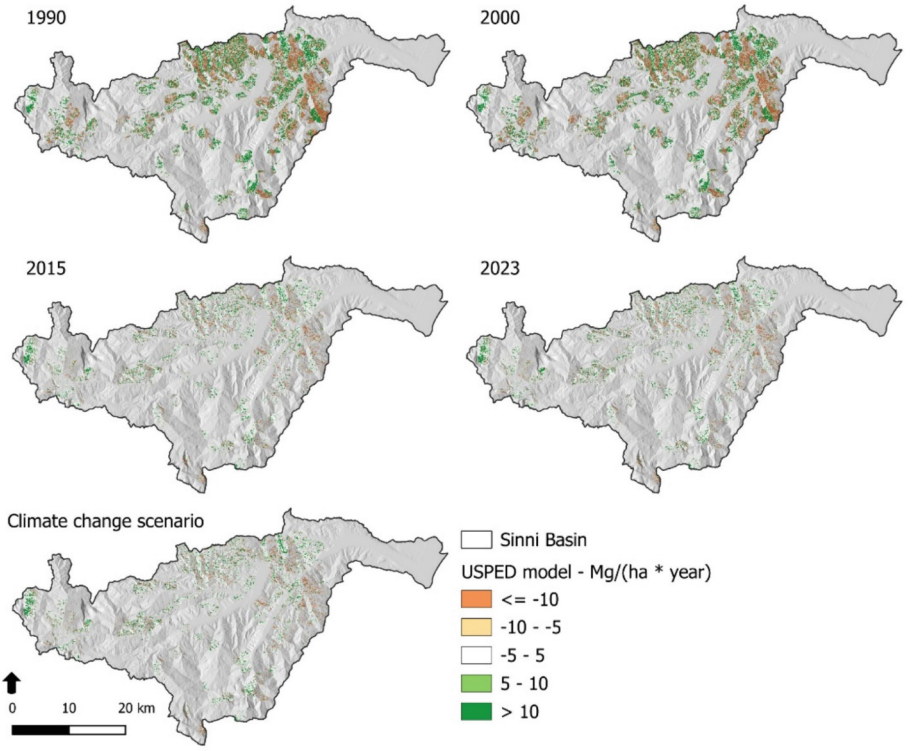

Fig. 7. USPED model for different year and scenarios inside areas with maximum level of vulnerability.

In fact, always taking into account the "maximum vulnerability" class in erosion, we go from about 8500 ha for 1990 and 1700 to about 2000 ha for 2015, 2023 and Ccs. While for deposition in the same vulnerability class it goes from about 9000 ha in 1990 and 2800 to about 3200 ha in the other years taken into account. The trend for the other vulnerability classes is similar.

This different behavior of the two sets of years is due to two different reasons, the first one to the nature of the input data in the USPED model and the second one to the change in land uses. The first difference derives from the different nature of the input data in the c-factor calculation. In fact, for 1990 and 2000, as land-use the CLC dataset was employed; this has a smaller scale and therefore a greater degree of uncertainty and a larger base pixel with a lower capacity to represent the single object (e.g. land-use change). While for the years 2015 and 2023 (also for Ccs, having the same land-use as 2023) the input data have a better resolution and consequently also a better representation of reality. The second reason that causes this difference in the dataset (pragmatically to a smaller extent than the previous one) is the change in land use over time. As time goes by, there is an increasing tendency for inland areas, which were previously used for agriculture, to be abandoned, with uncontrolled growth of vegetation. This results in a soil protection effect that tends to decrease erosion and soil deposition.

Table 2. Resulting USPED inside vulnerability areas in hectares for the different scenarios.

	1990			2000			2015			2023			Ccs		
Classes	Min vuln	Med vuln	Max vuln	Min . Vuln	Med vuln	Max vuln	Min vuln	Med vuln	Max vuln	Min vuln	Med vuln	Max vuln	Min vuln	Med vuln	Max Vuln
High erosion	1693	7694	8471	1850	7907	8570	433	1791	2027	358	1769	1988	405	1996	2238
Low erosion	209	1047	1104	197	1091	1159	173	810	883	164	807	894	173	843	938
Stable	4444	27693	28545	4247	27430	28463	6804	40090	41744	6970	40096	41802	6860	39509	41160
Low depos	199	1136	1229	196	1195	1270	188	1102	1151	171	1053	1115	175	1066	1138
High depos	1536	8830	9336	1591	8778	9225	484	2610	2857	419	2678	2888	469	2988	3213

5 Discussion and Final Remarks

A practical and affordable way to safeguard historically and culturally significant archaeological sites and monuments from environmental and human interference consists of preventive preservation and monitoring. Climate change may amplify cultural heritage exposure to climatic stressors by causing gradual changes in climate, sea level rise, and the occurrence of extreme weather events. In studies issued more than a decade ago, UNESCO underlined the need for greater research on such impacts [38, 39], and as a result, the number of published articles on this topic increased. Cultural heritage can be severely impacted by landslides, flooding, rising sea levels and the effects they have on coastal communities, and other catastrophic changes in the physical environment brought on by climate change [8]. One of the most significant effects of climate change on Europe's cultural heritage is flooding [40]. Europe is expected to see more frequent and larger floods, [41]identified areas that are especially vulnerable. Floods damage various heritage typologies in coastal locations by compounding other losses [42–45].

Increasing storm surge frequency and sea level rise will exacerbate coastal erosion, reshaping the shoreline, and increase the frequency of coastal flooding, which will affect coastal heritage sites. Climate change may increase the effects of eolian and marine processes, such as wave action and currents, on shoreline and submerged archeological sites, increasing erosion and perhaps leading to the collapse of cultural constructions [46]. The reshaping of the beach can affect several heritage typologies, some of which may disappear owing to erosion [47] and coastal retreat, but also due to silt accumulation.

Water-induced soil erosion is one of the main environmental hazards that has put several ancient sites in the Mediterranean region in danger. The detaching, transporting, and depositing of soil sediment on a site can be directly impacted by soil erosion; therefore learning about these two processes is crucial to the management of cultural assets. Increasingly intense rainfall due to climate change will raise the risk of rills/gully erosion [48] and landslides [49, 50]).

The methodology used was primarily focused on assessing the spatial extent and intensity of soil loss and deposition. The USPED empirical model was built by integrating a set of erosion-influencing parameters. USPED's spatial flexibility allows it to model physical erosion processes in a GIS setting. The model can estimate average yearly soil loss and deposition rates, which can then be connected with the archeological sites' topography.

The USPED maps for the different periods considered were intersected with the vulnerability maps given by the KDE (Figs. 2, 3 and 4). As shown in the results, there is different behavior on the areas under erosion/deposition for the different years considering the various degree of vulnerabilities. In conclusion, the paper shows: 1) how the USPED model is greatly affected by differences in the input data (in this case land use) (Fig. 8); 2) how climate change (modelled with rainfall events with the same amount of rainfall but at a shorter time - extreme events) has a fundamental role in the amount of soil erosion/deposition that is very dangerous for the conservation of archaeological sites in the Sinni basin. This is especially visible for the maximum erosion/deposition classes, which have a 20% increase in vulnerable areas compared to 2023 (Table 2 and Fig. 8). This value shows how climate change may endanger many sites/areas/monuments of archaeological interest that do not currently show vulnerability to erosion.

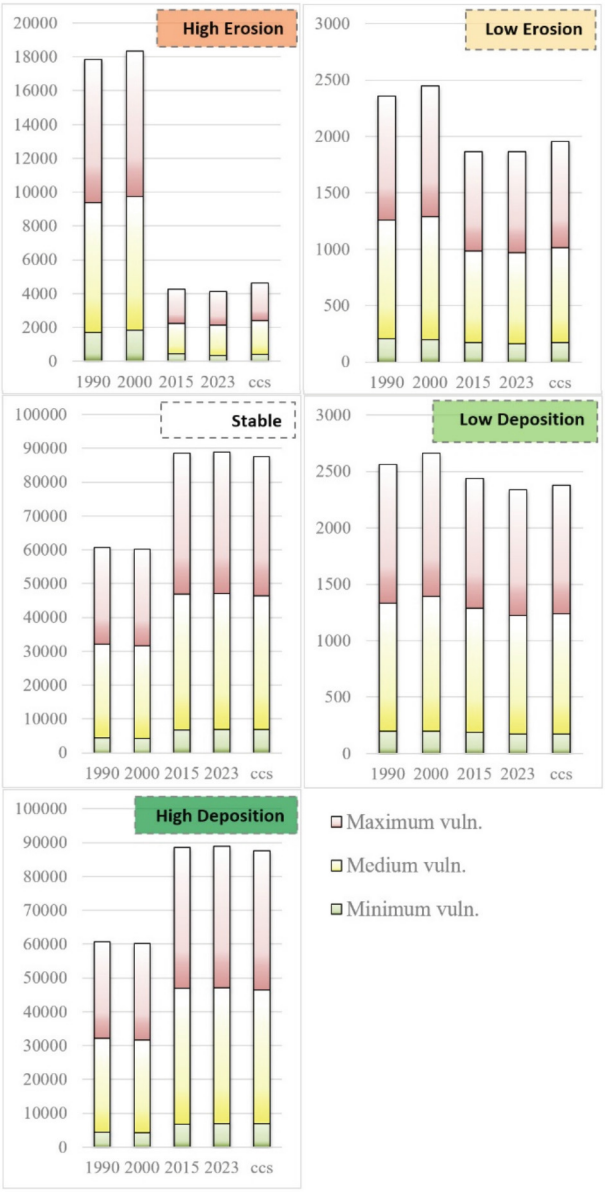

Fig. 8. Comparison between the different classes of USPED model found (in ha), calculated in the different years and scenarios and for the three vulnerability classes.

In this regard, the current study is one of the first to investigate the influence of both erosion-related processes on archeological sites.

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