Smart Innovations in Biosphere Reserves

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Abstract. The paper aims to define the smart innovations in biosphere reserve from the theoretical point of view and subsequently, identify the examples of good practice in their real conditions, based on it summarize the key features of smart innovation in biosphere reserves. The smart innovation is interpreted as a comprehensive ecosystem of solutions based on the use of digital technologies, data analytics, and interconnected systems enhancing process efficiency and support the sustainable development of regions. The paper draws on the theoretical foundations of innovation theory and collaboration models, particularly the Quintuple Helix model, which emphasizes collaboration between the public sector, the business sector, the academic community, civil society, and the natural environment. Special attention is given to the application in the context of biosphere reserves, where it is essential to respect nature conservation requirements while simultaneously supporting socio-economic development. The empirical part of the paper presents selected examples of good practice in smart innovations within biosphere reserves, which are subsequently analysed and discussed in relation to theoretical frameworks. The results highlight the importance of linking technological solutions to the needs of the area and the necessity of local stakeholder participation. The conclusion emphasizes that smart innovations represent a tool for achieving a balance between biodiversity conservation and sustainable development, with biosphere reserves serving as experimental sites for their implementation.

Keywords: Smart innovation · biosphere reserve · innovation ecosystem

1 Introduction

Innovation is widely recognized as a fundamental determinant of spatial competitiveness and long-term economic performance. Regions that successfully generate, adopt, and diffuse innovations tend to achieve higher productivity, greater value creation, and improved living standards. From an economic perspective, innovation contributes to growth through three principal mechanisms, namely new products or services, qualitative improvements in existing products and their characteristics, and increases in production efficiency and organizational effectiveness.

According to the Oslo Manual, innovation is defined as the implementation of a new or significantly improved product, process, or method within business practices, workplace organization, or external relations [1]. Thus, innovation does not refer merely to

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invention but to the practical application of knowledge that creates measurable economic or social value.

Innovation is not confined only to private firms but also plays a crucial role in public sector and regional development policy. Consequently, innovation capacity becomes a central component of regional development strategies and an essential prerequisite for the sustainable competitiveness of territories [2].

A new dimension of innovation has been driven by the advances in information and communication technologies, often captured by the term "smart". Such innovations leverage modern technologies to create personalized solutions based on data analytics, thereby better meeting users' needs. Moreover, in the case of biosphere reserve, they should reflect also the specific of this type of territory and limits given by its protection. Here we can identify the gap in research, in theory as well as in practice. It lies in addressing issue of smart innovations at the intersection of innovation theory, digital technologies, and environmental management of biosphere reserves. That is why the aim of the paper is to define the smart innovations in biosphere reserve from the theoretical point of view and subsequently, identify the examples of good practices in their real conditions, based on it summarize the key features of smart innovation in biosphere reserves. So, the added value of the paper is theoretical and empirical conceptualisation of the smart innovations in context of biosphere reserves.

In the paper, the theoretical section defines the key concept of smart innovation and applies it to the context of biosphere reserves. It also uses deduction and analogy to characterize the typology of smart innovations. The second part of the paper defines the research materials and methods. The third chapter presents selected examples of good practice in smart innovation within biosphere reserves. This is followed by a scientific discussion of the identified examples in relation to theoretical foundations, concluding with a summary of the specific characteristics of smart innovation in biosphere reserves.

2 Smart Innovations in Biosphere Reserves

The concept of smart innovation represents a paradigm shift in contemporary economic science in understanding the relationship between technological progress and socio-economic development. Smart innovation, often associated with regional development and digital transformation, is finding increasingly wider application in the specific context of biosphere reserves (BR), where technology is becoming a tool for achieving a balance between biodiversity conservation and sustainable socio-economic development in line with UNESCO's Man and the Biosphere (MAB) program [3].

Smart innovations in the context of BRs are not just a derivative of technological determinism, but a complex ecosystem of interconnected solutions using cyber-physical systems (CPS). While Schumpeter [4] defined innovation as a process of "creative destruction," in the "smart" era, this process is transforming into continuous adaptive optimization through data flows and interconnected systems [5].

The key theoretical pillar of smart innovation is the Triple Helix model [6], which assumes synergistic interaction between universities, industry, and government. This cooperation is essential for the emergence of so-called "smart specialization," which the European Commission promotes as a strategic framework for regional development [7].

However, in the context of BR, it is necessary to expand this model with a fourth element—civil society (the so-called quadruple helix), which emphasizes the participation of local communities and citizen science [8, 9] and a fifth element – natural environment in which knowledge moves in a circular fashion from system to system, generating new knowledge and innovations oriented towards sustainable socio-ecological transformation (the so-called quintuple helix model) [10, 11].

In the context of territories, smart innovations manifest themselves through the Smart City concept. According to Giffinger et al. [12], this concept is based on six smart pillars: economy, mobility, environment, people living, and smart governance. These pillars are also adaptable to BR, where their focus is primarily on the needs of protection, sustainable and resilient development of the territory.

Smart innovations are inextricably linked to the fourth industrial revolution, which brings a fusion of technologies that blur the boundaries between the physical, digital, and biological spheres [13]. Key technologies include the Internet of Things (IoT), artificial intelligence (AI) and machine learning, big data analytics, and others [5].

Critical discussion in the field of smart innovation points to the need to move from a purely technological focus to an anthropocentric approach known as Society 5.0. This concept, defined primarily for the Japanese government [14], envisions the use of smart innovation to address global challenges such as the climate crisis, in line with the UN Sustainable Development Goals (SDGs). Biosphere reserves are "learning sites" where smart innovations contribute to ecosystem resilience and a deeper understanding of complex systems [8].

In scientific literature (e.g., according to authors such as Schiavone [15], Greco, and Bencardino [16] or in the context of EU Smart Specialisation strategies), smart innovation can be defined as the process of applying digital technologies, data analytics, and connectivity to existing or new products, processes, and services in order to increase their efficiency, adaptability, and value to the user, often integrating aspects of sustainability and networking. Simply put, smart innovation is not just about doing something "better," but about adding "intelligence" to the system—the ability to collect data, learn from it, and respond autonomously or semi-autonomously to changes in the environment. The difference between traditional and smart innovation is not just in the use of more modern technology, but in the overall approach to solving the problem. While traditional innovation focuses on improving functionality, smart innovation adds a layer of intelligence and connectivity. Traditional innovations are characterized by static, independent functioning, while smart innovations are dynamic and often part of a network. For example, data collection in smart innovations is automatic and continuous, maintenance is provided by an algorithm, device decision-making is independent or semi-autonomous, and updates are done remotely.

While traditional innovation makes things better, smart innovation makes things smarter. Smart innovations use a feedback loop, where data from use continuously optimizes the process. On the other hand, some authors also draw attention to negative externalities of smart innovations. For example, Zuboff [17] introduces the term "surveillance capitalism," where human experience becomes a free resource for hidden commercial practices. This asymmetry of power is a major barrier to the socially just implementation of smart innovations. It is therefore essential to ensure that smart innovations in BR

primarily serve the good of the community and the protection of nature, and not just commercial interests. When introducing smart innovations into the BR environment, it is therefore important to bear in mind that they should serve as a catalyst for ecosystem resilience, not as a substitute for nature conservation

2.1 Taxonomy of Smart Innovations in BR

The scientific classification of smart innovations goes beyond the scope of conventional product innovation [5]. According to Rowley [18] and Quinta et al. [19], they can be categorized based on their functional application and technological depth. They list the following types of innovations - incremental smart innovations (optimization of existing systems using sensors, e.g., adaptive lighting), radical (disruptive) smart innovations (the emergence of completely new data-based business models, such as the "Product-as-a-Service" model) and socio-technical innovations (solutions where technology serves as a mediator of social change, e.g., blockchain in participatory budgeting).

According to the degree of originality, innovations can be divided into imitative and original. Imitative innovations involve the adoption or adaptation of solutions already implemented elsewhere and verified in practice. In contrast, original innovations represent the realization of entirely new ideas, concepts, or technological solutions [20].

In biosphere reserves, based on these authors, empirical evidence, and our own research [1, 5, 26] we have identified the following types: technical and technological innovations, process innovations, economic, process, and social innovations.

Technical and technological innovations form the core of digital transformation in BR, focusing on the physical properties of products (hardware, sensors) and changes in scientific know-how and algorithms [22]. In BR, they are transformed into so-called "Conservation Tech," which is a transition from isolated machines to cyber-physical systems (CPS). Most often, these can be IoT networks, e.g., for real-time monitoring of microclimate, soil moisture, and groundwater levels, which is key to predicting fire risk and drought impacts. Fassnacht et al. [23] for example, write about AI in phytocenology in the form of multispectral imaging from drones and satellites, with the aim of identifying, for example, invasive species or bark beetle calamities using neural networks. A very interesting possibility for technical innovation is the creation of a digital twin of BR. The creation of virtual models of BR (Digital Twins) based on satellite data and ground sensors can be used to simulate the impacts of climate change or the spread of invasive species [24, 25], but also the extinction of certain species or the impacts of human activity on biodiversity. Beyond the traditional static modeling tools, digital twin is a dynamic, virtual representation of a physical object continuously updated using sensor data and near-real-time information. A digital twin reflects the current state and behavior of its real-world counterpart, enabling ongoing analysis and prediction.

Process innovations are generally linked to the substantial changes in production or delivery methods, including improvements in service provision. In case of biosphere reserves, they are focused on implementing new or significantly improved methods of management and nature conservation. According to Davenport [26], this involves a radical rethinking of processes with the aim of achieving significant improvements in costs and quality.

One form of this can be, for example, Precision Conservation, which means a transition from periodic field research to real-time monitoring. This form helps to maximize data collection while minimizing anthropogenic impact (human impact on nature).

Economic innovations are changing the market structure and internal organization of local communities in biosphere reserve. They are mainly focused on monetization strategies. The smart economy in biosphere reserver is changing the way local communities profit from nature conservation without degrading it. In practice, this may involve the tokenization of ecosystem services, the use of blockchain for transparent payments for ecosystem services (PES). Local farmers can receive digital tokens for measurable increases in biodiversity on their land [27, 28].

Process innovations are changing culture and management [29], or substantial changes in production or delivery methods, including improvements in service provision [1]. In biosphere reserves, the most significant innovation in recent years is a participatory biosphere reserve management. This form can be further developed, e. g. to e-Governance of biosphere reserves through transparent decision-making processes on land use via digital platforms, reducing conflicts between conservationists and farmers [5]. Another process innovation could be various forms of smart ecotourism, e.g., through the use of augmented reality in visitor education, without the need to build infrastructure in core areas of biosphere reserve. Another possibility is to penetrate land cultivation with an emphasis on biodiversity protection through the use of small GPS-controlled mechanization, which would, for example, optimize fertilization and grazing. This would prevent soil erosion and damage to watercourses. Another process innovation could be the introduction of blockchain for local organic products. The implementation of a digital certificate of origin (Smart Label) for BR products will allow consumers to verify the "environmental footprint" of a product via a QR code.

Social innovation focuses on addressing societal challenges through new forms of collaboration [30]. Phills et al. [31] define social innovation as a solution that is more effective, sustainable, and equitable. In the UK, they reinforce the quadruple helix model, where civil society joins universities, industry, and government [32]. In context of social ecology and environmental problems social innovations are broadly associated with the quintuple helix model [33]. To the one of the modern forms how to develop the social innovation in biosphere reserves belong tools of participative governance and tools of Citizen Science, where, for example, mobile applications enable local residents and tourists to map the occurrence of protected or invasive species, thereby building social capital and increasing environmental awareness [34, 35]. Another form is smart education using AI or virtual reality, e.g., in information centers, which simulate historical developments, or impact of various natural phenomena and teach visitors the rules of behavior in nature.

In the next parts of the paper, based on the use of AI and review of available documents and websites, we identify and present the examples of good practices in smart innovation in biosphere reserves that can serve as inspirations for others.

3 Material and Methodology

This paper employs a theoretical analysis to develop a framework for smart innovations. Based on the general definition of innovation and innovation in smart development we analogically define the smart innovation and apply it in context of biosphere reserves. Subsequently, we use a deductive approach to define the various types of smart innovations supported by the modern technologies, examples of which we analyse in the analytical section of this paper.

The research part of the paper presents the selection of smart innovation across the biosphere reserves on the European continent identified as the best cases. The research sample consisted of 205 biosphere reserves on the European continent which are recognised by UNESCO and published on its website (https://www.unesco.org). However, biosphere reserves were not investigated individually but by countries. An AI tool was used as a key supporting tool for the initial mapping and preliminary identification of relevant innovative solutions in biosphere reserves. The analysis was carried out through a single prompt: "Analyze (selected country) biosphere reserves in three steps. I need to know if there are specific good examples of practice that use biosphere reserves (1) in data collection, (2) in the publication of data by a biosphere reserve or other entity, (3) the use of this data for maps, visualizations, applications, and subsequently public policy. " Then we checked the results and verified them with reality. It was done through the secondary research of relevant official documents, websites and social networks of individual biosphere reserves. If the identified innovation was confirmed, we elaborate it as example of good practice to demonstrate theoretically defined innovations. The list of good practice is not exhaustive, but it presents a set of representative examples illustrating the categories of the possible smart innovations in biosphere reserves as starting point for further research. The data collection took place in the period from September 2025 to February 2026.

Based on the analysis of examples of smart innovations and comparison with the theoretical framework, we elaborated the comparative evaluation of the smart innovations (Table 1) regarding the selected features (e. g. type of innovation, impact, stakeholders' participation, etc.). The selection of the features is based on innovation and smart governance theory. The evaluation of these features was based on expert opinion of authors and results of the conducted survey. Subsequently, we identified the key features of smart innovation in biosphere reserves and challenges for the future development.

4 Research Finding and Discussion

Biosphere reserves are internationally recognized model areas designated for the practical application of interdisciplinary knowledge aimed at understanding and maintaining the relationship between humans and the natural environment, as well as managing change, including conflict prevention and biodiversity conservation. The impacts of current global challenges emerge this model of territorial functioning even more clearly due to its focus on eliminating negative impacts of global challenges, but also on striking a balance between nature and humans and building the territory's resilience. Preserving the resilience of ecosystems and their ecosystem services—such as access to drinking

water, food production, soil fertility, climate regulation, and aesthetic values—along with the protection of biodiversity, is a fundamental prerequisite for eliminating poverty and promoting human health and well-being [36]. The development of modern technologies influences strongly the possibilities to strength the resilience of biosphere reserves, to map and analyse the territory and make policy decisions based on data and evidence. These possibilities are reflected in smart innovations which are gradually implemented also in this type of territory.

4.1 Best Examples of Smart Innovation in Biosphere Reserves

To the most advanced smart innovations in biosphere reserves and digital monitoring belong an integrated environmental sensor network in North Devon Biosphere. The system uses Internet-of-Things (IoT) technologies to collect real-time data on hydrology and ecosystem conditions, including water levels, rainfall, soil moisture and water quality [39]. These sensors transmit data to a central digital platform where they are integrated with additional environmental datasets. The resulting data infrastructure supports evidence-based decision-making [40]. The approach represents a model of a "digital biosphere reserve" or environmental digital twin, demonstrating how automated monitoring can support landscape management and provide real-time environmental intelligence. A comparable example of smart environmental monitoring can be found in the Archipelago Sea Biosphere Reserve, where automated marine monitoring systems are used to observe coastal ecosystem conditions. Sensor-equipped monitoring stations and research buoys collect continuous data on marine biodiversity, contaminants, marine litter, energy, including underwater noise, hydrographical conditions and others in the Baltic Sea [41]. These data are integrated into national environmental monitoring systems managed by the Finnish Environment Institute, making them accessible for environmental assessment, research or management [42]. Together, these examples demonstrate how biosphere reserves can apply sensor networks and real-time environmental data systems to improve ecosystem monitoring and evidence-based environmental governance. The Doñana Biological Station in Doñana Biosphere Reserve also operates networks of automated environmental sensors measuring hydrological and climatic variables in wetland ecosystems [43, 44]. These systems provide continuous environmental observations that complement traditional ecological surveys. In addition, researchers and field rangers use mobile applications such as CyberTracker to collect georeferenced biodiversity observations directly in the field [45]. This combination of sensor networks and digital field data collection significantly improves the efficiency and spatial accuracy of ecological monitoring, providing high-resolution data on ecosystem dynamics and biodiversity trends.

Another emerging smart innovation in biosphere reserve monitoring is the use of environmental DNA (eDNA) techniques to detect species presence through genetic material found in water or soil samples. This method allows researchers to identify fish, invertebrates and other organisms without direct observation or capture, enabling faster and less invasive biodiversity monitoring. In coastal ecosystems such as the Wadden Sea Biosphere Reserve, eDNA sampling is increasingly used to complement traditional ecological surveys and improve biodiversity assessments [46, 47]. Satellite remote sensing has also become an important tool for biosphere reserve management. Many reserves use

Copernicus Sentinel satellite data to monitor vegetation dynamics, wetland extent, forest cover changes and land-use patterns across large areas. These datasets provide consistent long-term observations that complement field measurements and allow managers to detect ecosystem changes and environmental pressures at landscape scale. The presented set of examples can be classified as technical and technological innovations with the strong impact on the policy making on territorial resilience. All collected data are relevant sources of information for the qualified decisions reflecting the real conditions in the territories and provide the possibility to simulate future development.

Social innovation as citizen science has become an increasingly important innovation in biosphere reserves monitoring systems. A good example is Kristianstads Vattenrike Biosphere Reserve, where public participation and citizen research is integrated into environmental monitoring and awareness programmes. Volunteers contribute observations on biodiversity and environmental conditions, while spatial information about the biosphere reserve is made accessible through digital mapping tools such as the Naturkartan outdoor platform [48, 49]. Similar approaches can also be found in several other European biosphere reserves. For example, the Dyfi Biosphere in Wales implemented the COBWEB citizen observatory project, enabling residents to collect environmental data using mobile devices [50]. In Archipelago Sea Biosphere Reserve, biodiversity observations from citizen scientists are integrated through global platforms such as iNaturalist, contributing to species monitoring in coastal ecosystems worldwide [51]. In Nordhordland Biospehre Reserve in Norway, the public database and open map portal Artsoservasjoner is used also as a citizen science tool for reporting and viewing various biodiversity observations [62]. These initiatives illustrate how citizen science can complement professional monitoring, increase data availability and strengthen local engagement in biosphere reserve management.

Another example of biosphere reserves smart innovations can be found in Sierra Nevada Biosphere Reserve, where the Sierra Nevada Global Change Observatory (OBSNEV) operates a long-term ecological monitoring infrastructure. The observatory integrates field observations, climate monitoring stations and satellite remote sensing data to track ecological and socio-environmental changes in mountain ecosystems [52]. Importantly, the observatory does not only collect data but also curates and publishes them as open datasets, making them accessible for scientific research and environmental governance. The Wadden Sea Biosphere Reserve thus represents one of the most sophisticated examples of international environmental monitoring in Europe. Through the Trilateral Monitoring and Assessment Programme (TMAP), Denmark, Germany and the Netherlands coordinate ecosystem monitoring across the entire Wadden Sea region [53]. The system harmonises monitoring protocols for biodiversity, water quality, sediment dynamics and habitat changes, allowing datasets to be directly comparable across national borders. Data generated through the programme are used to produce ecosystem maps, environmental indicators and policy assessments. This collaborative framework demonstrates how biosphere reserves can serve as platforms for transboundary data governance, enabling large-scale ecosystem monitoring beyond national administrative boundaries. The observatory with its infrastructure can be classified as institutional and process innovation that enhance the management of the biosphere reserve and provides a framework for developing data-driven policies.

Another emerging smart technical and technological innovation in biosphere reserves is the use of remote sensing and drone technologies for ecosystem monitoring. For example, in the Entlebuch Biosphere Reserve in Switzerland, researchers have tested the use of unmanned aerial vehicles (UAVs) to monitor recreational pressure and track the movement of visitors in sensitive alpine habitats. Drone imagery allows researchers to identify footprints, ski and snowshoe tracks and spatial patterns of visitor use in protected areas with high accuracy and relatively low cost [54]. Similar remote sensing approaches are increasingly used in biosphere reserves to monitor wetland dynamics, forest cover changes and vegetation health, often combined with satellite data from programmes such as Copernicus. These technologies provide detailed spatial data that help managers better understand landscape dynamics and manage human activities in ecologically sensitive areas. Recent advances in artificial intelligence and automated species recognition are also being applied in protected areas and biosphere reserves. In the Swiss National Park, which forms the core area of the Engiadina Val Müstair Biosphere Reserve, researchers have developed camera-trap monitoring systems combined with machine learning algorithms to automatically identify animal species and behaviors from large volumes of image and video data [55]. These camera networks continuously record wildlife activity and generate extensive biodiversity datasets that would be extremely time-consuming to analyse manually. AI-assisted monitoring can also significantly improves the efficiency of biodiversity observation and enables long-term monitoring of wildlife populations across large and remote landscapes.

Smart innovations in biosphere reserves also include the use of digital data sources to monitor tourism and recreational use of landscapes. In several protected areas, researchers have analysed geotagged photographs from platforms such as Flickr and other social media sources to identify spatial patterns of visitor use in protected areas [56, 57]. These datasets allow managers to map popular routes, seasonal visitation patterns and areas of potential ecological pressure. Combined with traditional visitor counters and mobile data analysis, this approach provides a cost-effective method for understanding tourism dynamics and supporting sustainable visitor management in biosphere reserves. This innovation contains the features of economic, social and technical innovation. Because the tourism is a key development sector in many biosphere reserves, the integration of appropriate, data-driven measures to regulate tourism, while preserving the uniqueness of the biosphere reserve, is a fundamental prerequisite for development of biosphere reserve.

An important dimension of smart process and technological innovations in biosphere reserves is the accessibility and sharing information through open digital platforms and dashboards. In Portugal, a relevant initiative is the CPLP Network of Biosphere Reserves, presented through the online platform Reservas da Biosfera da CPLP portal. This digital platform connects biosphere reserves from Portuguese-speaking countries and provides a shared interface for communication, documentation and exchange of knowledge among reserve managers, researchers and policy actors. The platform includes an interactive dashboard that visualises key information about the biosphere reserves within the CPLP network. The dashboard presents spatial and descriptive data such as the location and

boundaries of biosphere reserves, total area and distribution across countries. It also provides information on ecosystems and habitats, ecosystem services, conservation objectives, governance structures, economics, ongoing projects, cultural and natural heritage, science technology and innovation, well-being and quality of life, risks, itineraries and partnerships, as well as indicators related to sustainable development initiatives implemented in the reserves [58, 59]. By integrating these datasets into a single digital interface, the platform supports transparency and facilitates comparison between reserves while enabling users to explore information on biodiversity, territorial management and sustainability actions across the CPLP biosphere reserve network. Through this type of digital infrastructure, biosphere reserve networks can strengthen knowledge exchange, data accessibility and international cooperation, while providing a clear overview of the spatial distribution, ecological characteristics and management activities of participating reserves. The Nordhordland Biosphere Reserve in Norway also publishes overview dashboards in various areas, such as cultural heritage and cultural landscape, natural values, excursions in Nordhordland, the taste of Nordhordland, Wool Square, the art tour in Nordhordland, and UNESCO in the Vestland County [60]. Within Norway and this biosphere reserve, there is also the Norwegian biodiversity bank Artskart, which provides a database and open map that allows users to view specific species sightings [61].

Smart innovation in biosphere reserves does not only involve environmental data but also sustainable energy systems. The Entlebuch Biosphere Reserve provides also a strong example of how biosphere reserves can integrate renewable energy solutions into regional development strategies. The Entlebuch Biosphere Reserve is not just a model region, but also an international gold award-winning model region with the European Energy Award. The region has implemented several concrete initiatives aimed at increasing energy self-sufficiency while reducing greenhouse gas emissions with economic and social impact, influencing also the processes within the territory. One of the most prominent examples is the extensive use of biomass from local forests, where wood chips from sustainably managed forests are used in district heating systems that supply public buildings, schools and residential areas. In addition, several municipalities within the biosphere reserve have installed solar photovoltaic systems on public buildings and farms, contributing to local renewable electricity production. Small-scale hydropower plants on alpine streams also play a role in the regional energy mix, supporting decentralised renewable energy generation [63, 64]. These initiatives promote the use of local renewable resources and encourage cooperation between municipalities, farmers and energy companies.

Summary of research findings about the smart innovations in biosphere reserves evaluated by the selected criteria present Table 1.

Table 1. The comparison of identified smart innovations of biosphere reserves

Area	Engiadina Val Müstair (Swizz)	North Devon Biosphere (England)	Archipelago Sea Biosphere (Finland)	Doñana Biosphere Reserve (Spain)	Sierra Nevada Biosphere (Spain)	Wadden Sea Biosphere (Germany, Denmark, Niederland)	Entlebuch Biosphere (Swiss)	Dyfi Biosphere (Wales)	Kristianstads Vattenrike Biosphere (Sweden)
Type of innovation	technological	technological	technological	technological, process	technological, process	technological, institutional	technological, economic	social, technological	social
Technology	AI, camera	IoT sensors	IoT sensors buoys	sensors, mobile apps, eDNA	monitoring stations, satellites	monitoring systems, databases	UAVs (drones), renewable energy	mobile applications (COBWEB)	digital mapping (Naturkartan)
Objective	wildlife monitoring	environment	marine ecosystem monitoring	biodiversity monitoring	long-term ecosystem research	transnational ecosystem monitoring	monitoring, energy production	citizen-based data collection	citizen science
Function	automated analysis	data collection, decision making	data collection, analysis	data collection, validation	analysis, data publication	analysis, policy support	data collection, energy generation	citizen science	participation, data collection
Stakeholders	research institutions	public sector research	research institution, government	research institutions, reserve management	research institution, government	governments, research institutions (3 countries)	municipalities, businesses	community, research institution	community, public sector
Level of participation	low	medium	low	medium	medium	high (institutional)	medium	high	high
Geographical level	regional	regional	national	regional	regional	international	regional	local	local
Environmental impact	high	high (water, climate monitoring)	high	very high	high	very high	high	medium	medium
Economic impact	low	indirect (policy efficiency)	medium (water management)	low	indirect	medium	high	low	low
Social impact	low	low	low	medium	medium	medium	medium	high	very high
Implementation phase	implementation	implementation	implementation	implementation	implementation	scaling	implementation	pilot implementation	implementation
Data type	image-based, ai data	real-time quantitative	continuous environmental data	hybrid (genetic, digital)	open data	harmonized datasets	spatial + energy data	crowdsourced data	participatory data

4.2 Discussion

Our research has shown that there is no comprehensive theoretical and empirical framework that explains, classifies, and practically demonstrates the use of smart innovations in

biosphere reserves while maintaining a balance between nature conservation and territorial development within the reserve. Based on theoretical principles, smart innovations in biosphere reserves should be a result of the effective functioning of an innovation ecosystem based on the principles of the quintuple helix model, which emphasizes the importance of the natural environment. It is not possible to ignore the role of the other elements of this model, namely universities, industry, government, and civil society [8, 9, 10, 11,], because the final outcome requires their interconnection and synergy. The presented examples of good practice highlight the dominant role of new technologies, which are drivers of innovation in various areas of life, in implemented processes (digital biosphere reserves), social (digital mapping tools based on citizen science), economic (tracking tools for the tourism sector), and in the institutional framework of biosphere reserves (observatories and biosphere reserve networks). Although all presented innovations as good practices highlight technological sophistication, less attention is paid to the participatory and socio-economic dimensions, which are emphasized precisely by the theory of the quadruple and quintuple helix models.

The taxonomy of smart innovations [1, 5, 21] applied to the context of biosphere reserves, identifies four main groups of innovations (technological, process-related, economic, and social innovations). Our research and analysis of best practices indicate that technological innovations predominate in practice, while social and economic innovations remain less developed. A positive exception is Kristianstads Vattenrike or Dyfi Biosphere, where we identified examples of good practice in the form of social innovations based on citizen science as a part of biosphere reserve monitoring. However, in most cases, citizen participation and economic dimension are additional features, not the main pillar of the system. This shows that participatory innovations fall short of the expectations of theoretical models, which emphasize the involvement of local actors as a key element of smart solutions in BR. The most of identified innovations are innovations with lower economic impact. We suppose that it can be caused by generally low focus of biosphere reserves´ management on development function, or by other words, local economic development as well as due to the preference of conservative approach to management of biosphere reserves (a priority is environmental protection).

It is possible that the dominance of technological aspects is due to the implementation phase of innovations, which also opens up opportunities to strengthen them in the next period by focusing on people, society, and links to local governance, civic initiatives, and regional economic models. This would also eliminate the risk that the technological pre-phase of smart innovations might overshadow the original purpose of smart innovations, which is to support the transformation of socio-ecological systems, rather than merely their technical monitoring. This presumption corresponds with the progressive development of Society 5.0 that aims to tackle social challenges and achieve a sustainable, inclusive, people-oriented society and link it with the specifics of biosphere reserves development.

Zuboff [17] points out, in the context of progressive technological solutions, the potential problem of "surveillance capitalism," to which sensor-based systems and interconnected data platforms may contribute. For biosphere reserves as UNESCO model areas, it is therefore crucial to ensure data protection and transparency in data handling. While technological innovations increase the efficiency of monitoring, they simultaneously create new risks associated with unequal access to data, its control, and commercial use—which can lead to a violation of the MAB program's principles and jeopardize the relationship with the local community.

The innovations presented here focus primarily on monitoring and assessing climate change and natural phenomena, with the aim of using this information to formulate policies that reflect future developments and strengthen the region's resilience. This confirms that smart innovations are not a universal package of technologies but must reflect the ecosystem and management specifics of the biosphere reserves. At the same time, empirical data show that the transferability of innovations is limited by the context of the area, and it is not possible to create a uniform model of a smart biosphere reserve or a universally replicable smart innovation within a biosphere reserve. This also confirms the importance of applying a place-based and place-sensitive approach in the development of biosphere reserves [37, 38].

A key finding is that the identified examples of good practice in smart innovation within biosphere reserves focus on monitoring but less on transformative capacity. Their use for strategic decision-making or long-term planning is often less evident. This suggests that smart innovations in BRs have not yet fulfilled the full potential attributed to them by theory—namely, the ability to enable comprehensive socio-ecological transformation of the territory, support adaptive management, and foster interconnected learning among system actors. Given that this is still a relatively under-researched topic, there is significant room for further progress in this area, not only in terms of scientific research but also in the practical formulation of public policies.

5 Conclusions

Smart innovations in biosphere reserves represent a rapidly evolving field that integrates digital technologies, environmental science, and the principles of sustainable development. Biosphere reserves as "living laboratories" defined by experts create a space for the initiation and development of innovation not only for monitoring the state of ecosystems but also for supporting adaptive management, participation, and regional cooperation. An analysis of theoretical foundations and examples of good practice shows that technological excellence is today the most visible pillar of smart innovation—from IoT sensor networks, satellite data, digital twins, and UAV technologies to AI-supported systems for biodiversity monitoring. These solutions significantly improve the quality, accuracy, and availability of environmental data, thereby strengthening the ability of biosphere reserves to respond quickly to changes in ecosystems and fulfil their role as model sites of the UNESCO MAB Program.

At the same time, it appears that technological innovations currently dominate over socio-participatory, process-oriented, and economic innovations, which would utilize technology and data as means of implementation and are, at the same time, essential for the transformative management of biosphere reserves. To a greater extent, synergistic collaboration among scientific institutions, public administration, the business sector, local communities, and the natural environment is desirable. The participation of local actors should be an integral part of managing innovation processes. A challenge for the near future is to strengthen participatory mechanisms, transparent decision-making, and community-oriented innovation supported by digital solutions, but with a central focus on people, which would lead to more inclusive and equitable land management.

Another important aspect of smart innovations is that they must reflect the uniqueness of the BR ecosystem and management. It follows that smart innovations are not a universally applicable package of technologies, but a modular set of solutions that must be adapted to the ecological, social, and managerial conditions of each territory.

The relevant attention should also be paid to the issue of data quality, transparency, and how the data is used. For smart innovations to strengthen socio-ecological and economic resilience, they must be implemented transparently and in accordance with the principles of nature conservation, and not at the expense of local communities or ecological values.

Although our methodological approach has its limitations, the examined examples of good practice can be considered a reflection of current trends in smart innovation within biosphere reserves. Examples of good practice in smart innovation highlight the significant potential for implementing data-driven and evidence-based policy-making and managerial measures in biosphere reserves. but it is necessary to effectively integrate this not only into nature conservation, but also into the social and economic spheres and participatory land management. Only then can biosphere reserves become authentic living laboratories where innovations emerge as a result of the interconnection of people, technology, and the natural environment—and not as a collection of isolated technological experiments.

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