GeoAI Approach for Analyzing Territorial Specialization in Ecosystem Services Provisioning

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Abstract. The ecosystem services (ES) framework is an emerging topic addressing the issue of promoting sustainability in planning. One of its strengths is its ability to facilitate spatially explicit assessments, which can help elicit conflicts between human and nature in a functional perspective. This study aimed to exploit the informative potential of the ES framework to produce new geographies of the territory based on a formal and quantitative assessment of different levels and categories of territorial specialization in ES provisioning, using innovative geoAI techniques. The research was based on previous studies where ES supply had been computed at the national level and tested on a sample area. The study area included several environmental challenges, socio-economic underdevelopment, and potentials in the tourism sector. The paper discusses how the integration of ES with machine learning techniques enhances the informative potential in spatial explicit classification of a study area. The results show a high degree of spatial interpretation potential derived from the regionalization map in terms of statistical similarity of detected regions. The study concludes by highlighting the need to better define the concept of territorial specialization in ES provisioning to reinforce the methodological proposal extending to other relevant case studies.

Keywords: Ecosystem Services · geoAI · regionalization · spatial planning · unsupervised ML

1 Introduction

Ecosystem Services (ES) refer to the valuable services that nature provides to human societies, such as clean air and water, nutrient cycling, pollination, and climate regulation. It provides a robust methodology for evaluating the tradeoffs associated with land-use transformations, with relevant implication on Green Infrastructures [1, 2] and nature conservation policies [3, 4] and, widely, on the emerging topic of zero land take. ES framework reinforced, even if still not included in the normative planning framework, the monitoring capacity of Public Bodies entitled with competences and responsibilities in planning to detect and quantify land use transformation process [5–7]. The result is an extended potential to inform decision-makers and to let them aware of the costs or benefits

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of these changes, taking into account both the direct and indirect impacts on ecosystem services. The ES framework also enables the identification of complex dynamics between ecosystems and human societies, and promotes communication and joint implementation among stakeholders at different levels of governance [8, 9]. One of the key strengths of the ES framework is its ability to facilitate spatially explicit assessments, which can help identify areas where ecosystem services are most valuable and prioritize conservation efforts. Ultimately, the ES framework promotes sustainability in planning by elicitating the conflicts between human and nature in a functional perspective for humans.

This study is oriented to exploit the informative potential of ES framework in order to produce new geographies of the territory based on a formal and quantitative assessment of different levels and categories of territorial specialization in ES provisioning. In order to achieve this challenging objective the research was based on the application of innovative geoAI techniques according to the need to exploit the informative complexity derived from ES multivariate spatial appraisal without any ex-ante simplification of the information model.

The approach was based on previous studies where ES supply had been computed at national level (Italy) and tested on a wide sample area: the Province of Potenza in Basilicata region. This context includes several characterizing spatial features such as various environmental challenges, including air and water pollution, deforestation, and the depletion of natural resources, land take, socio-economic underdevelopment, potentials in tourism sector etc.

The paper starts to define how ES, integrated with ML techniques, extend the informative potential in spatial explicit classification of a study area. The third section describes the research methodology, input data and computational stages of the analysis.

In the fourth section the results are discussed expressing the high degree of spatial interpretation potential deriving from the regionalization map in terms of statistical similarity of detected regions. Conclusions presents main strengths of the approach and relaunch the need to better define the concept of territorial specialization in ES provisioning in order to reinforce the methodological proposal extending to other relevant case studies.

2 Ecosystem Services: From Multifunctionality to Specialization Perspective

The concept of Ecosystem Services (ES) has gained significant attention in recent years as a means of quantifying the benefits that ecosystems provide to human societies [10, 11]. The framework is based on the idea that nature provides a range of valuable services to people, including clean air and water, nutrient cycling, pollination, and climate regulation, among others. These services are crucial to human well-being and are often taken for granted.

ES provides a robust methodology for evaluating the tradeoffs associated with land-use transformations [12]. As human populations grow and expand into new areas, the need for land use changes increases, often at the expense of natural ecosystems. ES analysis can help decision-makers evaluate the costs and benefits of these changes, taking into account both the direct and indirect impacts on ecosystem services.

Moreover, the ES framework enables the identification of complex dynamics between ecosystems and human societies. By quantifying the benefits of ecosystem services, ES analysis can help stakeholders understand the links between human well-being and natural systems. This can help policymakers to develop more effective policies that balance the needs of society with the long-term health of ecosystems.

One of the key strengths of the ES framework is its ability to facilitate spatially explicit assessments. By mapping the distribution of ecosystem services, stakeholders can identify areas where these services are most valuable and prioritize conservation efforts. This approach can also help to identify areas where development may have the greatest impact on ecosystem services, enabling decision-makers to take a more informed approach to land-use planning [3–5]. Finally, the ES framework promotes communication and joint implementation among stakeholders at different levels of governance.

In particular we refer to ES framework as a powerful tool for decision-making in planning [6]. It enables the evaluation of tradeoffs associated with land-use transformations, identifies complex dynamics between ecosystems and human societies, facilitates spatially explicit assessments. The framework has the potential to promote more sustainable land-use practices that balance the needs of society.

The goal of this work is to learn more from ES assessment through a robust methodology [3, 13–16] that exploits the spatial relevance of ES information. Specifically, the aim is to define a first method for ES specialization analysis using ML regionalization tools [17]. In a general perspective, the results are intended to contribute to land-use planning practices, although many relevant sectorial planning processes may also benefit [18].

The land-use planning system faces structural weaknesses from both regulatory and informative perspectives [19–22]. The lack of flexibility of conventional zoning and prescriptive models applied in urban and regional plans is the first aspect of concern. Recent studies have analyzed the concept of ES multifunctionality as a way to take advantage of the multiple contributions that ES analysis defines in a specific territorial unit (Land Parcel). We refer to the Regulation and Maintenance Ecosystem Services (ReMES), previously computed by Pilogallo and Scorza [12], to consider a relevant stock of ES and scale down analytical tools to a specific study area.

We consider ReMES, defined by the Common International Classification of Ecosystem Services (CICES) [23], as "all the ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort, together with abiotic equivalents." Although not directly consumed, ReMES has a strong influence on the environment's ability to contribute to the quality of human life.

This paper analyzed in detail the close relationship between ecosystems and human well-being by highlighting the value of pinpointing specialized areas of beneficial delivery in policy and decision-making to land-use planning. In fact, the proposed model aims to explicit the values of environmental conditions and resources that link measures of ecosystem specialization to identified spatial functions in the land. This framework is geared toward measuring the multiplicity of services, functions, and benefits that ES provide in a specific spatial context. Environmental service variety has been widely recognized as a fundamental aspect of ecosystem functioning that can yield a plethora of ecological benefits. A variety set of ES provided habitats and species protection and

improvement, which coincides with biodiversity conservation and enhancement. This is useful because maintaining a functional heterogeneity of the territory ensures the preservation of biodiversity, greater adaptability to climate change, and ensures usability to different beneficiaries [24, 25].

This work develop a preliminary attempt to put in practice the concept of "specialization in ES provision". The perspective is to consider "specialization" not as the prevalence of one ES function over the other, but, rather, is intended to make explicit the complexity that environmental characteristics generating the provision of ES in a specific context (region). Measuring the level of specialization of an area, in comparison with other areas, is a topic widely developed in the ecological field on the bases of broad theoretical framework.

The concept of specialization, in the view of the authors, has to be considered as a geospatial problem generally known as the "Modifiable Areal Unit Problem (MAUP)" and, in these terms, has been faced by the means of robust of statistical analyses. MAUP deals with the choice of spatial units used to aggregate data and through which phenomena are visualized and analyzed [26]. This approach completely suitable to answer key urban studies questions related to the need to reinforce the analytical approaches capacity in managing spatial information complexity. The analysis of geospatial phenomena as well as the definition of regional specialization of ES requires the use of Geographic Information Systems (GIS) techniques, which enable the collection, analysis, and visualization of spatial data. However, the investigation of complex spatial phenomena, such as the search for sub-areas that take into account multidimensional geospatial information, may require the use of more advanced techniques, as traditional GIS methods may no longer be adequate, 'technical debt' [27, 28].

A new paradigm for geospatial technology is already in the pipeline and looks poised to take the stage in the upcoming new geospatial era [29]. Specifically, GeoAI is an interdisciplinary field that draws on a variety of disciplines, including mathematics, computer science and geography that enables the decoding of geographical challenges, with the aid of geospatial Big-data, and without any simplification or loss of valuable information [30, 31]. Wenwen Li illustrates the conceptual three-pillar of GeoAI: geospatial Big-data, computing power and innovation in Artificial Intelligence (AI). Indeed, the increasing availability of large-scale geospatial data can benefit various fields, including all the social sciences, through the use of innovative technologies like GeoAI [32]. By combining the strengths of Geography and AI, researchers can develop comprehensive and effective contribution to decision makers in developing effective strategies for managing spatial phenomena and promoting sustainability [33, 34].

3 Materials and Methods

The paper proposes a data-driven methodology for identifying new geographies of territorial specialization in the provision of ES. This constitutes a contribution to the innovation of spatial analysis techniques for complex phenomena that are fundamental in the context evaluation processes for sustainable planning of land use and transformation decisions. The selected analytical tools are Machine Learning (ML) algorithms, which have proven to be highly effective and statistically robust [35]. The adopted approach

is data-driven, thus, no ex-ante hypotheses have been formulated that simplify the complexity of the analytical dimension [36]. GeoAI allows for the consideration of all the informative complexity of the reference data lake, evaluating the relationships between data. In particular, regionalization is considered as a preliminary phase in the process of defining the concept of specialization for the ES of a particular territorial area.

The base spatial datasets used for the analysis were derived from the material provided and discussed in previous researches [15]. The following ES classes are included in the category of Regulation and Maintenance Services (ReMES) according to the CICES classification:

- Regulation of chemical composition of atmosphere;
- Control of erosion rate;
- Hydrological cycle and water flow regulation;
- Maintaining nursery populations and habitat;
- Pollination.

The methodologies used for evaluating the ES were selected from the suite of InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models. This is a set of models developed by Stanford University within the "Natural Capital Project" (Natural Capital Project, n.d.), InVEST [37] covers most of the evaluation requirements of the services considered for subsequent analyses. For each of the analyzed ES, corresponding maps were produced for the year 2018. The input database covers the whole Italy, but for the purposes of this research only the territory of the Province of Potenza was considered.

Input dataset refers to the following ES categories:

1. Carbon storage and sequestration (c_stock): This model estimates the amount of carbon (ton/ha) in relation to land use categories, referring to four major natural pools: aboveground biomass, belowground biomass, soil, and dead organic matter.
2. Sediment delivery ratio (SDR): This model calculates the amount of eroded sediment for each pixel and estimates the sediment transport coefficient (SDR) that represents the portion of sediment that actually reaches water bodies. The result is an erosion value per unit area (ton/ha).
3. Nutrient delivery ratio (NDR): This model estimates the surface flow of pollutants (N and P) by calculating a mass balance (nutrient load per pixel) combined with information on land morphology. The result is a nutrient delivery ratio value (kg/ha).
4. Water yield (w_yield): This model estimates the relative contributions of water from different parts of a landscape, providing information on how changes in land use patterns affect annual surface water yield and hydroelectric power production.
5. Crop production (c_prod): This model estimates the average yield (q/ha) of crops (in this case, wheat) and the value of nutrients for a fixed set of crops, derived from user-provided land cover information.
6. Crop pollination (I_abu, I_supp): This model provides an estimate of the abundance of pollinator species per unit area, calculated based on the suitability of the area for nesting and the presence of food.
7. Habitat quality (quality, deg): This model combines information on land use, their ability to support animal and plant species (i.e., biodiversity in a broad sense), and threats to them, resulting in a relative quality map (Habitat Quality) and a degradation

map (Habitat Degradation) of habitats in a range of variation from a minimum (0) to a maximum (1).

The Input data was scaled on the study area boundaries: the territory of the province of Potenza (NUTS2). The main city in the area is Potenza, the regional capital, where most of the population is concentrated and where the main citizenship services are offered. The second largest city in the province, by population, is Melfi, located in the northern part. The rest of the territory has a polycentric settlement structure consisting of small secondary centers and a widespread tendency towards the abandonment of rural settlements by residents in favor of more recently developed areas.

The Provincial Authority, entitled of territorial planning, mapped the Naturalistic Environmental System (SNA) for the Provincial Structural Plan of Potenza in 2013. This analysis highlighted the complex and extensive environmental system of the study area. In particular, there are areas with high naturalness, such as the Vulture area to the north, characterized by geomorphological and naturalistic singularities, already a Regional Reserve of Monticchio. The system runs along the entire Apennine range across three different Parks and ends to the south with the massif of Pollino, the largest protected area in Italy and one of the largest in Europe.

On the bases of the analytic methodology, from each of the national ReMES input maps, SE values were extracted at the provincial level using a regular grid of 178064 points (200 m). The grid works as a control matrix and allowed to develop a database including all statistical characters for each control point identified by the grid.

The dataset was analyzed and corrected for any sampling errors or null values. The subsequent Feature Engineering operations also allowed for the preparation of the dataset for GeoAI algorithms. This process was necessary to improve the performance of ML algorithms.

The Regionalization algorithm (AgglomerativeClustering) was selected in order to account both the statistical variance of characteristics of the spatial relationships in the process of formation of regions [17]. In this regard, the spatial contiguity condition was implemented with the Rook model, applied to a polygonal mesh obtained by applying Voronoi Polygons on the control grid. The Regionalization algorithm is based on a hierarchical agglomerative strategy that takes into account attribute similarity through the linkage criterion (dist) and adds the spatial constraint through the Connectivity matrix (W).

A critical step in the regionalization technique is to define the number (K) of regions that yields a significant result in both statistical and territorial interpretability terms [38, 39]. To identify this critical value, the process was iterated for K values ranging from [10–2000]. The validation process relied on criteria defined in the literature.

Based on this result, the concept of region specialization was explored in-depth. Initially, this concept of specialization was investigated within the dataset using purely statistical approaches. Specifically, the statistical distance between the centroids of each region within the feature space was evaluated as a multidimensional vector using the NearestCentroid algorithm. Finally, analysis of the resulting similarity matrices allowed for mapping the statistical similarity of each region relative to others, which through an empirical comparison approach, enabled identification of regions specialized in providing SE.

4 Results and Discussions

As a result of the whole analytical process, the ES values extracted from the national ReMES maps on the support layer at the provincial (NUTS2) scale represents a valuable dataset also for other applications. It results in a structured database of 178065 features and 9 statistical attributes. Each feature represents a control point of the grid and reflects the associated multidimensional information.

The dataset expresses a multidimensionality of territorial information useful to support subsequent analyses.

The analysis of the literature metrics and the territorial interpretability of the results of the Regionalization algorithm led to indicate K = 200 as the representative number of regions for the study area. The following figure (Fig. 1) shows the map of the 200 regions and the graphs of the criteria adopted in choosing this value.

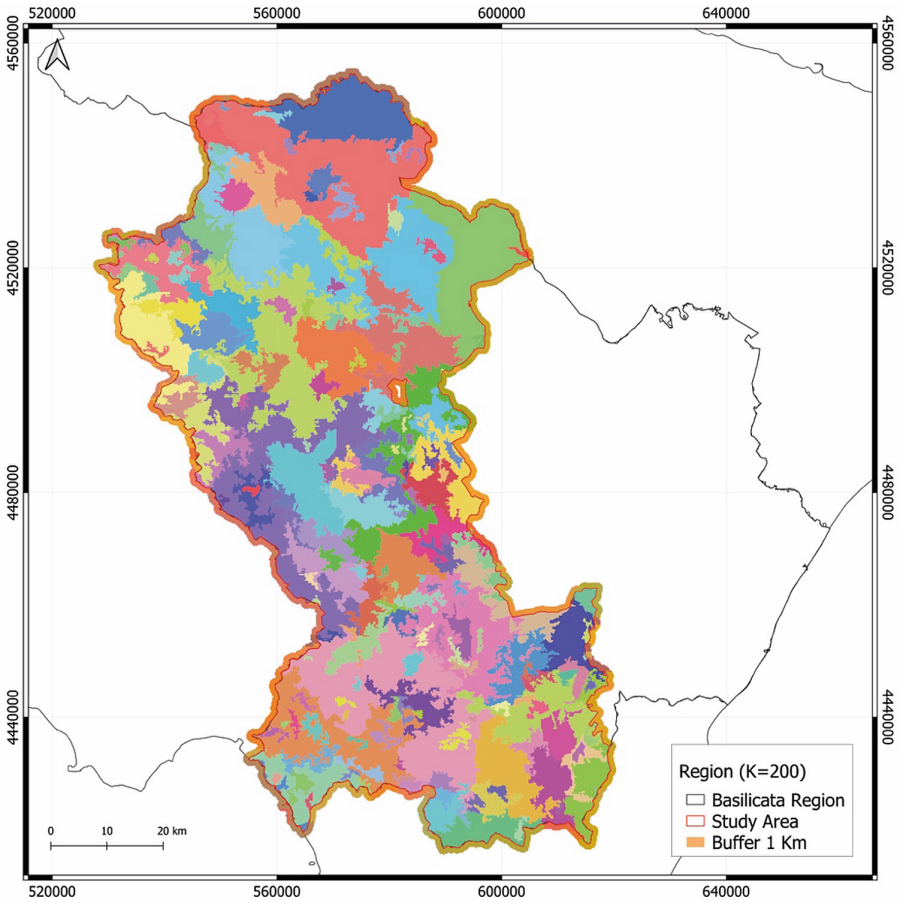

Fig. 1. Regionalization output

The map highlights how the regionalization for K = 200 regions offer a geographically consistent subdivision with the territorial scale of analysis and is particularly useful for evaluating the ES specialization of regions.

Based on this map, the concept of statistical similarity-based specialization of regions was further investigated. The map was classified on a chromatic scale into 5 equal intervals. The lighter tones show the similarity of attributes between regions, while the progressively darker tones highlight strong dissimilarity.

Figure 2 shows the result of this similarity analysis with respect to the region corresponding to the urbanized area of the municipality of Potenza.

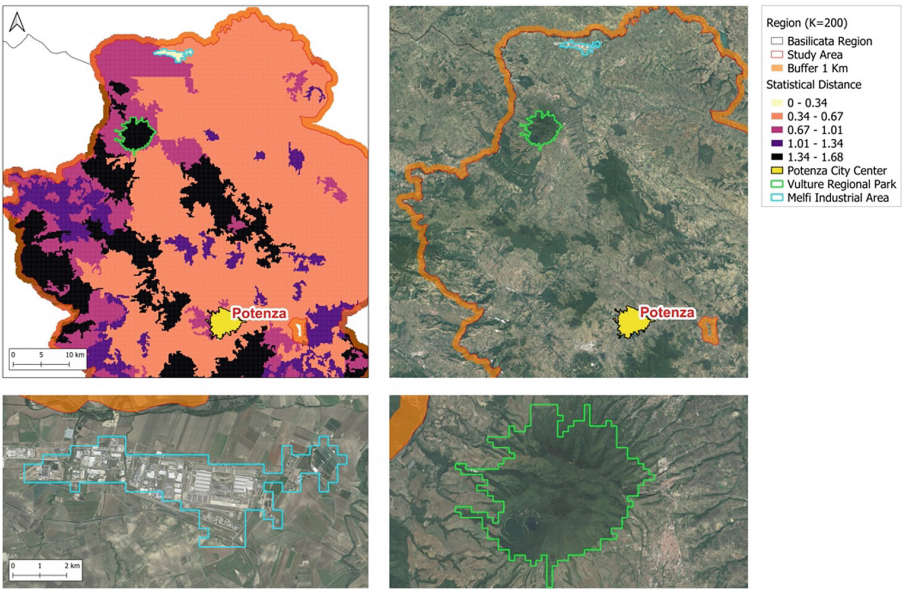

Fig. 2. Statistical similarity-based specialization map of the municipality of Potenza.

Compared to the distribution of the features, this region presents particularly high values of land degradation (deg), while the low values are related to the environmental quality characteristics (quality), the ability to store carbon (c_stock), and the presence and availability of pollinator species in the area (I_abu and I_supp).

This region, recognized as a homogeneous territorial unit in terms of settlement characteristics, shows a peculiar condition compared to the entire study area that makes it strongly dissimilar to those of the provincial territory with a greater naturalistic and environmental vocation. The maximum statistical similarity is evident only with the region that coincides with the industrial complex of Melfi, a heavily urbanized territorial context that shares similar characteristics in terms of environmental quality and degradation.

5 Conclusions

This paper proposes a methodology that integrates spatial evaluations of Ecosystem Services (ES) to define a measure of territorial specialization of ES supply. Such analyses lead to the identification of sub-regions specializing in the provision of specific ES. The concept of specialization, which could be further investigated in relation to research developments, represents a useful decision-making variable to guide territorial governance and management towards more sustainable scenarios.

The analytical procedure, defined to evaluate the spatial distribution of the considered phenomena, is based on the application of robust regionalization algorithms, specific to Machine Learning (ML), trained on a multivariate territorial information dataset. The outputs have been validated through statistical metrics defined in the literature.

The results highlighted the potential of the method, which has allowed the definition of new spatially homogeneous geographies for ES provisioning but also for other complex territorial phenomena [40–45]. The regionalization phase is a preliminary step for identifying specific territorial functionalities in terms of ES provision.

Therefore, the regionalization into homogeneous areas with respect to the characteristics of ES supply integrated with measures of statistical similarity to improve precision and robustness, allowed to overcome the concept of multifunctionality of ES proposed in previous studies.

In conclusion, the analysis of complex spatial phenomena and the identification of potential territorial areas suited for ES provision can offer new interpretations of the territory in the context of the functions and responsibilities [9, 45] that the Province of Potenza influencing multiple sectors: from renewable energy policies [46–48] to tourism development [39, 40, 49–51], from land take to natural capital preservation [5, 52].

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