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Climate crisis and spatial planning

Green infrastructure and supply of ecosystem services

The climate crisis and its impacts are affecting, with ever greater pace and intensity, urban, peri-urban, and rural contexts, thus significantly impacting the environment, local development, and quality of life. Therefore, the identification and implementation of planning actions aimed at strengthening the resilience of spatial systems and at accelerating the ecological transition are highly desirable, mainly based on the effective and sustainable use of the functions of nature and natural resources.

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The cover image: The pedestrian route of Via Chiaia in the City of Naples by TeMA Editorial Staff

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EDITORIAL PREFACE

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Climate crisis and spatial planning
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1 Introduction

The climate crisis and its impacts are affecting, with ever greater pace and intensity, urban, peri-urban, and rural contexts, thus significantly impacting the environment, local development, and quality of life. Therefore, the identification and implementation of planning actions aimed at strengthening the resilience of spatial systems and at accelerating the ecological transition are highly desirable, mainly based on the effective and sustainable use of the functions of nature and natural resources. Within this conceptual framework, this Special Issue has the general objective of proposing and discussing methodological and operational approaches oriented toward the identification of territorial policies directed at the pursuit of climate neutrality and adaptation to the climate crisis.

In this perspective, two research profiles of particular relevance in scientific and technical terms are identified:

- for all spatial contexts, urban, peri-urban, and rural, the strengthening of a set of ESs related to the quality of human life, to be considered as fundamental factors for achieving climate neutrality, among which carbon capture and storage (CCS) is identified as a fundamental reference;
- for urban areas, the enhancement of a set of ecosystem services (ESs) significantly linked to the urban microclimate and its quality, especially in relation to the mitigation of the heat island effect and to energy saving.

For both profiles, the knowledge of the situation and the evolutionary dynamics of the supply of ESs constitute effective foundations for the assessment of the impacts of planning actions, also with reference to the location and installation of plants for the production of energy from renewable sources.

This Editorial Preface proposes some points for reflection to facilitate the reading of the articles of this Special Issue, as follows. First, the conceptual category of green infrastructure is analyzed with reference to territorial contexts characterized by widespread urbanization. Subsequently, the relationships between the supply of certain ESs and the inclusion of parts of the territory in the spatial systems of green infrastructure are discussed, in relation to the current literature. The last section briefly describes the articles of the Special Issue.

2. Green infrastructure and urbanized spatial contexts

The European Commission regards green infrastructures (GIs) as essential territorial frameworks that support biodiversity preservation, strengthen ecological linkages across natural systems, and foster the overall capacity for ecosystem services (ESs) provision (Directorate–General Environment, European Commission, 2012). In this context, the advancement of biodiversity conditions together with the expansion of ES supply represent primary objectives within spatial planning strategies designed to reinforce the operational efficiency of GIs (Liquete et al., 2015; European Environment Agency, 2014).

Within this perspective, the notion of green infrastructure located in urbanized spatial contexts (UGI) aligns with the conceptual orientation promoted by the Commission, while contemporary planning practices in cities have progressively integrated it as a critical interpretive lens for the organization of urban green systems (Tzoulas et al., 2007; Sandström, 2002). UGIs are conceived as interlinked networks of natural or semi-natural components, explicitly arranged to maximize ES delivery. They encompass green areas, open landscapes, and aquatic environments, situated both within densely built zones and in areas completely transformed by impermeable surfaces. The maintenance, development, and enlargement of these ecological networks, which vary widely in dimension, spatial position, and ownership, are understood as a shared duty of governmental institutions, private stakeholders, and civic society engaged in urban governance.

As instruments of sustainable and socially responsive city-making, UGIs are distinguished by several functional roles (Breuste, 2021):

- ensuring universal accessibility for urban populations;
- safeguarding health and enhancing the well-being of inhabitants;
- promoting the protection of biodiversity alongside the continuous and meaningful interaction with natural resources;
- contributing to the visual identity of cities while elevating overall quality of life, particularly in densely inhabited districts;
- expanding the availability of ESs for diverse categories of urban users, from residents to commuters, tourists, and temporary visitors.

Even environments dominated by artificial surfaces can be reintegrated into UGIs by replacing impermeable cover with vegetation, through processes such as greening initiatives or tree planting. The inclusive nature of UGIs, emphasized by Tzoulas et al. (2007), highlights their relevance not only to urban conurbations but also to multicentric territories, peri-urban and transitional areas, and rural contexts.

A decisive contribution of UGIs in urbanized landscapes lies in mitigating the fragmentation of green areas caused by sealed surfaces, structural barriers such as buildings, and transport infrastructures, all of which severely disrupt biodiversity. While UGIs cannot always prevent such fragmentation, they provide additional ecosystem benefits not strictly dependent on spatial continuity, for instance, cleaner air derived from the presence of vegetated surfaces, a function particularly strengthened when trees are present in considerable numbers (Echevarria Icaza et al., 2016; Salata et al., 2016). Similarly, vertical greening systems such as living walls and rooftops mitigate excessive heat accumulation, reducing the impact of phenomena like the urban heat island effect (Eggermont, 2015).

The guiding principles for the stewardship and future development of UGIs can be summarized as follows (Breuste, 2021):

- adjust the provision of urban ESs to the differentiated needs of users through targeted spatial planning policies;
- foster multifunctionality and versatile uses of UGI assets;
- ensure continuity and efficiency of ESs provision by optimizing maintenance activities;
- reintegrate UGIs into highly sealed urban contexts via partial soil re-permeabilization and the adoption of nature-based solutions;

- design participatory urban planning policies aimed at maximizing UGI effectiveness, including the active involvement of profit and non-profit organizations, civic associations, labor representatives, environmental groups, and public administrations with responsibility for city management.

The adoption of inclusive, collaborative, and forward-looking urban strategies intended to consolidate UGIs embodies a holistic framework of spatial governance, merging sustainable growth with principles of social fairness at the local scale (Zoppi, 2012; Walmsley, 2006; Schrijnen, 2000; van der Ryn & Cowan, 1996). The compact city model integrated within ecological networks underpins Dresden's planning vision, which aspires to establish itself as a green city (Breuste, 2021). The city's approach is to embed dense urban settlements within a wider ecological matrix, with its river systems, comprising nearly 400 watercourses and the Elbe basin, serving as the backbone. This ecological system is envisioned to expand progressively while enhancing access to public green spaces. Its assigned functions include (Breuste, 2021):

- promoting air quality improvements and climate resilience;
- recharging groundwater reservoirs effectively;
- reducing flood risks and controlling runoff;
- providing more recreational spaces for outdoor activities;
- ensuring ecological connectivity through functional corridors for fauna and flora, thereby preserving habitat quality;
- maintaining and improving the aesthetic character of both built and natural urban environments.

In Dresden, UGI is shaped by interconnected hubs and corridors. Policies are directed toward enhancing the ecological standards of these nodes and links, while simultaneously regulating urban expansion to avoid further encroachment on open landscapes. The underlying intent of this planning model is to instill in the community a perception of urban ESs as a coherent and complex GI framework, in which open spaces are regarded not as residual land but as fundamental structural components of the city's ecological infrastructure (Buijs et al., 2019; Fors et al., 2015)

3. Green infrastructure and supply of ecosystem services: CCS, habitat quality and natural outdoor recreational spaces

CCS constitute an ecosystem service closely linked to the persistence of green areas within urban environments, and thus to the efficiency and resilience of urban structures in UECs (urban ecological corridors). This relationship is analyzed and discussed by Valente et al. (2022), with reference to the spatial arrangement of green spaces and the urban ecological network, using the Landscape Service Index spatial framework applied to the city of Lecce, Southern Italy. A notable aspect pertains to the functional relationship between carbon sequestration services provided by UECs, where the primary feature of these corridors is the provision of well-maintained urban green spaces containing high-quality vegetation, which results in substantial carbon dioxide absorption. This phenomenon is explored in several studies, including those by Lv et al. (2023) and Zhang et al. (2015), focusing on ecological restoration in Southwest China, particularly in karst landscapes.

Supporting these observations, Floris and Zoppi (2020) report, first, a negative correlation between temporal changes in land consumption and carbon storage potential, indicating a strong link between urban expansion and increased land use (Stachura et al., 2015). Second, they note that the reduction in carbon storage capacity caused by land consumption is quantitatively significant. Their study emphasises how the presence and extent of protected areas, represented in this analysis as the heads of UECs, can restrict urban sprawl and land take, thereby playing a crucial role in maintaining and potentially enhancing carbon sequestration (Martínez-Fernández et al., 2015; Mücher et al., 2009).

Concerning the association between habitat quality spatial classification and the suitability of spatial contexts to be considered part of UECs, Lai et al. (2018) highlight two key factors. Firstly, the mitigation of environmental pressures, including the renaturalization of sealed soils due to urbanization, removal of legal or illegal waste sites, restoration of urban understory, monitoring of fallow lands, and relocation of industrial installations. Secondly, processes of soil loss and land cover transitions associated with qualitative degradation are of limited importance (Vassilev; 2011; Ruiz Benito, 2010), as habitat quality depends primarily on the condition of land cover. These findings are corroborated by other research. He et al. (2017) propose a predictive tool for assessing the impact of land cover changes on habitat quality, integrating scenario simulations with cellular automata and the InVEST habitat quality model. Their results suggest two strategies to enhance habitat quality: controlling urban sprawl via managed growth of urbanized areas, and implementing agricultural policies to reduce dispersed rural settlements, which negatively affect surrounding habitat quality. Sallustio et al. (2017) present a methodology to assist decision-makers in identifying conservation priority areas and evaluating habitat quality and degradation within the current Italian protected areas framework. Their results indicate that habitat quality declines with proximity to densely populated or intensively farmed areas and where weaker conservation measures apply.

The issue of the inclusion of outdoor recreational spaces into UGIs align with Song & Liu (2024), who show that the network of movement patterns for leisure activities is influenced by the availability of accessible, equipped urban green spaces, ideally reachable without transportation. The study notes that the association between public green spaces and UECs as neighbourhood connectors has intensified during the pandemic, when perceived safety against contagion was higher in open green areas that enable multiple recreational activities while allowing for safe distances. The importance of outdoor recreation spaces, considered nodes and branches of UGI-related networks, for urban life quality and their reinforcement as a strategy to enhance it, is highlighted by Park (2017) in the Phoenix metropolitan area. Park emphasizes how community perceptions are shaped by public sensitivity to the protection and proper use of urban open spaces, a sensitivity particularly heightened in communities engaged in hiking and wildlife interaction. Richards et al. (2024), through virtual landscape simulations, underscore the role of ecological connectivity in enhancing attractiveness for outdoor recreational activities, especially those related to sports and relaxation, particularly in areas with high-value land covers, such as forests and native vegetation, especially near waterways or wetlands.

In urban settings, UECs play a critical role in connecting outdoor recreational areas, mitigating landscape fragmentation caused by impermeable surfaces and built infrastructure. Even if UECs do not provide fully continuous recreational corridors, they still supply significant ecosystem services, including air quality improvement due to the presence of trees and vegetated areas. This positive effect is amplified when patches are closely situated, if not fully continuous. Relevant studies include Lee et al. (2014) for Gwacheon, South Korea, and Samways et al. (2010), concerning Southern forestry production.

4. Renewable energy sources

Renewable Energy Sources (RES) are widely recognized as a key component of the global strategy to mitigate climate change and reduce carbon emissions. Their contribution to decarbonization and the transition toward a low-carbon economy is undeniable. However, a crucial issue that requires deeper examination is that RES, despite their environmental benefits, are not intrinsically sustainable. Their deployment inevitably generates environmental, social, and spatial impacts that must be carefully assessed.

Policies and programs at international, national, and regional levels increasingly encourage the development of new RES farms, often under ambitious targets for energy transition. While these initiatives are essential for achieving climate goals, they simultaneously create complex challenges for regional planners and administrators. The central question becomes: how can we effectively manage landscape transformation and territorial fragmentation in order to integrate these technologies in a manner that is both efficient and sustainable? (Opdam & Wascher, 2004; Akella et al., 2009; Saidur et al., 2011; De Montis et al., 2017).

The impacts of RES installations extend far beyond energy production alone. Land-use changes and land take may alter traditional agricultural systems, fragment ecosystems, and reduce biodiversity. The placement of

large solar or wind farms can also diminish aesthetic and cultural values associated with landscapes, thereby affecting local communities and heritage sites. Habitat quality often deteriorates as natural areas are disrupted by infrastructure such as access roads, transmission lines, and service facilities (Möller, 2006; Broto, 2017).
Significantly, the magnitude and nature of these effects are strongly influenced by spatial factors, including the specific location of plants, their density and spatial arrangement, the scale of the projects, and the technical design of the installations. Secondary infrastructure, often overlooked in early planning phases, can compound the negative effects by increasing fragmentation and altering natural dynamics (Saganeiti et al., 2018; Saganeiti et al., 2020). Consequently, evaluating the trade-offs between clean energy production and environmental protection requires not only technical assessments but also multidisciplinary approaches that integrate ecological, social, and cultural dimensions.
In this sense, RES development must be understood as part of a broader territorial strategy rather than as isolated technological interventions. Effective planning involves balancing climate mitigation objectives with long-term sustainability, ensuring that renewable energy systems contribute to a just energy transition while preserving landscape integrity, ecosystem services, and community well-being.
There are numerous implications, in several cases, that have not been thoroughly investigated. The water-related ecosystem services are used to holistically assess the hydrological impact of land-use transformations driven by renewable energy deployment. This approach examines how RES infrastructure modifies fundamental water regulation processes through three interconnected dimensions: the alteration of natural infiltration capacities and runoff generation patterns, the consequent effects on landscape-scale flood mitigation potential, and the fragmentation impacts on watershed connectivity. These analytical products collectively identify critical intervention areas where energy development interfaces with sensitive hydrological systems, providing a science-based foundation for sustainable resource management strategies that harmonize climate mitigation objectives with the preservation of water ecosystems.
The increasing focus on Renewable Energy Sources (RES) exemplifies the broader lack of structured management of technological innovations within spatial and urban planning systems. The diffusion of new technologies, and particularly RES, is characterized by a rapid and often uncoordinated spatial expansion, which tends to outpace the adaptive capacity of regulatory and planning frameworks. This misalignment generates a situation in which the territorial footprint of RES develops largely in the absence of comprehensive spatial strategies, producing unintended environmental, social, and economic consequences (Scorza et al., 2020; Romano et al., 2018).

5. Overview of collected contributions

This Special Issue comprises eight papers that concentrate on the intersection of the climate crisis and spatial planning, utilising various methodologies and scales. It is possible to categorise the papers into two main groups based on territorial scale: urban and rural. The first group consists of five papers, while the second comprises three papers.
The first paper, titled "Carbon sequestration and ecosystem services. Evidence from the functional urban area of Cagliari, Italy" by Sabrina Lai and Corrado Zoppi (University of Cagliari in Italy), proposes a methodological approach that combines ecosystem services modelling and mapping with inferential models to identify and evaluate the relationships between carbon sequestration, storage, and other ecosystem services. The approach was applied to the context of the Functional Urban Area of Cagliari (Italy).
The second paper, titled "Adaptation and energy saving through urban green spaces in climate action plans: the experiences of 20 global cities" by Laura Ascione, Carmela Gargiulo and Carmen Guida (University of Naples Federico II in Italy), proposes a systematic analysis of the Climate Action Plans of a sample of twenty cities recognised globally for their commitment to climate action. The objective is to identify significant relationships between the adaptation strategies implemented by the different cities and their urban, climatic,

physical, social, and environmental characteristics. Special attention is given to understanding the role of green spaces in mitigating the effects of global warming.
The third paper, titled "Divergent stakeholder valuations of ecosystem services in Batticaloa Lagoon, Sri Lanka: implications for payment for ecosystem services frameworks for sustainable management" by Partheepan Kulasegaram, Muneeb M. Musthafa, Thangamani Bhavan and. Beniamino Murgante (United Nations Development Programme in Sri Lanka and University of Basilicata in Italy), examined stakeholder perspectives on preservation versus degradation scenarios employing a choice experiment methodology. The survey targeted stakeholders through stratified sampling and successfully engaged 405 participants within the Batticaloa Lagoon Watershed (BLW). The findings provide empirical evidence that underscores the diversity of preferences among lagoon users.
The fourth paper, titled "Reducing UHI in historical centres: the greening transformation of open small spaces in San Lorenzo district in the city of Naples (Italy)" by Carmela Gargiulo, Tonia Stiuso and Floriana Zucaro (University of Naples Federico II in Italy), investigates the urban heat island effects that exacerbate thermal discomfort and energy consumption in densely built areas, particularly within historical city centres characterised by compact and stratified urban fabric. The focus is on the San Lorenzo district in Naples (Italy), a representative Mediterranean historic city where limited open spaces coexist with stringent heritage conservation regulations.
The last paper of the first group, titled "Analysis of factors affecting urban land use changes (1993-2023): a case study of Urmia City, Iran" by Keramatollah Ziari, Ahmad Pourahmad, Mohamad Molaei Qelichi and Shahriar Hamidi Kay (University of Tehran in Iran), analyses land-use transformations (1993–2023) to identify key drivers and to propose sustainable management strategies. Utilising satellite imagery from four distinct time points, land use was classified with high accuracy through the employment of ENVI, ArcGIS, and Google Earth platforms, applying supervised classification methods such as Maximum Likelihood and Neural Network.
The first paper of the second group, titled "Global climate crisis and regional contexts. A study on ecosystem services related to Sardinia, Italy" by Federica Isola, Bilge Kobak, Francesca Leccis, Federica Leone and Corrado Zoppi (University of Cagliari in Italy), aims to propose and implement a methodological approach for achieving climate neutrality through spatial planning policies. The methodologies used focus on evaluating and visually representing the five ecosystem services within the Sardinia region.
The second paper, titled "Predicting the aesthetic impact of wind turbines and their influence on landscape value" by Shiva Rahmani, Vito Pierri, Luigi Zuccaro and Beniamino Murgante (University of Basilicata in Italy), focuses specifically on wind turbines and their aesthetic impact on the landscape. Using the 'Scenic Quality' model from the InVEST software suite, the study evaluates the visual effects of wind energy infrastructure under both current conditions and a projected future scenario that includes turbines currently in the authorisation phase.
The last paper, titled "Identifying regional green infrastructure hotspots. A comparison between the Basilicata and Campania regions, Italy" by Federica Isola, Sabrina Lai, Francesca Leccis and Federica Leone (University of Cagliari in Italy), proposes a methodological approach for the identification of ecosystem services hotspots, defined as key areas that supply high levels of ecosystem services, to support more sustainable spatial planning. The developed approach was applied to the Italian regions of Campania and Basilicata.
As Guest Editors of this volume, we wish to express our gratitude to the members of the editorial staff of TeMA Journal (in particular, to prof. Gerardo Carpentieri) who, with passion and great professionalism, dedicate themselves to a challenging scientific undertaking, such as the publication of TeMA Journal, now in its eighteenth year of life (2007-2025).

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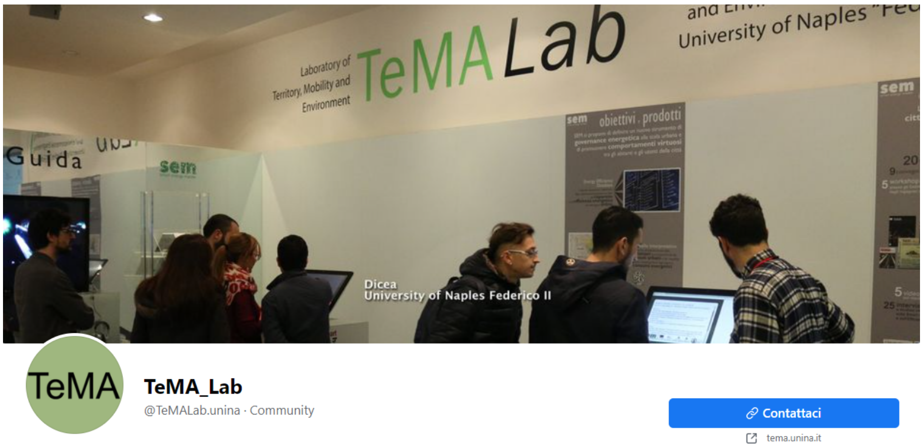

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Carbon sequestration and ecosystem services. Evidence from the functional urban area of Cagliari, Italy

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Abstract

Carbon sequestration and storage, i.e., the process whereby carbon dioxide is removed from the atmosphere by plants and stored in natural reservoirs such as soil or water pools, is a key regulating ecosystem service (ES) that contributes to mitigating climate change and its impacts. Its positive and negative relationships with other ESs, i.e., respectively, synergies and trade-offs, are yet to be fully understood, especially at the urban level. Therefore, this study proposes a methodological approach that integrates ES modeling and mapping with inferential models, with a view to identifying and assessing the relationships between carbon sequestration and storage and other ESs. The implementation of the proposed approach in the context of the Functional Urban Area of Cagliari (Italy) puts in evidence a positive and significant relationship between carbon sequestration and storage and other regulating ESs, i.e., pluvial flood retention, local temperature regulation, and habitat quality; to the contrary, a negative but quantitatively negligible relationship is unveiled as far as the potential supply of nature-based recreation is concerned. Relevant planning implications are identified based on these outcomes, which highlights the significance and usefulness of the proposed approach for planners and policy makers.

Keywords

Carbon sequestration and storage; Pluvial flood retention; Land surface temperature; Habitat quality; Nature-based recreation

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1. Introduction

Since carbon is the building block of complex molecules like proteins and DNA, it is fundamental to all biological processes and essential for life on Earth; as such, terrestrial life could not exist or continue without it (NOAA, n.d; Zehnder, 1982; Olah et al., 2011).

The continuous process of carbon transforming into different forms and traveling across the Earth is known as the carbon cycle (Fung, 2003). The carbon cycle on Earth controls the levels of carbon dioxide (CO_2) in the atmosphere, which influences global temperatures and affects the various processes that regulate the cycle (Hain et al., 2025). Carbon (C) cycle is generally divided into key components such as marine or oceanic C cycle, terrestrial C cycle, atmospheric C cycle, geologic (Fung, 2003), and anthropogenic C cycle (Olah et al., 2011). The marine C cycle is crucial for regulating atmospheric CO_2 levels, with the ocean serving as the largest carbon reservoir (Lal, 2008).

The global C cycle supports ecosystem services (ESs) through carbon sequestration in terrestrial ecosystems, aiding in climate change adaptation (CCA) while providing direct benefits to humanity and protecting against risks to Earth's stability and human wellbeing (Raupach, 2013).

Carbon sequestration (CS) is the long-term storage of carbon in the land, underground, or oceans to slow or reduce the buildup of CO_2 in the atmosphere. This can involve supporting natural processes or using new methods to manage and store carbon (Kambale et al., 2010). This could be geologic or biologic. Biologic CS can be described as the storage of atmospheric carbon in soils, vegetation, wood products, and aquatic ecosystems. Geologic CS, on the other hand, involves storing carbon in geological formations, a process that incorporates engineering approaches.

CS increases carbon uptake in natural systems, while disposals prevent CO_2 from re-entering the active carbon cycle. Techniques are generally categorized based on the part of the Earth system that needs to be managed: terrestrial sequestration, ocean sequestration, and geologic disposal (Dilling et al., 2003). Terrestrial carbon sequestration relies on photosynthesis to convert CO_2 into biological and soil carbon pools, offering benefits such as improved soil quality, enhanced agricultural efficiency, and better water quality (Lal, 2008). Thus, it plays a crucial role in enhancing biodiversity and supporting ESs.

Italy is within the top three CO_2 emitters in Europe, according to 2019 figures (European Parliament, 2024). However, it also plays a significant role in net carbon removals from the Land Use, Land-Use Change, and Forestry (LULUCF) sector, alongside Romania, Sweden, Spain, Poland, and France, which together account for nearly 87% of the EU's total LULUCF sink, although the European Environment Agency anticipates a decrease in these removals over the next decade (EEA, 2024).

As the primary greenhouse gas driving global warming, various technical solutions have been proposed to lower CO_2 emissions and stabilize atmospheric CO_2 levels, including natural carbon sequestration, which enhances the ability of ecosystems like forests and soils to absorb and store carbon (Ghommem et al., 2012). Improving the capacity of natural sequestration reservoirs to capture and store CO_2 should therefore be a significant aspect of land use planning.

Given the alarming rate of land use conversion, preserving existing trees and encouraging the planting of more, especially fast-growing species capable of absorbing significant amounts of CO_2 and storing carbon in new wood, could be the most intelligible way for carbon sequestration (Kambale et al., 2010). However, more comprehensive measures that consider long-term sustainability should be adopted for effective climate adaptation strategies. To address future global warming, substantial amounts of both anthropogenic and natural CO_2 emissions need to be sequestered (Ghommem et al., 2012). Implementing effective land use practices and following adequate soil and plant management strategies can improve the retention of photosynthetic carbon in both terrestrial and marine ecosystems, resulting in improved environmental quality (Lal, 2008).

A methodological approach is defined and applied in this study, which aims at implementing climate neutrality through spatial planning policies. CS is taken as a comprehensive reference to pursue this objective, based on a set of ESs. The study develops as follows. First, the spatial framework of CS is characterized through CS density maps, by using the InVEST suite (NCP, n.d.) "Carbon Storage and Sequestration" model which estimates the quantity of carbon stored in land parcels using land cover raster maps (Liquete et al., 2015).

Secondly, a methodology to feature the relations between CS and ESs is implemented, which models, and spatially assesses, such relations with reference to the following ESs: preserving levels of habitat quality that are suitable to support life cycles of wild plants and animals that can be useful to people; climate regulation through mitigation of land surface temperature (LST); runoff control; areas suitable for outdoor recreational activities.

Finally, correlations between the spatial taxonomies of CS capacity and ESs are detected and analyzed as for the Functional Urban Area (FUA) of Cagliari, located in Sardinia, an insular Region of Southern Italy, in order to assess how the supply of ESs can be effectively addressed to maximize CS capacity, while improving the spatial framework of the ESs. This leads to identifying place-specific policy recommendations to improve the environmental quality based on ESs supply in FUAs.

2. Materials and Methods

This section is organized as follows. First, the FUA of Cagliari is described. Second, the methodology used to detect the spatial taxonomy of CS and ESs supply is presented. Finally, a linear multiple regression is described, which estimates the spatial correlations between the ESs taxonomy and the spatial layout of CS.

2.1 Study area

The FUA of Cagliari (Fig.1) is chosen as study area for this research; according to EUROSTAT data[1], it has a size of nearly 2,000 km^2 and a resident population of 475,170 people as of 2023, and it comprises 32 municipal authorities, including Cagliari.

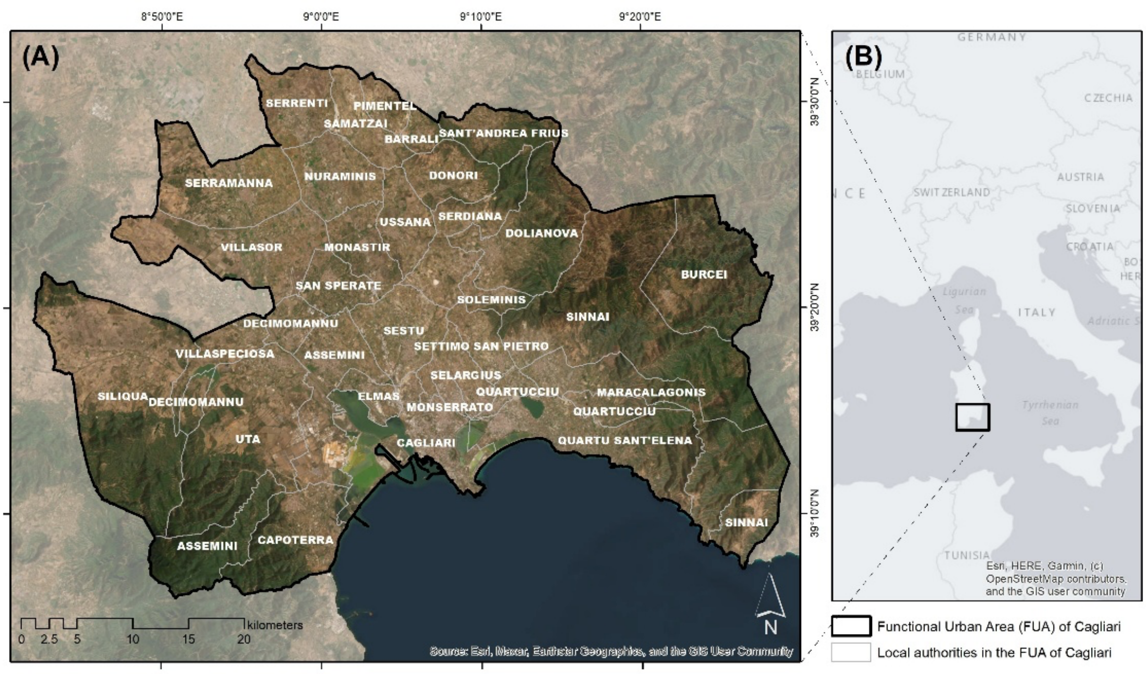

Fig.1 The functional urban area of Cagliari with its municipalities (A) within the Mediterranean context (B)

[1] https://ec.europa.eu/eurostat/databrowser/view/URB_LPOP1/default/table?lang=en. Accessed May 6, 2025.

Around 46 percent of the FUA consists of non-artificial land covers, i.e., green and blue spaces, mainly coinciding with inland wetlands that surround the built-up area of the core city and are shared with the adjacent municipalities. Agricultural and natural land covers, that potentially contribute the most to capturing and storing carbon, make up around 42 percent of the FUA. A vector fishnet, hereafter termed "grid," was developed to carry out the methodological procedures detailed in the following sections. This grid is composed of about 200,000 square units, each measuring 100 meters in width, and extends across the entire FUA. It serves as the foundational spatial reference for calculating the variables that feed into the model presented in Section 2.3.

2.2 CS and ESs assessment and mapping

To develop a methodological approach for identifying recommendations that help local planners and policymakers enhance environmental quality based on ES supply, spatial data on the distribution of CS and a selected set of ESs is essential. Besides CS, which is itself an ESs included by the Common International Classification of Ecosystem Services (CICES) within class 2.2.6.1 "Regulation of chemical composition of atmosphere and oceans" (CICES, 2018), the following four ESs were chosen for their significance in the FUA.

- Opportunities for nature-based recreational activities, class 3.1.1.1 "Characteristics of living systems that enable activities […] through active or immersive interactions";
- Pluvial runoff retention, class 2.2.1.3, "Hydrological cycle and water flow regulation (including flood control […])";
- Habitat quality, as an indicator of ecosystems' capacity to support life, class 2.2.2.3 "Maintaining nursery populations and habitats";
- LST, as an indicator of ecosystems' cooling capacity, class 2.2.6.2 "Regulation of temperature and humidity […]".

Variable (label)	Input Data	Data Sources
C_SEQ	Land use/land cover map	Regional geoportal (RAS, n.d.a)
	Lookup table associating land cover types with data on carbon sinks (above ground, dead organic matter, organic soil)	Italian inventory of forests and forest carbon sinks (INFC, n.d.) Regional geoportal (RAS, n.d.b)
RECR_ARE	Land cover map	Copernicus land monitoring service (Urban Atlas, 2018)
	Census tracts (vector map) Lookup table associating census tract codes with resident population	ISTAT – Italian national census (ISTAT, 2025)
ROFF_CTR	Land cover map	Regional geoportal (RAS, n.d.a)
	Watershed boundaries	Regional geoportal (RAS, n.d.c)
	Soil permeability map	Regional geoportal (RAS, n.d.d)
	Lookup table associating land cover types with curve number values	Regional environmental agency (ARPAS, 2019)
	Precipitation data	Regional hydrologic annals (RAS, n.d.e)
HABT_QUA	Land cover map (CORINE 2018)	Copernicus land monitoring service (CLC, 2018)
	Threats list and spatial layout	Natura 2000 standard data forms (EEA, n.d.) Regional geoportal (RAS, n.d.f)
	Threats table	Expert survey (Lai & Leone, 2017)
	Sensitivity table	
	Accessibility to threats	Regional geoportal (RAS, n.d.g)
SUR_TEMP	Landsat Collection 2, level 2 imagery	Earth Explorer (USGS, n.d.)

C_SEQ: carbon storage and sequestration; RECR_ARE: opportunities for outdoor recreational activities; ROFF_CTR: pluvial runoff water retention; HABT_QUA: habitat quality; SUR_TEMP: land surface temperature

Tab.1 CS and the four other ESs: input data and sources

Tab.1 provides a list of the input data used to spatially assess both CS and the other four ESs, as well as their sources. C_SEQ, ROFF_CTR, and HABT_QUA were mapped using InVEST (v. 3.14.1), a freely available suite of open-source models to assess and map ESs. This suite is widely used in the academic community because it relies on scientifically sound models, thoroughly explained in its user's guide; it has a neat interface which makes it comparatively easy to use, and it comprises standalone modules for the ESs being assessed. However, as with other spatial models, the outputs heavily depend on the quality of input data, in terms of both spatial and thematic resolution. As for C_SEQ, the InVEST tool "Carbon Storage and Sequestration" returns a raster map of carbon density (Pilogallo et al., 2019), i.e., the amount of carbon stored in a pixel, which is calculated as the sum of four contributions, namely, carbon densities stored in four carbon pools: aboveground biomass, belowground biomass, dead organic matter, and organic topsoil. The raster map of C_SEQ was produced based on a land cover map and on a look-up table that associates, to each land cover type, the amount of carbon that is stored in each of the four carbon sinks. Because no data was available on carbon stored in the belowground biomass, the model was run with only three carbon pools, for which data were retrieved from the 2005 Italian inventory of forests and forest carbon sinks, as well as from on-site surveys carried out within a regional pilot project by two regional agencies operating in Sardinia in the fields of rural development and of research and innovation in agriculture (Floris & Zoppi, 2020).

The second ES modeled through InVEST is ROFF_CTR. The InVEST tool "Urban Flood Risk Mitigation" makes use of the following input data: i., a land cover map; ii., a map of the soil hydrologic groups classed in accordance with the USDA-NRCS (2009) standards; iii, a biophysical associating curve number data to each combination of land cover type and soil hydrologic group; iv., the rainfall depth; v., a vector map of the areas of interest, corresponding to watersheds, over which the results are aggregated. The model returns a raster map with runoff retention values, where the volume of water retained in each pixel is a function of rainfall depth and runoff levels; because the latter ultimately depend on land covers and soil permeability (Cialdea et al., 2022), the retention value works as an indicator of the capacity of ecosystem to regulate floods. In this study, all of the input data required were retrieved from the regional geoportal and from regional reports; specifically, we used i., the 2008 Sardinian 1:10,000 land cover vector map; ii., a table providing curve numbers for each soil hydrologic group and land cover type listed in the regional map; iii., the regional permeability map to obtain the spatial layout of the soil hydrologic groups; iv., the regional hydrologic annals to retrieve the highest recorded precipitation value over a ten-year time span in the study area; v., the regional DTM to delineate watersheds.

The third ES for which the InVEST suite, namely the tool "Habitat Quality", was used is HABT_QUA. The assumption of the model is that ecosystems' health and conservation status depend on their degradation, hence on two factors. The first is presence and significance, in terms of both impact and distance, of threats to biodiversity; the second is protection levels which might regulate accessibility thus providing barriers against threats. The model relies on a raster land cover map as a proxy of the spatial distribution of habitats; to this end, a table scoring the suitability of each land cover type as habitat, where scores range from 0 (not suitable) to 1 (fully suitable), is also required. In this study, the CORINE 2018 land cover map was used, together with data on threats from the standard data form of Natura 2000 network and from the regional geoportal, while expert-based judgments were used to build the two tables concerning: i., the significance and decay distance of each threat and, ii., the scores expressing the suitability of each land cover as habitat and each land cover's sensitivity to each threat.

For the fourth ES (SUR_TEMP), raster maps with LST values, chosen as indicator of ecosystems' capacity to mitigate local temperatures (Lai et al., 2020), are freely available from the USGS website. Such raster maps have a 30-m resolution, much finer than those provided by other sources. For instance, Sentinel Hub[2] makes

[2] https://docs.sentinel-hub.com/api/latest/data/planet/planetary-variables/land-surface-temp/. Accessed October 20, 2025.

100-m and 1-km LST raster images available; similarly, the Copernicus Land Monitoring Service[3] provides 5-km raster datasets, whose coarser resolution is, however, compensated by its much higher temporal frequency. In this study, the full dataset of Landsat satellite imagery (Collection 2, Level 2) ranging from May to October 2023, was therefore analyzed, and images with cloud cover exceeding 10 percent were excluded from consideration. Among the thirteen remaining images, the one having the largest mean temperature value, dating July 30, 2023, was selected.

The indicator chosen for the fifth ES, RECR_ARE, accounts for two aspects of nature-based recreation: the first is the potential supply, i.e., availability of green and blue spaces suitable for outdoor recreation (Mobaraki, 2024) while the second is the potential demand (Pantaloni et al., 2024), i.e., the number of potential daily beneficiaries of the ES, identified in residents who live within a 500-meter distance from ES providing areas. The calculation of the indicator involved determining the proportion of green and blue spaces within each cell in the grid and multiplying this value by the number of residents residing within a 500-meter radius of the respective cell. For a full explanation of the methodological approach, the reader can refer to Isola et al.'s (2024) work. Concerning providing areas, in this study the identification of spaces suitable for nature-based recreational activities within the FUA was conducted utilizing the 2018 Urban Atlas land cover dataset, whereas, as far as population data are concerned, the most recent national census dataset, dating back to 2021 and comprising both the map of census tracts and a table with residents per tract, was used.

Once all the raster maps representing the spatial layout of C_SEQ and of the other four ES were obtained, their mean values within each cell of the 100-m grid were calculated through zonal statistics.

On land, the largest carbon pool is soil (Smith, 2019), whose presence, everything else being equal, is associated with largest values of C_SEQ. A control variable (LAND_CAP) accounting for this relationship was therefore introduced in the regression explained in Section 2.3, and a binary indicator based on land capability classes was used. Specifically, LAND_CAP equals 1 in case of arable soils, belonging to classes I-IV, whereas it equals 0 in case of non-arable soils, belonging to classes V-VIII, following Klingebiel and Montgomery's (1961) classification. To map this control variable in the FUA, Aru et al.'s (1991) soil map, which provides land capability classes in Sardinia, was reclassed and, through zonal statistics, the value of LAND_CAP was assigned to each cell in the grid.

Finally, a second control variable, CS_LAGGD, was introduced to account for the autocorrelation of C_SEQ. Representing the spatial lag of C_SEQ, CS_LAGGD was calculated using Moran's I test in GeoDa (Anselin et al., 2006) on the 100-m vector grid, where C_SEQ was one of the attributes, and the weight matrix was built based on first-order contiguity, queen criterion.

2.3 Regression model

The correlations between the spatial taxonomy of CS and the supply of the selected ESs are estimated through a linear regression, which develops as follows:

$$C\_SEQ = \alpha_0 + \alpha_1 REC\_ARE + \alpha_2 ROFF\_CTR + \alpha_3 HABT\_QUA + \alpha_4 SUR\_TEMP + \alpha_5 LAND\_CAP + \alpha_6 CS\_LAGGD \quad (1)$$

The dependent and explanatory variables are identified as follows, which refer to a one-hectare square cell:

- C_SEQ is carbon sequestration density (Mg/(100 m2));
- REC_AREA is the share-part of the area available for outdoor recreation multiplied by the population residing in a cell 500-meter neighborhood (percentage value multiplied by the number of residents);

[3] https://land.copernicus.eu/en/products/temperature-and-reflectance. Accessed October 20, 2025.

- ROFF_CTR is the volume of water from precipitation that can be retained, and which, therefore, does not become surface runoff (m3);
- HABT_QUA is habitat quality (this variable ranges in the interval 0-1; the identification of habitat quality is described in Section 2.2);
- SUR_TEMP is land surface temperature (LST), which is taken as the reference measure for the containment of urban heat phenomenon (°C);
- LAND_CAP is a variable which controls for the arability of soils (this is a dichotomous variable, equal to 1 if the soil is arable and equal to 0 otherwise; the identification of arable soil conditions is described in Section 2.2);
- CS_LAGGD is a covariate which controls for spatial autocorrelation of the dependent variable.

The estimated coefficients of the explanatory variables identify the quantitative correlations between the spatial taxonomies of CS and of the distributions of ESs supply and of the control variables. Regression models are routinely used when a priori assumptions about relationships among variables representing complex phenomena are not available (Zoppi et al., 2015; Sklenicka et al., 2013; Stewart & Libby, 1998; Cheshire & Sheppard, 1995).

In this conceptual framework, the regression estimate of model (1) represents a linear equation in an n-dimensional space, that is, a hyperplane tangent to a surface, of unknown equation, associating the dependent variable, in this case CS, with the four covariates and the three control variables. The hyperplane constitutes, therefore, a linear approximation of the n-dimensional surface in a neighborhood of the tangency point, then, in the neighborhood of this point, its infinitesimal trace, on a surface of unknown equation, defined in an eight-dimensional domain (Wolman & Couper, 2003; Byron & Bera, 1983).

The control variable LAND_CAP is related to the arability of the soil. In fact, arable soils, other things being equal, have lower CS capacity than other permeable soils, mainly due to losses of this capacity related to organic carbon mineralization, as described and discussed by Anuo et al. (2024).

The second control variable, CS_LAGGD, the spatially lagged variable derived from the spatial configuration of CS, controls for spatial autocorrelation of such dependent variable. CS_LAGGD is identified through the methodology implemented by Zoppi & Lai (2014), based on Anselin's studies (2006; 2003).

The model estimation is completed by p-value significance tests of the coefficients of the covariates and control variables.

3. Results

This section shows the obtained results of the methodology proposed in the previous section and implemented with reference to the Cagliari FUA. The spatial distributions of the CS and the four ESs is presented, followed by the outcomes of the estimation of model (1), whose coefficients define the framework of the correlations between CS and the supply of ecosystem services in urban areas.

3.1 Spatial taxonomies of CS and ES

Fig. 2A illustrates the spatial distribution of the variable C_SEQ. The highest values, corresponding to the ninth and tenth deciles, are concentrated along the outer edges of the FUA, where forests and several natural protected areas are prominent. These areas include large Natura 2000 sites that extend partially into the FUA from both the east and west, as well as the Gutturu Mannu Regional Park to the west and the "Sette Fratelli" public regional forest to the east. In contrast, the inner part of the FUA that includes the core urban area of Cagliari, as well as two extensive wetlands, consistently exhibits the lowest carbon density. Agricultural areas generally tend to show intermediate values.

Fig.2B depicts the spatial pattern of the indicator selected for ecosystem-based recreation opportunities. Areas falling within the tenth and ninth deciles are mostly located in the inner part of the FUA, corresponding to built-up areas where residents have access to green and blue spaces within 500 meters of their homes. To the west, a large green cluster with medium-to-high values is characterized by low-density development and by proximity to the previously mentioned "Sette Fratelli" forest. In contrast, to the east, a large yellow cluster devoid of green spaces overlaps with the Gutturu Mannu Regional Park; this area exhibits low recreational opportunity values due to the absence of resident population.

Fig.3A shows the spatial distribution of ROFF_CTR. Areas in the first decile are characterized by built-up surfaces and other impermeable soils, including the wetlands' bottoms; as a result, they are concentrated within and around the core city of the FUA, as well as in other urban settlements. In contrast, the highest values, corresponding to the ninth and tenth deciles, are clustered along the western and eastern edges of the FUA. Medium-high values, falling within the sixth and seventh deciles, are predominantly distributed across permeable agricultural areas in the Campidano Plain.

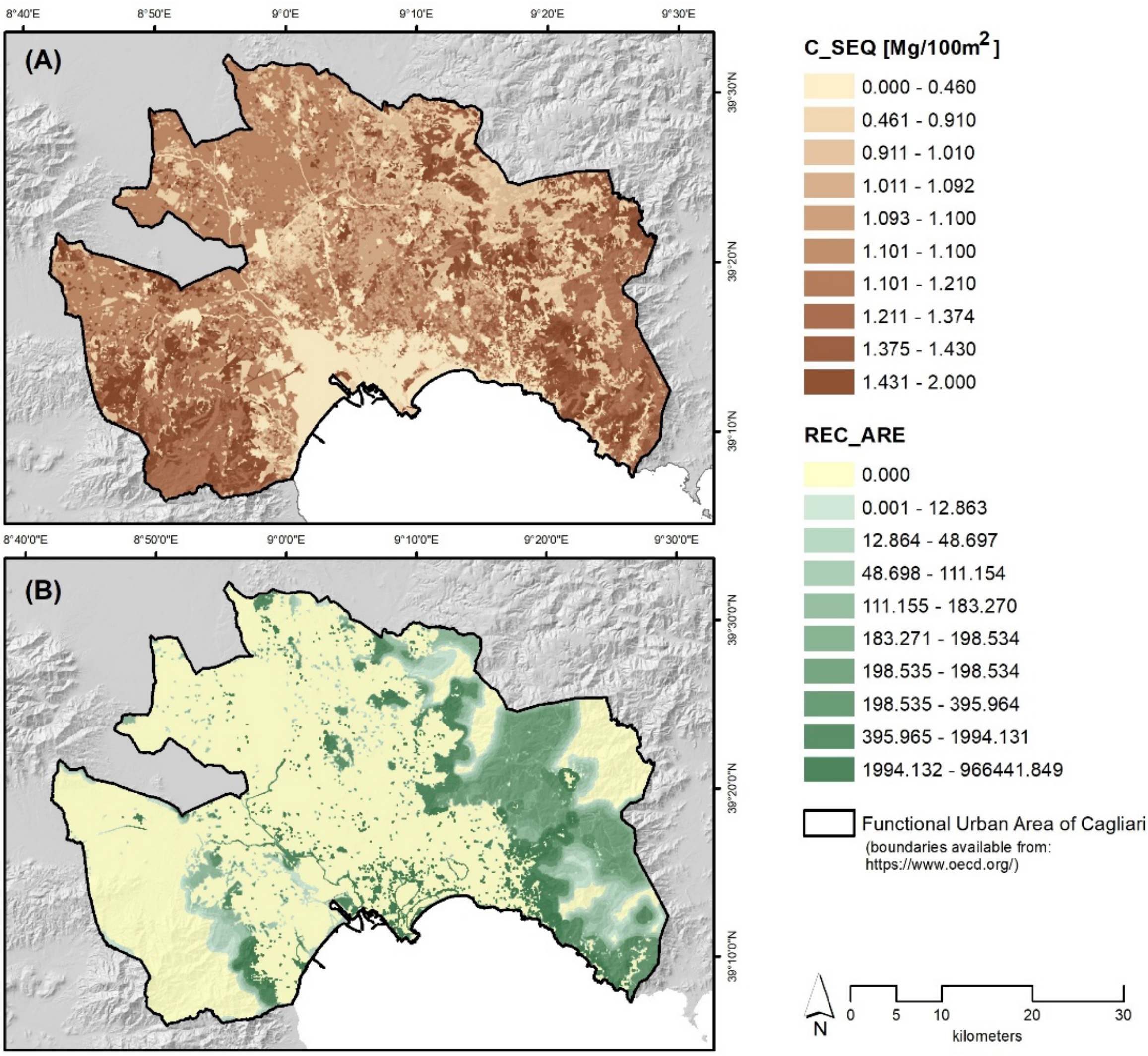

Fig.2 Spatial distribution of indicators for (A) C_SEQ and (B) REC_ARE, both classified by deciles

Fig.3B illustrates the spatial layout of HAB_QUA. The highest values, in the ninth and tenth deciles, are concentrated not only along the western and eastern edges of the FUA, encompassing the forested and protected areas of Gutturu Mannu and Sette Fratelli, but also around the core urban area of Cagliari and its hinterland. This counterintuitive pattern is due to the presence of two large wetlands, rich in biodiversity and relatively safeguarded from threats under existing legal protection frameworks, as both are part of the Natura 2000 network, with one also designated as a regional park. Conversely, areas in the first decile mostly correspond to artificial land covers. Rural areas, whether agricultural or natural, exhibit a range of values from low to medium-high, depending on their proximity and exposure to degradation sources.

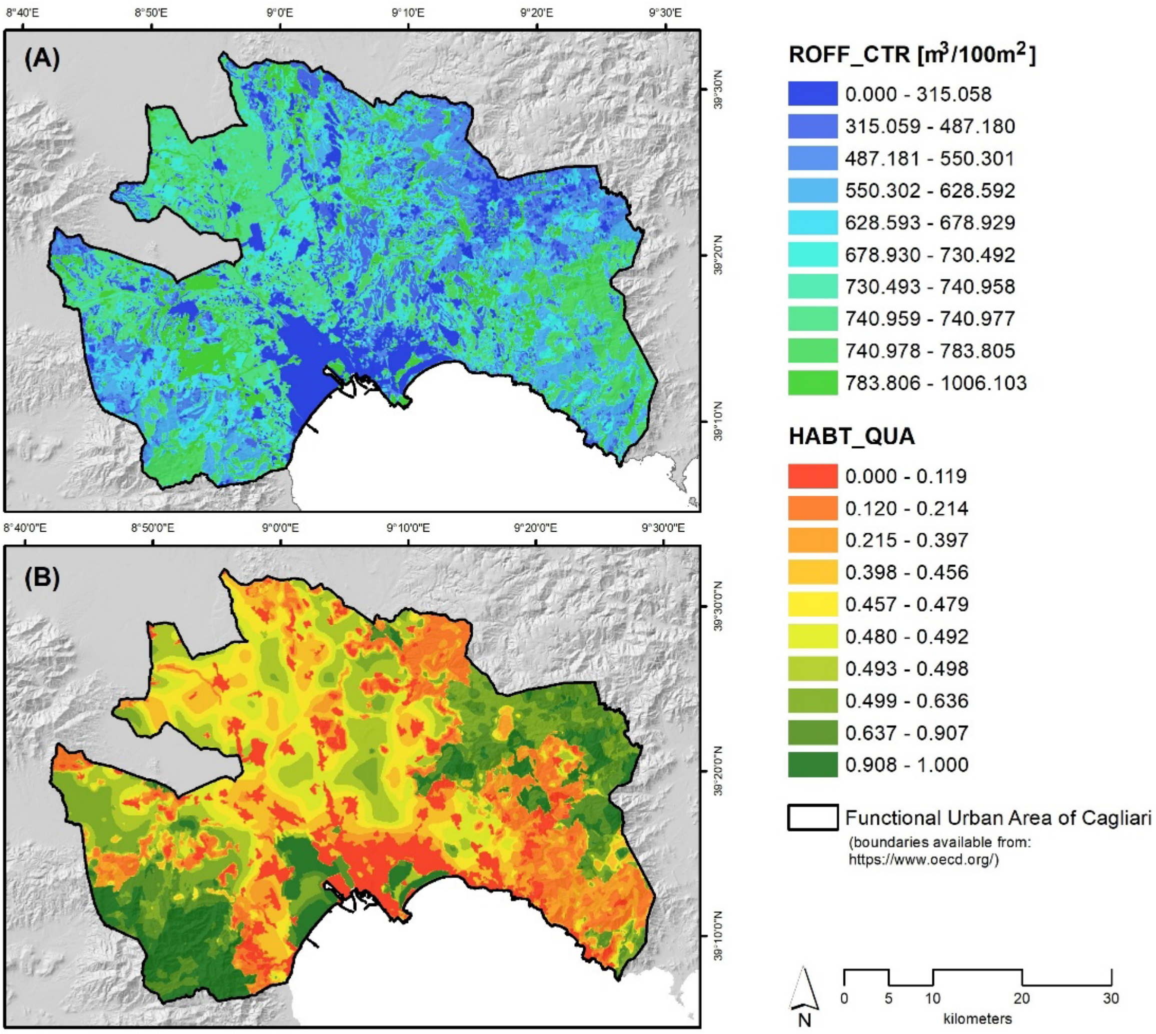

Fig.3 Spatial distribution of indicators for (A) ROFF_CTR and (B) HABT_QUA, both classified by deciles

Fig.4A provides the spatial variation of SUR_TEMP across the FUA, representing LST as recorded on the hottest day of summer 2023 in the FUA. This variable serves as an indicator of ecosystems' capacity to mitigate local climate conditions: the higher the LST, the lower the provision of this regulating ES. As expected, the lowest temperatures are observed in inland water bodies (first decile), followed by hilly and mountainous areas (second and third deciles).

The highest temperatures are concentrated in the Campidano Plain, encompassing both urban settlements and agricultural areas. The core city of Cagliari and its hinterland exhibit moderate values, possibly due to their proximity to wetlands and the coastline, as well as to a well-known phenomenon studied in arid regions, which in summer tend to exhibit higher temperature in rural areas than in urban ones (Marando et al., 2022). Finally, Fig.4B depicts the spatial pattern of LAND_CAP.

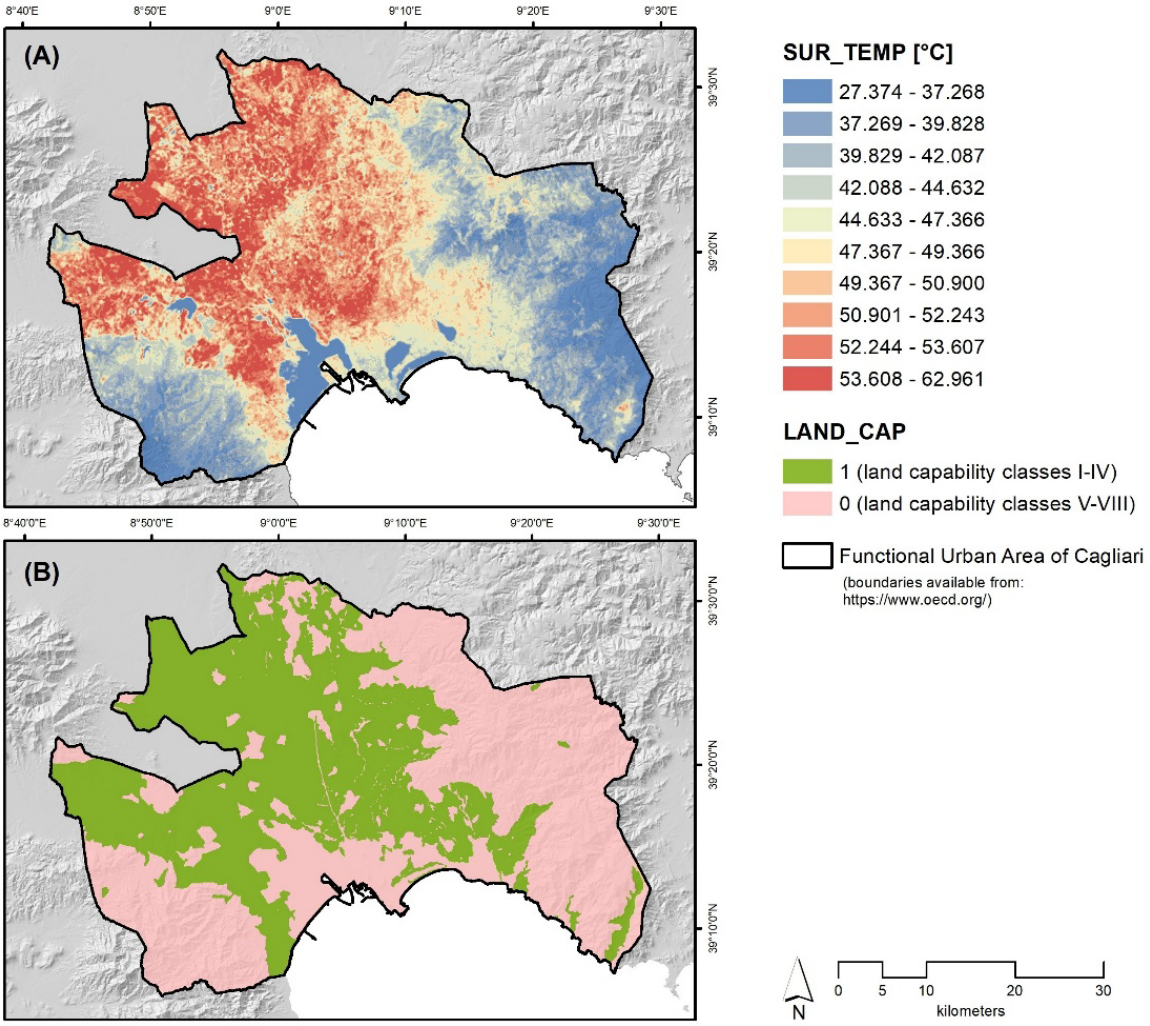

Fig.3 Spatial distribution of indicators for (A) SUR_TEMP, classified by deciles, and (B) LAND_CAP, 1 for arable and 0 for non-arable soils

3.2 Multiple regression model

The coefficient estimates of model (1) are presented, in the following, as reported in Tab.2, which shows, in value and sign, the marginal changes in CS in relation to the unit increase in the supply of the four ESs and control variables, and the values of the p-value significance tests, which allow us to assess the reliability of the regression outcomes.

The results are to be read bearing in mind that estimating a positive value of the sign of a coefficient implies that an increase in the supply of the corresponding ES is associated with an increase in C_SEQ, and the other way around. Such estimates all have significant values in relation to the p-value test. Such estimates, therefore, can be taken as reliable measures of the correlations between C_SEQ and availability of the ESs which are associated with the variables to which the estimated coefficients refer. The magnitude of the impact, positive or negative, is assessed by calculating the elasticities of CS capacity with respect to the supply of the different ESs. The calculation of elasticities is equal to the ratio of the percentage changes, in value and sign, of the dependent variable and the explanatory variables. The last column of Tab.2 reports the elasticities entailed by the coefficient estimates from the multiple linear regression, referred to the mean values of such variables. The values of the elasticities, always lower than 100 percent, configure CS capacity as an essentially inelastic phenomenon with respect to the supply of the targeted ESs, although substantial differences, both in value and sign, are evident.

Explanatory variable	Coefficient	t-statistic	p-value	Mean of the explanatory variable	Elasticity at the mean values of C_SEQ and expl. var's, related to a 10% increase in expl. var's [(Δy/y)/(Δx/x), %]
REC_AREA	-0.0000020	-66.7691210	0.000	2,074.3821441	-0.3896740
ROFF_CTR	0.0008137	220.3107902	0.000	628.7480144	48.2438526
HABT_QUA	0.2265020	86.5215270	0.000	0.4571412	9.7641556
SUR_TEMP	-0.0047290	-31.5592406	0.000	46.4666493	-20.7213618
LAND_CAP	-0.0527197	-29.5788868	0.000	0.4781383	-
CS_LAGGD	0.3135804	35.8959072	0.000	0.2567973	-

Dependent variable: C_SEQ: Mean: 1.0604442 Mg/(100 m^2); Standard deviation: 0.3269716 Mg/(100 m^2); Adjusted R-squared: 0.2985817

Tab.2 Regression results

Although, therefore, the coefficient estimates in model (1) are significant in relation to the p-value test, the impacts on C_SEQ associated with the supply of the four ESs are quite different. It can be seen, then, that a 5 percent increase in the average value of the SUR_TEMP variable, i.e., an average LST gradient of just under 2.5 °C, is associated with an average decrease in C_SEQ of about 1 percent. It should be pointed out in this regard that, in general, thermal gradients in diachronic terms are much lower than this value and, therefore, how the relationship between C_SEQ and SUR_TEMP, although, as discussed in the next section, is in line with the results available in the current literature, points to a rather weak influence of LST on CS capacity.

The positive elasticity with respect to the HABT_QUA variable, which is less than a half of the elasticity related to variable SUR_TEMP, implies that the improvement in habitat quality is a less significant factor, compared to a negative thermal gradient, in enhancing CS capacity. Indeed, a 10 percent increase in the HABT_QUA variable, linked, for example, to a significant decrease in threats to habitats in the spatial context of the Cagliari FUA, is associated with an increase of just under 1 percent.

Regarding the relationship between C_SEQ and the ES supply variable for outdoor recreation, it is shown that the negative impact of RECR_OUT is associated with a very low value of the elasticity of C_SEQ of about 0.4 percent. However, since, as indicated in Section 2.3, RECR_OUT is equal to the share of a cell area available for outdoor recreation times the population residing in a 500-meter buffer of such cell, it should be noted that a 10% decrease in such buffer resident population would be associated with an increase of about 10% in C_SEQ, which identifies an increase of about 0.1 Mg/(100 m^2), with an implied negative elasticity of about 100%. Thus, resident population in buffers of cells characterized by above-average recreational area emerges as an important factor in relation to CS capacity. As in the case of SUR_TEMP, however, the change in such buffer resident population is subject to very low diachronic variations. Therefore, at least in the short and medium run, this implies, as in regard to SUR_TEMP, a weak influence of this variable on CS capacity.

With regard to the control of flood phenomena, i.e., the variable ROFF_CTR, associated with runoff control, this presents a positive, significant and rather relevant marginal effect estimate in value, with an elasticity of just under 50 percent. Thus, it is shown that the ES associated with runoff control, although in a general situation of inelasticity of CS capacity, is configured as the one that most influences the C_SEQ variable.

As for the LAND_CAP dichotomous control variable, the coefficient estimate is negative and significant, and that a change in it, if relevant, can lead to a depletion of CS capacity of some importance as well. A 10 percent increase in arable soils, or just under 5 percent of the total, is, in fact, associated with a 0.2 percent decrease in the C_SEQ variable.

Finally, a positive and significant spatial autocorrelation is evidenced by the estimate of the coefficient of the spatially lagged variable CS_LAGGED, related to the dependent variable C_SEQ.

4. Discussion

The relationship between CS capacity and LST, highlighted by the implementation of the methodology proposed here to the spatial context of the Cagliari FUA, is reflected in several studies available in the current literature. Momo and Devi (2022) survey the trends in LST and CS, during a decade (2011-2021), with reference to the West District of Imphal, the capital of the Indian state of Manipur, and compare the results obtained through the implementation of different methodologies based on satellite remote-sensed data, highlighting how the results converge, both qualitatively and quantitatively, and reflect a steady decrease in CS capacity associated with a steady increase in LST. Similar results, albeit with a different methodological approach, are presented and discussed by Wang et al. (2021) with reference to the metropolitan context of Shenzen, located in a subtropical area of China. The study focuses on the impact of urban heat island on CS capacity in relation to different urban ecosystems, and points out that the empirical investigation shows a decrease in CS more pronounced in the central areas of the metropolis, where LST is higher than in the peripheral areas.

Studies that focus on positive correlations between habitat quality and CS capacity are numerous, covering different spatial scales, thus continental, regional, and local levels, and multiple definitions of the spatial arrangement of ecosystem service provision related to habitat quality. Generally, it is noted that CS capacity is regarded as a structural component of habitat quality and how, therefore, it is a feature of it, rather than a related phenomenon. As part of habitat quality, therefore, CS capacity connotes and catalyzes its improvement and enhancement. The improvement of habitat quality and enhancement of CS capacity is found, according to Bayley et al. (2021), in the regional context of the Falkland Islands, where this quality is linked to forest health and, therefore, to policies aimed at forest plantation and restoration. With regard to the urban context, the work of Hua et al. (2024) is significant, in which, with reference to the urban context of Xiamen, a major city in the Min Delta region, located in the southern coast of China, a spatial model is defined for the assessment of trade-offs between urban expansion and decreasing supply of ESs, identified with reference to CS capacity, habitat quality, water conservation and soil retention. These services are considered to be positively correlated with each other, and such that the changes, in value and sign, are structurally consistent with each other

The estimation of the negative correlation between CS capacity and resident population density is also reflected in the current literature. The study by Kinnunen et al. (2022), which proposes a general review of the international technical and scientific debate related to the interaction between the CS phenomenon and the urban residential context in which it occurs, points out that it is acquired, in general terms, that the contribution of highly urbanized contexts to CS is minimal, and structurally decreasing with increasing population density and building volume density. It should, moreover, be recognized, according to the conceptual approach of Gao & O'Neill (2020) how the increase in these densities leads to an increase in CO_2 emissions and a decrease, in situations that are already highly penalized from this point of view, in the areas suitable for storing carbon, especially when the form of urbanization processes is extensive and these are characterized by urban sprawl, that is, by a progressive consumption of natural soils with good CS capacity. Several areas of the spatial context of the river riparian zone, and the wetlands adjacent to it, function as strong carbon sinks. In a review article concerning the identification of synergies and trade-offs of the supply of different types of ESs in relation to forest planting, maintenance, and restoration, Pan et al. (2022) posit how forests, especially through the consolidation of root systems, increase the CS capacity of soils and, at the same time, improve their water retention, thus their runoff control capacity and hydraulic risk mitigation. Thus, a substantial positive interaction between flood control and CS capacity can be seen. The close positive correlation between forestation operations, flood control, and increased CS capacity is described and discussed by Kumar et al. (2020) with reference to an area characterized by troubled and barren orography in western India. Even in urban areas, the effectiveness of runoff control is, generally, associated with the improvement of CS capacity.

With reference to the case of the implementation of the nature-based solution represented by the construction of green roofs, Mihalakakou et al. (2023) point out, again in the context of a review article, how the benefits of these devices consist, in parallel, of the mitigation of flooding phenomena in dense urban building fabrics and of the significant increase in CS capacity, again partly to be attributed to the development and consolidation of root systems.

5. Conclusions

This study has proposed a novel methodological approach that integrates geospatial analysis and inferential modeling to examine the relationships between CS and other ESs. By applying this approach to the FUA of Cagliari, relationships between CS and pluvial runoff control, local temperatures, habitat quality, and outdoor recreation, were analyzed.

In urban planning, identifying these relationships and quantitatively assessing their magnitude and robustness is crucial, as this assessment provides an evidence-based foundation for spatial policies related to permeable soils and green spaces. In urban areas, effective strategies for enhancing carbon storage, reducing temperatures, and mitigating the impacts of heavy rainfall include soil desealing, urban afforestation, and expansion of green space coverage, including the utilization of residual areas.

These measures primarily target public spaces rather than private properties; in the latter, planning codes should focus on maintenance of unpaved and unsealed areas within individual plots and parking spaces, as well as guiding the appropriate selection of vegetation. In agricultural settings, appropriate management practices may play a more significant role than planning regulations in maintaining or enhancing carbon sequestration and its related synergic ESs.

The novelty of the proposed approach lies in its simplicity and adaptability to different contexts, as it applies standard inferential modeling to biophysical ESs assessments grounded on publicly available datasets. Such assessments may seem highly demanding, particularly in terms of required expertise and data collection, since the availability and quality of input data are crucial for ensuring reliable results. Researchers must consider and address issues such as data availability, constraints on spatial or temporal resolution, and the inherent subjectivity in expert-based evaluations. Such data-related challenges can translate into limitations, examples of which in this study include the lack of data on carbon stored in belowground biomass or the spatial resolution of the soil permeability and land capability maps.

Future implementations of this methodological approach could, therefore, explore the possibility of making use of readily available datasets on ESs provision. Moreover, a second direction for future research could involve a different, and maybe wider, selection of ESs included in the set of explanatory variables, to provide a bigger picture of the synergistic or antagonistic relationship between CS and other ESs, with a view to better ground suggestions for planners and policy makers.

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Image Sources

All images were prepared by the Authors.

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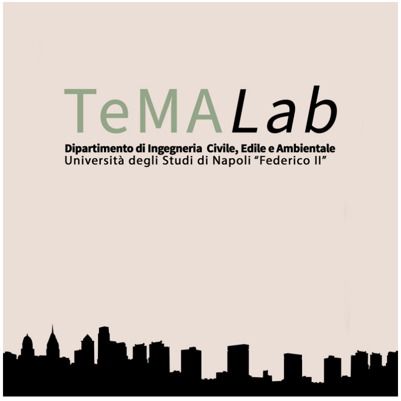

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Adaptation and energy saving through urban green spaces in Climate Action Plans: the experiences of 20 global cities

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Abstract
With the increasingly severe impacts of climate change in urban areas, city administrations worldwide are increasingly adopting Climate Action Plans. Among the most popular interventions are those on greening and energy-saving, offering cross-cutting benefits across mitigation and adaptation goals. However, the choice of these interventions is often out of context, as they are not informed by the specific urban characteristics of each city. The present study seeks to fill this gap by investigating the CAP of 20 global cities and identifying the critical relationships between their distinctive urban characteristics and their greening and energy-saving strategies. The final aim of the research is to develop an evidence-based foundation for a decision-support tool that assists decision-makers in selecting greening and energy-efficiency measures tailored to their city's unique context. To achieve this, a three-step methodology is applied to twenty leading cities from the C40 network. The proposed method integrates multivariate statistical analysis to cluster cities by urban features and topic modeling to classify greening and energy-saving actions within their CAPs. A subsequent comparative analysis links city clusters to action classes, revealing the strengths and weaknesses of different approaches across contexts. The results lay the groundwork for a tool to guide the design of more effective, context-specific climate interventions that enhance urban resilience.

Keywords
Climate change; Greening actions; Energy saving

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1. Introduction

Urban areas currently host more than half of the total global population. Besides that, metropolitan areas have made a significant contribution to the world's total greenhouse gas emissions, with their share exceeding 70% along with consuming almost 75% of power resources (UN-Habitat, 2024). The increase in the frequency and intensity of climate change effects, such as floods, heat waves, and rising sea levels, contributes to cities' high vulnerability. However, at the same time, urban areas' vast and well-connected infrastructure, capable institutions, and creative thinking enable them to be at the forefront of building climate change resilience (Batty, 2016; Scorza & Santopietro, 2024).

Over the last couple of years, climate change has, on the one hand, been a key part of mitigation efforts and, on the other, an essential part of urban climate strategies. More local governments are implementing Climate Action Plans (CAPs) whose purpose is not only to reduce emissions but also to prepare cities for the inevitable consequences of climate change (Stone et al., 2012; Aboagye & Sharifi, 2024).

Among the several strategies proposed in the CAPs, urban greening and energy efficiency stand out as the most important. The existing studies often treat these issues as if they were completely separate (Wamsler et al., 2013; Reinwald et al., 2024). On the contrary, there is a scarcity of research that examines how urban areas combine the two in a single action. A few comparative analyses have examined the relationship between green infrastructure and energy-saving measures, and the impact of city-specific characteristics on these ties. Because CAPs are customized to local conditions, the research aims to investigate how different city types integrate green space development with energy-saving measures into their plans. It will also analyze the extent to which climate, physical, and demographic characteristics influence these combined strategies. Our innovation in the empirical investigation of certain urban profiles tied to the combination of greening and energy-saving strategies within CAPs is very particular in the context of our research. Previous comparative studies have focused mainly on theoretical relationships, whereas intervention analyses have not systematically connected the different urban typologies. This research aims at empirically investigating the direct relationship between the city's climatic, physical and socio-demographic characteristics and the way in which the city's CAP integrates and articulates coherently green space development and energy-saving measures.

Hence, this study seems to be a step forward in urban resilience planning, as it relates urban attributes to the specific actions in CAPs. The idea is to analyze the overall worldwide scenarios through the urban context of different cities, while, at the same time, investigating the linkage between the physical characteristics of the cities and the way they are going about the integration of greening and energy-efficient efforts, thus encouraging different adaptation pathways. The proposed methodology consists of three parts: (1) categorizing the twenty cities selected for this study according to the characteristics they possess; (2) distinguishing the major adaptation themes through topic modeling; and (3) demonstrating how urban profiles are associated with integrated strategies through result comparison. The conclusions drawn from this investigation will provide the foundation for the development of a supportive tool for policymakers to use when they are preparing practical, context-sensitive adaptation measures.

The following section of the paper presents the authors' view and the reflections on how to better present the research questions by analyzing the most critical changes in the literature on urban greening and energy-saving measures taken in the context of climate adaptation. This will soon be accompanied by an in-depth explanation of the methodological framework, the presentation of the findings from the 20 case studies, and, lastly, a discussion of the implications for future urban adaptation policies.

2. Literature review

Cities should consider the adoption of climate resiliency through risk-reducing ways and strengthening the urban systems' ability to cope with extreme events. The scientific community has unanimously stated that the enhancement of urban greenery and transition to clean energy are the major factors among the two that lead to this change. The subsection elaborates the roles of these two measures in detail and also their overall contribution to climate change adaptation in cities (Sanfilippo et al., 2025). The tools of urban resilience are urban greening initiatives that establish green spaces, city forests, parks, and green roofs. The physical and biological effects of applying nature-based solutions in an urban setting are identical to those of nature; the urban area cools, more water is stored, which reduces runoff, and even the existing plants are given a boost, which lowers the energy needed for lighting and cooling. Since it also meets the needs of environmental justice, social inclusion, and public health, the notion that green infrastructure may have multiple uses has led to its recognition as an essential element of urban sustainability. According to studies, a building's need for air cooling can be reduced by roughly 30% when trees are planted, which results in significant energy savings. Additionally, if parks and gardens were planted, urban areas would emit significantly less carbon dioxide, be quieter, and have healthier residents. These areas are therefore crucial to strategies that combine adaptation and mitigation. Energy conservation measures are typically referred to as part of the mitigation strategy for climate change; however, their contribution to the adaptation process is not as well understood.

The above-mentioned policies increase the energy systems' resistance to climate change-related challenges and disasters. Global warming can impact the electrical networks negatively, for instance, by causing heat waves and heavy storms. Thus, outages due to overloaded grids can occur leaving people without power and at risk from life's thread, i.e., heat. Among the energy-saving measures are better building insulation, energy-efficient appliances, and advanced grid technologies, which all together contribute to the reduction of energy demand and consequently the prevention of disruptions. Turning to a small-scale solar PVs and battery storage solutions helps one to be less dependent on the grid and thus continue to have access to the essential services such as refrigeration and medical equipment during outages These days, most frameworks for adapting cities are putting energy efficiency and green infrastructure in the same category as strategies that work together. According to research, green infrastructure has many interconnections and increases a city's resilience in addition to saving energy. Green roofs, for instance, reduce the amount of energy required for heating and cooling by acting as a natural barrier to heat transfer. Planting trees along streets with care can also provide shade, which will further cool buildings and save energy (Canessa et al , 2025; Martinelli, 2025).

Increasing the biodiversity footprint within urban environment can help reduce the heat island effect and save a significant amount of energy. In actuality, the advantages of the previously created synergy are still far from being realised. The scholarly community is in favour of more comprehensive and mutually beneficial approaches to urban climate change mitigation. However, little research has been done to demonstrate how these ideas are actually implemented in city climate action plans. Whether the connection between energy efficiency and urban greening is a purposeful goal or just a consequence is still unknown.

There is still a significant disconnect between theory and practice, even with the compelling evidence for these synergies. However, proponents of integrated and co-beneficial approaches request more research on how municipalities integrate these into formal plans. Moreover, it is still unknown how economic, climatic, and physical factors affect the uptake of these tactics in various cities. The methodological framework developed to address these research concerns is described in the section that follows.

3. Materials and methods

In order to empirically determine the relationship between the urban characteristics of global cities and the energy-saving and greening initiatives that constitute significant interventions in their Climate Action Plans (CAPs), this study employs a multi-phase methodological framework. This framework's central assumption is that the success of such interventions primarily rests on how well they mesh with the particular context of a city and how they relate to other urban sectors.

n the first phase, the procedure for choosing a representative sample of twenty international cities was discussed. To include a range of cities and allow for thorough analysis at the same time, three main criteria were applied during the selection process. At least two cities were chosen from each continent to represent a range of population sizes, densities, and morphologies, as well as the socioeconomic profiles that go along with them. This was done in order to prioritise geographic diversity, which could have an effect on the creation and implementation of climate strategies. Second, the cities were chosen based on the different climate hazards they are likely to encounter, including extreme heat, sea level rise, and heavy precipitation. Third, all of the chosen cities have formally committed to climate adaptation and mitigation through resource allocation, policymaking, and active participation in global climate initiatives by joining the C40 Climate Leadership Network. The methodology described here was used to create a sample with a range of urban and environmental contexts. From the more dispersed Auckland to the heavily populated Mumbai and Istanbul, the chosen cities displayed a broad range of population densities. Additionally, their climate risks varied: Rotterdam and New Orleans face serious threats from sea level rise, while Milan and Ahmedabad face extreme heat. Severe storms frequently hit Mumbai and New York. Every city has a big impact on the economy and culture of the country and the world.

After sample selection, the methodology proceeded via two main analytical streams running in parallel. The first analytical stream was directed at cities classification according to urban characteristics impacting climate response (Reckien et al., 2025). Subsequently, the collection and cleaning of data for a range of variables denoting four domains that are frequently mentioned in literature: climatic, physical, socio-anthropogenic, and environmental was done. The climatic domain encompassed, for example, annual maximum temperature and cooling degree days as indicators which are closely related to cooling energy demand (Santamouris et al., 2015). In the physical domain, factors like total green area, and altitude range, were considered for assessment, and the socio-anthropological domain represented the demographic variables one of which was the proportion of old age people living in that area. The environmental domain encompassed data regarding CO_2 emissions which is a major contributor to global warming (Environmental Protection Agency, 2023; Özkan et al., 2025). A full list of the variables is presented in Tab.1.

The available data were collected from open-source databases and subjected to a strict cleansing guaranteeing its trustworthiness. For the purpose of data set stability, correlation coefficients were computed and those variables highly correlated were rejected (Asuero et al., 2006). After the Bartlett test of sphericity confirmed the dataset's suitability, latent structures within dataset were discovered using Principal Component Analysis (PCA). Based on the PCA results, cities with comparable features were grouped using hierarchical clustering. This identified trends that may influence their CAPs' selection and integration of greening and energy-saving measures. A hierarchical clustering method based on PCA results was used to group cities with similar characteristics in order to identify underlying factors that may influence the selection and blending of greening and energy-saving measures in the cities' climate action plans (CAPs).

The second line of analysis consisted of a comprehensive review of the climate initiatives covered by the CAPs (Fu, 2024). A database created to facilitate analysis contained all of the interventions in the selected cities' plans that were collected and put together as a whole. The actions were analysed using topic modelling and Natural Language Processing (NLP) techniques in compliance with the methodology proposed by Breton-Carbonneau et al. (2025). The well-known standard NLP preprocessing methods used to guarantee the accuracy and consistency of the classification included tokenisation, stop-word removal, and lemmatisation. A unique dictionary was created by combining terms from related academic literature with intervention descriptions from CAPs in order to further increase the interpretive reliability (Jin et al., 2023). Each action marked by the algorithm was then attributed not only to one main thematic area but also to one more sector demonstrating possible co-benefits or cross-sectoral linkages.

A key part of the methodology was a comparative analysis that aimed to link the city characteristics identified earlier to the corresponding greening and energy-saving actions. To achieve this, the city clusters obtained in the first analytical phase were compared with the climate actions taken from each city's CAP. In order to detect relationships between urban characteristics and the actions taken with regard to greening and energy efficiency measures, this process used a number of charts and diagrams that were intended to visually depict the development of patterns and the similarities and differences between cities.

System	Variable	Description	References
Climatic	Average annual temperature	Annual average of temperatures recorded in a year	IPCC, 2022; Ferranti et al., 2023
	Maximum annual temperature	Maximum temperature recorded from October 2023 to September 2024	
	Cooling degree days	Summation over a year of the days with average temperature in excess of thermal comfort temperature (25°C).	IPCC, 2022;
	The difference between the average temperature of urban and rural areas	Annual average of the difference in average temperature between urban and surrounding rural areas	IPCC, Isinkaralar et al., 2024,
	Maximum wind speed	Annual maximum wind speed	
	Average wind speed	Annual average wind speed	
	Maximum monthly average of mm of precipitation	Maximum value of the average monthly rainfall over one year	Ramli et al., 2023
	Average number of days per month when a rain event occurred	Annual average of the number of days per month with a rainfall event	
	Standard deviation of the number of days per month in which a rainfall event occurred	Annual standard deviation of the number of days per month with a rainfall event	
Physical	Range of elevation	Difference between maximum and minimum elevation	Ahmadi et al., 2022
	Linear extension of the coast	Linear measure of any coastal frontage	Wu, 2021
	Altitude	Weighted average altitude with respect to the territorial extension of the city, compared to the average sea level	Ahmadi et al., 2022
	Green space extension	Percentage of extension of total green spaces relative to the extension of the entire city	Ferranti et al., 2023; Sun et al., 2022
	Percentage of water coverage	Percentage of extension of water bodies relative to the extension of the entire city	Sun et al., 2022
	Extension of the urban area	Extension of the surface of the urbanized area	
	Building Coverage Ratio	Percentage of land occupied by buildings relative to the extension of the entire city	
Socio-anthropic	Population	Total number of residents	Ramli et al., 2023; Sun et al., 2022
	Population density	Ratio between population and urban area extension	Sun et al., 2022
	Percentage of the elderly population	Percentage of elderly inhabitants (over age 65) out of the total population	Ramli et al., 2023
	Percentage of population below the poverty line	Percentage of population living below the poverty threshold, defined at the national or local level	Leichenko et al., 2014; Ramli et al., 2023
	Unemployment rate	The percentage of the population that is unemployed	Leichenko et al., 2014; Sun et al. 2022
	Average monthly salary	Average monthly salary (net after tax) in euros	

System	Variable	Description	References
Environmental	Percentage of renewable energy used	Percentage of energy consumed from renewable sources relative to total energy consumed per year	IPCC, 2022; Olabi and Abdelkareem, 2022
	Percentage of energy consumed in the transport sector	Percentage of total energy consumed for transport relative to total energy consumed per year	Champman 2007
	Percentage reduction in CO2 emissions over the past ten years	Percentage reduction in CO_2 emissions over the past 10 years	IPCC, 2022; Hansen et al.,2013
	Percentage of use of sustainable modes of transport	Percentage of journeys made using sustainable modes of transport, i.e., walking, cycling, public transport	IPCC, 2022; Mashayekh et al., 2012

Tab.1 Urban system characteristics affecting cities' response to extreme events, according to the literature review

The comparative analysis identified the different types of cities that were more or less supportive of the adoption of specific interventions, while also emphasising that certain urban characteristics, such as density, climate exposure, or socioeconomic structure, had an impact on the type and intensity of the measures implemented. It also made it possible to see how these cities' combined efforts strengthened their overall climate adaptation plans. In summary, this stage illustrated the interaction between urban characteristics and natural solutions, as well as the possible effectiveness of energy-saving techniques.

The selection of energy-saving measures and nature-based solutions, as well as their integration and possible efficacy within urban resilience planning frameworks, are all determined by urban characteristics, it was also made clear.

4. Results

The results of the aforementioned methodology are presented in this section. To achieve the intended results, a number of analytical techniques were used, such as autocorrelation analysis to further refine the dataset. Maximum annual temperature (MaxTY) and maximum annual precipitation intensity (MaxPrecipIntensity), two highly correlated variables, were eliminated as a result of the process; as a result, the resulting analyses were more reliable and understandable.

Following data refinement, a p-value of less than 0.0005 was obtained from Bartlett's test of sphericity, indicating that the dataset was appropriate for Principal Component Analysis (PCA). With the first five principal components collectively accounting for over 70% of the variance, the PCA results were statistically significant. Each principal component highlighted a specific underlying dimension of the urban dataset, thus providing an understanding of the interaction between climatic, physical, and socioeconomic factors.

Principal Component 1 (PC1) combined the socioeconomic variables of average monthly salary and the percentage of the elderly population with several climatic indicators, including temperature and precipitation patterns. This element demonstrated the complex relationship between emissions, climate vulnerability, and cooling demand. However, the study did reveal an unexpected finding: there was a positive correlation between high emissions and high vulnerability to climate threats. This implies that cities with higher greenhouse gas emissions were also more vulnerable to climate-related risks.

Because it integrated variables related to age and income distribution with physical characteristics like elevation above sea level, Principal Component 2 (PC2) was essentially a representation of the socioeconomic dynamics. Elevation was included because it has a direct bearing on assessing the effects of climate change and communities' capacity to put solutions into place. Principal Component 3 (PC3) linked indicators of sustainable mobility with physical factors such as land use and population density. The component's green space denoting variables (GreenSup) had a moderately positive weight (0.239), suggesting that the existence of green space, specific physical urban features, and sustainable mobility patterns are positively correlated.

The complex relationship between the intensification of urbanisation and environmental sustainability is captured by Principal Component 4 (PC4), which was formed under the influence of both physical and social features, especially population density. The GreenSup component's more significant positive weight (0.336) indicates that green space is crucial for reducing the negative environmental effects of densely populated urban development areas.

Principal Component 5 (PC5) emphasised the environmental issues caused by urban sprawl and was based solely on CO_2 emissions and the total area of the city. Again, GreenSup's weight was moderate at the positive level (0.273), indicating that green spaces were generally linked to patterns of less intense urbanisation.PCA thus put forth a strong statistical basis for not only the identification of the hidden structure of the data but also for the determining of the variables that had the greatest influence in the first five principal components. The next steps were guided by these results which led to a clustering analysis that classified the 20 sampled cities into distinctive groups based on their urban characteristics similarities. The mean values of the standardized variables were then calculated for each cluster to show the deviations from the overall sample mean. This, in turn, enabled the traits and patterns across the clusters to be identified.

The distinctive characteristics of the five resulting city clusters are summarized below, supported by the standardized deviations presented in Tab.2. In the table, color coding denotes the magnitude and direction of deviation from the mean: red cells indicate positive deviations, whereas blue cells indicate negative deviations.

Cluster	1	2	3	4	5
Av Ty [%]	0,50	-20,45	13,50	6,21	0,24
Max TY [%]	5,12	-45,05	45,76	1,35	-7,18
CDD [%]	-5,57	-99,36	182,73	-2,03	-75,77
MaxWindSpeed [%]	-25,24	-57,47	46,00	49,22	-12,51
AvWindSpeed [%]	13,19	-12,65	-6,48	-7,41	13,35
MaxPrecipIntensity [%]	-23,06	28,08	89,75	-47,91	-46,87
AvPrecipFreq [%]	0,88	5,47	-5,77	-7,14	6,56
DevStdPrecFreq [%]	-9,17	-18,12	119,71	-57,40	-35,02
HeightRange [%]	191,49	-69,80	-38,77	-49,46	-33,45
CoastlineLength [%]	175,66	-100,00	-52,88	-76,36	53,59
Altitude [%]	21,30	-12,45	-11,54	66,21	-63,52
GreenSup [%]	30,41	14,67	14,67	-36,76	-22,99
UrbanSup [%]	-53,26	314,87	-82,73	-92,79	-86,08
Population [%]	20,20	75,37	39,22	-65,59	-69,20
Pdensity [%]	-24,69	-88,18	112,82	41,83	-41,78
POver65 [%]	-10,84	-11,20	-60,98	65,36	17,67
AvMonSalary [%]	9,35	-58,28	-74,60	-5,39	128,92
CO_2Em/pp [%]	-14,47	2,86	-70,14	-42,32	124,06
PercetSustMob [%]	-37,59	58,36	-46,29	28,77	-3,24

Tab.2 Percentage deviations from sample mean, by cluster

Cluster 1, made up of Cape Town, Auckland, Istanbul, Seoul, Rio de Janeiro, and Los Angeles, was marked by coastal areas (CoastlineLength: +176%), significant altitude differences (HeightRange: +191%), and huge parks and gardens (GreenSup: +30%). On the contrary, as the data showed, these cities also preferred to use the less Polluting transportation modes only to a certain extent (PercetSustMob: -38%).

The Cluster 2 was represented by nothing other than Wuhan, which was a regular outlier, in the whole arrangement. The city displayed the highest percentage of sustainable transport users (PercetSustMob: +58%) and the lowest population density of a city this size (Pdensity: -88%) as indicated in Tab.2.

Cluster 3, which included Accra, Ahmedabad, and Mumbai, was singled out for factors like these, but the cities were still very far apart. Thus, urban climates produced very cool regions with high cooling demand (CDD: +183%), huge climate variability (DevStdPrecFreq: +120%), and very little CO_2 emissions per inhabitant (CO2Em/pp: -70%). The cluster was characterized as well by population density which was double that of most urban areas in growing countries (Pdensity: +113%) and as well by a very young population where 65 years was the cut-off (POver65: -61%).

Cluster 4, which included Barcelona, Buenos Aires, Milan and Paris, was characterized by its consistent annual precipitation patterns (DevStdPrecFreq: -57%), medium-high population density (Pdensity: +42%) and a good percentage of sustainable mobility (PercetSustMob: +29%).Countries belonging to this cluster seemed to have taken the right way to cope with climate change through the application of measures favoring the development of urban areas sustainably, therefore, they were less prone to suffer from it.

Cluster 5, consisting of cities like San Francisco, New Orleans, New York, Copenhagen, Sydney, and Rotterdam, was characterized by temperate climates with minor cooling demand (CDD: -76%), but at the same time it had high carbon dioxide emissions (CO2Em/pp: +124%) and high average incomes (AvMonSalary: +129%). Additionally, some of these cities had low geographical height (Altitude: -64%) which made them more susceptible to climate risks like flooding from rising sea levels due to their location.

The table below (Tab.3) presents a summary of each city cluster’s principal urban characteristics.

Cluster	Cities	Feature (% difference from mean)
1	Cape Town, Auckland, Istanbul, Seoul, Rio de Janeiro, Los Angeles	– Coastal cities (+176% length of coastline) – High elevation range (+192%)
2	Wuhan	– Outlier for urban surface (+300%)
3	Ahmedabad, Accra, Mumbai	– High cooling demand (+183% CDD) – High population density (+113%)
4	Parigi, Barcellona, Milano, Buenos Aires	– High percentage of elderly population (+176%) – Stable climate (-2% CDD) – High use of sustainable mobility (+29%)
5	San Francisco, New Orleans, New York, Copenhagen, Sydney, Rotterdam	– High average annual income (+129% average monthly salary) – High CO_2 emissions (124 %)

Tab.3 Summary of characteristics defining each cluster, showing how selected variables deviate from the sample mean (in percentage terms)

The city clustering was followed by an analysis of the energy-saving and climate adaptation measures described in the municipality's climate action plans (CAPs). Similar to the methodological approach that Jin et al. (2023) validated, a categorization system for actions was developed using topic modeling and computational language processing. Urban Planning and Policy, Mobility and Transportation, Waste and Resource Management, Climate Emergencies, Community Engagement and Communication, Sustainable Economy and Finance, Responsible Consumption, and Monitoring and Evaluation were the ten primary areas of focus that were separated out by this classification framework.

According to the study, the two framework sectors that are most important for adaptation and energy conservation are "Energy and Buildings" and "Green Spaces and Biodiversity”. The Energy and Buildings sector encompasses strategic initiatives aimed at increasing the energy efficiency of the current building stock and transitioning to renewable energy sources. Energy retrofitting (Auckland), the development of renewable energy infrastructure (Los Angeles' 100% renewable plan), and advanced building standards (Paris's zero-net-energy buildings, Los Angeles' required cool roofs) were some of the specific measures that directly addressed the energy supply and demand. At the same time, the Green Spaces and Biodiversity sector reduced energy consumption indirectly and gave the city services of urban thermal regulation as the main ones. Examples of these green infrastructure implementations include vegetated roofs (Barcelona, Mumbai), urban forestry initiatives (Milan, Los Angeles), blue-green ecological corridors (Rotterdam), and the ingenious use of parks for heat mitigation (Ahmedabad). Since many interventions fell into more than one category, each action was given both a primary sector and a secondary "co-benefit" sector.

Determining whether these urban features and the implementation of climate action strategies were related was the final step in the analysis. Combining an action classification (mainly the Green Spaces and Energy and Buildings categories) with a city clustering outcome led to a thorough understanding of cities' strategic responses to climate change. A range of graphic techniques were used to map out these intricate relationships. A pie chart was used to show the proportion of all actions in each sector. A Sankey diagram, on the other hand, demonstrated the links and synergies between the Energy and Buildings sector and the Green Space and Biodiversity sector. The following section goes into further detail about the visualisations.

5. Discussion

The comparison of city clusters and their climate strategies shows different patterns between city features and CAPs' strategic priorities. Among the climate interventions identified, Fig.3 illustrates the 10 areas in which all of the planned climate interventions are contained within the CAPs. The area of Green Space and Biodiversity represents 9% of all planned climate interventions; Energy and Buildings represent 13%. The figure also includes 2 additional bar graphs illustrating the planned climate intervention distribution by cluster in each of these 2 areas. Through the combination of the city characteristics (Tab.3) and the planned climate action distributions (Fig.3 & Tab.4), we can identify how city characteristics influence planned climate action. A key finding of the study was the prevalence of greening actions in certain city type. Together, Clusters 1 and 4 account for approximately 70% of all planned climate actions in the area of Green Space and Biodiversity. These findings were not coincidental. Cities in Cluster 1 (e.g., Cape Town, Los Angeles), characterized by an abundance of coastline (+176%) and established green infrastructure, are using their unique natural resources as a central component of their adaptation strategy. Similarly, cities in Cluster 4 (Paris, Barcelona, etc.) have shown a robust and efficient governance structure that permits significant investments in energy and greening projects. These cities are distinguished by stable climates and higher rates of adoption of sustainable modes of transportation (+29%). On the other hand, because of the tremendous strains imposed by their high population density (+113%) and high demand for cooling (+183%), Cluster 3 cities (such as Mumbai and Accra) have less money available to invest in the areas of green space and biodiversity. Even though Cluster 3 cities have focused less of their efforts on these areas, it seems that they are using the little money they do have to deal with these problems while attending to other, more pressing infrastructure requirements.

The outlier status and distinct planning context of Cluster 2 (Wuhan) are reflected in its actions. The distribution of actions for the Energy and Buildings sector shows a similar but different pattern. Clusters 1 (37%) and 4 (31%) are the main players in this case as well, accounting for more than two-thirds of all energy-saving projects. Here, Clusters 1 and 4 are in charge, making up roughly 37% and 31% of all energy-related projects, respectively.

Cluster 1's dominance is likely due to its economic and technological strength. These are the cities that can afford to test out large-scale efficiency projects, such as retrofitting government buildings or investing in smart grid systems. Cluster 4, on the other hand, seems to be more impacted by governance than by financial resources. Its intentional policies have been impacted by its long-term energy strategy and regulations, which call for significant retrofits and stringent performance standards.

Using a more systematic approach, Cluster 3 makes up around 15% of the total. Their projects appear to be driven more by necessity than by ambition: cities caught between the urgent need for cooling and the competing demands of development.

Cities in Cluster 5 are rich, high-emission, but surprisingly energy-efficient (using only 11%). Although it may seem counterintuitive, it appears to be a logical decision because these cities are usually coastal and prioritise flood prevention, storm protection, and sea level rise, threats that reduce the amount of space available for energy efficiency investments.

All things considered, the pattern implies that a city's urban and economic environment influences not just the kinds of climate actions it takes, but also their relative importance. However, this is only a portion of the story. Finding out where cities behave the most does not show how various behaviours support or contradict one another. In order to investigate that, the analysis mapped sectoral relationships, which are depicted in the Sankey diagram (Fig.4) and indicate how one intervention sector might have a cascading effect on other sectors, such as trash or transportation. The true complexity of urban climate governance starts to emerge in such interdependencies.

Cluster	Cities	Actions in Green Space and Biodiversity	Actions in Energy and Buildings
1	Cape Town, Auckland, Istanbul, Seoul, Rio de Janeiro, Los Angeles	42%	37%
2	Wuhan	3%	5%
3	Ahmedabad, Accra, Mumbai	17%	15%
4	Parigi, Barcellona, Milano, Buenos Aires	27%	31%
5	San Francisco, New Orleans, New York, Copenhagen, Sydney, Rotterdam	12%	11%

Tab.4 Green Space and Biodiversity, Energy, and Buildings actions by cluster

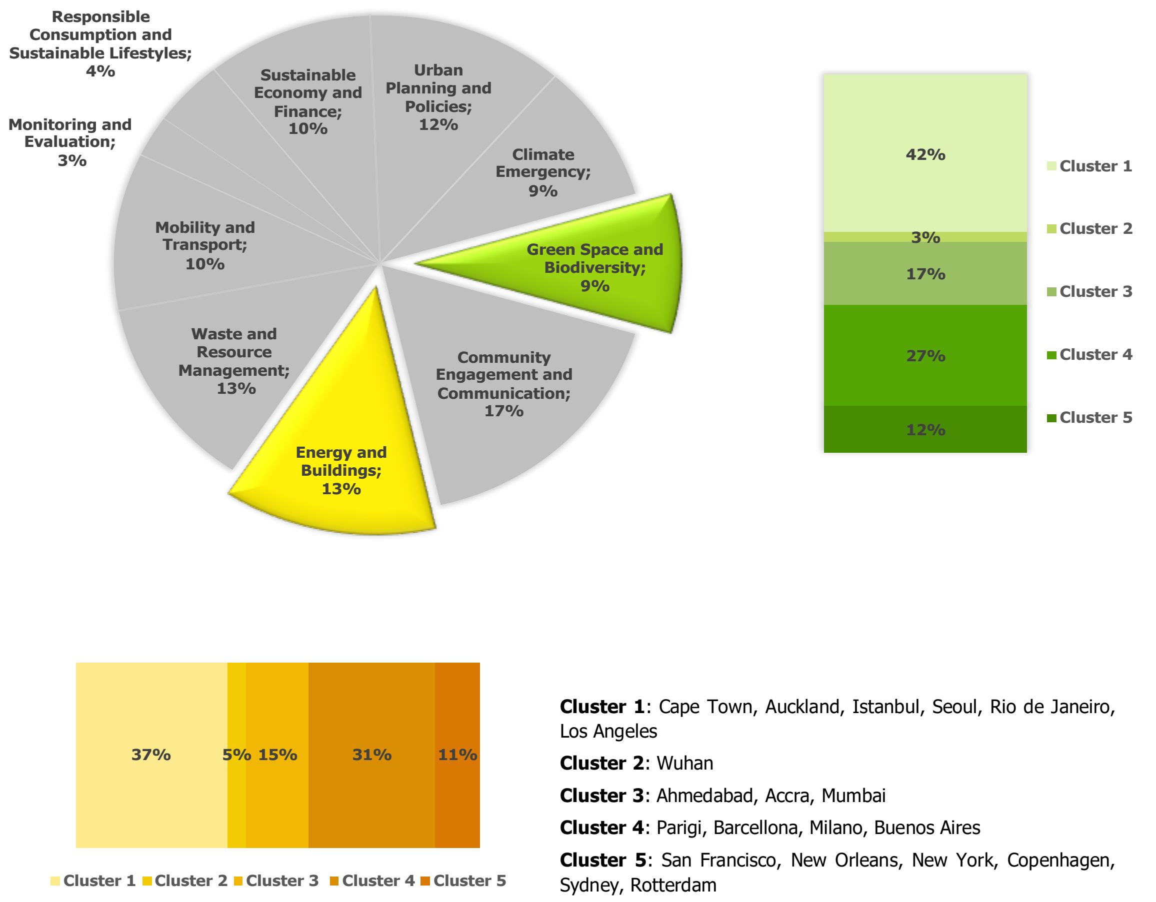

Fig.1 The pie chart illustrates the distribution of actions across ten sectors. The two bar charts summarize the distributions of Green Space and Biodiversity, and of Energy and Buildings actions, by cluster

The Sankey diagram (Fig.4) visually maps the flow of influence among different climate action sectors. On the left side, you can see the originating sectors —those planned actions that have the potential to impact Green Space and Biodiversity or Energy and Buildings positively. The diagram's central flow then traces how these originating actions connect to, and influence, the Green Space and Biodiversity sector and the Energy and Buildings sector. Conversely, the right side of the figure shows how actions within Green Space and Biodiversity and Energy and Buildings, in turn, contribute positively to other sectors, indicating resulting co-benefits.

Notable connections are found when the Energy and Buildings domain is examined. Mobility and transportation make up the largest portion, highlighting the intimate relationship between energy use and eco-friendly transportation. This demonstrates a strategic understanding that electrifying public transport requires coordinated efforts with building-centric charging infrastructure and power grid upgrades. Many projects have been proposed within this framework, including the replacement of specialised vehicles and machinery with less polluting alternatives (Barcelona and Los Angeles) and the extension of low-emission transit infrastructure (Wuhan). The second-largest input comes from the Sustainable Economy and Finance sector, underscoring the critical role that financial instruments play in advancing the switch to cleaner energy. For example, Cape Town's local government is investigating the possibility of creating a program that would encourage the use of inexpensive, safe energy sources. Furthermore, as demonstrated in Barcelona, tax-related incentives are employed to encourage the adoption of energy-saving measures. Surprisingly, the direct impacts of green space and biodiversity on the building and energy sectors were negligible and primarily restricted to natural cooling techniques like rooftop vegetation (Barcelona, Milan, and Mumbai). This might point to a large amount of unrealised potential for systematically incorporating green infrastructure into energy strategies at the city level. The primary spillover effects from Energy and Buildings initiatives recurred in terms of outflows to Urban Planning and Policies, indicating that effective energy upgrades have the ability to influence and shape new regulations, resulting in a vicious cycle.

As a result, energy-efficient city planning projects are being carried out, like creating technical guidelines for updated thermal performance standards. These criteria recommend improving the existing structural layers by installing double-glazed windows with low-emission qualities or adding cutting-edge insulation for the walls and roofs, as seen in recent projects developed in Auckland, in order to lessen the cooling load in Mumbai.

A unique network of connections is revealed by an examination of the field of green spaces and biodiversity. The largest inflows were observed in Waste and Resource Management, suggesting a direct correlation between organic waste management and preserving urban green space. To successfully carry out these initiatives, local leaders are directing restoration projects, turning disposal sites into parks, and requiring the expansion of water distribution to populated areas within supply-constrained protected woodland zones. Civic engagement and outreach were also significant factors, emphasising the critical role that collaborative projects play in promoting shared responsibility for urban ecosystems. San Francisco, for example, has tried to incorporate a variety of community viewpoints into ecological climate plans. In a similar vein, Auckland has improved resident involvement in habitat surveillance and bolstered connections to natural environments.

The outflows from this sector demonstrate how adaptable urban vegetation is. Green zones directly promote climate resilience through temperature regulation and carbon sequestration, as evidenced by the main outflow to Climate Response initiatives. New York concentrates on maintaining and restoring urban habitats to increase ecological diversity and human-nature relationships, while Buenos Aires expands accessible parks in key locations to reduce heat stress and enhance physical wellbeing. According to a significant return flow to Community Engagement and Communication, green spaces themselves may serve as catalysts for environmental education and social cohesion, increasing public awareness and support for broader climate goals. For instance, by providing support, direction, and guidance, a program sponsored by Auckland CAP encourages landowners to restore their private properties and plant trees. On the other hand, a network of urban green corridors is being developed with substantial public involvement as part of the Barcelona initiative. The more modest inflows from other sectors, however, demonstrate that the full range of co-benefits from green infrastructure, such as its role in mobility corridors or health and well-being, are still not being fully utilised in current planning. Finally, it is evident that policymakers need to have a firm grasp of urban context in order to effectively address urban climate change. To find the best ways to integrate energy efficiency and green infrastructure—and, most importantly, how to plan for the mutually reinforcing co-benefits that increase resilience, cities must empirically evaluate their unique urban features rather than relying on one-size-fits-all approaches. This strategy guarantees that adaptation efforts are as successful and resource-efficient as possible while enabling customised, successful interventions.

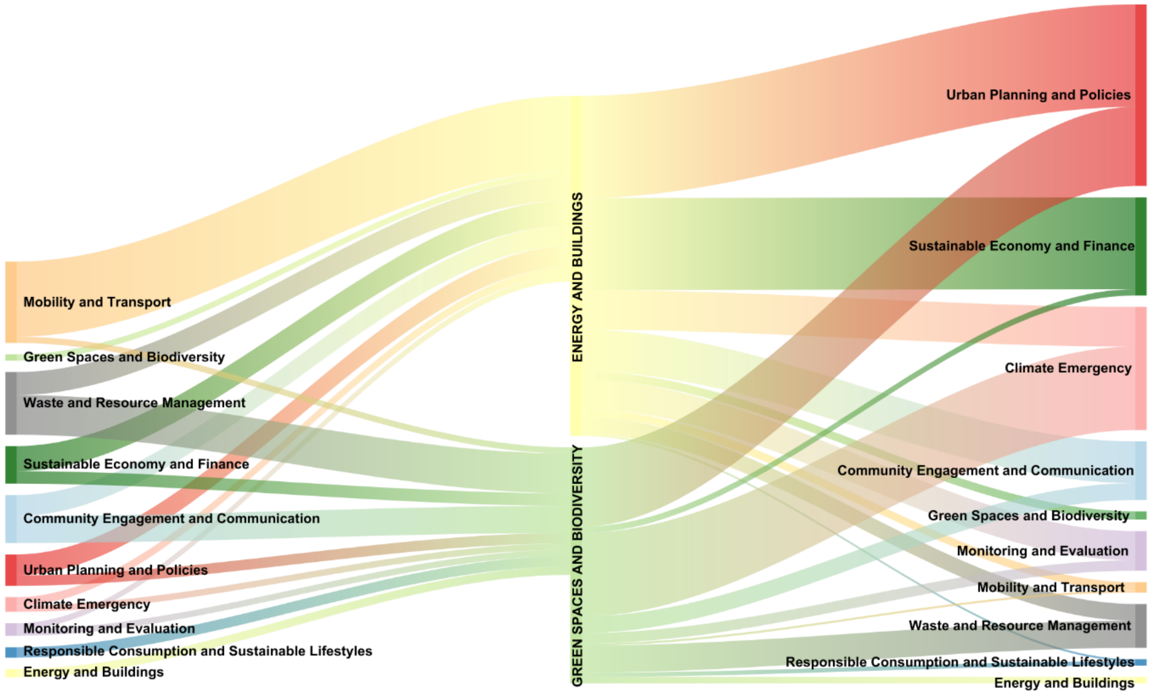

Fig.4 The chart shows, on the left, sectors generating benefits for greening and biodiversity, as well as for energy and building actions. On the right sectors benefiting from greening, biodiversity, energy, and building actions

6. Conclusions

Our study, in our opinion, is a crucial foundation for a research program that aims to develop a digital tool that will help decision-makers create plans of action and strategies to help cities become more resilient to the effects of climate change. This research sought to understand how particular urban characteristics influence the selection of greening and energy interventions, going beyond generally suggested actions, by conducting a systematic analysis of the Climate Action Plans (CAPs) of twenty cities worldwide. Our results are intended to provide empirical data on the current state of urban climate planning and to show not only the positive trends but also the areas where significant improvement is needed.

The major outcome of this study is that the climate action of a city must not be arbitrary but rather would be extremely influenced by its urban characteristics. Our study indicates that the cities under review have opted for a combination of climate actions and interventions that take into account their geographical and socio-economic circumstances, climatic conditions, and environmental characteristics. As an example, cities in Cluster 1 (like Cape Town and Los Angeles) make the most of their long coastlines and natural resources, whereas cities in Cluster 4 (like Paris and Barcelona) take advantage of the existing urban climate governance and the already established sustainable mobility systems to carry out integrated, ambitious actions. On the other hand, cities in Cluster 3 (e.g., Mumbai, Accra) that are vulnerable to climate change face a very different set of measures because of their heavy development pressures and acute vulnerability. This outcome provides empirical evidence for the need of context-sensitive climate planning.

Apart from the influence of context, our second discovery concerns a significant lack of synergy in modern climate planning, particularly between the Energy and Buildings and Green Spaces and Biodiversity sectors. Although they are not yet a significant component of core energy strategies, green spaces are regarded as crucial components of urban resilience. According to the cross-sectoral flow analysis, the relationship between energy efficiency and green infrastructure is primarily restricted to particular applications, such as green roofs. The enormous potential of natural solutions for passive cooling and general energy conservation is overlooked by this. This disparity represents a significant lost chance to create more robust, cohesive, and efficient urban systems, as the literature has also noted (Gargiulo et al., 2021; Gargiulo & Zucaro, 2023).

The goal of the project is to create a new framework for evaluating different cities' climate action plans. The approach provides a better understanding of how local conditions impact climate responses by examining trends across several cities. It concerns how cities respond to adaptation and mitigation challenges associated with their physical characteristics, socioeconomic vulnerabilities, and climate stressors. The goal is to provide policymakers with a useful tool while simultaneously advancing the theory of urban climate governance.

A top-down hanging approach is a hallmark of effective climate planning. Only after a thorough examination of the city's own structure, including its advantages, disadvantages, and limitations, can such mechanisms, like the clusters found in this study, be established.

By acting as global standards, they allow cities to learn from one another and comprehend their place in the larger urban ecology without having to argue over the policies of other cities. The decision-support tool created in this context builds on that exact concept. This tool's main goal is to help cities avoid resource-wasting tactics, take appropriate, context-specific actions, and progressively implement adaptation in meaningful, site-specific ways. In order to help cities incorporate their own efforts into larger climate frameworks, the study also produced an extensive compilation of climate actions by city type. The results will still be favourable despite the limitations, which should be noted. There are still some glaring drawbacks to open data, despite its many benefits, which include greater transparency and easier analysis replication.

Data collection and reporting practices vary by region, and occasionally there is no data at all. It eventually became necessary to eliminate some variables for the purposes of the analysis and to use a proxy to gauge the decrease in CO_2 emissions. In the end, this was a fair compromise, but it brought attention to a problem that often occurs in comparative studies: the uneven quality and availability of urban data. The limitations do not negate the results, even though they draw attention to the areas that require further development. There are limitations to the analytical process itself as well. Although the technique may oversimplify the complex and sometimes contradictory realities of local policymaking, topic modelling assisted in identifying recurrent themes in Climate Action Plans.

The requirement to separate activities into primary and secondary groups creates a division that does not exist in reality because many measures are interdependent. When every action has its own label, people lose sight of the fact that a program that reduces energy use also reduces the number of car trips and changes the way land is used. Analysts need those neat boxes, but the boxes hide how urban climate strategies are interwoven. Nevertheless, there are already several obvious next steps.

The list of cities will grow so that the map covers more places plus the numbers come from the same yardstick. Policy papers detailed stories from single cities and talks with city staff will add words to the numbers. Once the stories sit beside the figures, the picture will show not only what sits in each Climate Action Plan, but also why city leaders choose one path and drop another once politics, rules but also people push back.

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Bridging the divide: reconciling stakeholder values for payment for ecosystem services

A framework for sustainable management in Batticaloa Lagoon, Sri Lanka

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Abstract

Coastal lagoons are vital and productive ecosystems globally. However, recent anthropogenic pressures have substantially degraded these environments. The sustainability of lagoon resources critically depends on stakeholder engagement. Employing a choice experiment, this study quantifies the divergent preferences of key stakeholder groups–fishermen, tourists, and flood-affected residents–for preservation versus degradation scenarios in Sri Lanka's Batticaloa Lagoon. The survey targeted stakeholders using stratified sampling and reached 405 participants in the Batticaloa Lagoon Watershed. The analysis further assessed local perceptions of degradation and stakeholders' compensation expectations (WTA). The Choice Experiment and multinomial logit model identified significant conflicts between conservation valuations and compensation expectations. This novel empirical application directly compares within-subject Willingness-to-Pay and WTA measures, revealing significant valuation asymmetries that complicate Payment for Ecosystem Services (PES) design. These results provide empirical evidence of pronounced preference diversity among lagoon users in the study area. This study argues that management decisions must account for heterogeneous stakeholder valuations, rather than universal conservation ideals. The findings demonstrate the inevitability of one-size-fits-all PES policy failure and propose a differentiated PES framework with tailored incentives for fishermen, tourists, and flood-affected residents.

Keywords

Lagoon; Ecosystem; Resources; Land use; Willingness to accept; Willingness to pay

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1. Introduction

Ecosystem services constitute the fundamental contributions of natural systems to human well-being and economic activities. Since 1980, the Payment for Environmental Services (PES) framework has been applied globally, but empirical evidence remains limited in several regions. Successful PES implementation requires robust governance frameworks, which are deficient in numerous nations and necessitate improved water management policies (Bergkamp, 2006; Shaad et al., 2022)

Coastal lagoons are among the most productive aquatic ecosystems in the world. They span approximately 13% of the continental coastlines and estuaries and provide critical environmental and economic benefits (Sousa et al., 2020). The capacity of lagoons to provide ecosystem services depends on their ecological health. However, pervasive mismanagement has diminished this capacity. When maintained optimally, lagoons support water purification, carbon sequestration, flood prevention, and recreational opportunities (e.g. birdwatching) while harbouring biodiverse habitats, such as mangroves, salt marshes, and seagrass beds (Chacón Abarca et al., 2021). Consequently, these ecosystems are invaluable economic assets essential for human well-being (Clara et al., 2017). However, environmental degradation and anthropogenic pressures pose an escalating threat to these resources (Newton et al., 2018). Recent evidence confirms accelerating degradation rates in Asian lagoons, with tourism infrastructure increasing sediment load by 40-60% (Veettil et al., 2023).

Despite evidence that human exploitation compromises the long-term viability of lagoons (Murray et al., 2022), scholarly enquiry has disproportionately focused on cataloguing uses rather than investigating pathways for collaborative management. The critical deficit in stakeholder interaction data hinders the development of integrated sustainability frameworks. Understanding diverse stakeholder valuations is essential for reconciling ecological and economic imperatives (Pham et al., 2018). By quantifying stakeholder-specific values, this study moves beyond the counterproductive dichotomy that pits conservation against resource utilisation.

Fish biodiversity is a key asset in the lagoons. The escalating demand for fish has driven overexploitation, depleting fish populations, and compromising local nutrition (Maitland, 1995). Similarly, mangroves, which are critical for water filtration, coastal stabilisation, and juvenile fish nurseries, face unprecedented losses, with a 35% global decline over 20 years (Vo Trung et al., 2020). In Asia, mangrove deforestation occurs at an annual rate of 1.52% and is driven by aquaculture, infrastructure, development, and tourism (Mumby et al., 2006; Valiela et al., 2001)mby et al., 2006; Valiela et al., 2001). The Batticaloa Lagoon epitomises these challenges, hosting unique biodiversity and cultural traditions (Blanco et al., 2012). However, tourism poses a risk of resource depletion (Wolf et al., 2019). Hydrodynamic processes (e.g. water circulation) underpin lagoon resilience (Dolbeth et al., 2016). Finally, increased flooding negatively impacts the quality of life of those living near lagoons. However, the challenges associated with wetland protection and related costs have received little attention to date. This study proposes that human desires and exploitation must be factored into lagoon valuation. Environmental valuation is a tool for estimating the market value of natural ecosystem services without a market (Qiao et al., 2023). Beyond their ecological benefits, lagoons have significant cultural and recreational value, particularly for tourism, which introduces both opportunities and risks. Lagoons contain valuable resources that are often undervalued by society. Given the diversity, intricate socioeconomic backdrop, and structure of lagoons, it is difficult to assign value to them because they are not tradable goods (Pissarra et al., 2021). Four degradation fronts threaten Batticaloa lagoon: (1) declining water purity; (2) unsustainable mangrove loss; (3) reduced fish diversity; and (4) increased flooding. However, the costs of wetland protection remain understudied.

While discrete choice experiments are widely used in environmental valuation, few studies have concurrently elicited WTP and WTA from the same respondents to expose preference asymmetries and potential conflicts between stakeholder groups in a coastal lagoon context. This research fills this gap by evaluating stakeholder valuations of resources in the Batticaloa Lagoon, specifically examining the tension between conservation priorities and compensation demands. By integrating Willingness to Pay (WTP) and Willingness to Accept (WTA) measures, this study provides policymakers with actionable insights for balancing ecological and socio-economic objectives. This investigation addresses four key objectives: (1) to quantify WTP for specific lagoon attributes, such as fish diversity and mangrove coverage; (2) to assess WTA compensation for projected ecosystem degradation; (3) to evaluate the applicability of Payments for Ecosystem Services (PES) schemes for the lagoon's management; and (4) to elucidate the differential livelihood impacts on upstream and downstream communities.

2. The study area

2.1 Batticaloa Lagoon Ecosystem

Batticaloa lagoon, situated in Sri Lanka's Batticaloa District, is one of the nation's largest estuarine lagoons. It spans approximately 11,500 ha and extends 56 km from Chenkalady to Kalmunai (Partheepan et al., 2023). The watershed supports prawn farming, aquaculture, and crop cultivation, with seagrass meadows and mangroves dominating its borders. Notably, the lagoon harbours a significant diversity of aquatic fauna. As a shallow coastal feature, it is separated from the ocean by a barrier and intermittently connected via two restricted inlets (Fig.1). The formation and maintenance of lagoons are governed by sediment transport systems that create barriers requiring continuous sedimentation to counteract erosional forces (Harris & Wiberg, 2002; Stein et al., 2021).

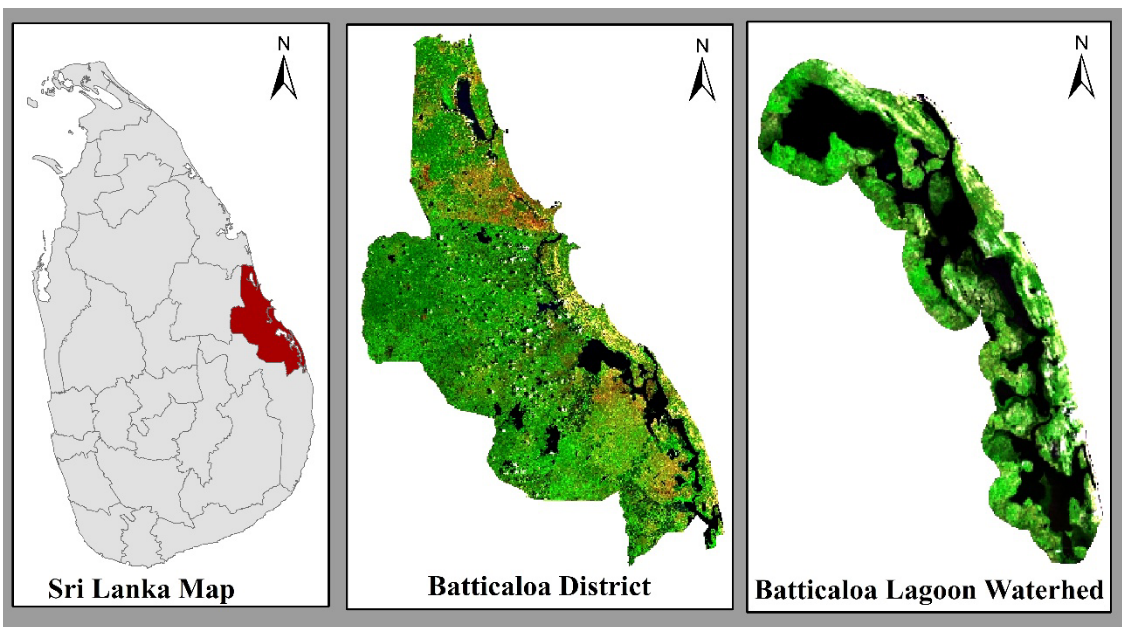

Fig.1 Batticaloa District and Batticaloa Lagoon, Sri Lanka

Designated as a nationally significant wetland, Batticaloa Lagoon hosts exceptional biodiversity but is facing anthropogenic stressors (e.g. wetland conversion to other land uses, agricultural runoff, and tourism). Poverty, population growth, and sociocultural conflicts further complicate the management of these problems. In addition, human activities, such as converting wetlands into intensive farming, commercial, and residential areas, drainage from unsustainable agricultural irrigation, and damage from nitrogen runoff from intensive farming, aquaculture runoff, and industry, are putting more stress on the lagoons. Factors such as poverty, economic deprivation, demographic growth, globalisation, mass tourism, and social and cultural conflicts significantly affect the management of lagoons (Suresh et al., 2021). Other possible lagoon management service beneficiaries and people's preferences in the western part of the lagoon for reimbursement of environmental services are not included in the PES system, necessitating further research on this topic.

3. Methodology

This section delineates the methodological approach, prioritising the questionnaire design, survey methodology, and econometric frameworks. The study then explains the methods used to estimate the average WTP and its underlying factors. This study focused on the Batticaloa Lagoon and its surrounding watershed, encompassing its key ecological and socioeconomic dimensions. A stratified sampling technique ensured data collection efficiency and guaranteed that the information sufficed to meet the study's objectives.

3.1 Questionnaire design and survey methodology

Questionnaire design

Theoretically, the fundamental economic value of an ecosystem service comprises two primary components: use and non-use values (Albani & Romano, 1998). Humans can directly benefit from the consumption of these lagoon resources. Additionally, non-consumptive use occurs when humans interact with natural resources. These non-consumptive uses include recreational activities such as birding or sightseeing that do not involve resource consumption. The knowledge that these resources exist for ecosystem function or are available for future generations generates non-use value (Barbier, 2011). These non-use values cannot be exchanged in the market. Environmental economics devises methods for measuring the value of ecosystem services for project implementation and policy development (Birol et al., 2006).

Focus groups with the village heads of the relevant communities under study and the lagoon management authority were convened to ensure the questionnaire’s applicability. The questionnaire elicited respondents' Willingness to Pay (WTP) for the preservation of Batticaloa Lagoon, focusing primarily on non-use values.

A total of 409 questionnaires were completed through comprehensive interviews. Of the 409 responses, 405 were considered appropriate for analysis. This study aimed to assess local perceptions of potential lagoon degradation from tourism and development and, consequently, their Willingness to Accept (WTA) compensation for these negative impacts.

The survey questionnaire was divided into three sections. The demographic and socioeconomic characteristics of the survey site were gathered in the first section for statistical purposes and used as explanatory variables in the regression analysis in the third section. Enumerators questioned the respondents regarding their age, marital status, employment position, degree of education, and other factors.

The second segment aimed to comprehend the respondents’ perspectives on lagoon ecosystem services. This section describes lagoon conservation and the risks to lagoon biodiversity. Respondents were provided sufficient information to determine the value of lagoon resources based on direct and other non-use advantages. Therefore, our enumerators presented the following scenarios to the locals: Our enumerators elucidated the vulnerability of the Batticaloa Lagoon based on scientific research. Respondents were given a visual representation of how vulnerable the Batticaloa Lagoon would be in the coming decades, using images depicting lagoon degradation and declining biodiversity. Respondents were asked to rate the importance of the reasons for conserving the lagoon on a scale of 1 (not at all important) to 5 (very important).

The scenario presupposed that between now and 2030, a local project would be undertaken and that all residents would be compelled to contribute money to conserve the lagoon resources. The next question was how much of a lump sum respondents would be willing to contribute to the project.

The final segment contained elicitation questions regarding WTP and WTA. Two methods are commonly used to elicit preferences: acceptance and refusal. Prior to the main survey, an open-ended pretest was conducted with 50 households in the buffer zone to evaluate and refine the survey's design.

In the pre-test survey, the lagoon management committee invited household members to participate in interviews with enumerators. This pre-test helped to determine the appropriate attribute levels and compensation rates for the choice experiment. The questionnaire was designed to encourage genuine and accurate responses regarding WTP. Enumerators recorded positive WTP declarations and enquired about the reasons for refusal when the respondents were unwilling to pay.

Survey method

The survey targeted the lagoon's 1-km buffer zone (9 DS divisions and 145 Grama Niladhari divisions within an area of 82.74 km^2; population ~116,000). Using stratified sampling, interviews were conducted with 405 respondents (fishermen, 16.05%; tourists, 62.47%; and flood-affected residents, 21.48%). Face-to-face interviews ensured the reliability of the data.

A stratified sampling strategy was designed to capture the geographic and socioeconomic variability within the lagoon watershed. The primary strata were the nine Divisional Secretariat (DS) divisions bordering the lagoon with a 1 km buffer zone, with further consideration given to the distinct environmental and socio-economic contexts of the eastern and western regions of the Batticaloa district. This approach ensured that the sample adequately represented population heterogeneity related to land use, dependency on ecosystem services, and socioeconomic characteristics, thereby enhancing the robustness and validity of the data collected.

3.2 Econometric framework

Lancaster's model of consumer choice provides the theoretical foundation for the Choice Experiment (CE) approach, while a multinomial logit (MNL) model provides econometric underpinnings based on Random Utility Theory (RUT) (Lancaster, 1966). According to Lancaster's theory, consumers derive pleasure from products or services and their features and benefits (Birol et al., 2006). Carefully planned experiments or tasks constitute the backbone of CE methodology, which is a highly structured approach to data production (Hanley et al., 1998). The CE approach integrates behaviour with economic valuation based on random utility theory, which characterizes decisions in a utility-maximising framework (Wang, 2007).

Respondents' decision-making is always guided by a random utility-maximising strategy in the choice experiment (Louviere et al., 2010). According to random utility theory, the choice of individual i is based on that person's utility from option j, denoted by Uij. Thus,

$$U_{ij} = V_{ij} + \varepsilon_{ij} \quad (1)$$

Systematic elements (V) and random elements (ε) are combined to form the utility (U). The independent and identically distributed (IID) error term is represented by (V_{ij}), which represents the systematic utility elements that person i places on alternatives (j), and (ij), which represents the random elements.

As a result, the multinomial logit (MNL) model can be used to begin the DCM. Eq. (2), where m is a scale parameter that is inversely proportional to the standard deviation of the error distribution and is typically assumed to be one, can be estimated using MNL regression, which assumes that scale factors persist persistently throughout the alternatives and permit various ranges of utility with repetition.

$$E(ij) = \frac{exp^{mV_{ij}}}{\sum_{n \in C} exp^{mV_{in}}} \quad (2)$$

The estimated linearity in the parameter utility framework for the jth option is.

$$V_{ij} = ASC_j + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots \ldots \ldots + \beta_k X_k + \gamma_p (S_p * ASC_j). \quad (3)$$

In the utility function, j stands for an option, k represents quality, and p reflects socio-demographic variables. The constant word ASC refers to all alternatives in a choice set. Interaction terms (e.g. Fish Diversity × Fishermen) were incorporated into the utility function to statistically test the differences between stakeholder groups. The Wald test confirmed significant differences ($p < 0.05$) in the coefficients of fish diversity ($\chi^2 = 12.34$, $p = 0.002$) and flora/fauna ($\chi^2 = 9.87$, $p = 0.007$) among the groups.

To compare the degree of conservation, this study evaluated respondents' WTP and WTA. As a result, the WTP and WTA display the marginal substitution rate between the value of the conserved traits and those sacrificed and the cost of conservation and compensation. The WTP for a slight modification of the kth attribute (k) is as follows:

$$WTP_k = -\frac{\beta_k}{\beta_\mu} \quad (4)$$

Therefore, the WTA clarifies that there is little exchange between conservation traits and the willingness to accept remuneration. The WTA for a slight change in the kth attribute (k) is described as follows:

$$WTA_k = \frac{\beta_k}{\beta_\mu} \quad (5)$$

(Hensher et al., 2015) claimed that this study used an MNL model to understand stakeholders' desires for lagoon conservation.

The within-subject design was deliberately chosen to enable a direct comparison of the same individual's trade-offs when framed as a gain (WTP) versus a loss (WTA), which is a key focus of this research. While this approach can introduce potential bias, such as cognitive dissonance or sequencing effects, the study mitigated this by randomising the choice tasks and enforcing a time gap between the WTP and WTA sections of the questionnaire (Carson et al., 2001).

3.3 Choice task Design

The initial phase of the Choice Experiment (CE) involved selecting attributes that represent the key ecological services of the Batticaloa Lagoon. Informed by a comprehensive literature review and focus group discussions with stakeholders and the lagoon management authority, four core attributes were identified: Fish Diversity, Mangrove Coverage, Waterbirds and other Flora & Fauna, and Flood Control. A Cost/Payment attribute was included as the payment vehicle. The selected attributes satisfied three criteria: (1) they pertain directly to ecosystem services (ES); (2) they are directly influenced by management practices; and (3) they lack established market values (Bateman et al., 2002).

Choice Task Model – Choice Set I -WTP

Attributes	Definition	Levels
Fish Diversity	Number of fish species/ types	Current Status (96)
		Level I (91)
		Level II (86)
		Level III (80)
Mangrove Coverage	Mangrove coverage in hectares (-20% and -40%)	Current Status (321 ha)
		Level I (257 ha)
		Level II (203 ha)
		Level III (175 ha)
Waterbirds and other flora and fauna	Species diversity	Level I Current
		Level II (10% Decrease)
		Level III (25% devastating)
Flood control	Flood control level by the meter (m)	Current Status (2. 75m)
		Level I (2.30m)
		Level II (2.00m)
		Level III (1.75m)
Cost/ Payment (LKR)	Willingness to Accept for recreational program/ monthly Compensation via a reduction in your monthly/ annual LA Taxes (LKR/Per month)	Level I (LKR 150)
		Level II (LKR 260)
		Level III (LKR 440)

Tab.1 Attributes and levels used in WTP choice modelling set 1 task

Choice Task Model – Choice Set II -WTA

Attributes	Definition	Levels
Fish Diversity	Number of fish species/ types	Current Status (96)
		Level I (100)
		Level II (105)
		Level III (110)
Mangrove Coverage	Mangrove coverage in hectares (-20% and -40%)	Current Status (321 ha)
		Level I (340 ha)
		Level II (385 ha)
		Level III (420 ha)
Waterbirds and other flora and fauna	Species diversity	Level I Current
		Level II 5% Increase
		Level III 8% Increase
Flood control	Flood control level by the meter (m)	Current Status (2. 75m)
		Level I (3.20m)
		Level II (3.75m)
		Level III (4.20m)
Cost/ Payment (LKR)	The monthly payment for Lagoon management via increasing in your monthly LA Taxes (LKR/Per month)	Level I (LKR 230)
		Level II (LKR 320)
		Level III (LKR 550)

Tab.2 Attributes and levels used in the WTA choice modelling set 2 task

The levels for each attribute, representing scenarios of enhanced or degraded environmental quality, were grounded in scientific research and expert consultation to ensure realism and policy relevance for the Batticaloa Lagoon Watershed. Tab.1 outlines the attributes, their definitions, and the specific levels used in the Willingness-to-Pay (WTP) choice sets, which framed scenarios as potential gains or improvements from the status quo. Conversely, Tab.2 presents the attribute levels for the Willingness-to-Accept (WTA) choice sets, which framed scenarios as potential losses or degradations requiring compensation. To construct the choice scenarios, a statistical design with orthogonality constraints was used, which allowed each attribute to be evaluated independently (Louviere et al., 2010). Using SAS software and following the D-efficiency rules, an orthogonal factorial design was generated, resulting in 18 unique choice scenarios. In line with established practices (Rolfe & Bennett, 2009), these 18 scenarios were structured into six blocks. Each block was presented to a subset of respondents and contained choice sets with three management alternatives and a status-quo option.

3.4 Choice Experiment (CE) approach

The final step was to present the designed scenarios to the respondents in a clear and intuitive format. Table 3 provides a concrete example of a choice set from the WTP survey, in which respondents selected their preferred option for conserving the lagoon at a specified cost. Table 4 shows a parallel example from the WTA survey, where respondents chose their preferred option for accepting a certain level of degradation in exchange for a monthly compensation. Prior to the main survey, the attributes and their levels were refined through in-depth interviews with representatives from key stakeholder groups (fishermen, flood-affected residents, and tourists) and consultations with lagoon specialists from relevant government entities. This process ensured that the scenarios were credible and meaningful to the respondents. To mitigate the potential influence of dominant opinions, this study relied on individual interviews rather than solely on group discussions. In the final survey, each respondent was presented with six choice sets. A respondent's consistent selection of the status quo option across all sets was interpreted as a preference for the current situation, a point verified through follow-up questions asking for their rationale for this choice. This design ensured that the data captured the nuanced trade-offs between lagoon attributes and monetary amounts.

Choice Modelling – Choice Set I-WTP

Attributes	Choice 1	Choice 2	Choice 3	Current Status
Fish Diversity (Number of fish species/ types)	91 Species	86 Species	80 Species	96 Species
Mangrove Coverage (Mangrove coverage in hectare (-20% and -40%))	257 ha	203 ha	175 ha	321 ha
Waterbirds and other flora and fauna (Species diversity)	Maintain the current biodiversity	Species diversity decreases by 10%	Species diversity decreases by 20%	No increase
Flood control (Flood control level by the meter -m)	2.30 m	2.00 m	1.75 m	2.75 m
Cost/ Payment via addition in your monthly (The monthly payment for Lagoon management via increasing in your monthly LA Taxes -LKR/Per month	LKR 150	LKR 260	LKR 440	LKR 0

Tab. 3 Examples of choice tasks used in the choice experiment approach for the WTP survey.

Choice Modelling – Choice Set II (via Local Authority tax)-WTA

Attributes	Choice 1	Choice 2	Choice 3	*Current Status*
Fish Diversity (Number of fish species/ types)	100 Species	105 Species	110 Species	*96 Species*
Mangrove Coverage (Mangrove coverage in hectare (-20% and -40%))	340 ha	385 ha	420 ha	*321 ha*
Waterbirds and other flora and fauna (Species diversity)	Maintain the current biodiversity	Species diversity increases by 5%	Species diversity increases by 8%	*No increase*
Flood control (Flood control level by the meter -m)	3.20 m	3.75 m	4.20 m	*2.75 m*
Cost/ Payment via addition in your monthly (The monthly payment for Lagoon management via increasing in your monthly LA Taxes -LKR/Per month	LKR 230	LKR 320	LKR 550	*LKR 0*

Tab.4 Examples of choice tasks used in the choice experiment approach for the WTP survey

4. Results

4.1 Individual characteristics

The respondents' demographics are summarised in Tab.5. Most respondents were male (59.51%), with a median age of 45 years and a median income of LKR 29,430 per month. Only 29.87% of respondents had tertiary education.

Demographic characteristics of the respondents (N =405)

Gender and Family		Type of respondents (%)	
Male (%)	59.51	Fishermen (%)	16.05
Female (%)	40.49	Recreational visitors (%)	62.47
The average age in years	45.14	Subject to flood damage (%)	21.48
Average family size	2.41	**Monthly income (%)**	
Average monthly income (LKR)	29,429.62	Below LKR 20,000a	11.36
Educational level (%)		LKR 20,000 – 40,000	45.19
Primary Education	26.92	LKR 40,000 – 60,000	36.05
Secondary Education	43.21	LKR 60,000 - 80,000	5.43
Tertiary Education	29.87	LKR 80,000 - 100,000	1.23
Willingness of lagoon conservation (%)	93.58	More than LKR 100,000	0.74

Tab.5 Demographic characteristics of the respondents

4.2 Local awareness of Batticaloa lagoon conservation

As shown in Tab.6, 37.28% of respondents attributed degradation to aquaculture/fishery, and 30.86% cited agricultural waste as the cause. Tab.7 shows that "benefits for future uses" (63.21%) and "provisioning services" (30.37%) were the primary conservation motivators. Notably, 93.58% of the respondents supported conservation, and 78.3% expressed their WTP (Fig.2).

Reasons	Percentage
Agriculture, Chemical Waste	30.86
Aquaculture, fishery, *etc*.	37.28
Land Degradation	4.44
Sedimentation	6.91
Urbanisation	20.49

Tab.6 Perceived causes of lagoon degradation.

Reasons	Very important	Important	Neutral Important	Not so important	Not at all important
Benefits for future uses	63.21	15.06	12.10	5.19	4.44
Preventing floods, erosion, and salinisation	2.96	9.88	22.96	32.10	32.10
Providing recreation	0.99	36.54	14.81	21.73	25.93
Conserving biodiversity	2.47	22.47	31.36	21.98	21.73
Providing wood, fish, and raw materials	30.37	16.05	18.77	19.01	15.80

Tab.7 Perceived motives for lagoon conservation

These results suggest two important reasons: benefits for future use, such as providing wood, fish, and raw materials, and providing recreation. The less important reason for lagoon conservation is the prevention of floods, erosion, and salinisation. In addition, 93.58% of respondents were willing to conserve lagoons. Of those surveyed, 78.3% expressed a willingness to pay, while 21.7% expressed no willingness to pay to protect the Batticaloa Lagoon (Fig.2).

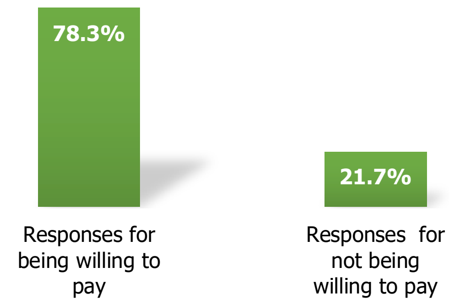

Fig.2 Responses for Willing to Pay

Tab.8 reveals that 78.2% of the respondents supported conservation for communal benefits, while 52.3% cited financial constraints as a barrier to WTP. The most important reason was that it was a good project for society (78.2%). Approximately 10% of respondents believed that their contributions were beneficial for their own sake, while 6.2% thought they would benefit future generations. However, household income restrictions, which accounted for 52.3% of the negative replies, were followed by the claim that payment for Batticaloa Lagoon services was the exclusive duty of LA (26.1%) as the primary justification for not being willing to pay for them.

Reasons	**Percent**
Respondent's reasons for being willing to pay	
This initiative program benefits the entire community.	78.2
This initiative program is beneficial to me.	10.0
This initiative is beneficial for future generations.	6.2
This initiative program is required to preserve culture and beliefs.	5.6
Respondent's reasons for not being willing to pay	
My family has no funds to donate.	52.3
Local government is solely responsible for lagoon conservation.	26.1
I am concerned that my family's donation will not be utilized correctly	11.4
I do not believe in the programme's success.	5.7
It is the beneficiary who should fund	4.5

Tab.8 Reasons for being willing and not being willing to pay

Tab.9 presents the MNL model's results. The MNL model revealed substantial variation in how stakeholders value lagoon resources. Stakeholders place a high value on the lagoon's flora and fauna, as reflected in the significant WTP and WTA for these attributes. All model fit statistics confirmed the final model's superiority. Lagoon users are prepared to incur significant costs to safeguard fish populations in the lagoon. However, research shows that lagoon users value fish diversity more highly and desire more significant compensation if it diminishes in the future. This could significantly impact the WTA, suggesting that many survey participants were fishermen who would benefit from increased lagoon fish diversity. Mangrove coverage significantly influences lagoon conservation value.

This finding aligns with (De Rezende et al., 2015), who reported strong public support for mangrove expansion in Brazil. Many of the respondents in the survey appeared to be tourists who would rather see an ecological service provided, such as protecting the lagoon's flora, fauna, and mangroves. The results indicate that stakeholders care about ensuring the longevity of the lagoon's flora and wildlife and that their WTP for conservation increases as the lagoon's flora and fauna improve. (Suresh et al., 2021) claimed that a decline in biodiversity affects the public's willingness to pay for the preservation of lagoon spaces. Thus, the aesthetic attractiveness of the areas surrounding lagoon ecosystems is enhanced by a wide variety of plants and animals, which increases the number of visitors to these areas. Flood control was a statistically significant negative variable, indicating that respondents valued flood damage more than flood control. The marginal values in Tab.10 indicate that stakeholders, on average, would require LKR 32 in compensation for the loss of one fish species, while their mean WTP to gain one fish species was LKR 8. The study suggests that fish diversity in lagoons is essential for their users. The WTA is approximately LKR 1 for every percentage point of decline, whereas lagoon users are prepared to pay LKR 5 for every percentage point of increased mangrove coverage. Although the loss of mangroves would severely affect the long-term viability of lagoon resources, stakeholders in lagoons have a low priority.

Choice Set	Attribute	Levels	WTP (LKR ± SE)	WTA (LKR ± SE)
Choice Set 1	Fish Diversity	Level I (91 species)	8.12** (±1.25)	32.02*** (±3.01)
	Mangrove Coverage	Level I (257 ha)	5.05* (±0.83)	1.25 (±0.22)
	Flora & Fauna	10% Decrease	-59.86*** (±18.90)	-120.18*** (±21.05)
	Flood Control	Level I (2.30 m)	3.25 (±20.72)	5.92 (±29.33)
	Payment/Compensation	LKR 230	-2.04*** (±0.00)	-1.72** (±0.00)
Choice Set 2	Fish Diversity	Level II (86 species)	6.78* (±1.98)	28.45*** (±3.45)
	Mangrove Coverage	Level II (203 ha)	-3.25 (±0.72)	-2.02 (±0.80)
	Flora & Fauna	25% Devastation	-127.81*** (±30.10)	-245.60** (±35.20)
	Flood Control	Level II (2.00 m)	-4.56 (±53.20)	-8.93 (±72.47)
	Payment/Compensation	LKR 320	-1.88*** (±0.00)	-1.53** (±0.00)
Choice Set 3	Fish Diversity	Level III (80 species)	4.52 (±10.21)	21.35 (±24.50)
	Mangrove Coverage	Level III (175 ha)	-6.72 (±7.55)	-4.10 (±8.42)
	Flora & Fauna	Current (No change)	Base	Base
	Flood Control	Current Status (2.75 m)	Base	Base
	Payment/Compensation	LKR 550	-1.23*** (±0.00)	-1.10** (±0.00)
Model Fit	Log-Likelihood	-	379.93	444.98
	Pseudo R²	-	0.204	0.165
	Constant	-	4.42*** (±0.00)	3.57*** (±0.00)
Respondents	N	405	-	-

***, **, * = significance at 1%, 5%, 10%, respectively; n.s. = not significant.

Tab.9 Results of multinomial logit models for WTP and WTA

A key finding was the significant disparity between the WTP and WTA values across all attributes. For instance, fishermen's WTA for the loss of a single fish species (LKR 32.02) was approximately four times higher than their WTP for gaining one (LKR 8.12), highlighting a strong endowment effect. The results (Tab.10) demonstrate that stakeholder perceptions of lagoon preservation and degradation are highly diverse. The positive and statistically significant coefficient for fish variety suggests that anglers place a higher valuation on this attribute than on others. The analysis revealed a consistent pattern in which WTA values substantially exceeded WTP values for equivalent changes in ecosystem attributes, a key finding explored in the subsequent discussion.

This supports the findings of (Suresh et al., 2021), who discovered that fishermen place high importance on maintaining fish populations because of their considerable economic benefits. In addition, WTA analysis indicated that fishermen regard flora and wildlife as crucial elements of lagoon ecosystems. Therefore, they are more inclined to seek significant compensation for the destruction of these resources and contribute financially to conservation initiatives.

Attribute	MNL model	
	Monetary value of WTP (Rs)	Monetary value of WTA (Rs)
Fish diversity	8.12**	32.02***
	-4.3612	-3.2985
Mangrove coverage	5.05***	1.25
	-0.8325	-0.2201
Flora and fauna	59.86***	120.18***
	-18.9004	-21.0485
Flood control	3.25	5.92
	-20.7235	-29.3274

***, **, * Significance at 1, 5, 10% levels, respectively.

Tab.10 Monetary value of the base model for WTP and WTA

Multinomial logit (MNL) model analysis revealed critical insights into stakeholder preferences for Batticaloa Lagoon's conservation attributes, highlighting synergies and conflicts in valuation. Key findings demonstrated statistically significant disparities in WTP and WTA across stakeholder groups, shaped by their dependency on specific ecosystem services (Tab.10). WTP and WTA responses were analysed independently using distinct MNL models to avoid conflating valuation contexts.

Tab.11 shows the implicit pricing of WTP for the three lagoon consumers to find improvements in the lagoon's features and WTA compensation for their loss. Increasing the variety of fish available would cost the fishing community an additional LKR 90, and increasing the diversity of flora and wildlife would cost an additional LKR 9. Meanwhile, fishermen asked for payouts three times more than the WTP (LKR 29) for every unit of biodiversity added to the fish population. In contrast, compensation for biodiversity loss tended to increase (LKR: 60). This could be because fishermen in developing nations are more concerned with making a living than having fun.

The statistically significant disparities in WTP/WTA across stakeholder groups (Tab.11) underscore the need for differentiated policy instruments. For instance, fishermen's high WTA for losing fish diversity (LKR 29.33) suggests compensatory payments for fishery-related restrictions. Simultaneously, tourists' elevated WTP for flora/fauna (LKR 65.34) justifies ecotourism levies (de Rezende et al., 2015), and the indifference of flood-affected residents to flood control ($p > 0.05$) highlights the urgency of awareness campaigns linking lagoon health and flood resilience. As fishermen place a significantly higher value on mangroves than other lagoon resource users, they are willing to accept only half of their WTP compensation. Corroborating previous WTA studies, our results show that vulnerable lagoon users assign high value to flood prevention. Globally, these findings resonate with coastal ecosystems facing analogous anthropogenic pressures, from Chilika Lake in India to the Celestún Lagoon in Mexico (Newton et al., 2018; Prosser et al., 2017). The WTA-WTP asymmetry observed here, a four-fold gap for fishermen, reflects broader behavioural economics principles, where stakeholders demand higher compensation for losses than they will pay for gains (Coursey et al., 1987; Plott & Zeiler, 2005). This underscores the urgency of reframing conservation incentives using equity-centred PES frameworks (Ureta et al., 2022). Also, the payment for ecosystem services performance based on fine-tuning measures which involve building and population densities and vegetation cover (Lai et al., 2023). The results reveal a key behavioural pattern: stakeholders are more inclined to demand compensation (WTA) for resource degradation than to contribute to conservation efforts (WTP). This asymmetry mirrors global studies showing that individuals often assign a higher value to losses than to gains, a phenomenon rooted in behavioral economics. Similar valuation asymmetries were observed in Brazil's Pantanal wetlands, where stakeholder-specific PES improved conservation outcomes by 45% (Guerra et al., 2025).

Attribute	WTP (LKR)	WTA (LKR)
Fish Diversity		
Fishermen	9.93** (±1.25)	29.33*** (±3.01)
Flood-Affected	3.25 (±2.10)	16.03* (±4.15)
Tourists	8.95* (±1.98)	33.21*** (±2.75)
Mangrove Coverage		
Fishermen	1.01*** (±0.15)	0.07 (±0.21)
Flood-Affected	0.46 (±0.30)	0.24 (±0.18)
Tourists	0.53 (±0.25)	0.17 (±0.22)
Flora & Fauna		
Fishermen	89.89** (±16.21)	60.01** (±31.26)
Flood-Affected	99.12** (±18.32)	82.23* (±47.70)
Tourists	65.34** (±9.26)	101.72*** (±23.26)

***, **, * denote significance at 1%, 5%, and 10% levels, respectively. Standard errors (±) are explicitly labelled for clarity.

Tab.11 Stakeholder-Specific WTP/WTA Values

5. Discussion

5.1 The behavioral economics of valuation

The core of the study findings reveals a landscape of stakeholder valuation fundamentally shaped by behavioural economic principles, challenging the standard economic assumption of a symmetric value for gains and losses. The pronounced disparity between WTA and WTP across all groups, most strikingly the four-fold gap for fish diversity among fishermen, is a classic manifestation of loss aversion (Johnston et al., 2006), where the disutility of losing an asset is psychologically far more impactful than the utility of acquiring it. For fishermen, fish stocks are not only a potential source of income but also a vital endowment central to their identity, food security, and economic survival. This endowment effect (Feng et al., 2024) explains why they demand significantly higher compensation (LKR 32.02/species) to relinquish this asset than they are willing to pay (LKR 8.12/species) to enhance it. Their valuation is not merely that of a commodity but of a foundational component of their livelihood, which they feel they already 'own' and stand to lose. This behavioural reality creates a critical policy challenge: conservation measures that restrict access are not perceived as a forgone future gain, but as an immediate and deeply felt loss, requiring commensurate compensation to be politically and socially viable. This loss aversion was

most acute for fishermen regarding the fish diversity. The highest WTA was demonstrated for fish diversity loss (LKR 32.02/species), reflecting their direct and heavy dependence on lagoon fisheries for their livelihood and food security (Suresh et al., 2021). This aligns with the context of Batticaloa, where over 16% of the respondents identified declining fish stocks as a threat to food security. This situation highlights a critical vulnerability: the economic pressures on fishermen, combined with other anthropogenic stresses on the lagoon, can lead to overexploitation, creating a feedback loop that undermines the long-term viability of fisheries and, consequently, regional food security. Therefore, fishermen are not a threat per se, but rather a key group whose economic stability must be addressed to break the cycle of resource degradation. This aligns with global studies in which small-scale fishing communities disproportionately value biodiversity because of their direct reliance on their livelihood (Dupras et al., 2017; Valiela et al., 2001). An elevated WTA reflects a defensive stance against potential income loss, consistent with observations in tropical fisheries where overexploitation threatens food security (Suresh et al., 2021). Notably, this mirrors the findings in Vietnam's Cat Ba Biosphere Reserve, where fishermen demanded higher compensation for mangrove restrictions than tourists (Pham et al., 2018).
Conversely, tourists exhibited a distinct preference for the flora and fauna of the lagoon. Contrary to what might be assumed, the results indicate that lagoon resource users highly value the preservation of flora and fauna. The WTA for a loss of species (LKR 120.18) was double the WTP for a gain (LKR 59.86), reinforcing the loss aversion phenomenon among Batticaloa residents. This suggests that the non-use and aesthetic values of biodiversity are strongly held, and its degradation would be perceived as a significant loss by the community. The status of Batticaloa as a nationally significant wetland with high biodiversity underscores the need to leverage ecotourism for conservation funding, as in Costa Rica (Locatelli et al., 2013). This behaviour echoes the principles of behavioural economics, where individuals assign greater weight to potential losses than to gains, and aligns with ecotourism studies that emphasise aesthetic values (Wolf et al., 2019). For instance, in Brazil's mangrove restoration projects, tourists prioritised scenic integrity over utilitarian benefits (De Rezende et al., 2015; Gatt et al., 2022). A critical and paradoxical finding was the statistical insignificance of flood control in both the WTP ($\beta = 3.25$, $p > 0.05$) and WTA ($\beta = 5.92$, $p > 0.05$) models, despite the lagoon's known role in flood mitigation. This finding mirrors the trends in Bangladesh, where immediate livelihood concerns overshadow long-term flood risks (Hoq et al., 2021; Islam et al., 2021). This undervaluation is critical in Batticaloa, where 21.48% of the respondents face flood risk. This paradox suggests that immediate socioeconomic pressures, such as income generation, overshadow long-term flood risks, a trend that has been observed globally in flood-prone communities (Newton et al., 2018). For example, in Bangladesh's coastal zones, residents prioritise fishing access over flood infrastructure investments until catastrophic events occur (Islam et al., 2021). Similarly, the regulatory services provided by mangroves are substantially undervalued. Despite their role in coastal protection, mangrove coverage had a negligible WTA (LKR 1.25/ha loss), likely because of limited awareness of these regulatory services. A similar undervaluation was observed in Southeast Asia until cyclones highlighted this importance. This aligns with Southeast Asian studies, where communities recognised the provisioning benefits of mangroves (e.g. firewood) but undervalued disaster resilience until cyclones caused irreversible damage (Vo et al., 2020).

5.2 An institutional blueprint: from monocentric pes to polycentric governance

These behavioural insights challenge the feasibility of universal, monocentric PES designs, which often fail because they cannot account for profound value heterogeneity (Ostrom, 2009; Bocca et al., 2024). Our results empirically demonstrate that a single payment mechanism would either grossly under-compensate fishermen (leading to non-compliance and conflict) or over-compensate other groups, wasting scarce conservation resources. Instead, we advocate for a polycentric governance system, a framework of multiple, overlapping decision centres operating at different scales with a degree of autonomy but under a shared set of rules (Lubell & Morrison, 2021; Van Der Plank et al., 2022). This approach is uniquely suited to managing the divergent preferences we have identified, moving from a one-size-fits-all payment to a suite of tailored and mutually reinforcing instruments. For fishermen, the high WTA for fish diversity loss suggests that direct restrictions without compensation are untenable. A viable mechanism involves "Payment for Seasonal Closure Compliance" or "Gear-Restriction Stewardship Payments." Rather than a simple cash transfer, payments can be structured as conditional contracts. Local fishery cooperatives can be contracted to adhere to scientifically determined seasonal bans or use selective fishing gear that reduces bycatch. Compliance would be verified by the lagoon management authority or the community monitors. The payment level should be calibrated to the fishermen's WTA (approximately LKR 29/species lost) to ensure it is perceived as a fair exchange for a loss, not as a welfare handout. This model, akin to Ghana's community-led marine reserves, transforms fishermen from targets of regulation into active, paid stewards of the resource. For tourists, the elevated WTP for flora and fauna (LKR 65.34) underscores the economic potential of leveraging non-use value. A practical mechanism is a "Transparent Ecotourism Surcharge." This levy could be a small, mandatory fee (e.g., LKR 100-200) bundled with existing entry fees to lagoon-side parks, boat tours, or registered hotels within the watershed. To overcome the trust issues revealed in our survey (Table 8), the revenue must be ring-fenced in a dedicated "Batticaloa Lagoon Conservation Fund", managed by a board comprising local government, community representatives, and tourism operators. Disbursements from this fund would be publicly documented and finance specific visible projects, such as mangrove sapling nurseries, anti-erosion fencing, or biodiversity corridors, creating a tangible feedback loop for tourists who contributed. For flood-affected residents, the paradoxical undervaluation of flood control points to a critical awareness gap that must be addressed. A program for this group must combine "Structural Mitigation with Environmental Literacy." This could involve co-investment in small-scale infrastructure (e.g. community flood barriers, mangrove replanting along vulnerable shores) coupled with mandatory educational campaigns. These campaigns should visually and convincingly demonstrate the direct causal link between mangrove root systems and wave attenuation, making the abstract 'regulating service' more concrete. By linking lagoon health directly to personal safety and property protection, such programs aim to shift long-term valuations and build a constituency for conservation beyond direct use.

5.3 Synthesizing the framework: addressing the "diversity of values"

Together, these proposed mechanisms exemplify a polycentric approach to PES that directly addresses the "diversity of values" theory (Barbier, 2011). They acknowledge that stakeholders hold conflicting priorities not out of irrationality but due to divergent dependencies, knowledge, and behavioural biases. The fishermen's compensatory system operates at a local, resource-user scale; the tourist levy functions at a regional, sectoral scale; and the resident program integrates municipal disaster risk reduction with community engagement. This multi-tiered, participatory governance model is more complex to establish than a top-down payment scheme; however, this complexity allows it to balance local autonomy with regional coordination, enhancing its legitimacy, equity, and long-term resilience (Chaffin & Gunderson, 2015).

6. Conclusion

This study demonstrates that sustainable lagoon management in Batticaloa requires strategically managing stakeholder divergence rather than seeking an unattainable consensus. By employing a novel within-subject choice experiment, this study uncovered fundamental valuation asymmetries that critically inform Payment for Ecosystem Services (PES) design. The four-fold disparity between willingness-to-accept (WTA) and willingness-to-pay (WTP) for fish diversity among fishermen provides empirical evidence of loss aversion rooted in direct livelihood dependency. Conversely, tourists' high valuation of flora and fauna underscores the economic potential of leveraging ecotourism for conservation funding in the region. A critical and paradoxical finding is the significant undervaluation of flood-control services, even among flood-affected residents. This reveals a pervasive disconnect between immediate socioeconomic pressures and long-term climate risks, highlighting a priority area for targeted environmental education alongside financial incentives. Consequently, these findings are a clear warning against one-size-fits-all conservation policies. The empirically demonstrated heterogeneity in stakeholder preferences necessitates a polycentric PES framework composed of parallel tailored instruments: compensatory payments for fishermen, ecotourism levies for tourists, and risk-mitigation programs coupled with awareness campaigns for residents. For policymakers in Sri Lanka and analogous Global South contexts, this study provides a replicable blueprint for designing equitable and effective conservation strategies that reconcile ecological integrity with socioeconomic well-being by explicitly accounting for the values and behaviours of those who depend on the resource.

7. Recommendation and future research

Building on the findings and limitations of this study, several promising avenues for future research have emerged. Integrating Underrepresented Stakeholders:

- Quantifying Long-term PES Equity: Research is needed to quantify the long-term equity and livelihood outcomes of PES schemes implemented in such socio-ecological systems, tracking how benefits and costs are distributed over time;
- Leveraging Predictive Analytics: The integration of machine learning with discrete choice data could help predict stakeholder-specific valuation thresholds and behavioural responses under different policy scenarios, thereby enhancing the adaptive management of PES frameworks;
- Fostering Comparative and Collaborative Learning: Expanding comparative analyses to other lagoon systems in the Global South can help identify transferable governance innovation. Furthermore, facilitating South-South knowledge exchange would be valuable for adapting the differentiated PES model developed for Batticaloa to analogous socio-ecological contexts.

Conserving Sri Lanka’s Batticaloa Lagoon and analogous ecosystems requires a multifaceted approach that balances ecological preservation and socioeconomic equity. Policymakers can ensure the long-term viability of vital ecosystems through stakeholder-specific incentives, enhanced environmental literacy, and community engagement. Investment in environmental education and local conservation initiatives will safeguard lagoon resources and fortify the synergy between ecological health and human well-being.

Data availability

The data are available upon request.

Declarations

Ethics approval and consent to participate: Ethical approval and consent to participate were obtained for this study. In the manuscript, it should be noted that, due to the absence of an institutional ethical board for approving social science research, there was no opportunity to apply for the approval of the Research Ethics Board (REB). This academic limitation resulted in an exemption from the requirement for ethical approval for this study.

Consent to participate: All participants provided informed consent for the use of their data in scientific publications. Minors were excluded from the study.

Competing interests: The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

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Image sources

All images are by the Authors.

Fig.1: Batticaloa District and Batticaloa Lagoon, Sri Lanka.

Fig.2: Responses for Willing to Pay

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Reducing UHI in historical centres: the greening transformation of open small spaces in San Lorenzo district in the city of Naples (Italy)

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Abstract
Urban Heat Island effects intensify thermal discomfort and energy consumption in densely built areas, particularly in historical city centres characterised by compact and stratified urban fabric. Such conditions necessitate targeted greening interventions in these urban fabrics, which are the focus of this study on the San Lorenzo district in Naples, a representative Mediterranean historic city, where limited open spaces coexist with strict heritage conservation constraints. Utilising ENVI-met 5.7 simulations, the research models microclimatic conditions under current and greening scenarios, considering detailed urban morphology, vegetation types, and local climate data representative of peak summer days. Physiological Equivalent Temperature, Mean Radiant Temperature and Universal Thermal Comfort indices are employed to measure thermal comfort improvements through targeted greening interventions in small yet strategically significant spaces like inner cohorts of historical buildings. The findings demonstrate the cooling potential of integrating green transformation also in the small inner courtyards of the noble buildings by restoring the original function of these spaces as gardens and orange groves. This kind of solution can be efficiently adopted for a sustainable urban planning, helping mitigate UHI impacts and improve residents' well-being amidst global warming challenges.

Keywords
Urban open spaces; UHI; Courtyards; ENVImet; Urban greening

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1. Introduction

Global warming determined by climate change, intensifies heat stress hazards in urban areas, threatening people's health (especially fragile ones like children, elderly and low-income) and the regenerative capacities of vegetated and permeable surfaces (Nita et al., 2022). IPCC data show that the global average surface temperature was 0.99 °C higher than the preindustrial period, as measured between 2001 and 2020 (Lee et al., 2024). Furthermore, the expected worldwide temperature rise by the end of this century is now estimated to be 2.7°C, rather than 2.2°C (Lee et al., 2024), due to the slow and still widespread unwillingness to implement concrete strategies and actions to reduce climate-altering emissions. The consequent heat waves risk seriously to be further long, intense and frequent, leading to an increase in illness and mortality, as already happened in the period 2019-2022 compared to the beginning of the 2000s: 72% vs 30% (WMO, 2024).

In Europe, the worst scenario of severe heat waves is expected to occur in the Mediterranean countries, especially the Southern ones that are characterised by highly dense built-up and populated urban areas (EEA, 2024).

In this context of heat risk, the Urban Heat Island (UHI) phenomenon, combined with an extreme heat climate, is expected to worsen by creating a negative feedback loop. On one hand, higher temperatures and the associated thermal discomfort experienced by people lead to an increased demand for air conditioning, resulting in greater energy consumption, elevated outdoor temperatures, and higher greenhouse gas (GHG) emissions. On the other hand, vegetated and permeable surfaces within built-up areas are subjected to increased heat stress, along with the related air pollutants emitted into the atmosphere (Yi et al., 2025). Furthermore, from a broader systemic perspective, it is important to note that these microclimatic dynamics within and around urban areas contribute to escalating anthropogenic pressure on the soil, which is already severely threatened by the sealing process. This results in a reduction in the interception, storage, and infiltration of rainwater, thereby intensifying the climate vulnerability of cities (Guida, 2021; Gargiulo & Zucaro, 2025).

Therefore, the knowledge and the measurement of the relationships between the built environment features and UHI are relevant to define effective measures and solutions to improve the resilience of cities. Scholars like Bardhan et al. (2020), Hong et al. (2020), Deng et al. (2024) develop methods based on building energy and thermal simulation tools to simulate the radiative exchanges and fluxes among the different urban physical elements and assess the positive impact of cooling surfaces, with particular attention to the greening ones. The release of water vapour from plants induces the humidity increase with the increase of air reflection of solar radiation and final temperature decrease, and these positive and synergic benefits can be obtained by greening the city from the building level (cool and green roofs) to the district and urban one (open spaces and streets) concurrently (EEA, 2024; Lee et al., 2024; Cutini & Mara, 2025). However, the most advocated solution of localising vegetated surfaces within urban systems is hindered by two main obstacles:

- the amount of spaces (places and streets) that can be suitable for the greening transformation is limited in urban highly built-up cities and this presence is even more limited in their historical centres due to the building density, the stringent regulatory constraints and limits to transformations whose purpose is to protect and enhance historical-architectural-cultural heritage (peculiar to stratified urban contexts) and which are therefore incompatible with the needs of adaptation to climate change;
- the limited ability to develop a resilient urban project aimed at providing target-based greenery interventions integrated among them, according to the different physical (e.g. fabric type), functional (e.g. service offerings), socio-economic (e.g. needs of the prevailing segments of the population) and micro-climatic (air and soil temperature, etc.) characteristics of each part of the city.

The second aspect turns out to be particularly true for the Italian context, where the high number of climate adaptation and sustainable energy action plans is contrasted with an increase in green areas that is negligible in the last 10 years (Varbova, 2022) and inadequate compared to both the European and beyond European context, those further afield such as Medellin in Colombia and New York in the United States (Ascione et al., 2026; Gargiulo et al., 2017; Stiuso, 2025).

The historic centre of a city, especially if it is a layered city such as those found in the Mediterranean basin, constitutes a large part of the area where average temperatures are higher due to intrinsic physical characteristics that lead to high heat peaks (Donateo et al., 2023; Giannaros & Melas, 2012). The widespread use of highly emissive materials such as asphalt or stone paving, the geometry and orientation of road axes that can hinder natural ventilation, high building density and the (almost) total absence of vegetation and trees are among the main factors that accentuate the UHI phenomenon and therefore the severe thermal discomfort of those who live in and use this part of the city, both during the day and at night, given that the heat accumulated during the daytime remains trapped even after solar radiation due to the high emissivity of the surfaces present (Ahmed et al., 2024; Hu et al., 2023).

In historic centres, such as in the emblematic case of Naples, the fabric is characterised by a strong physical and functional stratification, which leaves limited open spaces available, often residual in relation to the building process. These open spaces are mainly constituted by small squares or internal courtyards, which are the only areas available for UHI mitigation measures (Gargiulo & Zucaro, 2023).

Fig.1 Typical green courtyard in the historical centre of the city of Naples

The limited availability of green areas, combined with the compact and consolidated layout of the historic centre, makes mitigation measures particularly challenging. Added to this are stringent urban planning restrictions aimed at preserving the cultural, architectural and identity value of these parts of the city. These constraints severely limit the possibilities for transforming and renovating open spaces, thus requiring careful and innovative consideration of the methods of intervention, which must reconcile climate effectiveness, respect for heritage and urban usability.

Therefore, rising temperatures require the ability to transform and reorganise urban spaces and activities to ensure both resilience to the unexpected effects of climate change and the preservation of urban assets and, above all, an improvement in people's quality of life.

With this in mind, the work, which focuses on historic city neighbourhoods with the highest building densities, proposes an experiment aimed at greening open spaces, such as the courtyards of noble buildings, or squares and open spaces, to measure the possible benefits in terms of lowering the perceived temperature. The conversion of built-up areas within historic neighbourhoods into permeable, tree-lined spaces could be an effective measure both for reducing the impact of the UHI and for enhancing historic city centres. In fact, in many cases, converting them back to their original function as gardens and vegetable plots, in direct contact with residences, could improve the microclimate, encourage social interaction and increase the attractiveness and liveability of historic centres (Diz-Mellado et al., 2021, 2023). Most of these spaces are currently used as private parking areas and, as such, are difficult to convert into green spaces due to the very high demand for parking spaces. To overcome the constraint of high private parking demand, a staged redevelopment approach can be adopted, as a portion of existing parking areas can be repurposed for greening during off-peak hours or in coordination with local urban mobility initiatives (e.g., pedestrian zones) ensuring continuity of access while gradually increasing green coverage.

The cooling thermal benefits and the lower perceived temperature obtained by greening the widespread open spaces and turning back to gardens the courtyards of buildings in a historical district of the city of Naples (in the South of Italy) are measured through the micro-climate simulation tool ENVI-met providing Physiological Equivalent Temperature (PET), Mean Radiant Temperature (MRT) and and Universal Thermal Comfort Index (UTCI) output parameters. By applying these interventions, this study seeks to deliver practical design guidance to enhance the thermal comfort and sustainability of these spaces, delivering useful findings for urban planners, architects, and policymakers operating in comparable climates. Indeed, the research question that orients this paper is as follows: What is the potential impact of greening the systems of open small spaces and courtyards of buildings on improving the microclimate conditions of historical high-density, densely built-up districts in hot climates?

The work provides part of the results obtained in a wider research project PRIN-funded research project 'Definition of a handbook of guidelines for implementing climate neutrality by improving the effectiveness of ecosystem services in rural and urban areas' (GICNES), aimed at defining an energy-efficient decision support tool based on urban and open space characteristics.

2. The benefits of small open spaces for reducing UHI impacts: the role of courtyards

The transformation to green and permeable surfaces of small open spaces in cities characterised by high building density, is a key intervention for climate change adaptation and urban resilience. These spaces, which are often fragmented, are widespread in stratified cities, where the ratio of built-up areas to open spaces is strongly skewed in favour of the former type, and where the UHI phenomenon manifests itself with increasing intensity, making a spreading and widespread adaptation strategy essential.

Despite their key role from a micro-climatic point of view, these spaces are particularly challenging to transform because they require specific design solutions that respect the urban context, capable of combining conservation with the introduction of green and permeable elements. Moreover, these spaces are often used for urban functions that seem to conflict with the need for increased green surfaces, as they are mostly necessary to meet urban mobility and accessibility needs. This adds layer of difficulty because transformations must consider multiple and coexisting urban functions.

Beyond the contemporary emphasis on small open spaces, historical and regional evidence further illustrates how courtyards have long served as climate-responsive elements across regions, influencing thermal comfort and indoor conditions through architectural and vegetation strategies. Courtyards have historically featured building architecture in many parts of the world, like South America, Asia, and the Mediterranean area, as they are an effective way to cope with various climates, proving their widespread functionality and appeal (Pelorosso et al., 2017; Miśkowiec, 2023). These outdoor spaces have been used to improve thermal comfort in hot climatic territories by providing natural ventilation, daylight, and thermal mass through the strategic use of sunlight, wind, and shade to allow residents to engage in various outdoor activities (Almhafdy et al., 2013;

Azimi & Shafaat, 2024). Furthermore, the inner presence of vegetation is a simple yet effective way to control a building's indoor temperature and sunlight exposure (Gonzalez et al., 2025; Sadat et al., 2025).

In general, the inner courtyards of buildings, historically conceived as the lungs and articulations of urban life, housed citrus groves, vegetable gardens, and spaces of sociability that defined the environmental quality and the relationship between inside and outside. In these courtyards, a local micro-economy linked to subsistence agricultural activities was developed, providing, at the same time, an aesthetic and symbolic value that reflected the wealth and residential or mercantile function of the building. After World War II, the growing economic prosperity and the resulting urban expansion, at least in the European context, and the greater demand for private mobility, accelerated the conversion of many courtyards into parking lots, warehouses, or new buildings, resulting in a shift away from the agricultural and social function that courtyards had served for centuries (Gargiulo & Zucaro, 2023, Francini et al., 2021). This process has often resulted in the closure or transformation of frontages, the sealing of interior surfaces and the removal of tree rows, exacerbating the consequences of UHI, increasing surface runoff and worsening the quality of interior public space, which has progressively closed in on itself, hindering pedestrian access, natural light and the perception of safety.

In all these cases, the climatic functionality of the courtyard is consequently reduced, and it would be beneficial to restore these spaces, reconnecting them with their historical purpose, while also satisfying current requirements.

The need to reduce UHI impacts has prompted numerous studies investigating how microclimate changes within a courtyard by determining lower air temperature, resulting in energy consumption reduction due to lower energy loss through surfaces that are in contact with the courtyard itself, by reducing the usage of conditioning systems (Tabesh & Sertyesilisik, 2016; Azimi, 2024). For instance, Ghaffarianhoseini et al. (2015) and Zhu et al. (2023) demonstrate the influence of orientation, height, wall albedo, and vegetation in optimising courtyard performance in hot-humid climates. Bulus et al. (2017) and Natanian et al. (2019) found that in dry and hot climates like Kuwait, Iran, Tunisia, the Middle East, and Nigeria, the microclimate created by courtyards significantly improved indoor comfort: it decreased by over 88% the time with severe indoor discomfort and proved to be superior in terms of energy balance in free-running conditions.

Generally, most of the existing literature focuses the attention on geometry and design (e.g. orientation, surface materials, aspect ratio) of these urban places with the main aim to assess the potential improvements in boosting natural cooling, minimising energy demand for cooling and heat loss and reducing heating requirements by working at the building scale (Dody et al., 2025; Zheng et al., 2023; Zhu et al., 2023). Interactions between courtyard properties and the surrounding urban contexts where they are distributed are less frequently analysed, even if the weight and the extent of these links can be useful to cool the built environments. To contribute to filling this gap, the present work proposes climate-response greening reconversion of San Lorenzo district in Naples, characterised by the presence of numerous sealed courtyards nestled within this dense built-up fabric.

3. Method

To measure and interpret the numerous interactions among micro-climate (thermal comfort, air temperature, etc.), physical (geometry, surface materials, etc.) and geomorphological (slope, surface typology, etc.) characteristics of the system of open small spaces and courtyards and their urban context, the software ENVI-met is used. Compared to the other modelling tools like CitySim Pro, RayMan, and Grasshopper plug-ins Ladybug, ENVI-met results are one of the most effective for simulating the spatial distribution of thermal parameters in different climatic settings and urban assets, plus variations in building configurations and vegetation types (Zhnag et al., 2022; Kotharkar & Dongarsane, 2024; Ye et al., 2025).

This tool, developed by Bruse's team in 1998, simulates vegetation-atmosphere-soil-building feedback through the laws of fluids and thermodynamics in 3D grid-based models that are now integrated in GIS environment.

Urban Data		
Physical characteristics	Building height, surface, Road width, length Outdoor surface materials	0000B1- Brick wall (aerated) 0200C3 - Concrete wall (hollow block) 0200PP-Pavement (Concrete), used dirty, Albedo:0.25 – Microscale roughness length 0.1 m
Geomorphological characteristics	Slope Vegetation	Land surface coverage within Copernicus DEM – GLO-30 (C.D.S.E., 2025) 0100XX-Grass 25 cm average dense 0100XY – Grass 50 cm average dense 01SLSM- Spherical, large trunk, sparse, medium (15m)
Climatic data		
Simulated day	July 31, 2024	
Simulated hours	14:00 - 15:00	
Time of Max Air Temperature	14:00	
Time of Min Air Temperature	05:00	
Time of Min Relative Humidity	16:00	
Time of Max Relative Humidity	25°C	
Min Air temperature	25°C	
Max Air temperature	34°C	
Min humidity	20%	
Max humidity	74%	
Wind speed at 10 m height	2 m/s	
Simulation Settings		
Grid size	x =3 m; y=3 m; z=3 m	
Model size	1000 m x 1000 m	
Simulated time	1 h	
Human Parameters (Biomet)		
Age	35	
Height	1.75 m (ISO 7730)	
Weight	75 kg	
BMI	18.5 - 24.9 kg/m2 (healthy weight)	
Clothes	0.90 clo in summer (pants or skirt and shirt made of thin fabric)	
Metabolic rate	164.49 (W)	

Tab.1 ENVI-met model settings and inputs

Existing studies demonstrate that material composition, vegetation, and shading affect microclimate conditions, supporting the use of ENVI-met to evaluate and optimise courtyard thermal performance (Soflaei et al., 2020; Diz-Mellado et al., 2021; Unal, 2025).

The ENVI-met Science version 5.7, released at the beginning of 2025, is used in this work, and the data required to run the simulations are summarised in Tab.1: urban and climatic data, simulation settings and personal characteristics for thermal comfort indexes calculation. The urban data refer to the characteristics of the urban system that are useful for the aims of this study: physical features of buildings, road network and open spaces and geomorphological ones related to the permeable soil, its slope and the existing vegetation. Raster images and vector data collected from available open databases are used to measure these characteristics and, consequently, to develop the 3D model of the study area in current and future greener scenarios, thanks to the interoperability between GIS and ENVI-met environments.

From Tab.1, it is also possible to read the materials in the ENVI-met Library, selected according to relevant physical properties (albedo, water absorption capacity, roughness, shading). If matching the 3D model elements is not possible, materials can be customised through the physical properties editor, allowing for realistic simulation (Darbani et al., 2023). This process allows a local library of interventions to be built, which is useful for comparisons between scenarios.

In parallel, the GIS layers needed to spatially represent the interventions are created, using software such as QGIS. Polygons and points describing surfaces to be modified, such as grassy soils, forested areas, and point trees, are digitized. Each geometry is coded through an identifying attribute, ensuring a consistent and georeferenced representation of the transformations envisioned in the project (Muniz-Gäal et al., 2019).

The climatic data are required to launch the simulations, and they refer to the hottest day of the year for the city of Naples on the basis of the historical meteorological archive provided by ilMeteo.it. The selected date is representative of a dry and clear summer day with peak summer conditions in a typical Mediterranean city, with high solar radiation and extreme air temperature.

The simulations were conducted in ENVI-met v5.7.1 on a domain of 1,000 × 1,000 m with a vertical and horizontal step of 3 m (grid size x=3 m; y=3 m; z=3 m), for a simulated duration of 1 hour (14:00–15:00), corresponding to the hottest time of day on 31 July 2024. The boundary conditions were taken from the historical archive for 31/07/2024 and were entered as: Tmin 25 °C (05:00), Tmax 34 °C (14:00), UR min 20% (20:00), UR max 74% (05:00), wind 2 m/s at 10 m. Given the district scale of our study and the need for multiple simulations, the chosen grid size ensures reliable results while maintaining practical processing times. The simulation date is July 31, 2024, a dry and clear summer day representing peak summer conditions in Naples with high solar radiation and extreme air temperature. The simulations covered a time interval from 2:00 to 3:00 pm, in order to focus on the most critical time in terms of microclimatic impact.

All the data in Tab.1 are used to compare the current scenario (sailed courtyards) and the greening one, simulated by planting trees and grass within the system of courtyards and open spaces localised in the selected district. The project greening scenario involves the creation of new green areas totalling approximately 0.1 km², distributed within the sample area subject to simulation, through the planting of 200 new trees and the permeabilisation of some currently impermeable surfaces. The selected area falls within a high-priority neighbourhood for intervention, according to the guidelines of the PAESC (Sustainable Energy and Climate Action Plan) of the City of Naples, which highlights the presence of high energy consumption, high thermal vulnerability of the population, risk of flooding and health costs associated with heat waves. For these reasons, it represents an emblematic urban context for assessing the effectiveness of adaptation strategies. The definition of the project scenario was supported by an analysis that considered the availability of open spaces, as well as compatibility with existing infrastructure and urban and cultural constraints. In fact, part of the area falls within the UNESCO Zone and areas subject to cultural heritage protection, conditions that limit the possibility of structural or invasive interventions. For this reason, the simulated scenario includes low-impact and temporary categories of intervention. Although no formal participatory process was conducted, the choice of intervention types is based on evidence from previous studies and municipal guidelines. These strategies are also consistent with the mitigation and adaptation objectives set out in the PAESC and municipal urban plans, presenting realistic scenarios that are potentially feasible in the medium term. The quantity and distribution of trees in the intervention scenario were defined based on the actual availability of open spaces suitable for planting, excluding areas that would interfere with traffic or that are not large enough to accommodate a canopy with an average radius of 5 m. As for green areas, "grass" was applied to all selected open spaces, not as a literal representation of a uniform lawn, but as a proxy for permeable surface material. In the ENVI-met library, the "Grass 25 cm" or "Grass 50 cm" category is the closest to the thermal and hydrological characteristics of draining paving or urban flower beds and is therefore suitable for simulating the effects of widespread permeability in the consolidated urban fabric. This pervasive greening transformation allows for maximizing the thermal benefits induced by the presence of trees in all open spaces (public and private), representing a theoretical and ideal benchmark useful for assessing the maximum potential for microclimate improvement achievable in densely built urban fabrics, where single and isolated greening interventions may have smaller positive effects (both in terms of temperature reduction and the parts of the built environment that benefit) because of the intrinsic characteristics of the built environment itself.

On the other side, the simulation of the real scenario represents a fundamental step to understand the current climatic conditions of the urban area analysed and to define a useful baseline for comparison with the proposed intervention solutions. The use of ENVI-met makes it possible to assess the behaviour of the urban fabric under current conditions, highlighting the most critical areas and the main sources of thermal stress (Muniz-Gäal et al., 2019).

The objective of this phase is twofold: to provide a detailed determination of the current state; to further validate the model, verifying the consistency of the simulated results with the collected data. The simulation of the real scenario also allows the model parameters to be refined, improving its calibration according to the specific characteristics of the urban context. This phase thus constitutes an indispensable reference for assessing the effectiveness of the interventions simulated subsequently and for building a solid methodological basis to support urban planning and climate adaptation decisions.

This comparison between current urban assets and the potential whole green one allows us to assess the impact of heat-adaptation interventions on urban thermal comfort, including changes to surface materials (e.g., grass, water, concrete) and the introduction of 3D vegetation. The thermal comfort is evaluated using specific indices like the Physiological Equivalent Temperature (PET) and Mean Radiant Temperature (MRT). Selecting thermal indicators is a crucial step in microclimate research (Azimi & Shafaat, 2024; Liu et al., 2020). This study prioritises PET, UTCI and MRT over alternative indices due to their appropriateness for microclimate analysis and their pronounced sensitivity to radiative heat exchange, a factor of particular relevance in courtyard environments. MRT plays a key role in elucidating the effect of radiation on thermal perception, given that courtyards are strongly shaped by both direct and reflected solar radiation. Meanwhile, PET measures the actual sensation of heat perceived by people. PET, which uses MRT as input, provides a human-centric evaluation of thermal comfort by combining meteorological conditions with individual metabolic responses, thereby explaining its widespread application in urban heat mitigation research. Finally, It is important to measure UTCI because it provides a comprehensive assessment of heat stress for humans, taking into account temperature, humidity, wind, and solar radiation, to improve well-being and protect people's health.

Indicator	**Root Mean Square Error (RMSE)**	**Source**
PET	±2.0 – 2.5 °C	Koletsis, 2023; Zhao et al., 2021
T Aria	±0.44 – 3.05 °C	Tsoka et al., 2018; Liu et al., 2023
UTCI	±1.5 °C	Koletsis, 2023; Silva et al., 2025
RH	±3.88 – 8.70 %	Ouyang, 2021
SET	±1.8 – 2.4°C	Yuan et al., 2024
MRT	±6.08-13.32 W/m^2	Aleksandrowicz et al., 2023
Wind Speed	±1.63 m/s	Aleksandrowicz et al., 2023
LST	±2.0 – 4.0°C	Huang et al., 2015

Tab.1 RMSE of ENVI-met Microclimatic Indicators from Literature

As with any other simulation tool, the reliability of ENVI-met results should be carefully examined, also based on the simplification of input parameters and the size of the study area of the simulations to be performed. Therefore, in this study, the results have been validated by using the ranges reported in the literature relating to the Root Mean Square Error (Tab.2).

4. Study area

The study area is the San Lorenzo neighbourhood located in the historic part of the coastal city of Naples in southern Italy. The district is included within the fourth Municipality, with the neighbouring ones of Vicaria, Poggioreale and Zona Industriale, and together with that of San Giuseppe constitutes almost the entirety of the ancient centre of Naples, which immediately denotes its strongly compact and stratified layout (Fig.ss 1 and 2).

The lack of permeable spaces both in the study area and in surrounding areas reflects the significant influence that urban development and morphology have on the distribution and location of open and green spaces within the city. The density of buildings, the road network, and the type and distribution of buildings are among the main drivers determining the availability of open spaces, which vary considerably depending on the type of urban fabric.

In the historic area, characterised by high density and often by an organic or pre-planned urban structure with irregular layouts (e.g. medieval centres), the availability of permeable or unbuilt land is more than limited. This leads to a scarcity of large open and green spaces, which mainly take the form of small, fragmented areas such as squares, internal courtyards or historic gardens. Their potential effectiveness in terms of improving thermal comfort may be limited at the level of individual spaces, but their widespread integration can greatly contribute to enhancing the cooling effect, determined by the new presence of vegetation, as well as enhancing their value and cultural identity.

On the contrary, in more recently developed (post-war) areas, such as the peripheral areas, characterised by lower building density and, above all, greater availability of permeable areas, it is possible to integrate existing and newly created continuous open space systems. The urban layout in these contexts tends to be more regular, often based on road grids that can facilitate the creation of green corridors connecting open spaces. The latter are sometimes the result of a process of transformation that is not continuous over time, which can lead to the presence of isolated green spaces that require better connectivity between themselves and with the rest of the fabric in which they are located.

An analysis of the distribution of open spaces in the city of Naples, covering a total area of approximately 118,469 km², reveals significant disparities in the provision of green areas, with a clear distinction between the historic city centre and the suburbs.

In particular, the neighbourhoods with the highest presence of trees and wooded areas are located in the suburbs like San Carlo all'Arena, with the Capodimonte Forest, and Pianura, Fuorigrotta, and Bagnoli close to the largest forest areas and the city's main green lungs. Ponticelli and Poggioreale, although characterised by a strong presence of brownfield areas, have areas of spontaneous vegetation which, despite having a lower ecological value, contribute to increasing the amount of urban greenery. However, the quality of this greenery is uneven and requires redevelopment. In contrast, the historic central areas (San Lorenzo, Pendino, Avvocata, Stella, San Giuseppe, Porto) have a high building density and a scarcity of permeable surfaces, with courtyards and squares often completely impermeable.

The census data confirm these trends, although they are not complete: Table 3 and Figure 1 show that forest areas (approximately 8 km²) cover the northern urban ring, without benefiting the historic part of the city in terms of thermal comfort, where only 332 of over 4,400 courtyards have vegetation and/or trees inside them. Of 318 squares, only 45 have a percentage of greene ry greater than 50% of the total surface area, and of

575 parking lots, only 17 have vegetation cover. To conclude, out of 5,679 open spaces, a total of 5,295 have no vegetation, which is a worrying number, especially for the established historic central areas.

	N°	m²	Km²	% of the city area
Impermeable Sqaures	273	62.358,134	0,062	0,053
Green Squares (>50% of green areas)	45	494.262,570	0,494	0,417
Total Squares	318	556.620,704	0,557	0,470
Impermeable Inner Courtyard	4.454	916.813,431	0,917	0,774
Green Inner Courtyard	332	430.729,997	0,431	0,364
Total Inner Courtyard	4.786	1.347.543,428	1,348	1,137
Impermeable Parking Area	558	1.074.069,392	1,074	0,907
Green Parking Area	17	66.667,072	0,067	0,056
Total Parking Area	575	1.140.736,464	1,141	0,963
TOTAL Impermeable Open Spaces	5.295	2.053.240,957	2,053	0,000002
TOTAL Green Open Spaces	384	991.659,639	0,992	0,000001
TOTAL Open Spaces	5.679	3.044.900,596	3,045	0,000003

Tab.3 Average surface and amount of the different kinds of open spaces located in San Lorenzo district, compared to the whole city of Naples

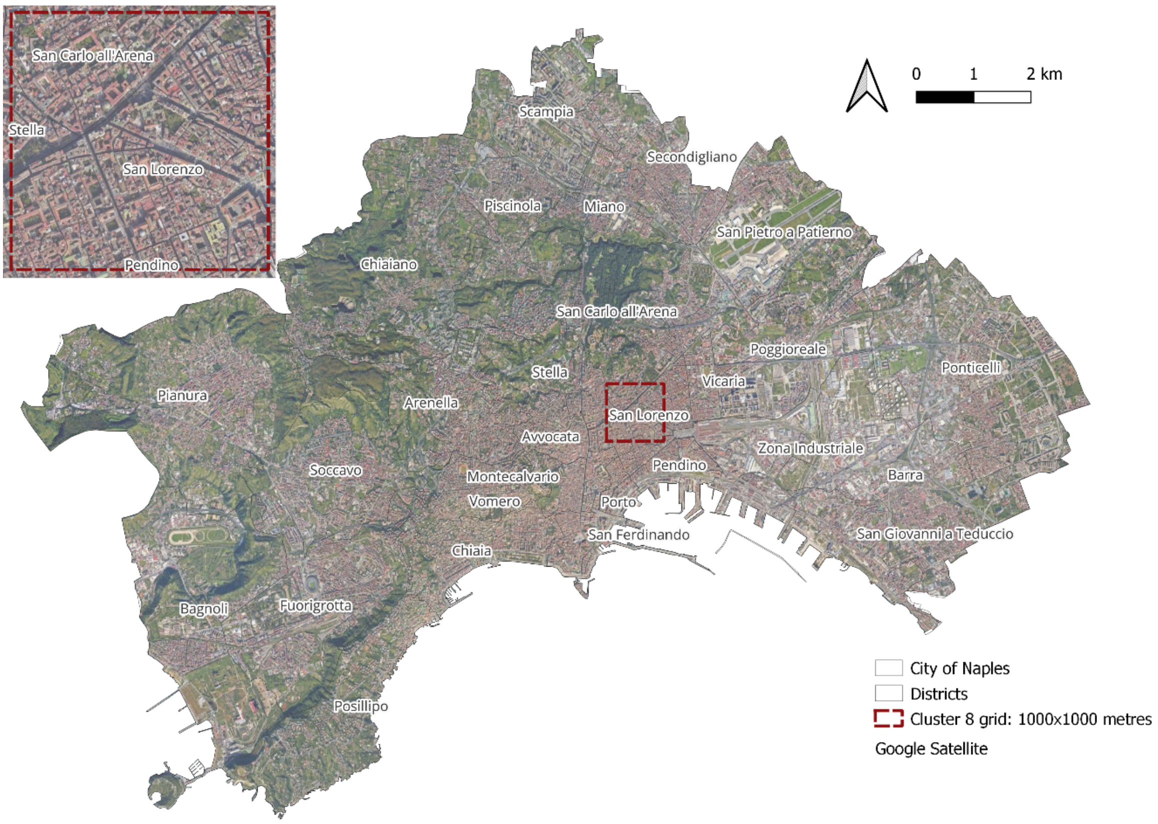

Fig.2 Study Area allocated in San Lorenzo District

Moving the attention to the district under study, San Lorenzo has been affected by the Naples Redevelopment Project promoted in 1885 and aimed at redefining the urban layout of the central-eastern part of the city through the construction of new residential buildings and road axes, to reorganise the urban layout of this part of the city, improving its usability and liveability for residents.

The settlement fabric of this district is characterised by the widespread presence of stately mansions, which, inside, contain square courtyards hosting, at one time, also gardens, citrus groves, vegetable gardens and social spaces that defined the environmental quality and the relationship between inside and outside (Fratini, 2023).

In fact, the layout and building pattern that strongly characterises San Lorenzo is representative of the typical "insule" (islands) of the city of Naples, i.e. building blocks consisting of single, large historic buildings where the open spaces inside, the cohorts, were used for agricultural, recreational and social purposes until, after the war, continuous sealing interventions converted them into areas for parking vehicles and/or for building (Fig.3). This progressive and inexorable transformation has led to the loss of their original functions, preventing greater and better use of them, even by those who live in the buildings to which these cohorts belong, and reducing their architectural and naturalistic value. Reclaiming this type of space, enhancing their original ecosystemic and recreational functions through their conversion to green areas, means improving the urban quality of large parts of cities where these spaces are pervasive and, above all, implementing targeted and effective adaptation measures in view of the dense urban context in which they are located (Lai & Zoppi, 2023). Therefore, San Lorenzo represents an interesting case study in applying greening interventions in densely built cities, due to its compact fabric, the high presence of open small spaces and courtyards, such as the lack of permeable surfaces. Furthermore, according to the first results of the research project, including this paper, San Lorenzo is among the districts that require prior climate adaptation interventions and solutions to reduce UHI effects and related energy consumption levels (Carpentieri et al., 2026).

Fig.3 Built-up areas, green areas and impermeable open spaces in the study area

5. Results and discussion

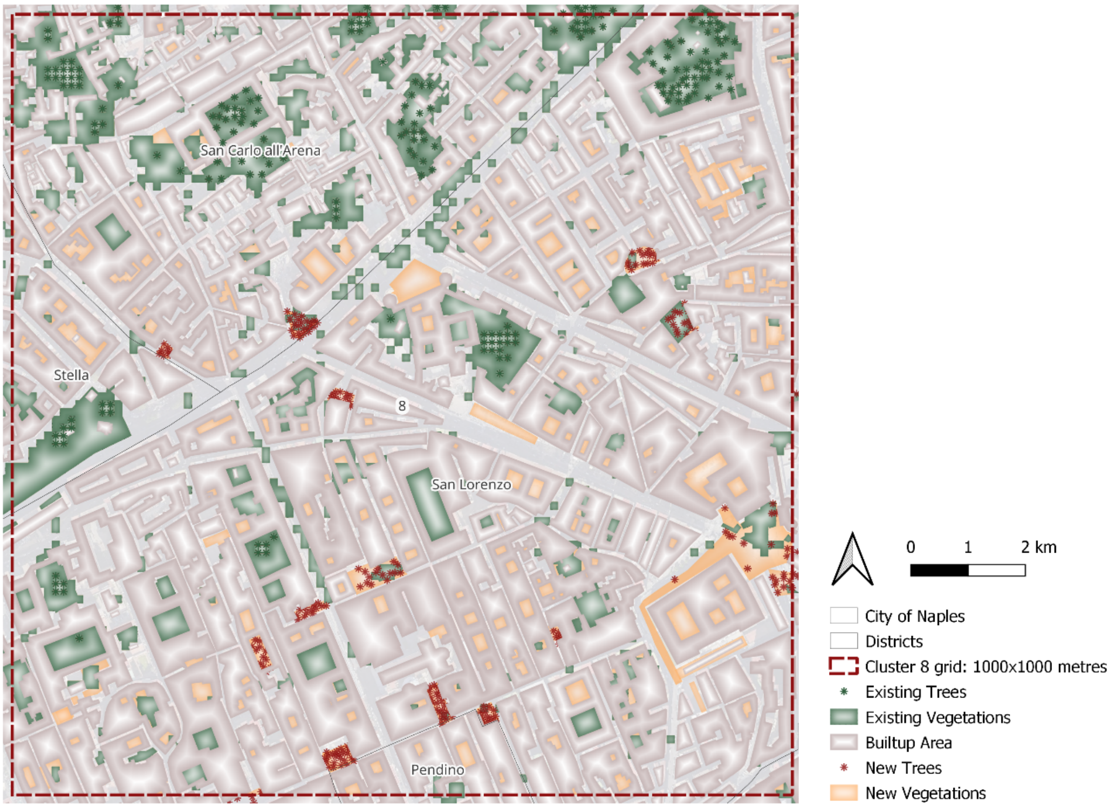

Fig.4 Real and interventions scenario layers of the selected study area

The results obtained for each of the three thermal comfort indicators considered are described below, reporting both the absolute values calculated in the simulations and the variations (Δ) obtained following the simulated greening interventions located in open spaces, courtyards and road axes in the San Lorenzo district.

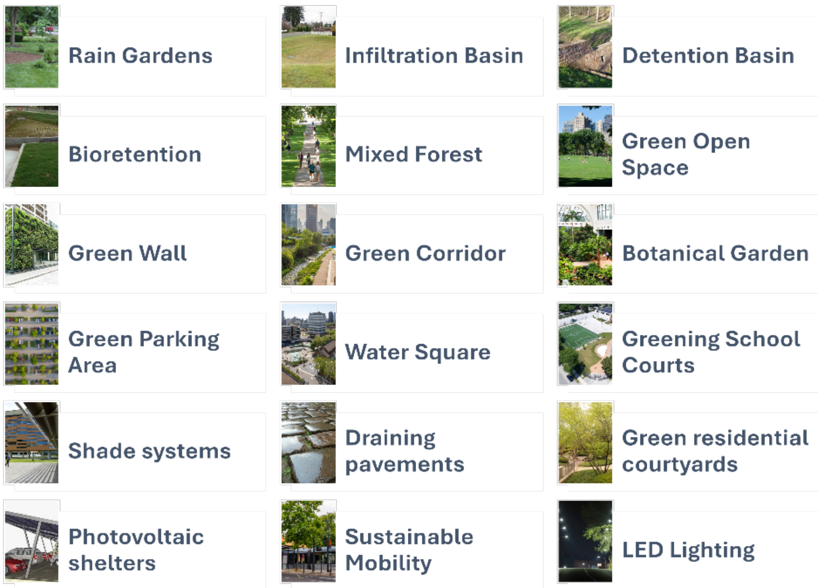

Fig.5 Climate change adaptation and energy saving interventions category

Although it is not possible to simulate specific interventions using ENVI-met software, it was decided to add vegetation layers of 25 and 50 cm, but these are translated into the list in Fig.5. Moreover, to reduce errors from ENVI-met outputs, an RMSE interval consistent with recent literature for each indicator was subtracted from the Real – Green Interventions difference (Tab.2).

5.1 ΔMRT (Mean Radiant Temperature)

Fig.ss 6 and 7 show that the ΔMRT variation (current scenario vs. simulated greening scenario), reduced by the RMSE error rate obtained from the scientific literature, shows significant reductions (>15 °C) localised around the new trees and "green islands" restored in the courtyards and squares, due to direct shading and the effect of screening the sky from solar radiation (reduction in the Sky View Factor value).

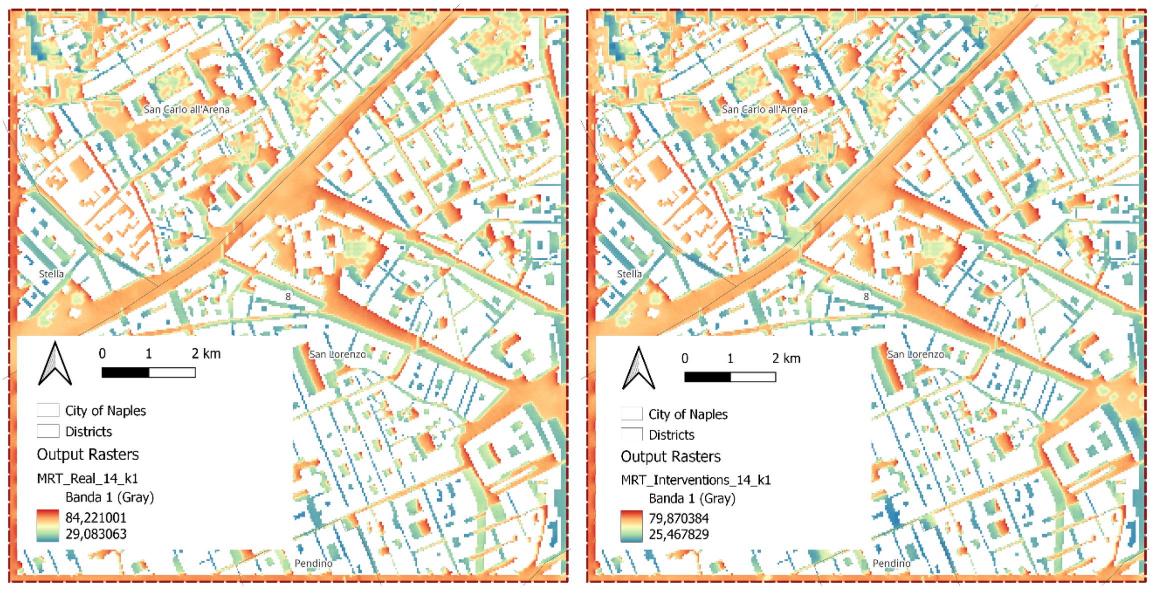

Fig.6 MRT absolute values distribution in the study area in the current scenario (left) and in the simulated one with greening interventions in open spaces and streets (right)

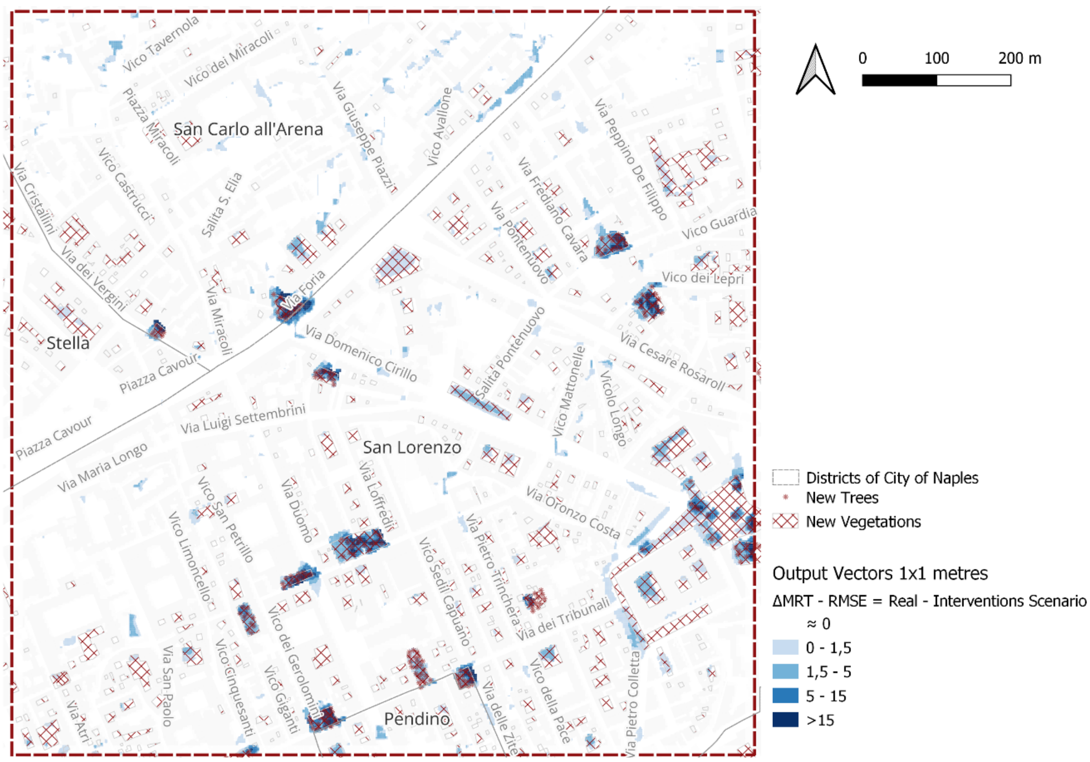

Fig.7 ΔMRT values distribution in the study area

The MRT value gradually decreases from open spaces to adjacent road axes, going from current values between 5–15 °C to 1.5–5 °C, which become almost irrelevant (≈0–1.5 °C) in small internal courtyards located near these spaces. These benefits are also attributable to the combined effect of the presence of (new) trees and the natural shade provided by the height and location of buildings along roads and in open spaces, which contributes to the reduction of incident and, in part, reflected radiation.

The validity of the MRT values obtained, as evidenced by the fact that no decreases are observable in open spaces where greening has not been proposed, even after subtracting the RMSE, indicates that the radiant effect of trees is immediate and limited, but more effective in terms of the surface area that can benefit from the presence of trees if extended over multiple road axes. In a fabric such as the stratified one of San Lorenzo, the precise but widespread choice of inserting green elements of this type can contribute to creating a diffuse network of cooling areas, which can affect the improvement of thermal comfort along the main and most frequented routes of the city district.

5.2 ΔPET (Physiological Equivalent Temperature)

Fig.9 shows that the reduction in PET (including the RMSE error rate) is distributed more uniformly and continuously within the study area than in the case of MRT: decreases in values between 3 and 6°C affect almost the entire San Lorenzo district, with "hot-spot areas" of 6–12°C (and locally >12°C) corresponding to the arboretums to be restored in the courtyard and also along some tree-lined axes connecting part of the open spaces.

This result is consistent with the very nature of PET, which integrates radiation, air temperature, wind speed and relative humidity: shading (MRT reduction) and evapotranspiration from the new vegetated surfaces contribute to this widespread benefit, thanks also to the increased ventilation along the roads.

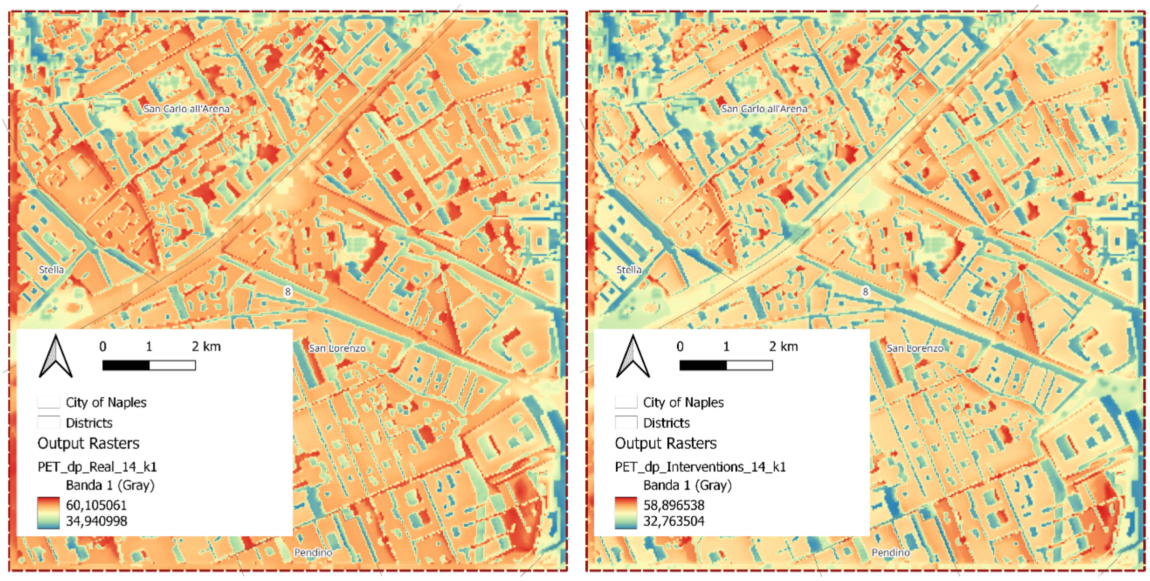

Fig.8 PET absolute values distribution in the study area in the current scenario (left) and in the simulated one with greening interventions in open spaces and streets (right)

This results in a reduction in the perceived heat stress not only in the proximity of linear greening interventions, but also in the surrounding areas (courtyard), with a plausible gradient along the canyon (Fig.8 and 9). Finally, it is worth noting that the widespread decrease in PET values between 0 and 3 °C mainly affects the main pedestrian paths, such as Via Foria and its cross streets, and the open spaces and courtyards that face them.

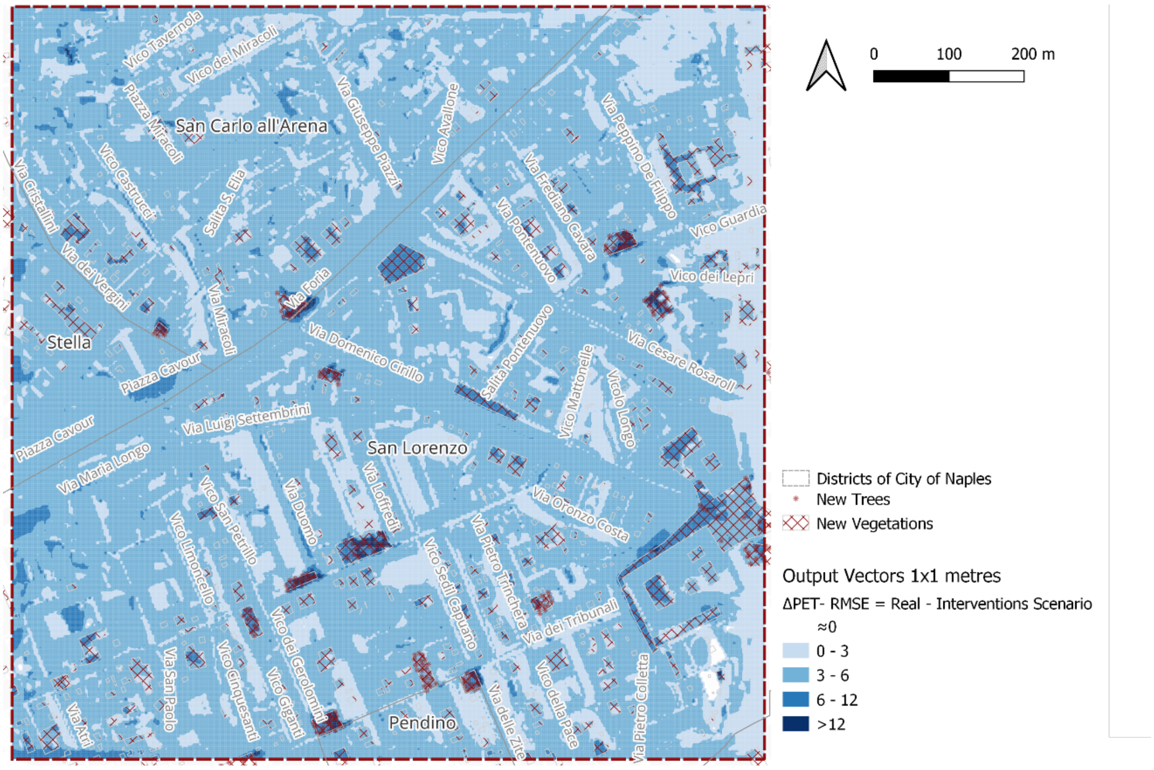

Fig.9 ΔPET values distribution in the study area

5.3 ΔUTCI (Universal Thermal Climate Index)

Fig.11 shows a more moderate variation in UTCI compared to the previous two indicators, PET and MRT. In fact, the classes with decreases in values between 0 and 1.5 °C and 1.5 and 3.5 °C prevail, with variations greater than 3.5 °C near the new trees and more extensive permeable surfaces.

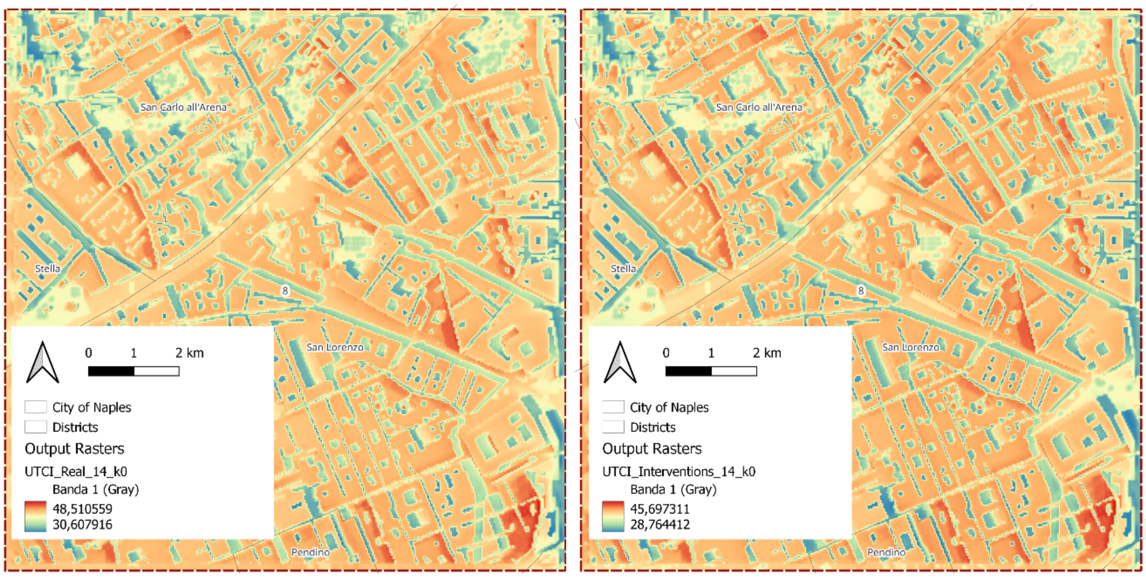

Fig.10 UTCI absolute values distribution in the study area in the current scenario (left) and in the simulated one with greening interventions in open spaces and streets (right)

The UTCI confirms a reduction in physical discomfort compatible with appreciable changes in comfort categories, for example, from "strong" to "moderate" (EEA, 2020), in the areas adjacent to the green axes connecting the restored gardens and citrus groves.

Fig.11 ΔUTCI values distribution in the study area

This improvement in thermal conditions for road users is reliable due to the RMSE rate subtracted and more than appreciable due to the fact that reductions of more than 1–1.5 °C are still found in the simulated peak hour (14:00) of the hottest day of the year (31/07).

6. Conclusions

This study aims to propose the restoration of the original functions of gardens and citrus groves in the inner courtyards of the San Lorenzo district (Fig.1), with a view to implementing distributed and interconnected greening interventions to increase the adaptive capacity of highly densified and stratified urban systems such as that of Naples.

Starting from the observation that the anthropogenic transformation of these spaces, from agricultural functions to car parks or warehouses, has generated degradation and climate vulnerability, the work has demonstrated how their conversion represents a strategic lever for the resilience of urban areas.

The simulations confirm that reforestation and permeability solutions can bring significant microclimatic benefits even in a dense and compact urban fabric such as that of San Lorenzo. The MRT, which measures the radiant energy perceived by the human body, shows the most marked reductions of over 15° in the areas immediately adjacent to the new trees, thanks to the shade and reduction in the Sky View Factor. The PET indicator, which integrates radiation, air temperature, humidity and wind to provide a direct measure of perceived thermal stress, shows a widespread improvement across the entire area, especially near internal courtyards and tree-lined avenues, where there are widespread reductions of between 3 and 6°. Finally, the UTCI, which translates microclimatic conditions into universal thermal comfort levels, confirms a more moderate but still significant reduction, with values generally between 1 and 3.5°, sufficient to shift the discomfort categories from "strong" to "moderate".

Overall, these results show that even targeted and widespread urban greening interventions can produce tangible and perceptible effects on microclimatic comfort, strengthening the resilience of historic districts to heat waves.

The conversion of open sealed spaces, even those of limited size, to green ones can produce measurable and significant benefits in terms of thermal comfort:

- capillary planting is the most effective solution for reducing the MRT, directly influencing comfort indices such as PET and UTCI in the canyons of the historic fabric. The contextual creation of lawns helps to increase the proportion of permeable surfaces capable of contributing to the cooling effect determined primarily by the presence of trees, favouring rainwater runoff;
- the integration of interventions in courtyards, streets and squares reinforces the cooling effect obtained from their greening and proximity, creating corridors and pedestrian areas of thermal comfort that make the urban environment more liveable, attractive and resilient. Courtyards, especially if made accessible or semi-public, act as "emitters" of radiant cooling towards adjacent streets, improving the local temperature gradient;
- in areas subject to protection restrictions, the adoption of soft, non-hard and reversible interventions (e.g. linear flower beds, compatible trees, draining paving, removable shading system) proves to be a particularly effective strategy for balancing heritage conservation with the need for climate adaptation.

Summarizing, this study demonstrates that widespread conversion to green and permeable surfaces, even on a micro scale, can significantly reduce the main summer comfort indices, stating that priority interventions have to take into consideration not only large parks, but also, and above all, courtyards and streets in historic centres.

The positive effects of increasing greenery on UHI reduction and runoff management improvement are clear to see in contexts such as the district under study, which has high energy consumption and a tendency to flood (Carpentieri et al., 2024 and 2026; Gargiulo & Zucaro, 2023). These results provide a solid basis for local administrators, technicians, designers, real estate companies and citizens called upon to define and implement targeted adaptation strategies. In this context, even small transformations (e.g., courtyards and parking areas made permeable or planted with trees) have a significant impact on microclimate quality, thanks to a widespread overlap effect. It is therefore necessary to enhance large forested and disused green areas and to take widespread action on smaller open spaces, which represent the real potential for climate adaptation in the historic centre.

7. Study limitations

While providing significant results, the present study can be deepened from a methodological point of view, offering opportunities for future research. The simulation was targeted at an extreme day and time, and the data on vegetation and buildings are not detailed by species, type or seasonality. This was a conscious methodological choice, aimed at clearly measuring the impact of the interventions, leaving ample room for improvement in this direction.

In the future, we intend to extend the simulation to a longer time frame and to integrate more precise botanical data (e.g. species, seasonal LAD - Leaf Area Density) in order to obtain even more accurate outputs. It would also be valuable to explore the social and economic impact of these interventions, assessing aspects such as increased biodiversity, improved air quality, perception of safety and strengthening of local identity. This more holistic approach would allow for a full quantification of the environmental, social and economic capital returned to the territory, providing a more comprehensive assessment of the sustainability of the proposed strategies.

Acknowledgments

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Image sources

Fig.1: authors' elaboration;

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Fig.10: authors' elaboration.

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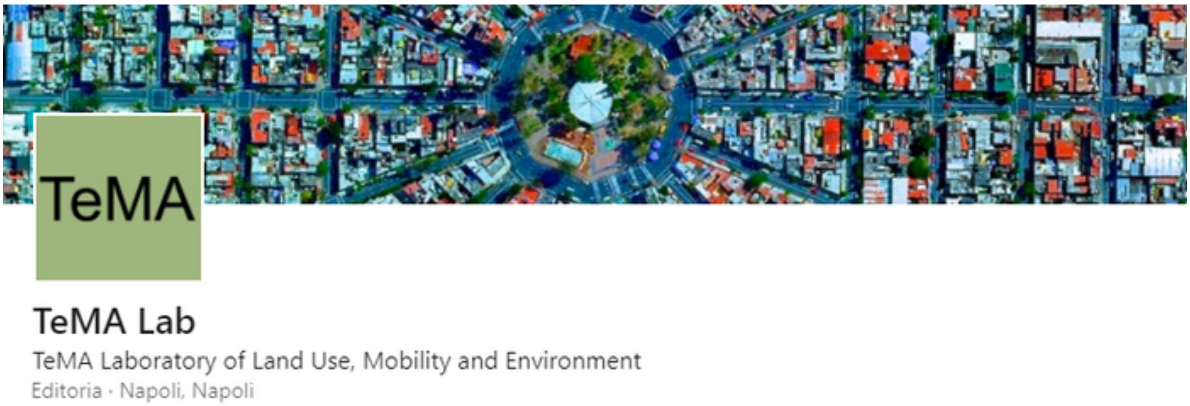

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Analysis of factors affecting urban land use changes (1993-2023): a case study of Urmia City, Iran

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Abstract
Urban land use changes are profoundly reshaping cities and often accelerating environmental degradation and unsustainable growth. In Urmia, a rapidly expanding mid-sized city in northwest Iran, these transformations have intensified over the past three decades without sufficient spatial or policy coordination. This study examines the dynamics and driving forces of land use change in Urmia from 1993 to 2023 using multi-temporal Landsat imagery and integrated analytical methods. Supervised classification in ENVI and ArcGIS was used to map land transformations, while the Fuzzy Delphi method and factor analysis identified the underlying social, economic, living standards, technological, political, and cultural drivers. The results reveal a 66 percent increase in urban areas, primarily at the expense of gardens, which declined by 56 percent, reflecting a pattern of unplanned sprawl and environmental decline. The findings indicate that rapid population growth, rising living standards, and technological advancement are the main forces driving urban expansion. This study provides an integrated spatial and analytical framework for understanding mid-sized city transformation and offers practical recommendations for managing urban sprawl and promoting sustainable land use in developing contexts.

Keywords
Land use planning; Change detection; ENVI; Urmia City; Iran

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1. Introduction

Urban growth and land-use change are just two of the many factors that will shape cities in the future (Alwedyan, 2022). The land is a unique and finite economic resource with diverse uses for various land uses that cannot be separated from the urbanization process (Borawski et al., 2019). As urban settlements expand, substantial changes occur in land use and ecosystems, notably the uncontrolled consumption of urban land and low-density urban sprawl. Urban sprawl, characterized by the irregular and unplanned expansion of urban areas into surrounding rural or undeveloped land, is often marked by low-density development, land-use segregation, and automobile dependence (Chettry, 2023; Dadashpoor & Shahhossein, 2024). This expansion leads to increased land consumption, environmental degradation (including loss of biodiversity and increased pollution), landscape fragmentation, and increased energy consumption and carbon emissions (Lu et al., 2019). These changes play a crucial role in addressing climate change, as urban growth and sprawl increase exposure to climate hazards and disasters.

The consequences of urban sprawl are multifaceted and often detrimental to both the environment and social fabric of communities. The consumption of agricultural land and natural habitats leads to significant environmental degradation. The dispersed nature of development in sprawling areas fosters automobile dependency, resulting in higher traffic congestion and air pollution. This dependency, coupled with a lack of efficient public transportation, can lead to a decline in public health and overall quality of life. In developing countries, particularly in rapidly urbanizing mid-sized cities, urban sprawl presents unique challenges. Haphazard growth patterns, driven by economic policies and inadequate land-use planning, can result in social inequalities and inadequate access to essential services (Chettry & Surawar, 2021; Dadashpoor & Shahhossein, 2024). Urban land-use planning examines how urban activities and functions are used, distributed, protected, organized, and spatially arranged based on the desires and needs of the urban community (Ziari, 2004). Analyzing the dynamics of urban growth and expansion, and the factors that influence it, provides a foundation for effective urban management and sustainable urban development (Ghorbani et al., 2014). The relationship between urban land-use changes and urban sprawl is characterized by the shifting of urban functions to urban fringe areas, leading to agricultural land conversion and subsequent urbanization (Giyarsih, 2017). This process is influenced by various factors, including groundwater availability, climate, terrain, employment patterns, transportation infrastructure, and uncertainties about metropolitan growth. The resulting socio-economic, cultural, and physical environment transformations vary across metropolitan areas (Burchfield et al., 2006). The world is witnessing a rapid urbanization process due to the remarkable growth of population, socio-economic development, and rapid urban expansion (Yuan et al., 2018). This rapid development strains infrastructure and services, leading to shortages, inequities, and the growth of slums and marginalized peri-urban areas. Land-use changes, including the conversion of forests and agricultural land into urban areas, are a significant factor in environmental degradation (Hersperger et al., 2018). Urbanization is a global phenomenon, with Asia being the fastest urbanizing region in the world (Bakker, 2022). Urbanization has led to changes in economic, social, and environmental aspects (Dolley at al., 2020). Urban land consumption is outpacing population growth, with substantial increases in urban area expected in the coming years (Biello, 2018; World Bank-Urban Development, 2023). Urmia, Iran, like many cities, has experienced significant expansion and land-use change due to population growth, rural-urban migration, and land speculation. This has resulted in uncontrolled physical growth, high-rise construction, and unplanned expansion, leading to challenges such as environmental pollution, traffic congestion, and infrastructure deficiencies. The lack of comprehensive data management hinders effective assessment and planning. Therefore, a comprehensive urban land-use plan is urgently needed to guide Urmia's expansion, identify the drivers of land-use change, and promote sustainable urban growth. This study aims to address the research gap by analyzing land-use changes in Urmia City over the past three decades. While the general phenomenon of urban sprawl and its drivers have been studied, there is a need for a detailed analysis focused on Urmia, a rapidly growing mid-sized city, using integrated spatial and analytical approaches. Despite extensive research on urban sprawl and land use dynamics in large metropolitan regions, mid-sized cities in developing countries remain underexplored, particularly in terms of long-term, integrated spatial analyses. Previous studies have often focused on short temporal periods or relied solely on either remote sensing or socio-economic data, without combining both to uncover underlying drivers. Partheepan et al. (2023) demonstrated the importance of integrating multi-temporal satellite imagery in analyzing land-use transformations in mid-sized cities, while Pultrone (2023) highlighted how external agents and governance structures shape urban expansion. In the case of Urmia, the absence of comprehensive studies that link multi-decadal satellite observations with expert-based analytical methods has limited understanding of the complex interactions between demographic, economic, and policy factors shaping urban growth. This research addresses this gap by integrating geospatial analysis with the Fuzzy Delphi method and factor analysis over a 30-year period to identify and quantify the key forces driving land use change. The study advances the existing literature by offering a holistic framework for analyzing urban transformation in mid-sized cities, where unplanned expansion often occurs without the governance structures seen in larger metropolitan areas. Specifically, this research seeks to:

- Analyze land use change patterns in Urmia City over past three decades using advanced geospatial techniques;
- Identify key socio-economic, political, and environmental factors driving these changes;
- Assess the ecological and urban planning implications of these transformations;
- Propose actionable recommendations for sustainable urban development and land management in Urmia City.

2. Study area

Urmia, the capital of West Azerbaijan province, is the tenth most populous city in Iran. Urmia is bordered by Lake Urmia to the east, and is surrounded by mountainous terrain (Fig.1).

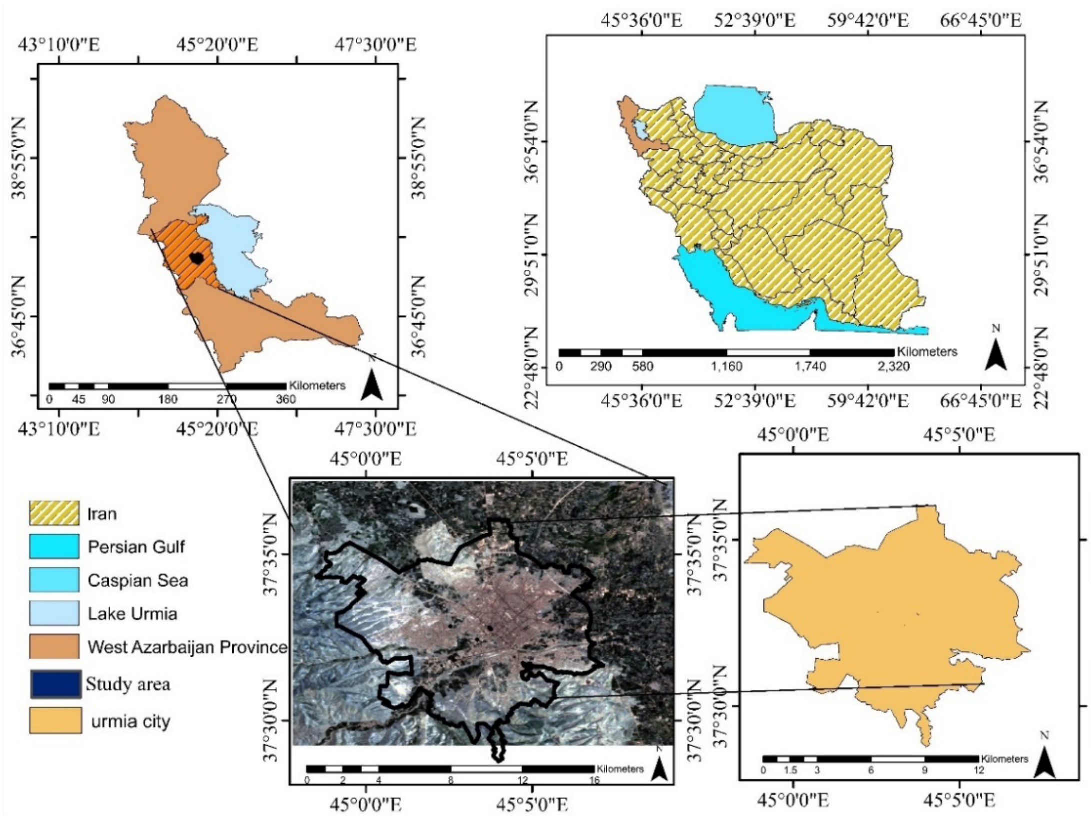

Fig.1 Study area of Urmia City, Iran

Urmia County[1] is one of the twelve counties in West Azerbaijan Province, situated in its central region. It is bordered by Salmas County to the north, Naghadeh and Maku counties to the south, Lake Urmia to the east, and the Iran-Turkey border to the west. With an area exceeding 5,251 square kilometers, the county encompasses approximately 14% of the province's total area.
From a national administrative perspective, Urmia County is divided into 5 districts, 20 rural districts, 5 cities, and 615 settlements. The city of Urmia itself is located approximately 18 kilometers away from Lake Urmia, positioned at 45 degrees and 4 minutes east longitude and 37 degrees and 33 minutes north latitude. It spans 70 kilometers in length and 30 kilometers in width within a plain.

3. Methodology

This study adopts a descriptive-analytical approach, employing an exploratory research design with both quantitative and qualitative methodologies. Data collection involves library research, document analysis, field studies, and the utilization of comprehensive urban plans, statistical centers, and municipal data from various sources such as the municipality of Urmia, the Environmental Protection Agency of West Azerbaijan, the Governorate of West Azerbaijan, the Department of Roads and Urban Planning, the Provincial Budget Planning Organization of West Azerbaijan, the Iranian Statistical Center, and satellite imagery. The research is structured into three main phases:

1) Examination and analysis of changes over the past three decades;
2) Analysis of spatial growth and urban development in both past and present contexts;
3) Analysis of factors influencing changes in land use.

In this research, Landsat and OLI satellite images from 1992 to 2023 are initially processed in ENVI software, incorporating various indices after geometric and atmospheric corrections. Land use patterns are then analyzed using Google Earth and ArcGIS software, enabling the identification and assessment of land use changes. Final land use maps are generated and the observed changes in the years 1992, 2003, 2013, and 2023 are compared and evaluated.
For the analysis of factors influencing land use, statistical data from the National Statistical Portal are utilized, along with the Fuzzy Delphi method and factor analysis techniques implemented in SPSS software. SPSS was used to compute eigenvalues, variance explained, factor loadings, and scree plots, facilitating the interpretation of how multiple observed indicators grouped into six meaningful dimensions. To identify the underlying drivers of land use change, expert input was collected using the Fuzzy Delphi Method (FDM). Sixty urban planning and geography experts participated by rating the importance of 60 pre-identified indicators related to social, economic, living standards, technological, political, and cultural factors. Their responses were processed using triangular fuzzy numbers to generate consensus scores. Indicators with low fuzzy consensus values were excluded from further analysis, allowing a refined set of 25 effective variables to be retained for statistical modeling. The reduced set of variables was analyzed using exploratory factor analysis (EFA) in SPSS to uncover the latent dimensions driving land use change.
To assess land use changes in the city of Urmia, satellite imagery (Landsat) from the past three decades (2023, 2013, 2003, and 1993) was obtained from the United States Geological Survey (USGS) website. Images were downloaded for all four periods within a consistent and specified area, ensuring minimal cloud cover, using data from three satellites: Landsat 8/9, Landsat 7, and Landsat 5, and relying on the Landsat Collection 2 – Level 1 dataset. The images underwent radiometric corrections, addressing atmospheric and sensor-related errors, to process the data effectively and determine the extent of changes (Tab.1).
For image classification across the four time periods, a supervised classification method was employed, with sample data selected for each class. In this study, four land use classes were defined for the years 2023 and

[1] Urmia County's strategic location along historical trade and invasion routes has made it vulnerable to repeated invasions and damage, but it has also fostered rich ethnic-cultural diversity and a valuable historical heritage.

2013: (1) Urban (man-made structures), (2) Gardens (forested areas), (3) Agricultural land (plowed), and (4) Barren land (mountains and other uncultivated areas). For the years 2003 and 1993, a fifth class, Water bodies, was included in addition to the aforementioned four classes (Fig.2).

Year	Date Acquired	Scene Center Time
1993	1993-06-24	07:01:04.1860940Z
2003	2003-05-11	07:27:20.7352759Z
2013	2013-06-15	07:40:34.9676120Z
2023	2023-06-27	07:38:09.6369179Z

Tab.1 The dates of images acquired for each year

After classifying the images and determining the number of classes, the selected samples were validated through a supervised classification process. The accuracy of the classifications was assessed by comparing satellite imagery with Google Earth data. Multiple classification algorithms were applied, including Maximum Likelihood, Minimum Distance, Neural Network, and Support Vector Machine (SVM) methods, to ensure robust and reliable results.

An initial list of 60 indicators related to demographic, economic, technological, political, and cultural drivers of land-use change was developed through an extensive review of international and Iranian literature on urban growth, land-use dynamics, and spatial development. These indicators were also cross-referenced with sustainability frameworks and previous studies focusing on land transformation in developing urban contexts. The intention behind starting with a broad set of indicators was to ensure that all potentially relevant dimensions were included before applying expert-driven refinement.

Using the Fuzzy Delphi Method, these indicators were evaluated by experts to determine their relevance and importance for explaining land-use changes in Urmia. In this process, each expert provided linguistic assessments that were converted into triangular fuzzy numbers. The fuzzy consensus threshold was set at 0.7, meaning that indicators with a fuzzy consensus value below 0.7 were excluded from further analysis. Application of this threshold reduced the initial list of 60 indicators to 25 variables that met the minimum agreement level among experts.

Experts were selected through purposive sampling to ensure that participants possessed strong and directly relevant knowledge of land-use dynamics in Iranian cities. The panel consisted of 60 experts with academic or professional backgrounds in urban planning, urban geography, environmental planning, GIS, remote sensing, or land-use management. To ensure high-quality judgments, only individuals with a minimum of ten years of experience were invited, and preference was given to those with direct familiarity with Urmia or comparable mid-sized cities in Iran. The panel deliberately included experts from a diverse range of institutions, including universities, municipal planning departments, environmental organizations, and provincial development agencies, in order to capture multiple perspectives on land-use change. The final number of 60 experts was chosen to enhance the reliability of the Fuzzy Delphi process, exceeding the standard minimum requirements for Delphi studies and ensuring a robust and balanced consensus.

Following the refinement of indicators through FDM, Exploratory Factor Analysis (EFA) was applied to the 25 retained variables to identify the latent dimensions influencing land use change. Before extraction, sampling adequacy was assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's Test of Sphericity. Factors were extracted based on eigenvalues greater than 1, and variables with factor loadings below 0.5 were removed to ensure meaningful correlations within each factor. An oblique rotation (Promax) was used because the underlying dimensions (e.g., population growth, economic conditions, political structure) were expected to be correlated rather than independent. This procedure resulted in six interpretable factors, which together explained more than 71 percent of the total variance.

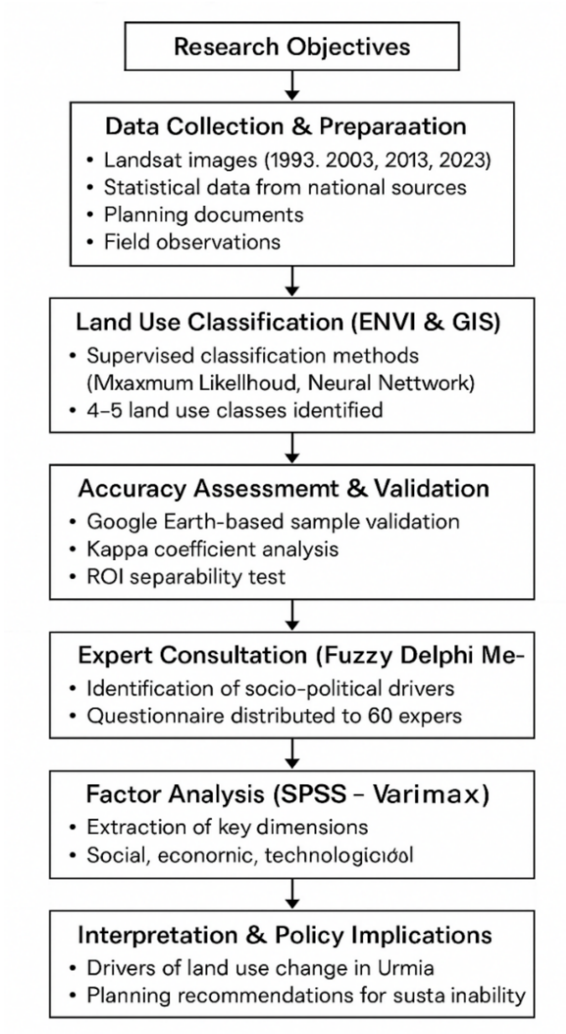

Fig.2 Research methodology Sequence

4. Results

4.1 Classification

To determine land uses in the years 2023 and 2013, four land use classes were used: Urban (man-made), Gardens (forest), Agricultural lands (plowed) and Barren lands (mountains, etc.) Additionally, for the years 2003 and 1993, five classes were utilized, including the aforementioned four classes plus a class for water bodies. For the classification of images in the four time periods, a supervised classification method was employed. For each class, 70 samples were used, totaling 280 samples for the 2023 and 2013 maps and 350 samples for the 2003 and 1993 images.

4.2 Class separability

The accuracy of separating the selected classes depends on the accuracy, number, and size of the samples. To compare classes and selected samples, the Compute ROI separability command is used, which yields results in a table or matrix around the number 2. If the values are closer to 2, it indicates a higher possibility of separating classes from each other with greater ease. However, as the distance from the number 2 increases, the homogeneity of the area decreases, making it harder to discern phenomena or classes, and the likelihood of errors increases.

The fundamental point in producing land use maps lies in the precision of determining the training samples (first sample) and, importantly, the validation sample (essentially based on a thorough understanding of the region through either physical survey or software such as Google Earth). Furthermore, increasing the number of selected pixels for each category in each sample will enhance the accuracy of the generated raster map. This is reflected in the ROI Separability report, where in this study, the minimum separability value is 1.94150149 for the barren lands with agriculture in 1993, 1.995442302 for gardens with agriculture in 2003, 1.98556922 for agricultural lands with barren lands in 2013, and 1.99945853 for gardens with urban lands in 2023.

4.3 Validation using Kappa Coefficient

The Kappa coefficient measures accuracy inversely to the overall accuracy based on all pixels that are correctly and incorrectly classified. In the current paper, Kappa coefficients above 79% along with appropriate accuracy of classified images will yield acceptable results. Following the classification, classes are supervised and necessary sampling is done using Google Earth software, which requires precise knowledge of the study area. Sampling for each image is done separately; for each class in ENVI, 70 samples are taken, and for images of 2023 and 2013 in Google Earth Pro, 50 samples per class are taken, totaling 200 samples for each image. For images of 2003 and 1993, considering they have five classes, 250 samples are selected, totaling 900 samples for all four images and all classes. Specifically, 400 samples are for images of 2013 and 2023, and 500 samples are for images of 1993 and 2003 in Google Earth. In total, approximately 1260 selected samples are drawn. The results, including the concordance of these samples in terms of error percentage and Kappa coefficient for each year using the introduced methods, are presented in the Tab.2.

	Classification method	overall accuracy	Number of errors	kappa
1993	**Maximum likelihood**	85.42%	164.192	0.8114
2003	Maximum likelihood	75.3676	205.272	0.6782
2013	Neural network	90.243	259.287	0.869
2023	Neural network	92.029	254.276	0.8932

Tab.2 Results of error matrix, Kappa coefficient and the classification method for each year

Based on the Kappa coefficients obtained, the best classification method for the year 1993 (Tab.2) is the Maximum Likelihood method, with a Kappa value of 0.81 and an accuracy of 85%. Out of 192 selected samples, 164 samples were accurately classified while 28 samples were misclassified. Among these, 56 samples were urban areas, 47 samples were agricultural land use, 31 samples were barren land, 45 samples were gardens, and 13 samples were water bodies. The highest error occurs between the barren land and agricultural land use classes, while the lowest error is observed in the urban land use class, with an accuracy of 93%.

For the land use classification of the year 2003, 272 samples were selected. The Maximum Likelihood method exhibits the least error, with a Kappa coefficient of 0.67 and an accuracy of 75% (Tab.2). Out of these samples, 205 samples were consistent with the Google Earth imagery. Specifically, 64 samples were urban areas, 86 samples were agricultural land, 40 samples were barren land, 73 samples were gardens, and 9 samples were water bodies. Gardens achieved the highest accuracy at 99%, followed by agricultural land at 79%, urban areas at 78%, barren land and water bodies at 48% and 42% accuracy respectively. However, in terms of error, it's notable that barren land and water bodies exhibit relatively higher inaccuracies, which could potentially result in significant inaccuracies in area estimation.

Considering the classifications conducted using the four methods, the neural network emerges as the best approach with an accuracy of 90.24% for the image of the year 2013 (Tab.2). The error rate for the four classes is 10%, which is acceptable, resulting in a Kappa coefficient of 0.8625. This coefficient is deemed acceptable for validation and matching the selected classes with reality. According to the Kappa coefficient table, out of the 28 errors observed, 7 errors occurred between urban areas and agricultural land, barren land, and gardens; 8 errors occurred from agricultural land to urban areas, barren land, and gardens; 9 errors occurred from barren land to agricultural land and gardens, and 4 errors occurred from gardens to both barren land and agricultural land classes. Urban areas had a 91% accuracy rate, agricultural land had an 89% accuracy rate, barren land had an 88% accuracy rate, and gardens had a 95% accuracy rate. Among the employed methods, the neural network appears to be the most suitable approach for the image of the year 2023, achieving the highest possible accuracy (Tab.2) Out of the 276 selected samples, 254 were correctly classified, while 22 samples contributed to errors across all classes. The overall measurement accuracy for this image was 92%, with a corresponding Kappa coefficient of 0.89.

In this image, urban areas had a 90% correct selection rate, agricultural land had a 64% correct selection rate, barren land had an 88% correct selection rate, and gardens had a 97% completely correct selection rate. The distribution of errors in terms of percentages is as follows: the highest error rate, at 2.63%, occurred between agricultural land and urban areas and gardens. Barren land had a 12% error rate with agricultural land, gardens had a 3% error rate with agricultural land, and urban areas had the highest error rate of 8% with barren land.

Based on the satellite image of the year 1993, the areas of the five land use classes - urban, agricultural, water, barren, and gardens - with pixels measuring 30*30 meters, are respectively 4,630.63, 6,448.03, 227.26, 5,210.61, and 10,252.15 hectares out of a total area of 26,768.7 hectares. These areas cover the specified region, with gardens covering the largest area at 38.3% and water covering the smallest area at 0.85%, which is linear and only represents the Silvana River. Agricultural land, barren land, and urban areas represent 17.30%, 19.47%, and 24.1% of the total land, respectively (Fig.3).

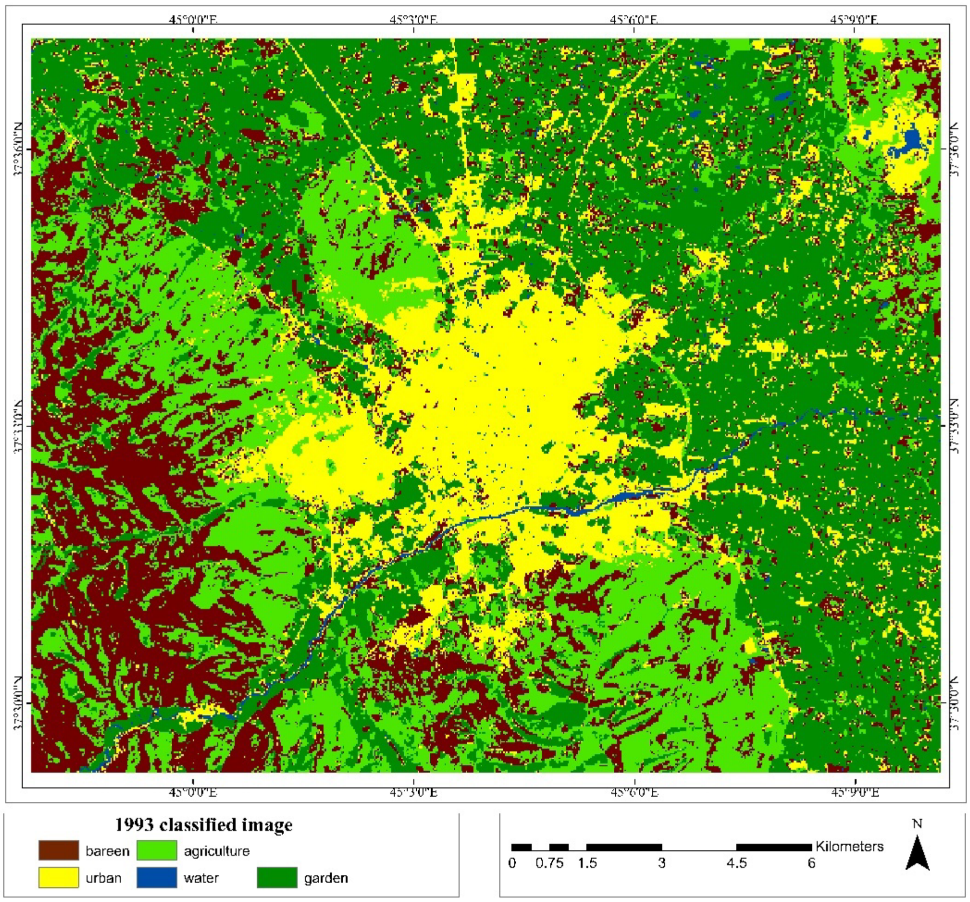

Fig.3 Classified image in 1993

The satellite image of the year 2003 comprises 5 land use classes with a total area of 26,768.7 hectares, with pixels measuring 15*15. Urban areas cover 5,569.77 hectares, water areas cover 89.1 hectares, agricultural

land covers 7,854.64 hectares, barren land covers 4,254.98 hectares, and gardens cover 9,000.08 hectares. Barren land constitutes the largest area at 33.62%, while water areas constitute the smallest area at 0.33%. Gardens, agricultural land, and urban areas account for 20.81%, 29.34%, and 15.90% respectively.
Compared to 1993, the changes in each class are as follows: a decrease of 18.3% in barren land, an increase of 21.8% in agricultural land, a decrease of 12.2% in gardens, a decrease of 60.8% in water areas, and an increase of 20.3% in urban or human-made areas (Fig.4).

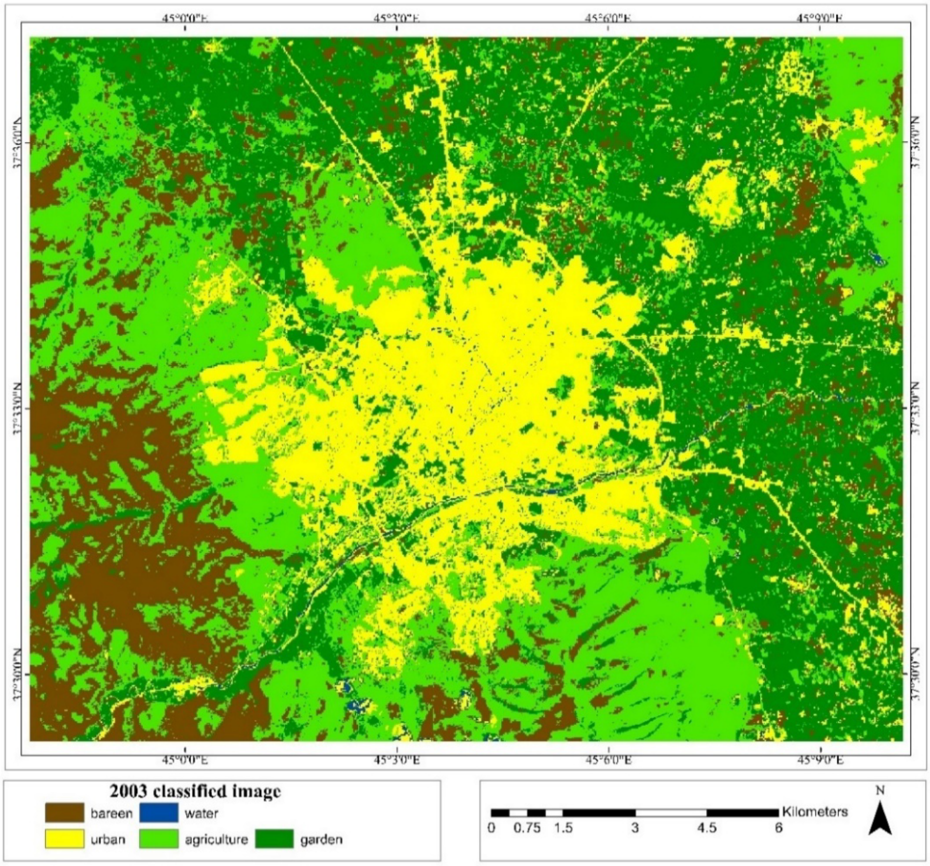

Fig.4 Classified image in 2003

The changes in the year 2013 are as follows: Initially, the reduction in the number of classes from five to four is due to the fact that after the completion of the Silvana Dam project, the Silvana River, which flows from Urmia City to Lake Urmia, partially opens its reservoirs solely for agricultural purposes. Consequently, the riverbed remains dry for most seasons and days of the year.
Therefore, starting in 2013, the water class was removed. Urban areas slightly decreased by about 1.22%, from 5,569.7 hectares to 5,501.57 hectares. Agricultural land, in terms of cultivation, experienced a 2.73% change, increasing from 7,854 hectares to 8,585 hectares. Barren land also increased by 6.9%, from 4,254 hectares to 6,104 hectares, and gardens decreased by 9.05%, from 9,000 hectares in 2003 to 6,576 hectares in 2013.
The satellite image of 2013, with pixels measuring 15*15 meters, covers a total area of 26,768.7 hectares. Agricultural land constitutes 32.07% of this area, gardens cover 24.57%, urban areas cover 20.55%, and barren land covers 22.81% (Fig.5).

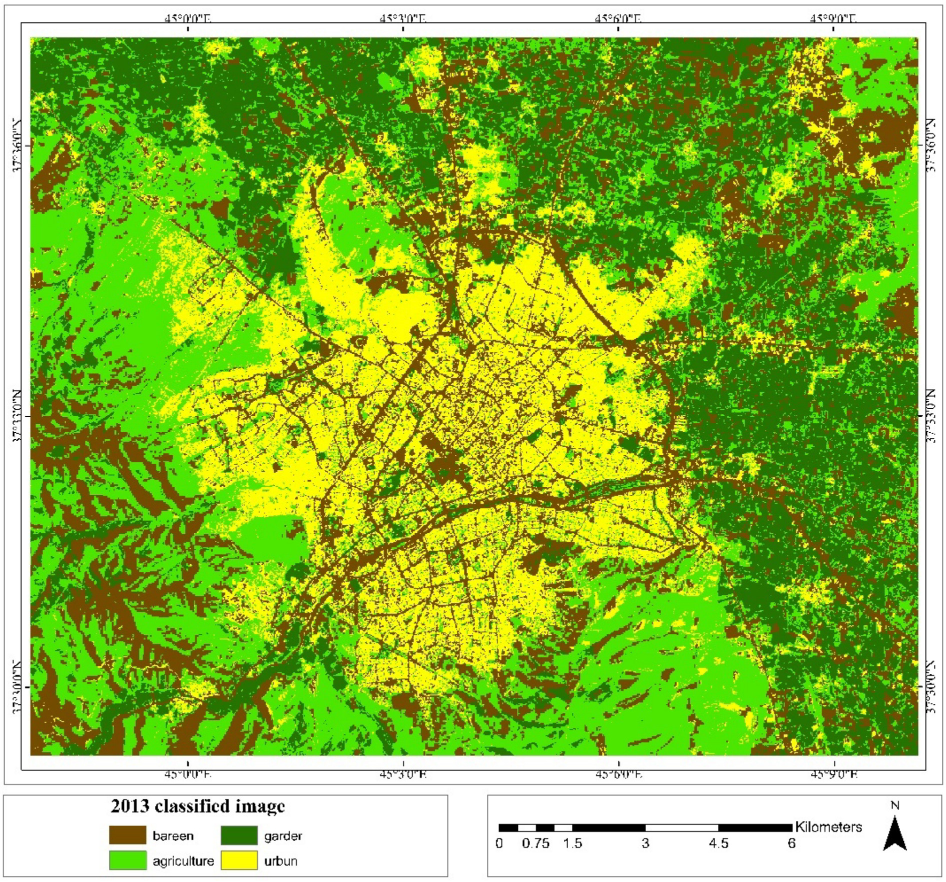

Fig.5 Classified image in 2013

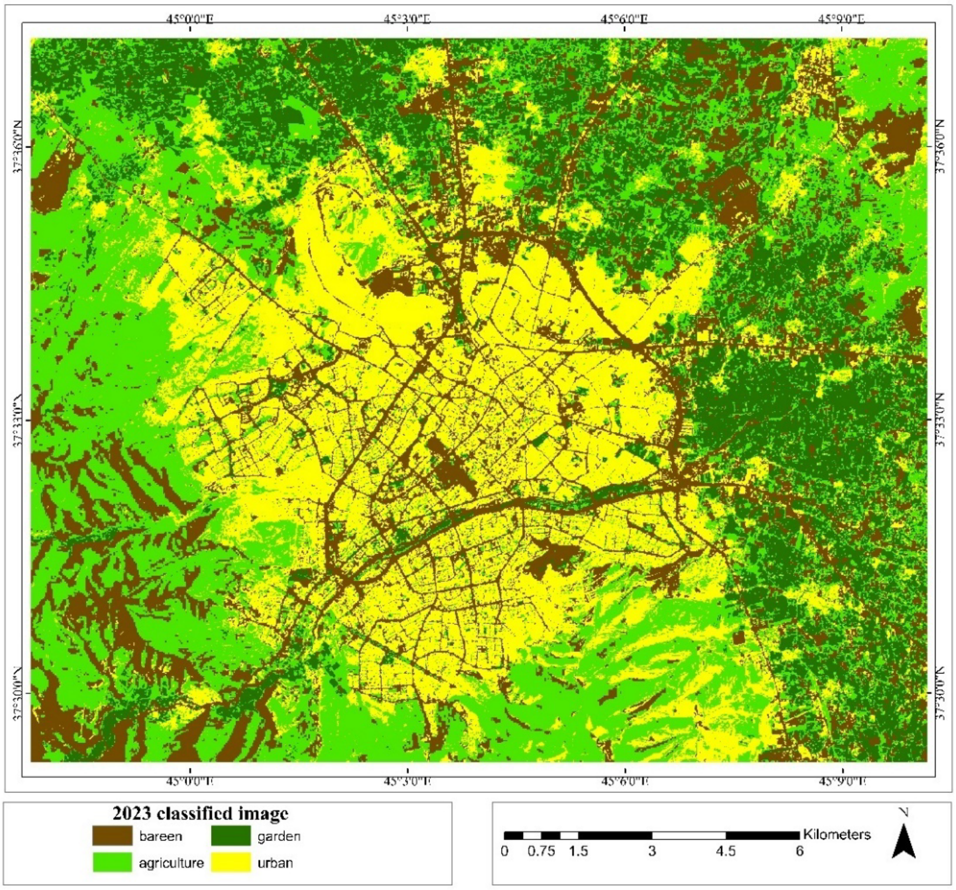

Fig.6 Classified image in 2023

In 2023, relative to the year 2013, there have been notable changes in the four existing land classes over a span of 10 years. Urban lands have experienced a 39.8% increase in area, expanding from 5,501 hectares to 7697 hectares. Agricultural lands have seen a negligible increase of 10.2%, maintaining a relatively stable figure over the decade. Barren lands have decreased by 2.85%, shrinking from 6,104 hectares to 5,930 hectares. Additionally, gardens have witnessed a significant decline of 31.7%, decreasing from 6,567 hectares in 2013 to 4,487 hectares in 2023. In 2023, out of the total area of 26,768.7 hectares, agricultural lands cover 8,652.81 hectares, gardens cover 4,487.68 hectares, urban and human-made lands encompass 7,697.96 hectares, and barren lands contribute 5,930.24 hectares to this total. This distribution is observed within a grid of dimensions 15*15 meters (Fig.6 and Tab.2).

The results obtained from the four periods of 1993, 2003, 2013, and 2023 are as follows:

		urban	**agriculture**	**barren**	**garden**	**water**	**Total**
1993	Area(ha)	4,630.63	6,448.03	5,210.61	1,0252.15	227.26	26,768.7
	percent	17.3	24.1	19.45	38.3	0.85	100
2003	Area(ha)	5,569.77	7,854.64	4,254.98	9,000.08	89.21	26,768.7
	percent	20.81	29.34	15.9	33.62	0.33	100
2013	Area(ha)	5,501.27	8,585.91	6,104.7	6,576.7	-	26,768.7
	percent	20.55	32.07	22.81	24.57	-	100
2023	Area(ha)	7,697.96	8,652.81	5,930.24	4,487.68	-	26,768.7
	percent	28.76	32.33	22.16	16.75	-	100

Tab.3 Land use area in 4 time periods (1993-2003-2013-2023)

According to the Fig.7, over three decades from 1993 to 2023, the changes in land use within the studied area of 26,768.7 hectares are as follows: riparian lands for the Silvana River, which were only flowing in 1993 and 2003 due to the completion of the Silvana dam construction, are now only used for agricultural purposes. Therefore, since 2003, water reservoirs have only opened in the spring and summer months, and the riverbed also passes linearly through the city center; its width has decreased and urban constructions and vegetation cover have been established around it. This classification was omitted in the 2013 and 2023 images.

Urban or human-made lands, which are among the most significant objectives of this study, have consistently shown an upward trend from 1993 to 2023, as indicated in the chart. There has been significant growth in such a way that during these three decades, an area of 3,067 hectares has been added to it, approximately doubling its area compared to 1993, representing a 66% increase in area over these three decades. This expansion consistently leads to environmental degradation and the destruction of natural lands, steppes, and gardens.

Agricultural lands, typically cultivated with wheat, barley, and chickpeas within the study area, have also undergone incremental changes. Due to the proximity to Urmia City and expansion beyond its boundaries, coupled with advancements in agricultural tools, more steps are being cultivated, and more natural lands are being destroyed. Specifically, these lands increased from 6,448 hectares in 1993 to 8,652 hectares in 2023, representing a 34% increase over the past three decades. Steppes increased from 5,210 hectares in 1993 to 5930 hectares in 2023, partly due to methodological errors.

The most significant degradation and transformation occurred in the classification of gardens, which consistently showed a declining trend. Its area decreased from 10,252 hectares in 1993 to 4,487 hectares in 2023, marking a 56% reduction compared to the total area. It can be said that this area halved in 2023 compared to 1993. Most of the changes observed are related to the conversion of gardens to urban or human-made lands and agricultural lands (Tab.3).

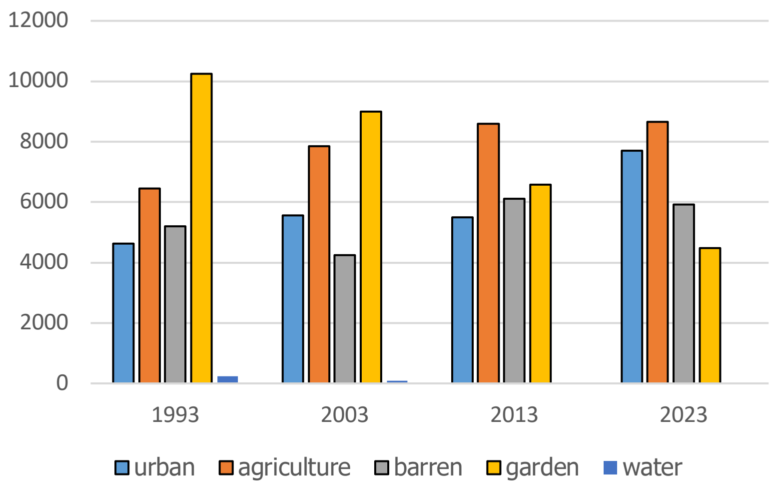

Fig.7 Land use area in 4 time periods (1993-2003-2013-2023)

4.4 Investigating changes

Using the Thematic Change Workflow, we derive land use changes from 1993 to 2023 by comparing images from different periods. Initially, we compare the images of 1993 with 2003, then the changes obtained from the 2003 images are compared with those from 2013, and finally, we compare the images of 2013 with 2023. Ultimately, to ascertain the land use changes over the past three decades within the study area, we utilize a comparison between the images of 1993 and 2023.

Changes from 1993 to 2003

In the examination of land use changes within the study area, according to the land use change map of 2003 compared to 1993, alterations have occurred in 35 different scenarios among the defined 5 land use change classes. However, in 7 instances of these classifications, where no changes have occurred, the least change is attributed to barren lands remaining as barren lands, amounting to 18 pixels with an area of 3.05 hectares. The most substantial land use transformation over the span of 10 years for barren lands amounts to 621.91 hectares, converted into agricultural lands. This transformation is primarily due to human activity, as barren lands surrounding and extending beyond the urban limits have been cultivated, leading to environmental degradation.

Agricultural lands have experienced minimal changes, with 9.17 hectares transitioning from agriculture to water bodies, and the most significant change being 775.8 hectares of agricultural lands remaining uncultivated and barren. It should be noted that due to seasonal fluctuations when crops are not cultivated, most agricultural lands are identified as barren during certain months of the year.

The least changes observed pertain to water bodies, particularly the Silvana River basin, where the least alteration along its course amounts to 11.19 hectares, converted into barren lands. This segment could be attributed to the depletion of water resources in this area, leading to the emergence of barren lands. The most significant transformation involves the conversion of these lands into urban areas, amounting to 92.64 hectares.

Subsequently, changes in gardens exhibit the least alteration, with 17.67 hectares transitioning into water bodies, while the most substantial change involves their conversion into gardens in the vicinity of Urmia City, totaling 832.36 hectares.

The most crucial changes pertinent to this study are those associated with urban and human-made lands. It is imperative to understand the predominant types of transformations occurring within urban areas and identify the predominant land use changes. The least urban land use change amounts to 9.2 hectares transitioning

into water bodies, converted into riverbeds. Conversely, the most significant change amounts to 490 hectares transitioning into gardens. It can be inferred that urban areas have experienced more extensive development than expansion into surrounding areas over the ten-year period from 1993 to 2003 (Tab.4 and Fig.8).
Furthermore, the most substantial urban degradation has occurred on the outskirts of the city, with changes from suburban to agricultural and gardens, indicating a population influx towards the city center, resulting in high population density. The largest area of land transformed into urban areas is attributed to the conversion of gardens in the northern and northeastern parts of Urmia, totaling 781.13 hectares. Conversely, the least transformation into urban areas amounts to 92.64 hectares, transitioning from water bodies to urban and human-made lands.

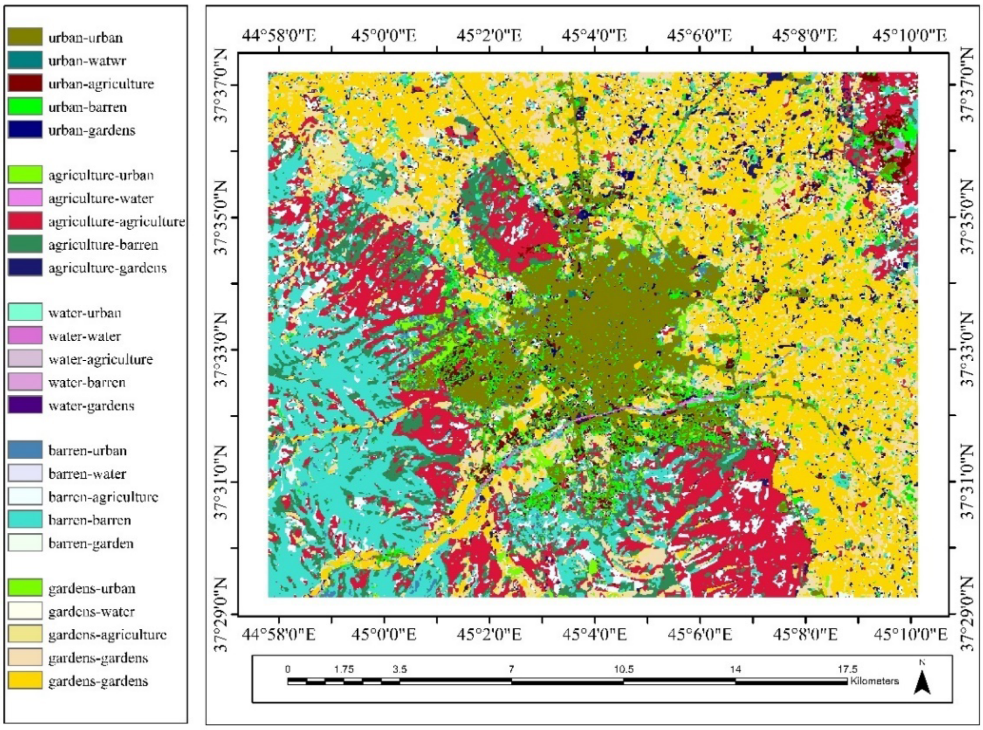

Fig.8 Changes from 1993 to 2003

2003 / 1993	Urban [ha]	Agriculture [ha]	Barren [ha]	Garden [ha]	Water [ha]
Urban	3635	353.87	140.93	490.91	9.2
Agriculture	666.85	4401	775.8	557.2	9.17
Barren	454.33	1,671.07	2,384.19	621.91	3.05
Garden	781.13	1,268.47	832.36	7,380.77	17.67
Water	92.64	23.4	11.19	46.7	40.06

Tab.4 Land use change from 1993 to 2003

Changes from 2003 to 2013

The changes that occurred from 2003 to 2013, according to the table and land use change map, indicate that the least alterations in the water bodies class amount to 1.93 hectares, which have been converted into agricultural lands, while the most significant changes in this class amount to 46.09 hectares, transformed into barren lands in 2013.
In the agricultural land's class of 2003, the least changes amount to 1,125 hectares, converted into barren lands, while the most substantial alterations in this class amount to 522 hectares, transformed into gardens. This implies that more than 522 hectares of agricultural lands were destroyed and converted into gardens

from 2003 to 2013 (Tab.5). The least changes in the barren lands class amount to 202.75 hectares, converted into urban areas, while the most significant alterations in this class over the ten-year period amount to 1621.58 hectares, transformed into agricultural lands. These changes predominantly occur in the northern and southwestern outskirts of Urmia City. The most minor changes in the gardens class amount to 523 hectares, converted into urban and human-made lands, while the most significant alterations in this class over the ten-year period occur in barren lands. However, this change is not in the form of gardens disappearing entirely; rather, it is due to the preservation of garden land use itself, but changes arise due to alterations in irrigation methods and the age of gardens. The most significant changes occur in urban lands, with the least area of change being 8.946 hectares, converted from human-made lands into agricultural lands, while the most substantial alterations amount to 110.997 hectares, transformed into barren lands. Most of these changes manifest as access roads between urban areas and their surroundings. Furthermore, during this period from 2003 to 2013, the most significant changes in transitioning to urban lands amount to 1,901.745 hectares, converted into urban areas (Fig.9).

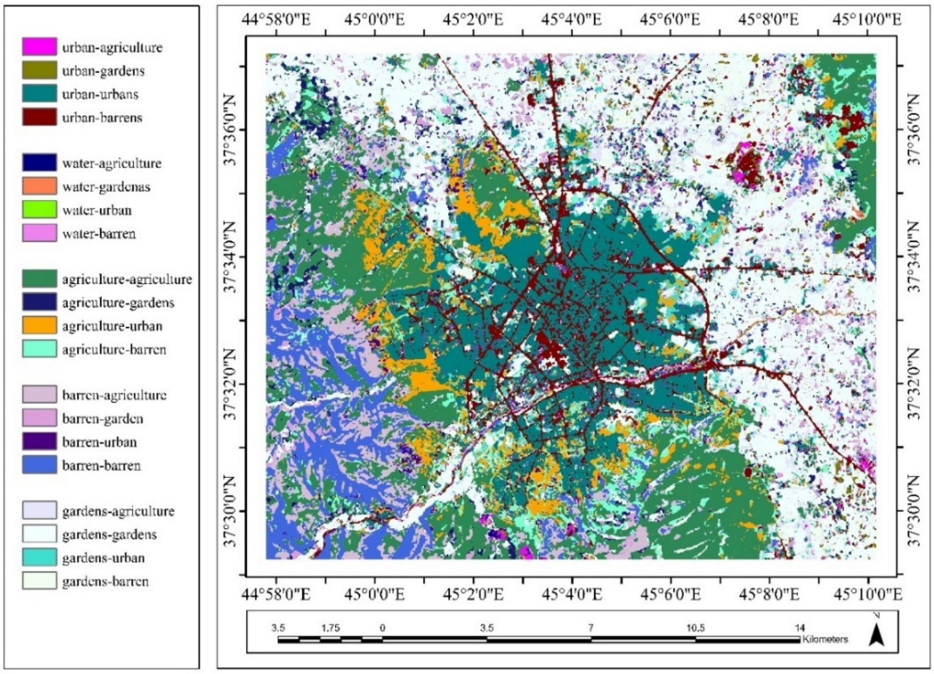

Fig.9 Changes from 2003 to 2013

2013 / 2003	Urban [ha]	Agriculture [ha]	Barren [ha]	Garden [ha]	Water [ha]
Urban	3,550.87	234.3	1,695.28	185.43	-
Agriculture	1,376.82	4752	1,125.53	522.56	-
Barren	202.75	1,621.58	1,842.84	490.15	-
Garden	523.14	1,693.95	1,851.55	5,017.21	-
Water	1.93	14.46	46.09	19.52	-

Tab.5 Land use change from 2003 to 2013

Changes from 2013 to 2023

During the years 2013 to 2023 (Tab.6), in the agricultural lands class, the least changes occurred, amounting to 313.16 hectares, which were converted into barren lands, while the most significant changes amounted to

1020.55 hectares, transformed into urban and human-made lands. In the gardens class, the least area of change was 80.49 hectares, converted into urban and human-made lands, while the most substantial change was 598 hectares, converted into agricultural lands. In the urban lands class during this period, the least transformation occurred, with an area of 19.51 hectares converted into gardens, while the most significant change, with an area of 346 hectares, was converted into barren lands. Most of these alterations occurred in large areas outside the city, such as access roads and abandoned workshops, which were transformed into barren lands. Barren lands experienced the least conversion to urban areas, with an area of 905 hectares, while the most significant changes, amounting to 2,959 hectares, were converted into agricultural lands (Fig.10). Over the course of these ten years, the least area converted to urban lands was 80 hectares, transformed from gardens into urban areas. The most significant changes to urban lands occurred in the outskirts and urban expansion areas, with an area of over 1020 hectares converted from agricultural lands into urban areas. In total, more than 2000 hectares of garden, barren, and agricultural lands were transformed into urban areas over the ten-year period, indicating urban expansion within Urmia City.

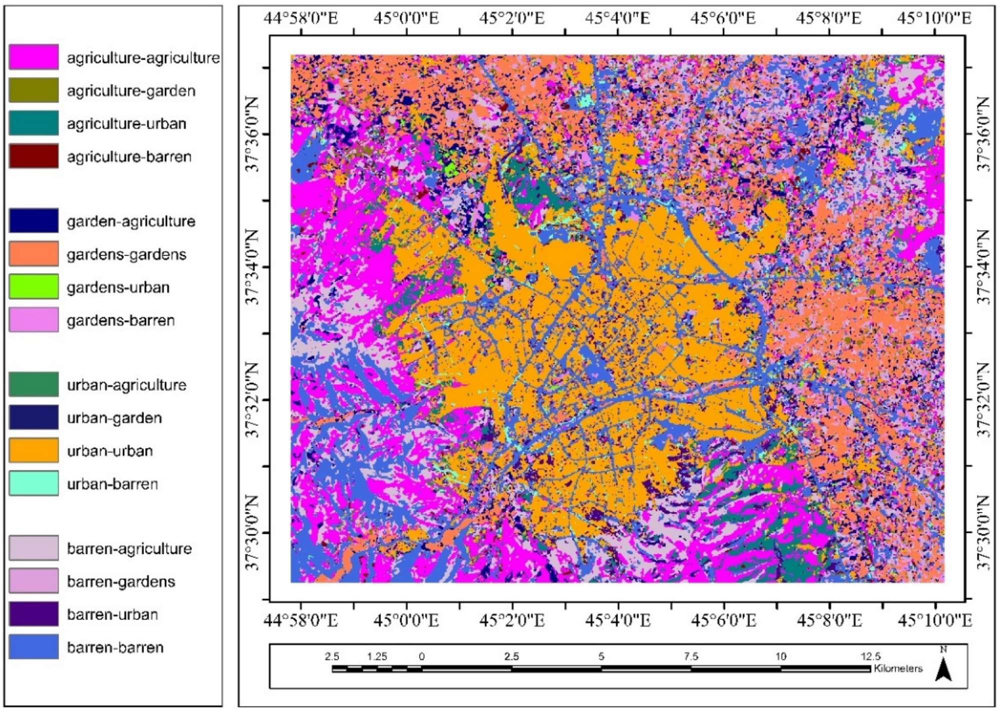

Fig.10 Changes from 2013 to 2023

2013 \ 2023	Urban [ha]	Agriculture [ha]	Barren [ha]	Garden [ha]	Water [ha]
Urban	5,851.44	199.78	346.02	19.51	-
Agriculture	1,020.55	4,067.72	313.16	377.76	-
Barren	905.1	2,959.96	4,671.63	924.11	-
Garden	80.49	1,127.11	598.32	3,305.96	-
Water	-	-	-	-	-

Tab.6 Land use change from 2013 to 2023

Changes from 1993 to 2023

Over the three decades from 1993 to 2023 (Tab.7), the summary of changes for five land use classes between 1993 and 2003, and four land use classes between 2013 and 2023 is as follows.

For urban lands, the least changes occurred, amounting to 233.33 hectares converted into gardens, while the most significant area transformed, totaling 1,384 hectares, was converted into barren lands. In agricultural lands, the least changes observed were 165 hectares converted into gardens, whereas the most significant alteration amounted to 2518 hectares transformed into urban areas. In the water class, measured only over two decades, the smallest conversion area was 20.65 hectares, transformed into urban lands, while the most substantial changes were 121.39 hectares converted, respectively, into urban and barren lands. Throughout these 30 years, barren lands experienced the least changes, with 295.31 hectares converted into gardens, and the most significant alterations, with 2183 hectares converted into agricultural lands. Gardens had the least changes, with 1546 hectares converted into urban lands, and the most substantial changes, with 2887 hectares converted into gardens (Fig.11). The most considerable changes occurred in the urban and human-made land use class, with the least transition observed in water class, converting 20.65 hectares into urban lands, and the most significant change, with 2518 hectares converted from agricultural to urban lands. Moreover, over these three decades, the least change occurred from water to urban lands, with 20.65 hectares, and the most significant transformation was from gardens to agricultural lands, with 2,887.41 hectares.

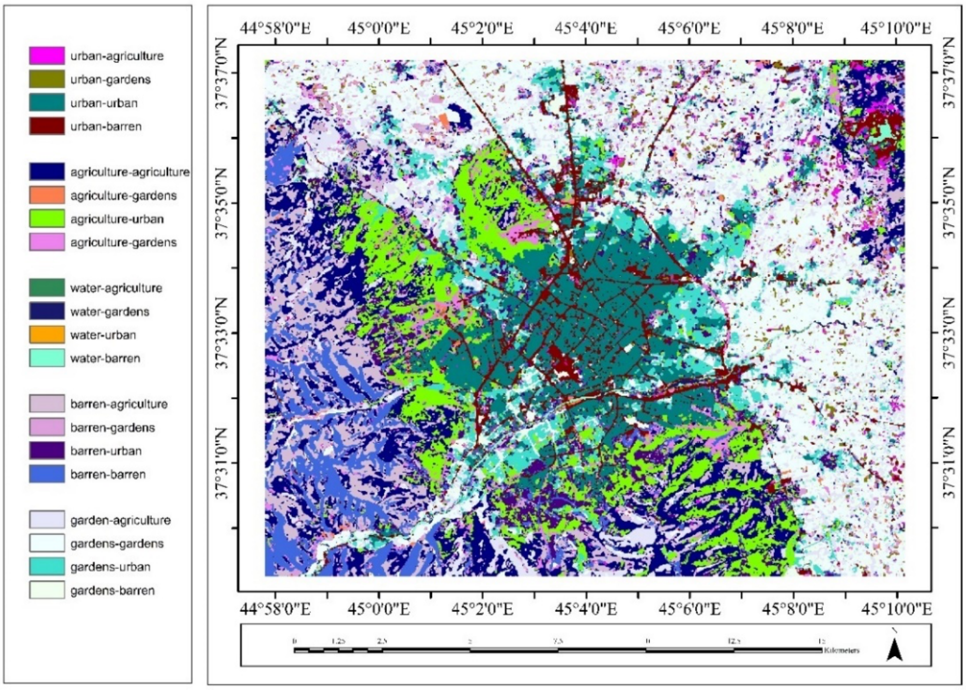

Fig.11 Changes from 1993 to 2023

2023 / 1993	Urban [ha]	Agriculture [ha]	Barren [ha]	Garden [ha]	Water [ha]
Urban	2,691.8	316.34	1,384.08	233.33	-
Agriculture	2,518.85	2,973.33	763.82	165.79	-
Barren	1,059.81	2183	1,622.62	295.31	-
Garden	1,546.21	2,887.41	1,972.77	3834.4	-
Water	20.65	34.93	121.39	43.67	-

Tab.7 Land use change from 1993 to 2023

The land-use analysis across the four study periods reveals several clear and consistent trends that characterize Urmia's spatial transformation. Urban areas expanded steadily from 1993 to 2023, reflecting the city's outward growth and the conversion of surrounding agricultural and garden lands. The most pronounced decline occurred in garden areas, which experienced a continuous reduction over the three decades. This pattern indicates a shift from traditional orchard-based landscapes toward built-up structural development. Agricultural lands displayed moderate fluctuations, largely influenced by seasonal cultivation cycles and periodic expansion into barren lands, while barren lands experienced gradual reduction as they were repurposed for either cultivation or urban development. These trends demonstrate a long-term transition from a mixed agricultural-garden landscape to a more urban-dominated pattern, consistent with broader regional shifts in mid-sized Iranian cities.

4.5 Urban areas

According to the results obtained from land use changes, urban areas do not deteriorate over time and are converted to other uses. Therefore, urban areas should increase compared to previous periods. To rectify this error, we utilized the ERASE tool in GIS software to minimize these errors on urban land parcels according to the maps (Fig.12).

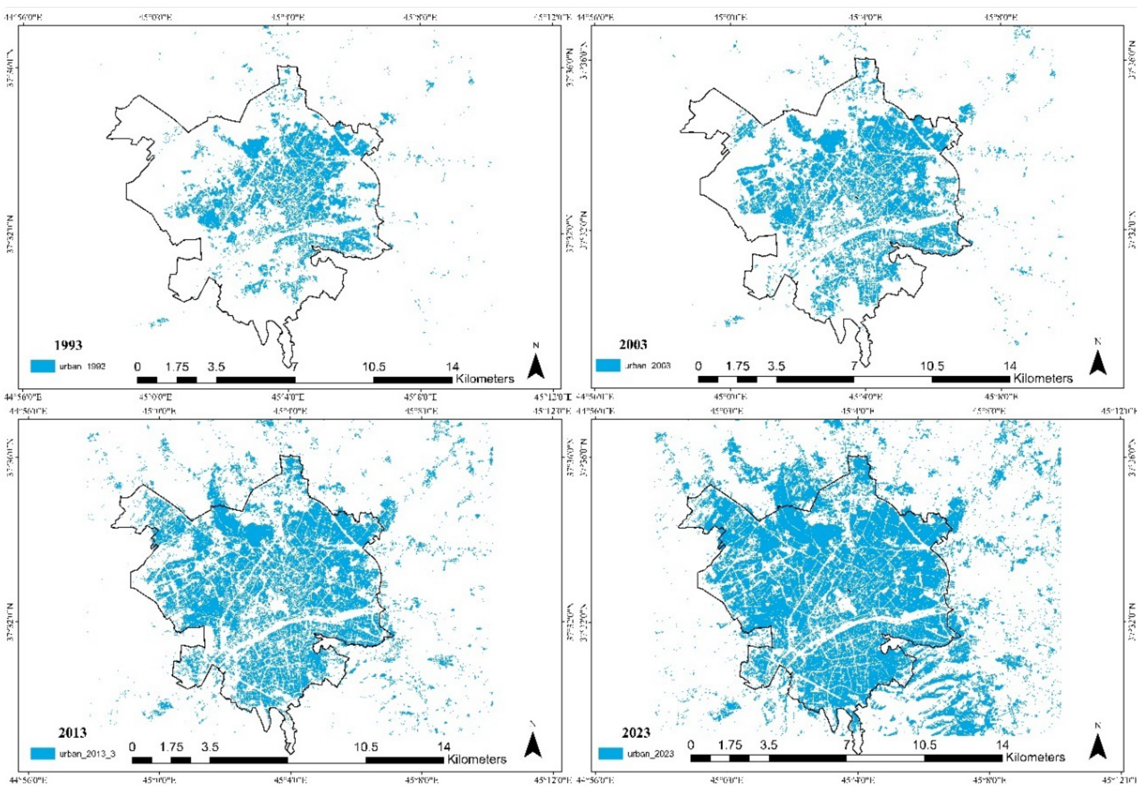

Fig.12 Urban Lands 1993-2003-2013-2023

In 1993, the urban land area was 3,953.95 hectares, which increased to 5,179.74 hectares in 2003. By 2013, the urban or human-made land area had reached 5,411.37 hectares, and finally, in 2023, it reached 7,697.96 hectares. In the comprehensive plan of Urmia City in 2016, the urban area boundary was declared as 10,000 hectares. However, the results obtained indicate discrepancies due to processing errors, unclear delineation of the urban boundary, and the absence of a road network matching the declared boundary in the Urmia comprehensive plan.

4.6 Factors

To identify the factors influencing land use changes, various dimensions and reasons for urban growth and expansion at a global level were identified after research in various sources. In this regard, the Fuzzy Delphi method was used to achieve this goal. By collecting opinions from urban experts in Urmia, several steps were taken to identify the factors affecting land use changes in Urmia through defining the research problem, dimensions, and various components using factor analysis. The criteria introduced by the experts categorized these factors into 6 dimensions as follows (Tab.8). In these 6 categories, the first three dimensions are particularly important and are the main drivers of changes, while the other three dimensions are supportive and complementary to the first three dimensions, hence not significantly impactful on land use changes.

Criteria	**Explanation**
Social Dimension (Population)	Rate, growth, and density of the population
Living Standards	Economy, income levels, and livelihood of individuals
Technological Advancement	Transportation, construction of power plants, industries, etc.
Political Economy	Production and distribution of income and public wealth in various regions of Urmia
Political Structure	Political system, role of the government, plans and policies, management
Attitudes and Values	Culture, customs, and traditions of the city's ethnic groups and religions (Urmia)

Tab.8 Defined dimensions

By selecting these 6 dimensions according to the experts' opinions, the main criteria for each dimension were determined. Then, through reviewing the literature of various research studies and investigations and considering the opinions and suggestions collected from 60 experts, 60 indices were introduced for each of these dimensions. To identify the effective factors, 25 components out of the mentioned 60 sub-criteria entered the analysis. The oblique rotation method was used for Factor analysis, determining the factors based on the assumptions of the test, with eigenvalues of 0.5 or 1. The aim was to identify the best model and eliminate inefficient variables with lower factor loads that had insignificant correlations with other variables. Meaningful factor loads with higher significance coefficients in each factor analysis round, exceeding 0.5, were selected for a more precise and better analysis. As a result, 6 factors were extracted, encompassing 19 variables.

Based on the analyses conducted using the Fuzzy Delphi method and the results derived from factor analysis, the driving forces behind land use and land cover changes in Urmia can be broadly categorized into six main groups: socio-demographic factors, economic conditions or living standards across social classes (wealth), technological advancement, political economy, political-administrative structure, and cultural attitudes and values. Among these, the first three categories (population, wealth, and technology) are primarily associated with environmental changes, accounting for 18.499%, 14.509%, and 11.765% of the variance, respectively. These findings suggest that environmental transformations are largely driven by population growth, economic conditions, and technological progress, with population being the most influential factor in altering land surfaces. In addition to these three primary forces, three other categories also contribute to land use changes, though to a lesser extent: political economy (including exchange systems, private property, state control, and planning mechanisms), political structure (referring to governmental institutions and administrative organizations), and cultural attitudes and values of individuals and groups. These latter factors account for 9.610%, 9.175%, and 7.716% of the variance, respectively. While these additional drivers are indeed relevant, their impact on land use change in Urmia is significantly less than that of the primary demographic and economic forces, especially population growth, which remains the most influential variable in shaping urban land transformations.

Tab.9 represents the number of factors extracted from the data (initial variables). Factors in this section are considered influential if their characteristic value (sum column) is greater than one. The last column of this table indicates the percentage of variance explained by all factors (from the first factor to the current factor) together. According to the table, 6 factors have been extracted, which collectively account for 71.274% of the variability of the main variables. The total variance for each test is equal to 100%. The closer this value is to 100, the better the interpretation of the number of factors. The eigenvalue for the first factor is 4.625. Other eigenvalues for subsequent factors are also listed in the Total column.

	Initial Eigenvalues			**Sum of Squared Loadings**			**Sum of squared loadings after rotation**
	Total	Percentage of variance	Cumulative percentage	Total	Percentage of variance	Cumulative percentage	Total
Social Dimension (Population)	4.625	18.499	18.499	4.625	18.499	18.499	3.908
Living Standards	3.627	14.509	33.008	3.627	14.509	33.008	3.521
Technological Advancement	2.941	11.765	44.773	2.941	11.765	44.773	3.185
Political Economy	2.402	9.61	54.383	2.402	9.61	54.383	2.582
Political Structure	2.294	9.175	63.558	2.294	9.175	63.558	2.572
Attitudes and Values	1.929	7.716	71.274	1.929	7.716	71.274	2.728

Tab.9 Eigenvalues, Percentage of Variance, and Cumulative Percentage

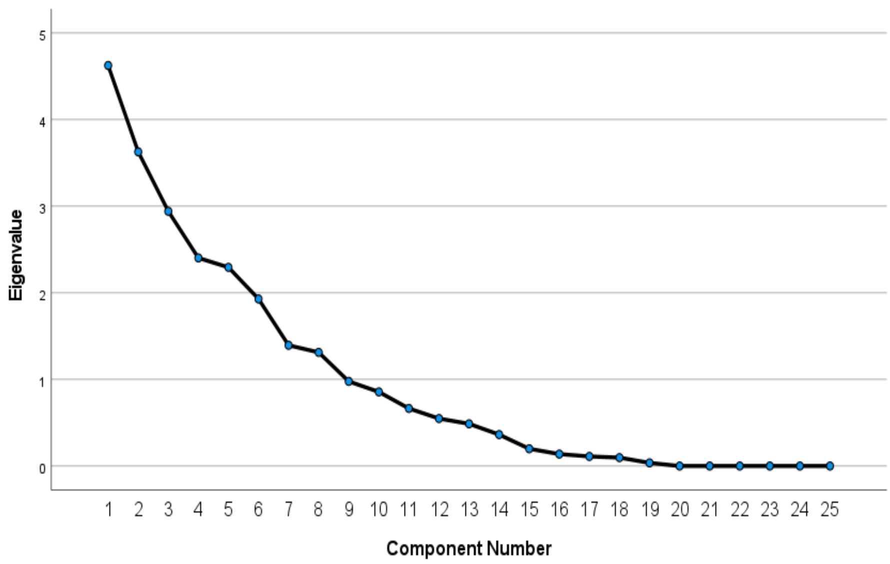

Fig.13 Scree plot

The scree plot (Fig.13) graphically displays the eigenvalues of each of the extracted components, starting from the largest eigenvalue. It consistently exhibits a descending slope. The scree plot indicates which factor had a noticeable change. It's quite evident that the initial 3 factors have a steeper slope compared to the second set of 3 factors. In fact, the results from the Total Variance Explained table are observed graphically in the scree plot, revealing which factor contributes to a higher percentage of variability in the variables. It's apparent in the plot that the initial 3 factors encompass more variability, covering 44% of the total, while the subsequent 3 factors also cover nearly 27% of the variability, as visible in the plot. Considering the scree plot, factors 7 and 8 could also be taken into account.

The higher contribution of social and economic factors to land-use change in Urmia can be explained by several key trends:

Social Factors: Rapid Population Growth and Urban Expansion: Urmia has experienced rapid population growth; driven by factors such as rural-urban migration and natural population increase. This population growth has created a substantial demand for housing, infrastructure, and services, leading to the expansion of urban areas into previously agricultural and garden lands. In many cases, urban planning efforts have not been able to keep pace with this rapid population growth, resulting in unplanned urban sprawl and encroachment on valuable agricultural land. For example, the city's population has increased from 500,000 in 1993 to over 800,000 in 2023, placing significant pressure on existing urban infrastructure and land resources. Economic Factors: Investment in Construction and Real Estate: Economic development in Urmia, particularly in the construction and real estate sectors, has also played a significant role in driving land-use change. Increased investment in housing and commercial development has led to the conversion of land from agricultural to urban uses. For instance, government policies aimed at stimulating economic growth have sometimes inadvertently encouraged land speculation and the conversion of agricultural land for development. Technological improvements, including new highways, ring roads, and mechanized agriculture, opened up undeveloped areas and accelerated land transformation around Urmia. Economic and policy forces also played a major role: government-backed housing programs such as the Mehr Housing scheme, the creation of industrial townships, and weak taxation on vacant land encouraged speculation and drove rapid conversion of land, especially in western and southwestern areas. Cultural shifts also contributed, with many families moving away from traditional orchard-based lifestyles toward suburban villas and leisure properties, especially in Silvaneh, Nazloo, and the northeastern outskirts, leading to widespread conversion of gardens into residential and recreational land uses.

5. Discussion

Based on the changes from 1993 to 2003, the smallest change was from barren land to water land, covering an area of 11.19 hectares. The largest change during this period was from barren land to agricultural land, encompassing 1671 hectares. From 2003 to 2013, the smallest change was from water land to urban land, with an area of 1.93 hectares, while the largest changes involved barren land transforming into both barren and agricultural lands, totaling 1,851 hectares, and agricultural land converting to urban land, covering 1376 hectares. In the period from 2013 to 2023, the smallest changes were from urban land to garden land, and the largest change was from barren land to agricultural land, spanning 19.51 hectares. Additionally, 2,959.96 hectares of agricultural land were converted to urban land.

According to the land use changes from 1993 to 2023, the smallest change was from water land to urban land, with an area of 20.65 hectares. The largest changes over the 30 years were from agricultural land to urban land, covering 2,518 hectares, barren land to agricultural land, spanning 2,183 hectares, and garden land transforming, totaling 2,887 hectares, primarily converted into agricultural lands. This indicates that the most significant land use changes over the three decades pertain to urban and man-made lands, with their area approximately tripling.

Water Bodies: The water bodies in the specified area encompass the Silvana River, also known as the Berdeh Soo River, which flows through the city of Urmia and empties into Lake Urmia. In 1993, this stretch of land had an approximate area of 227.26 hectares, which decreased to 89.21 hectares by 2003. According to analytical tables, this reduction in area can be attributed to various reasons. Firstly, the widening of the riverbed due to urban development and beautification projects by the Urmia Municipality. Additionally, the construction of the Silvana Dam both upstream and downstream has led to a significant portion of the riverbed being utilized for agriculture and gardens due to reduced river volume. Furthermore, in the past decade, due to drought and limited rainfall across the country, water from the dam has only been released for agricultural purposes on specific days and months of the year, resulting in periods of water scarcity in the riverbed. Therefore, in 2013 and 2023, the classification of water classes in the images was omitted due to these reasons.

Urban Areas (Human-made): In 1993, the total identified urban area in Urmia was 4,630.63 hectares, which significantly increased over three decades to 7,697.96 hectares in 2023. Over 3,000 hectares have been added during this period, representing a 65% increase compared to 1993. All land conversions to urban areas were calculated in season 4. The major reasons for the tripling of Urmia's urban area over these three decades include population growth and subsequent construction activities, particularly unauthorized constructions, mass housing developments in the northern, northwestern, southern, and southwestern parts of the city, along with infrastructural developments, highways, factories, industrial workshops outside the city limits. Residential and commercial township constructions outside the city limits and obtaining top positions in industrial township constructions nationwide, along with achieving the third position nationally in the executive performance of the construction movement, have contributed to numerous economic activities and constructions across the city. Gardens constructed outside the city limits have, inevitably, led to changes in culture and the construction of small orchards or garden villas, subsequently necessitating the construction of access roads for transportation due to the high cost of land and the consequent influx of people to the outskirts and suburban areas for housing construction. Additionally, the construction of large administrative centers in the city's periphery has been another major factor driving urban expansion and growth in the specified area.

Agricultural Lands: Agricultural lands covering 6,448.03 hectares in 1993 increased to 8,652.81 hectares in 2023, representing an addition of 2204 hectares, approximately a 35% increase compared to 1993. While the percentage change in agricultural lands may not seem significant at first glance, a closer examination reveals substantial changes in land use over the three decades. It's notable that for every unit of agricultural land converted to urban areas or gardens due to various reasons, such as construction activities, an equivalent area of agricultural land has been added annually. Barren lands have been increasingly cultivated, leading to the degradation of natural and pristine lands.

Barren Lands: Barren lands are among the most critical lands from an environmental perspective, upon which human life depends. In 1993, these lands covered an area of 5,210.61 hectares within the specified area, but by 2023, this area decreased to 5930.24 hectares, nearly halving compared to 1993. More than 44% of the land area in 1993 has been lost, which is approximately 462 hectares converted from barren lands to other uses by 2023. Barren lands have undergone significant changes, being converted to agricultural lands, gardens, and most significantly, urban areas.

Land Use Changes: Urmia had 10,252 hectares of gardens in 1993, primarily consisting of vineyards and apple gardens. However, by 2023, due to significant urban development and human interventions, the area of these lands has decreased to 4,487.68 hectares. More than 22% of these gardens, totaling 129 hectares, underwent transformation into other land uses. This transformation mainly occurred through the construction of various urban roads, resulting in a change of land use along these roads. Additionally, all gardens in recent years have been equipped with recreational facilities such as garden pavilions or at least one residential structure within the gardens for leisure activities and other purposes.

Through fuzzy Delphi analyses and factor analysis results, the driving forces behind land use changes and land cover in Urmia can be broadly categorized into six socio-demographic, economic or lifestyle strata (wealth), progress and technology, political economy, political-administrative structure, attitudes, and values (culture). The first three categories are associated with environmental changes, where environmental impact is a function of population, wealth, and technology.

Among these three categories of driving forces, the population generates the most significant changes in land use. Additionally, three other groups are added to these driving forces: political economy, which includes exchange systems, private ownership, government controls, and planning; political-administrative structure, which encompasses governmental institutions and organizations; and attitudes and values of individuals and groups. The categorized driving forces in this classification are much fewer than the previous three groups, and particularly, population growth is confirmed to have caused the land use changes in Urmia.

The findings of this study show that socio-economic factors had a stronger influence on land-use change in Urmia compared to political or cultural drivers. This reflects the city’s development pattern over the past thirty years, during which rapid population growth, rising living standards, and expanding technological capacity directly shaped land transformation. Political and cultural factors had a weaker role because they often influenced land use indirectly. In Urmia, political institutions have generally responded to demographic and economic pressures rather than guiding or regulating long-term spatial development. Planning regulations were not consistently enforced, and administrative structures lacked the continuity required to manage growth effectively. Cultural influences were also less prominent because traditional practices related to orchard cultivation and the preservation of community landscapes have gradually diminished. These practices have been overtaken by the economic appeal of property development and by modern residential preferences. As a result, socio-economic forces tended to overshadow political and cultural mechanisms that might otherwise have moderated the pace or direction of land-use change.

The land-use changes observed in this study have several broader implications for Urmia's social, economic, and environmental future. Socially, the rapid expansion of built-up areas and the decline of garden and agricultural zones have intensified spatial inequalities. Former rural areas that were absorbed into the urban boundary did not always receive corresponding improvements in infrastructure or public services, creating uneven access to transportation, utilities, and social facilities. Economically, the loss of productive agricultural and garden lands reduces long-term food security and weakens the livelihoods of households that historically depended on orchard-based income. Although construction activity has attracted investment and created employment, it has also stimulated speculative land markets. This can raise property prices and limit access to affordable housing for many residents.

Environmental consequences are equally significant. The reduction of garden areas has removed an important source of green cover that once helped regulate temperature, support biodiversity, and improve air quality. Their disappearance contributes to higher heat stress and increased dust emissions, particularly in an area already affected by the ecological challenges surrounding Lake Urmia. The expansion of impermeable urban surfaces increases surface runoff, heightens flood risks, and places additional pressure on already strained water resources. These environmental effects match patterns seen in many mid-sized cities in arid and semi-arid climates, where rapid urbanization exceeds the capacity of natural systems to absorb and adapt to change.

Overall, the dominance of socio-economic drivers over political and cultural influences suggests that Urmia's land-use trajectory is shaped by short-term development pressures rather than long-term strategic planning. Without stronger governance structures and coordinated land management policies, continued expansion may intensify environmental degradation, social disparities, and economic vulnerabilities. This highlights the need for integrated planning approaches that protect remaining green areas, regulate urban expansion more effectively, and balance development needs with ecological and social sustainability.

The findings of this study align with and expand upon established hypotheses in the urban geography and land change literature. Specifically, the 66% increase in urban areas and the simultaneous 56% decline in gardens over the three-decade study period reflect well-documented global patterns of urban sprawl driven by rapid population growth, socio-economic development, and inadequate planning (Lu et al., 2019; Burchfield et al., 2006; Yuan et al., 2018). These outcomes reinforce the hypothesis that unregulated urban expansion often occurs at the expense of agricultural and vegetated lands, a phenomenon also observed in studies across Asia and the Global South (Dolley et al., 2020; Dutta et al., 2020). Moreover, the identification of six key dimensions social, economic, technological, political, and cultural supports frameworks that consider land-use change as a multi-dimensional process influenced by demographic pressures and institutional weaknesses (Hersperger et al., 2010; Wang et al., 2020).

The role of governance and urban planning policies has been pivotal in shaping the trajectory of Urmia's land use changes. Mass housing developments, industrial zones, and extensive road network construction were largely facilitated by government policies that prioritized rapid economic development over controlled urban growth. During the 1990s and early 2000s, zoning regulations in Urmia were either weakly enforced or selectively applied, allowing construction projects to expand into peri-urban agricultural and garden lands without sufficient environmental assessments. Economic incentives, such as low-interest loans for housing and subsidies for industrial establishment, further accelerated construction beyond the formal urban boundary. Although government plans such as the Comprehensive Urban Plan of Urmia (2016) nominally aimed to curb sprawl by promoting satellite cities and designated growth corridors, implementation was inconsistent. Informal settlements and speculative developments often bypassed regulatory oversight, resulting in fragmented and unplanned urban expansion. Thus, policy failures played a central role in enabling unregulated growth.

Regarding hydrological changes, the reduction of water bodies, notably the Silvana River and adjacent wetland areas, was influenced by a combination of factors: urban development along riverbanks, dam construction, and climate change-induced drought. Among these, the construction of the Silvana Dam and related water diversion for agricultural irrigation had the greatest direct impact on the observed reduction in surface water. By altering the river's natural flow regime, the dam significantly decreased water availability downstream, leading to seasonal desiccation of river channels and the disappearance of wetlands. Reduced rainfall and higher temperatures exacerbated this trend but were secondary compared to anthropogenic water management practices. This pattern mirrors trends observed in other arid and semi-arid regions globally, for instance in parts of Central Asia (e.g., the Aral Sea basin), where river flow regulation for agriculture has led to large-scale hydrological degradation, even before climate change impacts became predominant. Urmia's case thus highlights how localized water management decisions can accelerate hydrological vulnerability in urbanizing landscapes, requiring integrated watershed and land-use planning to mitigate long-term risks.

6. Conclusion

This study not only confirms established urban geography theories regarding the drivers of urban expansion, such as rapid population growth and technological development, but also extends them by highlighting the crucial role of political economy and socio-cultural attitudes in shaping land use changes in a mid-sized city context. While Urmia's urban expansion mirrors global trends of outward growth and garden loss, it exhibits distinct local patterns. In particular, the city has experienced a dramatic decline of private gardens and peri-urban agricultural lands tied to informal governance practices, speculative land markets, and fragmented administrative control. These localized dynamics underscore the interplay between global forces and local contexts in shaping Urmia's urban form.

This research offers a fresh perspective by linking long-term satellite observations with expert-driven insights to uncover how diverse factors interact in shaping urban land use. Beyond documenting spatial change, it introduces a multi-dimensional analytical framework that captures the influence of social, economic, technological, and institutional forces. The study's integration of geospatial and qualitative methods provides a valuable tool for diagnosing land transformation processes in rapidly evolving cities like Urmia and can inform more adaptive, locally grounded urban planning strategies.

To promote sustainable urban development in Urmia, planners should implement several key strategies: enforce zoning laws to control sprawl, incentivize green infrastructure, support higher-density mixed-use development, protect remaining agricultural and garden lands, and improve public transportation systems. These measures collectively aim to reduce informal expansion, enhance resilience, and guide the city toward more sustainable and compact growth. This study provides valuable insights into urban land use change in Urmia through the integration of geospatial analysis and expert-based methods. However, several limitations should be noted. The temporal starting point of 1993 restricts long-term historical analysis, and classification challenges arose in peri-urban areas due to overlapping land use types. The omission of water bodies in later years may have led to an underestimation of hydrological impacts, while the ecological consequences of garden loss remain underexplored. Additionally, the use of the Fuzzy Delphi method introduces subjectivity, as expert selection and indicator weighting may reflect institutional biases. Although focused on a single case, the study's methodological framework is adaptable to other rapidly urbanizing mid-sized cities, particularly in developing regions.

Future research should consider comparative analyses involving multiple cities and extend the temporal scope to include earlier historical periods. Employing econometric models and scenario-based forecasting could also provide insight into the long-term impacts of various urban planning strategies. Furthermore, integrating ecological and social metrics, such as biodiversity, carbon emissions, and community perceptions, would contribute to a more comprehensive and policy-relevant understanding of urban land dynamics. Ultimately, this study highlights the importance of interdisciplinary approaches in addressing the complex challenges of urbanization. By integrating spatial, socio-economic, ecological, and political dimensions, it advances theoretical understanding and supports the development of more resilient, sustainable, and inclusive urban planning strategies.

To enhance the practical value of this research, the study offers several specific and context-driven policy recommendations for urban planners and decision-makers in Urmia. A central priority is the establishment and strict enforcement of a clear urban growth boundary, since the city has expanded well beyond the limits defined in its 2016 Comprehensive Plan. Preventing new construction outside the designated boundary would help curb informal sprawl and protect the remaining agricultural and garden lands. Within the existing urban area, redevelopment and densification should be encouraged, particularly in underutilized or low-density neighborhoods. Incentives such as reduced permitting times, tax benefits, or density bonuses could motivate developers to focus on infill rather than outward expansion. Protection of garden and agricultural lands also requires targeted zoning regulations supported by economic incentives, including subsidies for orchard maintenance and compensation programs for landowners who choose to maintain green land uses rather than selling to developers.

A systematic land monitoring program, based on periodic satellite imagery, would help local authorities detect and respond to illegal construction and rapid land transformations. Integrating water resource management with land-use planning is also essential, since the decline of gardens in Urmia is closely linked to water scarcity. Coordination with water authorities to modernize irrigation systems and preserve riparian areas would support both agricultural sustainability and environmental resilience. The municipality could also designate ecological corridors that link remaining gardens and natural areas in order to reduce heat stress, preserve biodiversity, and guide development away from environmentally sensitive zones. Additionally, reforms in the land market, such as taxing vacant land or regulating land subdivision in peri-urban villages, would discourage speculative practices that have accelerated unplanned expansion. Improving coordination among the various agencies involved in land and development decisions would further strengthen the city's capacity to manage growth effectively.

The study also contributes to both theory and practice in several important ways. Theoretically, it advances understanding of urban land-use change in mid-sized cities by combining long-term satellite observations with expert-based evaluation methods. This integrated approach addresses a gap in the literature where most studies either rely solely on remote sensing or focus primarily on socio-economic indicators without linking the two. The findings also refine existing theories of urban sprawl by showing that in semi-arid, rapidly developing contexts like Urmia, socio-economic drivers can overshadow political and cultural influences, particularly when institutional capacity is limited. Furthermore, the multi-decadal assessment presented here adds empirical depth to theoretical discussions about the relationship between demographic pressure, economic restructuring, and land-market dynamics.

Practically, the study provides urban planners in Urmia with clear insights into the dominant forces shaping land-use change. By identifying population growth, rising living standards, and technological expansion as the most influential drivers, the research supports more targeted planning interventions. This is consistent with

Partheepan et al. (2023), who observed similar socio-economic pressures in Batticaloa, and with Pultrone (2023), who emphasized the role of external agents in accelerating urban sprawl. The work also demonstrates how geospatial tools can be operationalized by local agencies to track urban expansion and environmental degradation. The policy-oriented recommendations derived from the results offer concrete steps that can be implemented in the short and medium term, contributing directly to urban management and sustainability efforts. Finally, the methodological framework developed in this study can be applied to similar mid-sized cities in Iran and other developing countries, making the research relevant beyond the specific case of Urmia.

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Global climate crisis and regional contexts. A study on ecosystem services related to Sardinia, Italy

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Abstract

Global climate change threatens human health, impacting both physical and psychological well-being. Mitigating these effects requires balancing the carbon cycle, as carbon dioxide regulates Earth's temperature through its role in greenhouse gases. In line with the Paris Agreement's goal of climate neutrality by century's end, the objective is to limit global warming to 1.5 °C by balancing carbon emissions and removals. Yet, existing atmospheric carbon could still add about 0.6 °C of warming, even if emissions ceased today. Achieving net-zero emissions is therefore crucial and underscores the need to understand ecosystems' capacity for carbon storage and sequestration. This study proposes a methodological framework to support climate neutrality through spatial planning policies, using the Carbon Capture Capacity (CCC) indicator to assess current conditions and trends. CCC is examined alongside five ecosystem services (ESs): heat mitigation, habitat quality, crop and timber production, scenic quality, and potential for outdoor activities (POA). Focusing on Sardinia, spatial correlations between CCC and these ESs are analyzed to assess how multifunctional ecosystems enhance carbon sequestration and contribute to global climate goals. CCC mapping, based on the InVEST "Carbon Storage and Sequestration" model, reveals strong positive correlations with heat mitigation and habitat quality, while POA shows moderate influence. Weaker links with production and scenic quality stress the need for careful siting of renewable energy to preserve landscape integrity.

Keywords

Carbon sequestration; Climate neutrality; Ecosystem services

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1. Introduction

Climate change (CC) is expected to place significant strain on human health, affecting both physical well-being and mental health in diverse and far-reaching ways (Driga & Drigas, 2019). To mitigate the risks associated with CC, maintaining a balanced carbon cycle is crucial, given that carbon dioxide is a fundamental component in regulating the planet's surface temperature through its influence on atmospheric greenhouse gas concentrations. In accordance with the Paris Climate Agreement, which seeks to achieve climate neutrality by the latter half of this century, a target of limiting global warming to 1.5 °C has been established to maintain a balanced carbon cycle, reducing CC impacts through a long-term balance between emissions and removals. This process is challenging because the carbon dioxide already in the atmosphere will cause an additional warming of approximately 0.6 °C over the next century due to the greenhouse effect (Riebeek, 2011), even if emissions stop immediately; therefore, achieving net zero carbon emissions is essential to limit global warming to the set target and avoid exceeding it, highlighting the critical importance of understanding the carbon storage and sequestration capacity of natural systems.

Human activities, particularly the burning of fossil fuels and land clearing, are causing significant disruptions to the carbon cycle. Land use changes, along with the intensification of agriculture to produce more food on less land and similar trends, have led to increased emissions and a reduced capacity for carbon sequestration. Currently, human activity affects over 70% of ice-free land and utilizes up to a third of its potential biological productivity for food, energy, and materials, underscoring both its ecological importance and vulnerability (IPCC, 2023).

In the European context, Italy has experienced increasing land consumption, especially in agricultural and natural areas, leading to urban sprawl, biodiversity loss, and environmental risks such as floods and heat islands (Mussinelli et al., 2024). Sardinia emerged as the Italian region with the highest increase in artificial land cover in both 2023 and 2024, recorded as +0.57% in the latest year. This trend highlights persistent pressures on ecosystems and the urgent need to align climate adaptation strategies with ecosystem service (ES) preservation to advance toward climate neutrality (Munafò, 2023; SNPA, 2024). Land-based strategies aimed at CC and achieving climate neutrality require integrating diverse adaptation and mitigation actions that simultaneously enhance ecosystem health and the delivery of multiple ESs (IPCC, 2023).

Within this conceptual framework, the study aims to propose and apply a methodological approach for the implementation of climate neutrality through spatial planning policies. The Carbon Capture Capacity (CCC) measure is taken as a reference to estimate the status and evolutionary dynamics of this phenomenon, analyzed and evaluated as associated with the supply of five ESs, Heat Mitigation (HM), Habitat Quality Level (HQL), Crop and Timber Production (CTP), Scenic Quality (SCQ), and Potential for Outdoor Activities (POA). Specifically, the correlations between the spatial taxonomies of CCC and the supply of the five ESs, with reference to the regional context of Sardinia, are detected and analyzed in order to assess how the characteristics and specificities of the multifunctional supply of ESs are effective in maximizing CCC, and, thus, the contribution of the Sardinian Region to the improvement of global climate neutrality. In particular, the spatial configuration of CCC is delineated through the generation of density maps, employing the "Carbon Storage and Sequestration" model from the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) toolset. This model quantifies the stock of carbon retained within defined spatial units, based on raster data derived from land use/land cover classifications in relation to four carbon pools, aboveground and belowground biomass, dead organic matter and soil.

The study is organized into five main sections. Section two outlines the selected case study and details the methodologies employed for the evaluation and spatial representation of the five ESs, as well as their relationship with CCC. Section three presents the empirical findings, while section four offers a critical interpretation and discussion of the results. Finally, section five summarizes the key conclusions and proposes avenues for future investigation.

2. Materials and methods

This part is structured in the following way. Initially, the regional context of Sardinia is introduced, focusing on its characteristics concerning the provision of CCC and the other essentials that are part of this research. Secondly, the approach utilized to identify the spatial taxonomy of CCC provision and other ESs is outlined, which is executed by recognizing the spatial taxonomies of CCC capacity, HQL, land surface temperature (LST) mitigation, crop and timber production, scenic quality, and potential for outdoor activities. In conclusion, a multiple regression is conducted to identify spatial correlations between CCC and the supply of ESs.

2.1 Sardinia Region

The Sardinia Region (see Fig.1), Italy's second-largest island, spans 24,100 km² (ISTAT, 2024) and features a predominantly hilly and mountainous terrain with significant geological diversity. Its rivers follow a torrential regime, and despite limited freshwater lakes, the island hosts numerous coastal lagoons. Sardinia includes national and regional parks, 131 Natura 2000 sites (EEA, 2024a), and extensive agricultural areas. It plays a key role in Italy's livestock farming and has a growing renewable energy sector, mainly wind and solar.

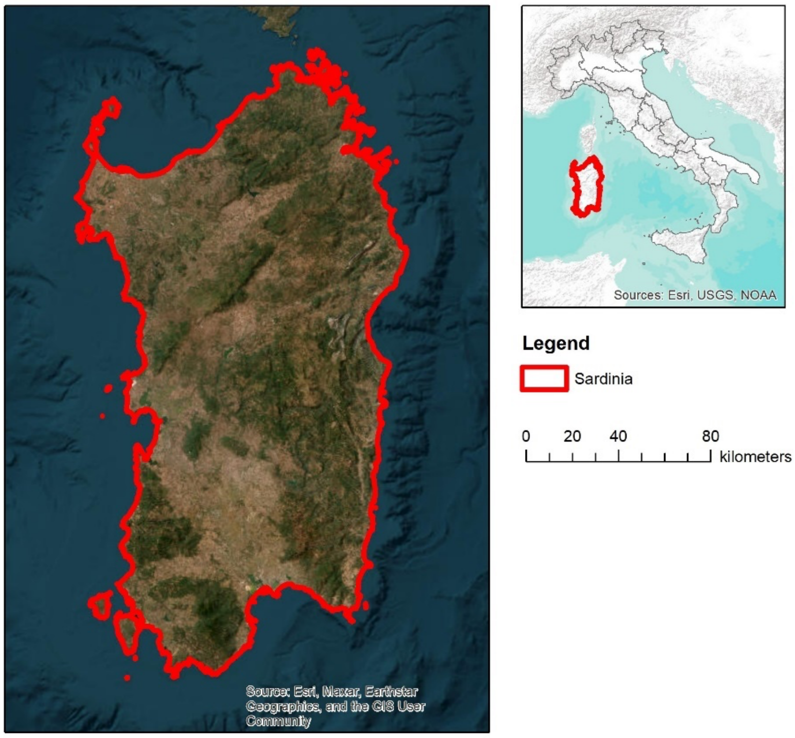

Fig.1 Location of the study area

2.2 Ecosystem service supply

This subsection presents synthetic summaries of the five ecosystem services that are evaluated for their effect on CCC and, consequently, whose role in climate neutrality is examined. The description entails the measurement techniques and spatial classification of ecosystem service supply.

Heat mitigation

Heat mitigation is a vital ES that affects quality of life on earth. In this study it is measured through satellite images provided by the United States Geological Survey (USGS)'s Earth Explorer[1]. The relevant information is

[1] Earth Explorer by U.S. Geological Survey. https://earthexplorer.usgs.gov/ (last accessed:20/06/2025).

extracted using Band 10 of the "Landsat 8-9 OLI/TIRS C2 L2" imagery where Band 10 corresponds to the thermal infrared range which captures LST data. The search criteria included a maximum cloud cover level of 6% and a date range of the final week of June (25/06/2023) to the first week of September (02/09/2023) in order to cover the summer season with the highest temperatures. The method involves comparing all available satellite images within the selected threshold and selecting the imagery with the highest mean value, while accounting for potential anomalies that may influence the mean; these anomalies were identified by analyzing the percentile rank distribution of raster values, using turning points in the curve to determine the thresholds for valid minimum and maximum values. The USGS Guide[2]'s scale factor is applied to raster images' digital number (DN) data to determine the mean values in Celsius degrees (°C):

$$0.00341802 * DN + 149.0 - 273.15\ (°C) \qquad (1)$$

In the case of Sardinia, 5 satellite images were used to cover the whole region.

Habitat quality level

HQL refers to the capacity of an area to support the flora and fauna to thrive as well as maintain ecological processes and is closely linked to biodiversity. It can be measured by analyzing spatial patterns by examining land use and land cover (LULC) maps along with threats to the habitat of species. This study uses InVEST Habitat Quality[3] model is to map HQL. The model requires information on habitat types corresponding to a LULC map, threats and habitat suitability scores which are informed by Sallustio et al. (2017). Their study defines 8 threats and 12 habitat types, the habitat type "mixed forest" is added in the case of Sardinia totaling up to 13. 8 threats are defined as follows:

1. Roads 1: Motorways; Trunks; Primary roads.
2. Roads 2: Secondary and tertiary roads.
3. Roads 3: Residential and service roads.
4. Roads 4: Tracks and bridleways.
5. Railways
6. Intensive agricultural lands
7. Extensive agricultural lands
8. Buildings and other artificial areas or imperviousness soils

13 habitats are as follows:

1. Beaches, Dunes, and Sands
2. Water Bodies
3. Wetlands
4. Grasslands
5. Shrublands
6. Broadleaves Forests
7. Conifers Forests
8. Inland Unvegetated or Sparsely Vegetated Areas
9. Intensive Agricultural Lands
10. Extensive Agricultural Lands
11. Buildings and Other Artificial Areas or Impervious Soils

[2] U.S. Geological Survey. (2024). Landsat 8-9 Collection 2 (C2) Level 2 Science Product (L2SP) Guide. https://www.usgs.gov/media/files/landsat-8-9-collection-2-level-2-science-product-guide (last accessed:20/06/2025).
[3] The Natural Capital Project (n.d.) InVEST User's Guide. Habitat Quality. Stanford University. https://releases.naturalcapitalproject.org/invest-userguide/latest/en/habitat_quality.html (last accessed:20/06/2025).

12. Open Urban Areas
13. Mixed Forest

In total, four inputs are required: LULC map, threat maps, a sensitivity table and a threats table. CORINE Land Cover[4] 2018 is utilized as LULC in tiff format with 13 values corresponding to the habitat types, threat maps are created using OSM Geofabrik[5] , sensitivity and threats table are derived from the same study, using the average between "broadleaved" and "conifers" for the added 13th category. The model generates two final maps, one of which demonstrates the HQL on scale from 0 to 1, a unitless score representing the relative level of habitat quality within the area.

Crop and timber production

Provisioning ESs including goods such as food, freshwater, timber, fiber, and energy, represent one of the four ES categories defined by the Millennium Ecosystem Assessment (CICES, 2022; MA, 2003). Agricultural and forestry production are key examples within this category, particularly significant in Italy's diverse landscapes characterized by extensive agricultural activities and rich biodiversity (ISPRA, 2020). In line with the EU Common Agricultural Policy (CAP) reforms (COM(2017)713), aligned with the Paris Agreement[6] and 2030 Sustainable Development Goals[7], efforts focus on enhancing sustainability and rural development through technical and financial measures (National Strategic Plan 2023-2027). Economic valuation of provisioning ESs is increasingly integrated into strategic environmental assessments to guide land-use planning and ecosystem conservation (Santolini & Morri, 2017).

The valuation of crop and timber production (CTP) employs land monetary value as a proxy, refined by geographic and environmental factors such as location, altitude, morphology, and orography (Isola et al., 2022). This approach utilizes two primary datasets: CREA's national land value[8] dataset for agriculture and the National Revenue Agency's (NRA) forestry land values (2023). Data on agrarian and forestry regions are organized by municipality, province, and elevation zone, facilitating spatial analysis. Correspondences between 2018 CORINE Land Cover classifications and crop taxonomies from CREA and NRA allow spatial overlay mapping, enabling estimation of CTP per spatial unit.

Scenic quality

The InVEST scenic quality model is used to assess scenic quality (Sharp et al., 2018). The model evaluates overall scenic quality by combining topographic data and beauty detractors (Singh et al., 2020). To map their visibility and create viewshed maps, it employs the Digital Elevation Model (DEM) and a point vector layer representing visual disamenities (Griffin et al., 2015; Sieber & Pons, 2015). It also accounts for terrestrial curvature and atmospheric refraction of visible light (Singh et al., 2020).

Whole numbers between 0 and 4 are assigned by the model based on the Visual Impact (VI) that visual detractors have on the landscape. These dimensionless numbers, which are inversely correlated with levels of scenic quality, allow comparisons between the different areas of the landscape (NatCap, n.d.). In comparison to the surrounding areas, higher values imply greater visual impact and, therefore, diminished scenic quality, whereas lower values indicate less visual deterioration and, thus, higher scenic quality. Locations completely unaffected by visual disamenities are assigned a score of 0 (Ibid.).

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[7] The 17 Goals. Available online: https://sdgs.un.org/goals (last accessed: 20/06/2025).
[8] National Research Council of Agriculture and Agricultural Economics (Italian acronym: CREA).

Since Renewable Energy Sources (RES), such as solar farms and wind turbines, are acknowledged for degrading landscape aesthetics (Saganeiti et al., 2020; Zardo et al., 2023), they are classified as aesthetic detractors within this study. Their locations are sourced from the database provided by the Global Energy Monitor (GEM, 2024a; 2024b), the DEM is obtained from the European Space Agency's Copernicus DEM at 30m resolution, and the refractivity coefficient is established as the default value of 0.13.

Potential for outdoor activities

The ESTIMAP (Ecosystem Service Mapping Tool) model is a GIS-based framework designed to spatially quantify and map potential for outdoor activities. This study employs the first part of the ESTIMAP model, as adapted by Vallecillo et al. (2019) and Barton et al. (2019), and implemented by Isola et al. (2022), to assess the potential provision of recreational services. The approach is divided into three phases. Phase A evaluates the availability of areas that support recreation based on the degree of naturalness, using the hemeroby index, which reflects anthropogenic influence (Paracchini & Capitani, 2011). The resulting raster output classifies areas in a range from [0] to [1]. Phase B considers the presence of recreationally relevant landscape features, such as protected areas and assets of landscape interest. Each area is assigned expert-based scores according to its IUCN classification, reflecting its recreational value, following approaches by Zulian et al. (2013) and La Notte et al. (2017). The resulting raster output classifies areas as [0] for no value, [0.8] for moderate, and [1] for high recreational value. Phase C incorporates coastal components, assessed through three indicators: proximity to the coastline, coastal geomorphology, and bathing water quality. The integration of these three phases enables the spatial representation of the potential for recreational service provision in coastal and inland areas. The resulting raster output classifies areas within the range [0-1]. The POA is obtained by summing the values of the outputs of phases A, B and C.

Variable	Description	Data	Source
CCC	Density of carbon in Mg/m^2	Land cover map	Copernicus Land monitoring service (2018)
		Carbon density values for each land cover type in relation to the four pools	ORNL DAAC (2010) (aboveground and belowground biomass) INFC (2015) (aboveground biomass and dead organic matter) INFC (2005) (soil) ISPRA (2022) (soil) AGRIS (2016) (soil)
HMR	Maximum values of Land surface temperature in °C	Landsat, Collection 2-Level 2 imagery (Landsat 8-9 OLI/TIRS C2 L2)	United States Geological Survey though the interface Earth Explorer (https://earthexplorer.usgs.gov/)
HQL	Value of habitat quality in the 0-1 range	Land cover map	Copernicus Land monitoring service (2018)
		Raster map of treats	Geofabrik. OpenStreetMap Data Extracts, Europe, Italy (https://download.geofabrik.de/europe/italy/)
		Treat table	Sallustio et al. (2017)
		Sensitive table	Sallustio et al. (2017)
CTP	Crop and timber production in euro per hectare	Land cover map	Copernicus Land monitoring service (2018)
		Land monetary value per unit area [€/ha].	National Research Council of Agriculture and Agricultural Economics (CREA) (https://www.crea.gov.it/documents/68457/0/Regioni+agrarie+indagine+MF+INEA.xlsx/8019a0cb-f3d4-dcd9-6639-d178e9f2e89e?t=1561366035978)

Variable	Description	Data	Source
		Mean agricultural value (MAV) per unit area [€/ha].	National Revenue Agency (NRA) (https://www.agenziaentrate.gov.it/portale/schede/fabbricatiterreni/omi/banche-dati/valori-agricoli-medi/valori-agricoli-medi-sardegna)
SCQ	Scenic value in the 0-4 range	Interest area	ISTAT (Istituto nazionale di statistica) [National Institute of Statistics] (2024) https://www.istat.it/notizia/confini-delle-unita-amministrative-a-fini-statistici-al-1-gennaio-2018-2/
		Aesthetic detractors	Global Energy Monitor (GEM) (2024b) https://globalenergymonitor.org/projects/global-solar-power-tracker/
		Digital Elevation Model	Copernicus GLO-30 Copernicus DEM - Global and European Digital Elevation Model https://doi.org/10.5270/ESA-c5d3d65
		Refractivity coefficient	Default value of the model
POA	Potential for outdoor activities	Hemeroby index (agricultural areas)	ISTAT (2019)
			National Livestock Database (https://www.vetinfo.it/j6_statistiche/#/)
		Hemeroby index (forestry areas)	Bacchetta et al. (2009)
		Land cover map	Copernicus Land monitoring service (2018)
		Protected areas and landscape assets	Sardinian geoportal (https://www.sardegnageoportale.it/)
		Coastal geomorphology	EEA (2004)
		Bathing water quality	EEA (2024b)

Tab.1 CCC and the five selected ESs: Information and data sources

2.3 Linear regression

As in many studies on correlations between spatial variables, a regression model is used because no preliminary hypothesis seems plausible regarding the effect of the explanatory variables on the dependent variable (Cheshire & Sheppard, 1995; Sklenicka et al., 2013; Stewart & Libby, 1998; Zoppi et al., 2015). Therefore, a surface, characterized by an unknown equation, representing a spatial phenomenon characterized by n (6, in this particular case) factors, is approximated, in an infinitesimal neighborhood of one of its points, by its tangent hyperplane. The infinitesimal area shared by the hyperplane and the surface is identified by the known equation of the tangent hyperplane, i.e., by the linear relationship between the variables.

This linear relationship locally approximates the unknown surface. That being the case, the multiple regression model estimates the trace of a six-dimensional hyperplane on a six-dimensional surface whose equation is unknown (Byron & Bera, 1983; Wolman & Couper, 2003), showing the linear correlations between CCC and the five dependent variables.

Through a linear regression the spatial taxonomy of CCC is correlated with the five spatial distributions of the ESs described in section 2.2. The model develops in the following manner.

$$CCC = \alpha_0 + \alpha_1\,HMR + \alpha_2\,HQL + \alpha_3\,CTP + \alpha_4\,SCQ + \alpha_5\,POA \quad (2)$$

where measures of the CCC dependent variable and related explanatory variables are associated with a basic spatial unit of 200x200 square meters, and the variables are identified as follows (units of measurement are given in parentheses):

- CCC is the density of carbon capture capacity (Mg/m^2);

- HMR is the heat mitigation reference, namely LST, which serves as a measure for urban heat fluctuation and, consequently, for assessing its changes; if it were to decline, it would highlight an enhancement in life quality for users of the local environments (°C);
- HQL measures the habitat quality level, and holds rational values ranging from 0 to 1, as described in section 2.2;
- CTP is the value of crop and timber production (€/ha);
- SCQ is the value of scenic quality, and holds rational values ranging from 0 to 1, as described in section 2.2;
- POA measures the potential for outdoor activities, and holds rational values ranging from 0 to 1, as described in section 2.2.

The estimated coefficients of the explanatory and control variables show the marginal impacts of such covariates on CCC.

The significance tests concerning the estimated coefficients is evaluated using the p-values.

3. Results

This part is structured in the following manner. Initially, the spatial classifications pertaining to the regional spatial context of Sardinia are introduced regarding the variables linked to CCC and the explanatory variables of model (1). Secondly, the relationships suggested by the coefficient estimates of the regression model (1) are presented to uncover indications related to the association of CCC with the covariates.

3.1 Carbon capture capacity

The spatial distribution of CCC (Fig.2, panel A) across Sardinia indicates that the highest contributions originate from wooded areas which are concentrated in the central and eastern parts of the island, where mountainous areas more prevalent, including Gennargentu ranges, Sulcis mountains and regional parks. Notably, the mean values associated with coniferous forests are higher than those of broadleaved forests. The areas exhibiting the lowest contribution to CCC are predominantly water bodies, urban and artificial surfaces, as exemplified by the Cagliari Metropolitan Area, as well as agricultural zones, located in the western parts of the island. Compared to other land cover types, shrublands and areas characterized by transitional vegetation demonstrate an above-average capacity, whereas agro-forestry areas exhibit a below-average capacity.

3.2 Heat mitigation

The region shows LST values between 27.7-61.95 °C (See Fig.2, panel B). In the western parts of the island, which coincide with agricultural areas, the greatest temperatures are recorded except rice fields. Lowest temperatures are observed in water areas, mountainous areas with high altitudes, hills and forests including regional parks. Mean LST values are consistently high in agricultural areas, with the highest maximum temperatures recorded particularly in the land-use types classified as ‘Non-irrigated arable land’ and ‘pastures.’ However, the highest mean temperature is observed in artificial surfaces, reflecting the urban heat island effect, especially in ‘construction sites,’ which exhibit a mean temperature of 54 °C. Additionally, dump sites and airports also display very high mean temperatures exceeding 50 °C. Mean temperatures in water-related areas range from 32 to 36 °C, while forested areas show a narrower range of 39.14 to 40.24 °C.

3.3 Habitat quality level

Consistent with earlier ESs, the highest HQ levels (see Fig.2, panel C) are observed in forested areas, predominantly located in the eastern part of the island, whereas the lowest levels occur in urbanized zones, followed by intensively cultivated agricultural lands. In Sardinia, broadleaved forests have a slightly higher HQL (scoring 0.85) than coniferous forests (0.75). The lowest values, approaching zero, are observed in artificial areas and impervious surfaces, with a score of 0.09. Similarly, areas classified as 'open urban areas' contribute minimally, with a score of 0.21, representing the second lowest HQL after artificial surfaces. The difference between intensive and extensive agricultural practices considering the HQL is also evident as intensive agricultural lands score 0.23 while extensive agricultural lands score 0.43. The average HQL in the island is 0.54, and 40.86 % of the territory exhibits high levels with scores exceeding 0.66.

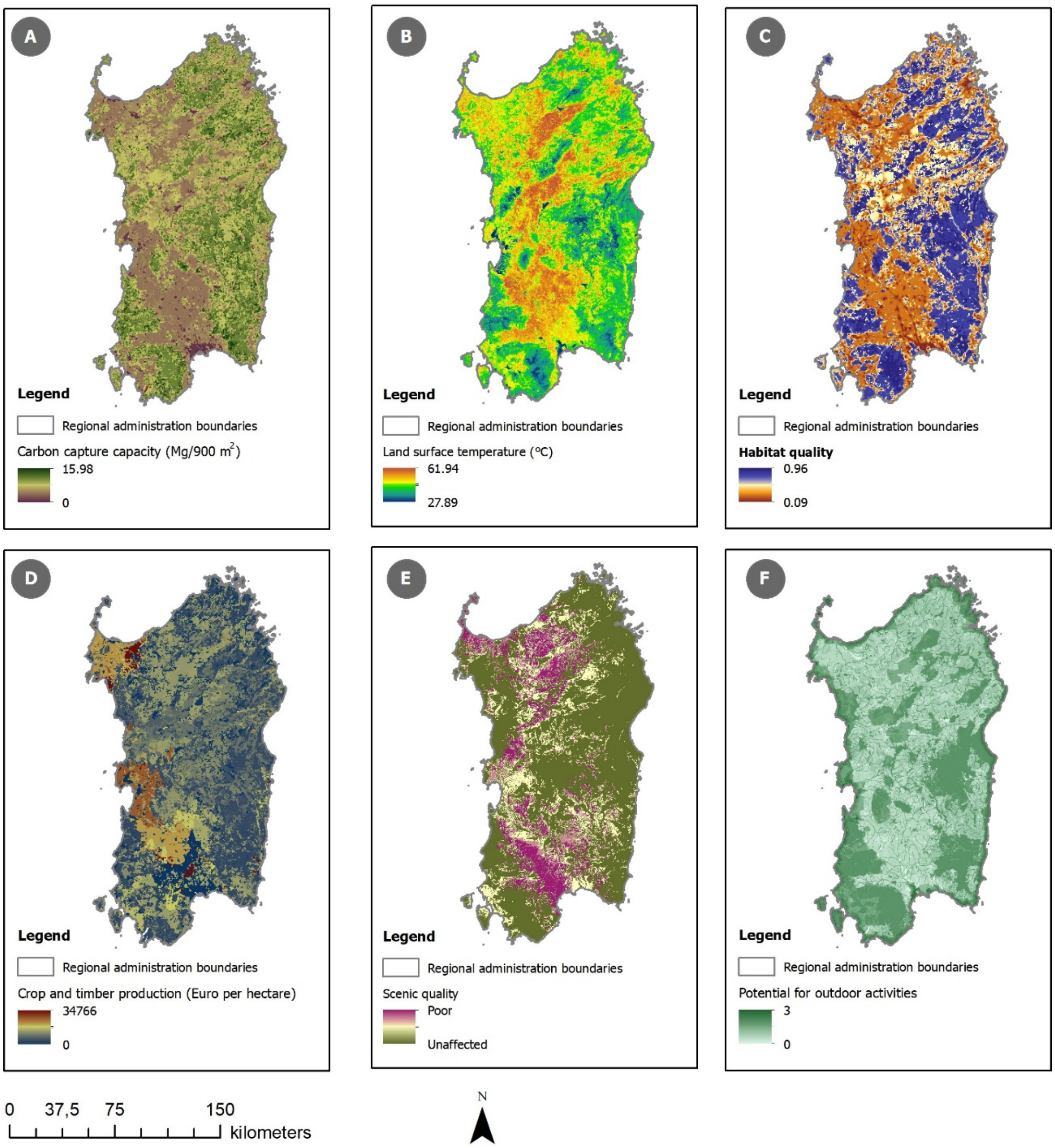

Fig.2 Spatial distribution of Carbon Capture capacity in Mg/900 m^2 (panel A), Land surface temperature in C° (panel B), Habitat quality (panel C), Crop and timber production in Euro per hectare (panel D), Scenic Value (panel E) and potential for outdoor activities (panel F)

3.4 Crop and timber production

The CTP value, representing the economic worth of agricultural and forestry land, was mapped across the region for 2023 (€/ha). The analysis reveals a heterogeneous distribution (see Fig.2, panel D): values range from 0 to 34,766 €/ha, while 17.41% shows values below €1,000/ha. The average value stands at €5,090.62

/ha. Higher valuations, exceeding €10,000/ha, are concentrated in fertile plains such as Campidano di Cagliari, Campidano di Oristano, and Nurra, typically associated with vineyards, orchards, citrus groves, and horticulture. Exceptional values, surpassing €30,000/ha, are in the coastal hill areas of Sarrabus, particularly within the municipalities of Villaputzu and San Vito, in the plain agrarian region of the Lower Tirso in the province of Oristano, and in the agrarian region of the Campidano of Serrenti.

3.5 Scenic quality

Fig.2, panel E, depicts the spatial distribution of scenic quality values across the Sardinia Region. The average scenic quality value is 0.97. When examining the distribution of scenic quality across the Region it emerges that unaffected landscapes (VI=0) are admirable in 66% of the Sardinian Region, while medium values (VI=2) are found in 16% of Sardinia's territory. In contrast, low scenic quality (VI=3) characterizes 7% of the Region, whereas poor scenic quality areas (VI=4) account for 11% of Sardinia. The highest VI is primarily observed in agricultural areas, where solar farms and wind turbines are frequently installed. Nonetheless, adjacent areas are also affected by RES presence, which degrades the scenic quality to medium or low values. Conversely, scenic quality is largely preserved in designated protected areas, although visual degradation is noted in some Sardinian national and regional parks.

3.6 Potential for outdoor activities

Fig.2, panel F illustrates the spatial pattern of the supply of potential for outdoor activities in Sardinia, with values ranging from 0 to 3 (average: 1.21). Although the full spectrum is represented, zero values are limited to marginal zones. Higher scores cluster along coastal areas, due to the added influence of aquatic elements, and within forested mountain systems, especially when overlapping protected zones such as regional parks or Natura 2000 sites. Notable examples include Gutturu Mannu Park, Monte Arcosu, Monte Limbara, Supramonte, and Monti del Gennargentu. These areas benefit from combined effects of high ecological integrity and distinct landscape features. Additional moderate-to-high values emerge in hilly forest regions and conservation zones, linked to naturalness or scenic attributes. In contrast, agricultural lowlands, such as Campidano, Nurra, Flumendosa, Cedrino, Coghinas valleys, and unprotected hilly interiors show lower scores due to ecological disturbance from farming, grazing, and vegetation alteration.

3.7 Linear regression

The outcomes of the linear regression (1) are presented in Tab.2, whose coefficients describe the marginal impacts, expressed in terms of the change in the dependent variable CCC, associated with a one-unit increase in the variables representing the supply of the five ESs under consideration, and whose p-values allow us to assess the significance of the results of the coefficient estimates themselves.

Variable	Coefficient	t-Statistic	p-Value	Mean of the explanatory variable	Elasticity at the average values of CCC and explanat. var's [(Δy/y)/(Δx/x)]
HMR	-0.54388	-104.71477	0.00000	45.66415	-0.43584
HQL	93.54459	751.61056	0.00000	0.541637	0.88914
CTP	0.00040	71.912244	0.00000	2,483.98915	0.01750
SCQ	-5.95032	-85.414754	0.00000	0.24163	-0.02523
POA	-4.32887	-27.99609	0.00000	0.40475	-0.03075
Mean and Standard deviation of dependent variable CCC: 72.75331, 30.98471 - Adjusted R-squared: 0.66863					

Tab.2 Linear regression estimation

The linear regression estimate (1) should be read bearing in mind that a positive coefficient is associated with an increase in CCC in relation to growth in the supply of the ES corresponding to it, while a negative value of the coefficient is correlated with a decrease in CCC. The only exception is the variable associated with scenic quality, SCQ, whose supply increases as the value of the explanatory variable decreases. It should also be noted how the p-value tests for the estimates of all coefficients signal a generalized reliability of the estimates. The elasticities are always, in absolute value, less than one, configuring, therefore, a generalized inelasticity of CCC supply with respect to the explanatory variables. The values of the elasticities configure, however, rather differentiated correlations, in terms of orders of magnitude. The outcomes report how a 1% growth in HMR, i.e., an average increase in LST of about 0.45 °C, is associated with a decrease in CCC of about 0.32 Mg/ha, thus just about 0.44%. It should be highlighted, in this regard, how annual thermal gradients are, in general, close to this level and, therefore, how the correlation between CCC and HMR shows a statistically significant medium-sized relevance of HMR with respect to CCC.

Particularly important is the impact of HQL on CCC, which shows an elasticity of about 89%, implying that a 1% growth in this variable corresponds to a growth of about 0.64 Mg/ha in average CCC. Since the improvement of habitat quality status is closely dependent on the protection of the areas in which they are located, exercised, directly or indirectly, for the most part with reference to potential threats, it is clear that the implications of the spatial taxonomy of HQL are significantly relevant to the definition and implementation of planning policies aimed at improving the conditions of climate neutrality.

The covariate associated with crop and timber production, CTP, has a positive elasticity, and almost insignificant in quantitative terms, of about one-hundredth the value of that of HQL. This implies that in order to have a quantitatively relevant impact of CTP on CCC, major market fluctuations in crop and forest production of 50% or more would be required, corresponding to increases of at least 1,250 €/ha, and would be associated with growths of 0.63 Mg/ha or more, similar in magnitude to the impact on CCC of HQL.

In relation to the representative variable of scenic quality, SCQ, referring to the presence of visual disturbances that limit the aesthetic quality of landscape views, such as, for example, those generated by wind turbines or photovoltaic installations, the negative estimate of the coefficient of linear regression (1) shows a negative correlation between CCC and scenic quality, as the latter increases as the value of the SCQ variable decreases. The elasticity is, however, almost insignificant, on the order of 2.5%. This outcome highlights a very low significance of the functional connection between SCQ and scenic quality.

The covariate for the supply of the ES associated with the POA has a negative elasticity, as in the case of the SCQ, of about 3.1%, and, therefore, slightly higher. Indeed, in this case, a 10% decrease in POA supply is correlated with a growth of about 0.22 Mg/ha in CCC. The close link between the size of the POA and the accessibility of attractive places for outdoor recreation gives, arguably, reason for this result, since accessibility is linked to the presence, albeit limited, of infrastructure that facilitates transportation, both individual and collective.

4. Discussion

The discussion that unfolds in the subsequent subsections relies on the implications of model (1), regarding the connections between the availability of CS and the accessibility of other ESs.

4.1 CCC and heat mitigation

The correlation between CCC and HMR, i.e., LST, arising from the outcomes of linear regression (1), with reference to the regional spatial context of Sardinia, is in line with what has been presented and discussed in numerous articles in the scientific and technical literature (Cialdea et al., 2022).

Wang et al. (2021) propose a study referring to the Shenzen metropolitan area in subtropical China, in which the effects of heat islands on carbon storage capacity are analyzed, in the context of a territory that discloses varying degrees of urbanization. These findings are consistent with the results offered by Dibaba (2023) who, with reference to the spatial contexts of the Ethiopian cities Nekemte and Jimma, points out that the negative impacts of heat waves, in relation to CCC, are most dramatically manifested in areas of the urban fabric characterized by urbanization- and sealing-oriented land cover transitions (Mobaraki, 2023; Pantaloni et al., 2024). Also, in this scientific and technical perspective is an article by Bounoua (2015), who, through the integration of MODIS and Landsat data, points out, in relation to the United States, evidence of a correlation between the increase in LST, urban sprawl and the decrease in CCC.

4.2 CCC and habitat quality level

According to the results of linear regression (1), the relationship between HQL and CCC is positive, consistent with earlier research (Cardinale et al., 2012; Chaplin-Kamer et al., 2015; Ren et al., 2023). Looking at this correlation, to achieve carbon neutrality, HQL needs to be improved. As it is strongly linked to biodiversity, one effective way to support this is by increasing plant diversity, which enhances CCC in soils (Lange et al., 2015).

Especially in areas with low HQL such as urbanized areas, implementation of urban trees might help achieve carbon balance (Vaccari et al., 2013). Raymond et al. (2013) examine how protecting natural ecosystems, such as mature forests and wetlands, supports HQ, which in turn enhances CCC in urban environments. Therefore, the protection and conservation of biodiversity in regional natural parks and wooded areas in Sardinia is important not only to sustain the high HQL in these areas but also to increase the regional capacity.

4.3 CCC and crop and timber production

The relationship between CCC and CTP are emphasized in several scientific studies on agricultural systems. Evidence from Paris et al. (2019) and Frank et al. (2024) highlights the role of agroforestry and agricultural practices in promoting ecologically sustainable productivity. Legesse et al. investigated how changes in land use and land cover affect the carbon storage capacity of forest ecosystems in Ethiopia's Upper Awash Basin, employing remote sensing methodologies. Their analysis, covering the period from 1993 to 2023, reported a 15% decline in carbon storage, primarily associated with a 27.4% reduction in forest cover and a 41.58% decrease in shrub vegetation.

A case study on olive groves in the Umbria Region of Italy (Bateni et al., 2021) further highlights the role of perennial crops in carbon conservation, revealing that a substantial proportion of soil organic carbon is retained within the top 30-60 cm of soil. The continued management of olive cultivation is therefore identified as a strategic measure to enhance soil carbon retention and reduce carbon emissions associated with land use change and intensive soil managing.

4.4 CCC and scenic quality

Numerous studies recognize the link between CCC and scenic quality, with the inverse relationship between the SCQ variable and CCC supporting the expectation that higher aesthetic quality correlates with greater CCC. Lee and Kim (2024), for instance, illustrate how parks and forests are not merely vital in carbon capture and storage but also bestow considerable scenic value. Similarly, Mundher et al. (2022) highlight that urban forests are pivotal for carbon sequestration while concurrently offering significant social, tourism, and aesthetic benefits that enhance human health and well-being. Mitsch (2015) supports this perspective by demonstrating how wetlands simultaneously function as effective carbon sinks and as sources of scenic aquatic landscapes. This is supported by Quevedo and Kohsaka's systematic review of the cultural services provided by blue carbon ecosystems, which revealed that in addition to their essential role in capturing carbon, mangrove forests, seagrass meadows, and saltmarshes provide 14 different types of cultural ecosystem services, including aesthetic value.

4.5 CCC and potential for outdoor activities

The findings reveal an inverse relationship between the provision of POA and CCC, which may be attributed to limitations in the accessibility of high-CCC areas for recreational use. Costanza (2008) characterizes recreational ESs as inherently linked to human mobility, identifying accessibility as one of three fundamental components, alongside ecosystem functionality and the spatial pattern of potential demand. Furthermore, Paracchini et al. (2014) emphasize that proximity plays a pivotal role in determining the appeal of a location, noting that individuals typically prefer recreational sites located within an approximate 8-kilometer radius of their homes for daily use. In addition, the method used to map POA provides a high value to coastal areas, characterized in Sardinia by sparse or sometimes absent vegetation with a low capacity to absorb and stock carbon.

5. Conclusions

The methodology defined and developed in this study is aimed at investigating the functional connections between the CCC, as the reference ES for analyzing and assessing the contribution to the global climate neutrality of regional spatial contexts, and the provision of five ESs, of which: two regulating ESs, heat mitigation, detected through the spatial taxonomy of the LST, and habitat quality; one provisioning ES, crop and timber production; and two cultural ESs, scenic quality and potential for outdoor activities. The regional territory of Sardinia is taken as the spatial context for the application of this methodological approach.

This study offers a conceptual framework that systematizes, in integrated manners, some methodologies aimed at constructing spatial taxonomies of different ESs, which connote environments of the city, conterminous territories and rural areas. The spatial distribution of ESs is associated with the taxonomy of CCC, as an overall indicator of the contribution that the reference spatial system makes to global climate neutrality. This contribution is, therefore, characterized as an expression of a system of ESs that cooperate or conflict with climate neutrality, thus integrating their potential, synergistic or divisive, in a holistic reading of ecosystem factors affecting global climate. The outcomes, referring to the regional territorial context of Sardinia, report that the ESs identified by heat mitigation and habitat quality present the greatest positive impacts in relation to CCC, while POA is lower in quantitative terms, although of some significance. Decidedly less relevant are the impacts found with regard to CTP and scenic quality, although, with regard to the latter, the estimated linear regression signals the need to carefully consider the location of photovoltaic and wind power plants as relevant threats to scenic quality.

The methodological approach proposed in this study demonstrates a high degree of exportability across diverse national and European contexts, while retaining sufficient flexibility to enable the integration of additional ESs as new data and policy needs emerge. On the other hand, the methodological approach presents two problematic aspects. The first concerns the data used. It is evident that the information regarding the supply of ecosystem services related to outdoor recreation, carbon sequestration and storage, as well as habitat quality, does not derive from primary survey observations—which are unavailable—but rather from estimations grounded in secondary data sources. The second issue concerns the individual methods used to assess and map the five ecosystem services. For example, the model used to assess scenic value only considers energy plants as environmental detractors. Furthermore, the method used to assess habitat quality has certain limitations dictated by the choice of threats to be included and the assessments provided by experts.

Since the data base on which the study proposed here is based consists, for the most part, of sources available, at the regional level, with reference to Italy and other European Union countries, as well as to many non-European national contexts, a future development of the research is certainly represented by the export of the methodological approach applied here for the purpose of highlighting similarities and differences in the outcomes, and, therefore, in the resulting spatial policy implications. Another issue, certainly relevant in this perspective, is the expansion of the set of ESs to be considered in the integrated assessment of the impacts they generate in relation to climate neutrality (Pilogallo et al., 2019; Lai et al., 2020), from the five considered in this study. Among these, ESs aimed at hydraulic and landslide hazard mitigation are certainly significant, particularly relevant with reference to Sardinia and other Italian regions.

A final relevant aspect, in terms of future research development, is represented by the implementation, with reference to the same database, of methodologies other than linear regression to analyze and interpret the correlations between the covariates associated with the supply of ESs, such as conjoint analysis, spatially-weighted linear regressions or principal component analysis.

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Image Sources

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Predicting the aesthetic impact of wind turbines and their influence on landscape value

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Abstract

The growing reliance on renewable energy sources (RES) is a direct response to global challenges such as climate change and the limited availability of fossil fuels. Due to their low costs and scale suitability applications, wind turbines and solar panels are among the most widely adopted RES technologies for electricity generation. Their benefits are generally considered to outweigh the disadvantages. However, despite their image as green alternatives these technologies face opposition due to concerns about noise, visual impact, and possible negative effects on ecosystem services. Following the EU Green Deal and its goal of achieving climate neutrality by 2050 the adoption of green energy technologies requiring immediate implementation beyond legislation. The Basilicata region in Italy is among the most affected areas having the highest percentage of wind farms and experiencing notable territorial fragmentation due to their installation. This study aims to assess not only the environmental impacts of wind turbines but also their social and aesthetic effects. Expert-based assessments and spatial analyses will be conducted followed by the Scenic Quality Model within InVEST to evaluate visual impacts. The findings provide valuable insights for policymakers, planners, and researchers involved in sustainable land management and renewable energy planning.

Keywords

InVEST model; Sustainable land management; Scenic quality; Renewable energy planning; Environmental assessment

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1. Introduction

Rising the global demand for energy, represents one of the most urgent and complex issues of the 21st century (Codemo et al., 2021). While, to address climate change, we need to reduce our reliance on fossil fuels. One of the direct solutions that proposed to us is to increase the use of renewable energy sources (RES), such as wind and solar energy (Bhatti et al., 2024; International Energy Agency, 2023) The use of RES, especially in European countries, intensified in November 2019 when the European Parliament adopted a plan known as the Green Deal. This plan aims to produce 100% of electricity from renewable sources by 2050 and achieving climate neutrality in Europe (Bäckstrand, 2022). Given that the shift toward renewable energy must be prioritized to overcome this challenge and to move toward sustainability which is a global necessity, it is crucial to conduct environmental assessments in a critical and systematic manner, because it is closely linked to land-use change and its environmental implications (Kishore et al., 2025). Italy is one of the countries that has actively participated in this plan until now, and it has taken on a prominent role as a leader in advancing it. The Basilicata region in southern Italy is one of the provinces that has been heavily impacted by the establishment of RES (Scorza et al., 2020).

Regarding to the data available on the official website of the Basilicata region (*https://Rsdi.Regione.Basilicata.It/Dbgt-Ctr/*, n.d.), in addition to the wind farms that have been established currently (around 2,100), there are currently 780 structures under development, and there are 230 wind turbines that are awaiting final authorization. Environmental assessments become crucial for the Basilicata region, especially since this region due to its low population and the gaps in its urban planning frameworks has become somewhat marginalized. Additionally, it’s important to consider that Italy and the Basilicata region are rich in cultural and natural resources which must be preserved (Gizzi et al., 2019). The Basilicata region is a unique combination of environmental, geological, and cultural heritage. This area includes national and regional parks, notable archaeological sites such as the UNESCO World Heritage city of Matera, and the abandoned town of Craco which showcases a remarkable intersection of natural and human-made features, as well as the region’s global significance (Bentivenga et al., 2024). The region also hosts 113 geosites of remarkable educational, scientific, and touristic importance, strengthening its reputation as an “open-air laboratory” for research, environmental education, and geotourism (Pilogallo et al., 2019).

This historical and natural heritage, requires a comprehensive environmental assessment. However, given the aesthetic impacts that wind structures, in particular, have on the landscape, this aspect has always been a focal point in environmental evaluations. Therefore, in this research, our goal is to focus on the impact that wind energy facilities have on the landscape aesthetics of the Basilicata region.

The case study focuses on a cluster of seven municipalities in the Basilicata region; Livello, Montemilone, Venosa, Maschito, Palazzo San Gervasio, Banzi, and Forenza. These areas were selected based on the concentration of authorized RES. Furthermore, given that environmental assessments require ultimate data and a comprehensive understanding of the study area, the initial phase of the methodology involved extensive data collection and preliminary analyses conducted in collaboration with domain local experts. Subsequently, the Scenic Quality Model within the InVEST software was employed to evaluate the aesthetic impacts of wind turbine installations, considering both the current conditions and the proposed developments in the near future.

The research findings, in addition to providing a more realistic perspective on renewable energy, can also highlight the importance of local experts and position Basilicata as a model for European cities. It will demonstrate how the integration and implementation of RES in the region can have environmental implications. The originality of this research lies in the fact that, until now, methods used to assess visual impact have typically relied on conventional approaches, such as viewshed analysis. However, in this study, we employed a newer and more advanced method.

2. Methodology

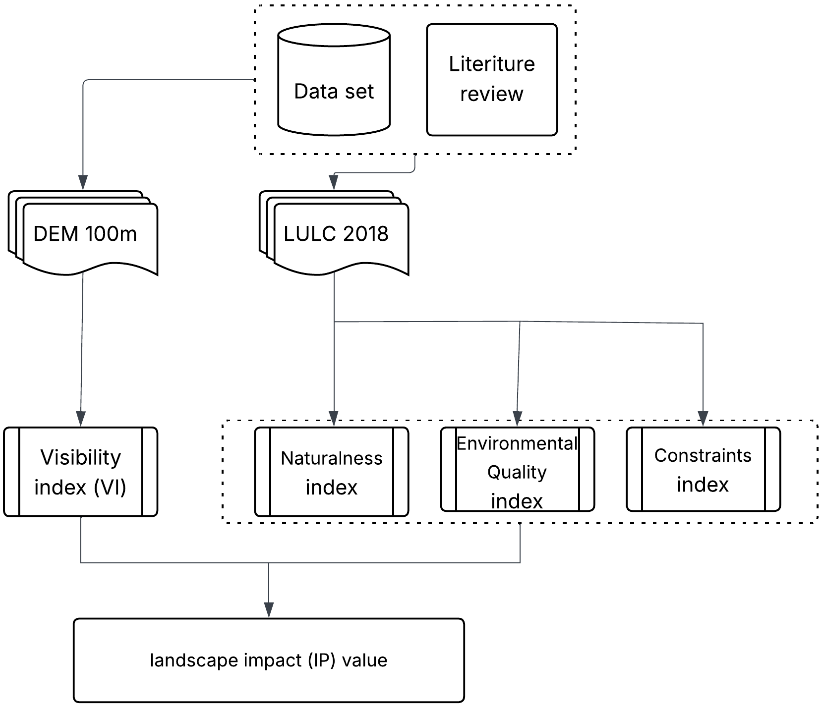

Fig.1 Methodology framework

In the methodology section, as outlined in Fig.1, it is generally divided into three parts. In the first part, we review the theoretical framework, emphasizing the importance of expert opinions and expert-based methods for local and regional projects, as well as identifying gaps and shortcomings in the evaluation methods for the visual impact of wind energy facilities. In the second part, to calculate the landscape value, we employ an expert-based approach. This was carried out during the training period at the *F4 s.r.l*[1] company, which consists of around seventy specialists in architecture, agricultural engineering, environmental science, technicians, legal experts, consultants, and researchers. They collaborated in designing the questionnaires, and the industry specialists, including geologists, have spent about ten years working on environmental bases for projects related to water, energy, and aquatic environments. In the third part, the focus is on calculating the visual impact of wind facilities on the environment, using the InVEST software and the Scenic Quality Model.

1.2 Input data

In the process of selecting indicators for the assessments, careful attention was given to aligning them with upper-level plans and relevant national, international, and European frameworks such as the Basilicata energy plan (CONSIGLIO REGIONALE DI BASILICATA PIANO DI INDIRIZZO ENERGETICO AMBIENTALE REGIONALE, n.d.). Regarding this plan, we can understand what restrictions exist during the selection of indicators, considering the specific characteristics of the study are, and which factors are more significant in environmental assessments, as well as the protocols we need to consider at both local and national levels. Corine Land Cover data of Copernicus for the year 2018, which is the most recent available land use data, is going to apply for the base of analysis in this work. To map the location of wind turbines within the study area, vector point

[1] This study was conducted with the collaboration and permission of F4 Ingegneria S.r.l. (Italy, P. IVA 01822640767), an engineering firm based in Potenza, specializing in design, analysis, and technical consulting for civil, environmental, and energy projects.

layers primarily obtained from the official website of the Basilicata region, and GSE website, the primary resource for renewable energy information in Italy. These layers were later updated through orthophoto and google map additionally, using data from F4 a professional company actively involved in local and regional environmental assessments of renewable energy projects in the area. The current number of wind facilities case study sample is 279, and this number is going to increase to 327 regarding regional plan. In summary, the Tab.1 outlines the data used for this research, including both data formats and sources.

Data	Format		Link
Digital Elevation Model (DEM)	Raster (100m)	TinItaly	https://tinitaly.pi.ingv.it/
Corin Land Cover 2018	Raster & Vector	Copernicus	https://land.copernicus.eu/en/map-viewer
Layer points of wind turbines installation for current and future scenario	Vector	Geoportale Basilicata GSE	https://rsdi.regione.basilicata.it/ https://www.gse.it/dati-e scenari/atlaimpianti https://earth.google.com/web/
-UNESCO World Heritage Sites - Monumental heritage - Archaeology assets - Landscape properties - Areas included in the territorial functional ecological system the territory of the Basilicata region - Agricultural areas - Areas in hydraulic and hydrogeological disruption	Vector	Geoportale Basilicata	https://rsdi.regione.basilicata.it/

Tab.1 Input data information.

2.2 Literature review

Expert involvement in landscape assessment

Environmental impact assessment (EIA) of landscapes integrates ecological, cultural, and perceptual analyses, employing quantitative and qualitative models to address the complexity of landscape changes (Medeiros et al., 2021). Not all aspects receive equal attention. Ecological and land-use indicators typically receive the most focus due to their direct connection to habitat quality and biodiversity (Palermo A. et al, 2024). In contrast, cultural and socio-economic aspects, such as cultural heritage and visual aesthetic quality, often receive less consideration (Schüpbach et al., 2020). Over the past three decades, a wide range of methods has been developed to assess landscape values (Solecka, 2019). Two fundamental approaches can be distinguished in the assessment of landscape values: the expert-driven approach and the subjectivist approach(Lothian, 1999).Expert approaches, rely on generalized public preferences for specific landscape features, drawing on foundational research related to landscape perception and visual amenities, expert judgment, and legal frameworks (Dramstad et al., 2006) Such assessments are based on intersubjective values, which, while not objectively measurable, represent broadly shared preferences and are supported by a core set of common landscape values frequently cited in the literature. Existing expert assessments frequently focus on landscape aesthetic quality (LAQ), which is understood as the enjoyment derived from the aesthetic appreciation of landscapes (Solecka et al., 2022). Furthermore, stakeholder engagement and the integration of local perspectives are recognized as essential for defining sustainability objectives, selecting appropriate indicators, and ensuring that assessments reflect both expert knowledge and community values (Dale et al., 2019). Considering that nowadays there is a growing trend of using machine learning in decision-making, it is still important, especially for local and regional plans, to involve field experts. Since the assessment is a process rather than a one-time decision, it is crucial to engage individuals who have detailed knowledge of the plans' history and context (Gennatas et al., 2020). Additionally, because these individuals are human and interact directly with other stakeholders, their experiences can greatly contribute to the decision-making and assessment process. Moreover, these experts are often local residents, and thanks to their background, they have a deep understanding of all the relevant aspects of the area (Maitland & Sammartino, 2015).

Wind turbine visual impacts and methodological gaps

One of the critical points to consider for implementing RES installation is their aesthetic impacts on the surrounding area, especially at a local scale in Italy as a country that keeps many historical and natural sites, one such barrier is the aesthetic impact of renewable energy facilities on the landscape (Wüstenhagen et al., 2007). It is crucial to carefully select their locations to minimize the visual impact of RES installations and increase social acceptance. To emphasize the importance of the visual impact of RES on the landscape, we address a gap identified in the existing literature through, a bibliometric summary generated using the Bibliometrix R package, based on a custom dataset of scientific publications related to RES and their aesthetic and visibility impacts on the landscape. The Tab.2 contains the summary of general information about bibliometrix review.

MAIN INFORMATION ABOUT DATA	
Timespan	2005:2025
Sources (Journals, Books, etc)	103
Documents	174
Annual Growth Rate %	4.69
Average citations per doc	44.44
Author's Keywords (DE)	609

Tab.2 Main information of bibliometrix analysis

The dataset covers a period from 2005 to 2025 by reflecting a sustained and evolving scholarly interest in the visual and landscape impacts of RES. Comprising 174 documents, the dataset represents a relatively small but concentrated body of research that appears to be gradually expanding. The dataset draws on 103 distinct sources, including both journals and conference proceedings, indicating a moderately broad field with contributions spanning multiple disciplines such as environmental science, energy policy, landscape planning, and sustainability. The annual growth rate of 4.69% points to a steady increase in publications over time, suggesting that scholarly attention to the visibility and aesthetic dimensions of RES is gradually gaining prominence in both policy discussions and public discourse. A rich and diverse keyword set (609 keywords) reflects thematic complexity. This likely includes terms such as "landscape integration", "visual impact", "wind farms", "solar panels", "public perception", etc. Average Citations per Document (44.44) is an unusually high citation count, indicating that the field contains high-impact publications, or that some seminal works are highly cited. It also reflects the growing academic and policy relevance of the visibility and aesthetic dimensions in RES deployment. The annual scientific production illustrated in the figure 9 shows steady growth in publication output over two decades, which aligns with the increased deployment of RES technologies and rising public concern over their integration into landscapes. Publication reaches its peak in 2024. Further analysis using Bibliometrix indicates that Italy and Spain are particularly active in this research area. This prominence likely reflects both the regional significance of renewable energy deployment and national priorities related to sustainable landscape planning and policy.

The thematic (Fig.2) map provides a strategic overview of the conceptual landscape within the literature on renewable energy and its connections to landscape and sustainability issues. Dominant "motor themes" underscore the increasing attention given to visual and environmental dimensions in renewable energy research. Meanwhile, the presence of themes such as ecosystem services and territorial planning in the lower-left quadrant points to areas of either emerging or waning scholarly interest, highlighting the need for longitudinal studies to better understand their developmental trajectories.

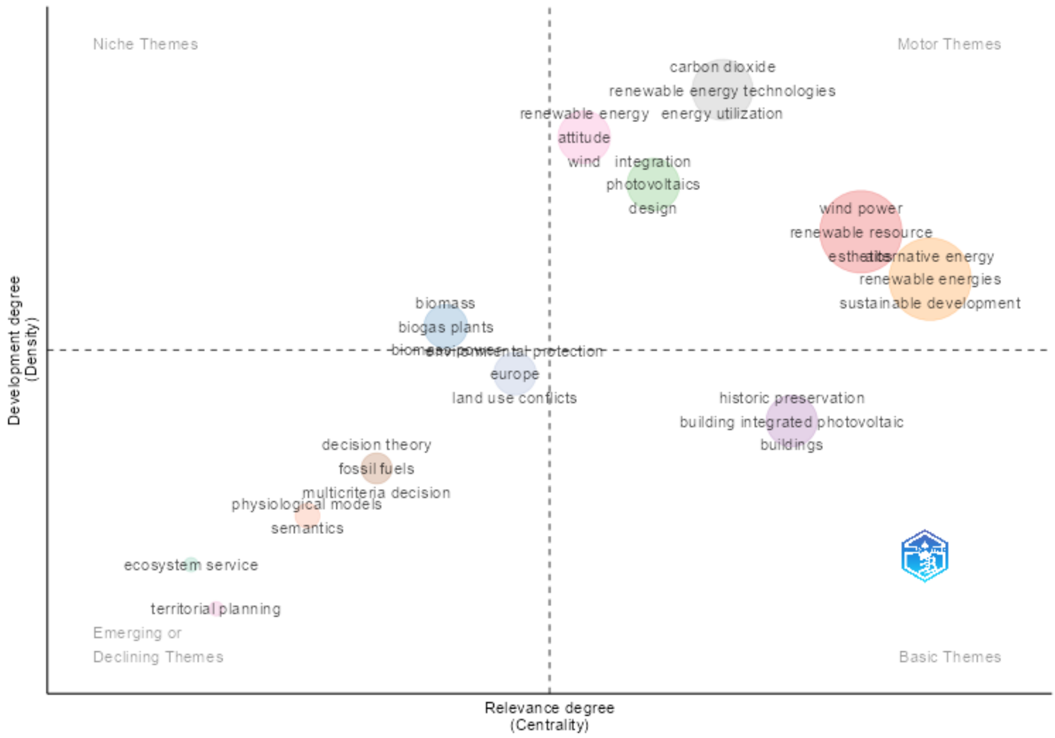

Fig.2 The thematic map offers a strategic visualization of the conceptual landscape

While visual impact emerges as one of the most frequent keywords and suggesting a strong scholarly interest, there remains a lack of standardized methodologies for its assessment. The literature frequently discusses visual impacts of renewable energy installations (especially wind farms), but often relies on qualitative, case-specific, or subjective approaches rather than consistent, replicable tools. This reveals a clear gap between thematic interest and methodological maturity in the field. In this study, we aim to address this gap by employing a GIS-based methodology and by using the InVEST tool, a widely recognized and professional framework for assessing ecosystem services. Through this approach, we seek to elevate the concept of ecosystem services from an emerging or declining theme to a more central topic within the literature.

2.3 Case study

The case study focuses on a cluster of seven municipalities in the Basilicata region (Livello, Montemilone, Venosa, Maschito, Palazzo San Gervasio, Banzi, and Forenza). Selection of areas is based on the concentration of authorized RES installations, as identified in official data published on the Basilicata Region's institutional website (Https://Rsdi.Regione.Basilicata.It/Dbgt-Ctr/, n.d.). Basilicata is an administrative region in Southern Italy, bordered by Campania to the west, Apulia to the north and east (Https://Www.Istat.It/, n.d.). Basilicata is the most mountainous region in southern Italy, with mountains covering approximately 47% of its 9,992 km² territory. The remaining area is composed of 45% hills and 8% plains. Compared to central and northern Italy regions, Basilicata presents relatively favorable spatial conditions for specific types of land use and development, particularly in relation to renewable energy installations and rural land management (Https://Www.Istat.It/, n.d.). Furthermore, in 2018, the Basilicata Regional Authority approved a regional law entitled 'Decarbonisation and Regional Policies on Climate Change' to support the transition toward a low-carbon economy and strengthen climate resilience across the region (Regbasilicata_l.r.-15-Ottobre-2018--n.-32, 2018) (ITALIAN MINISTRY OF ENVIRONMENT AND ENERGY SECURITY, 2022).

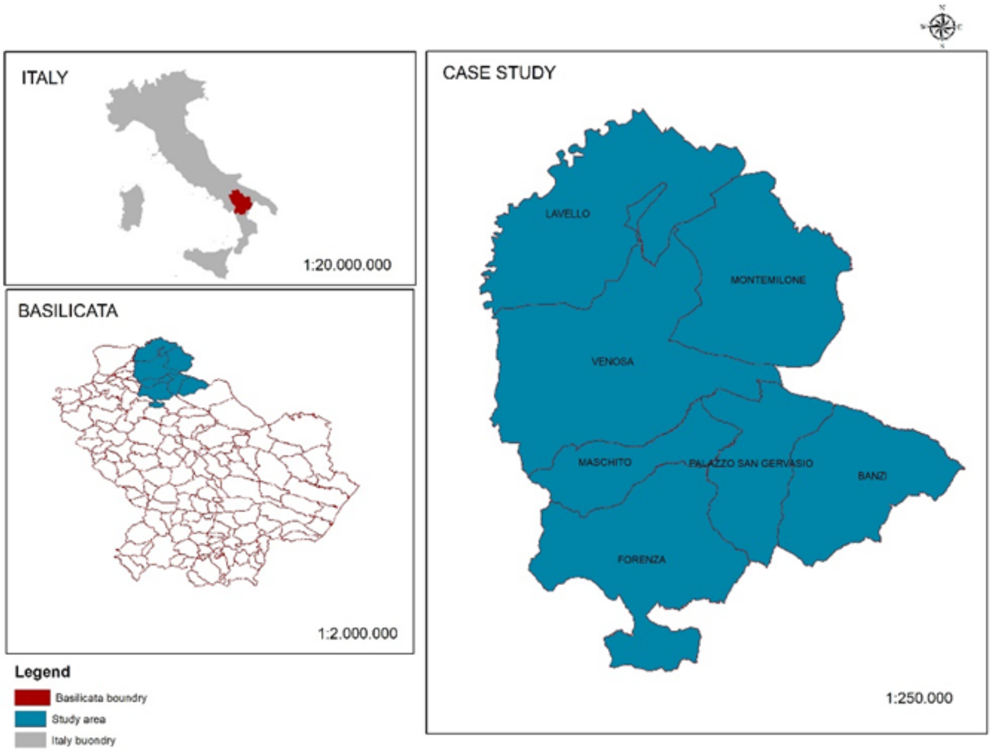

Fig.3 The location of the case study in Basilicata, Italy

2.4 Definition of the visual impact area

Aesthetic impacts on the landscape have long been a central source of opposition to renewable energy projects (Mazzola, 2025). Yet, the current uncertainty regarding the spatial extent and the validity of reported impacts continues to prevent the development of effective strategies for their mitigation (Ioannidis & Koutsoyiannis, 2020). In this paper, the methodology applied for assessing the landscape visual impact of RES is based on a standardized approach that quantifies the degree of visual and contextual transformation induced by such projects, according to the following formula. A common methodological approach proposed by the University of Cagliari quantifies the landscape impact (IP) by calculating two indices; 1) VP index, representing the value of the landscape 2) VI index, representing the visibility of the plant (Loc, 2013). The IP, based on which decisions can be made regarding mitigation measures or system modifications that improve visual perception, is determined by the product of the two indexes.

$$IP = VP * VI \tag{1}$$

The VP and the VI, both expressed on a scale from 0 (no impact) to 4 (maximum impact). VP captures the intrinsic characteristics of the territory through three sub-indices: Naturalness (N), Environmental Quality (Q), and Landscape Constraints (V) according to the formula 2, derived from land use data and spatial overlays of protected or regulated areas. The intervisibility analysis is conducted using DSM-based viewshed models within the Scenic quality model of InVEST software, under different scenarios (current installation and authorized for adding in near future). The final IP raster map is obtained by multiplying the reclassified VP and VI raster maps, enabling a spatially explicit evaluation of visual impact and supporting informed decision-making for mitigation or planning purposes.

$$VP = N + Q + V \tag{2}$$

VP calculation

Evaluating the values attributed to landscapes provides essential insights that can inform landscape policy and support decision-making processes. Over the past thirty years, numerous methods have been developed to assess landscape values. Two primary approaches are commonly distinguished in this field: expert-driven and subjectivist (Lothian, 1999)(Johnson et al., 2024). The following tables present the expert-based values used for calculating landscape values.

The N index was calculated based on land use data derived from the Regional Technical Map (CTR), assigning values from 1 to 10, where 1 represents highly artificial areas and 10 indicates areas with the highest naturalness. Tab.3 illustrates the N value corresponding to each land use classification used in the Basilicata region, at about 74.69%. Following that, with a significant difference, around 13.24% is dedicated to vineyards, olive groves, and orchards, all of which fall under the agricultural lands category. Close to that, about 10% is allocated to broad-leaf forests, which belong to the natural environment category. The remaining percentages are roughly similar, and each is less than 1% for our study area.

	Land Use	**Index N**
Artificially modeled territories	Industrial or commercial areas	1
	Mining areas, landfills	1
	Urban and/or tourist fabric	2
	Sports and hospitality areas	2
Agricultural lands	Arable and uncultivated land	3
	Protected crops, various types of greenhouses	2
	Vineyards, olive groves, orchards	4
Woods and semi-natural environments	Cyst areas	5
	Natural grazing areas	5
	Coniferous and mixed forests	8
	Bare rocks, cliffs, crags	8
	High, medium and low Mediterranean scrub	8
	Broadleaf forests	10
	Maritime waters	8

Tab.3 Index of naturalness and classes of land use

Like the N index, environmental quality values are assigned on a scale ranging from 1 to 6, with each value representing a distinct level of environmental quality linked to various land use typologies. Consequently, areas characterized by more ecologically beneficial or less intensive land uses (e.g., natural habitats or forests) are assigned higher scores. In contrast, areas with more intensive or environmentally degrading uses (e.g., industrial zones or urbanized areas) receive lower scores. Tab.4 included all Q values for each category.

The Q value that can somewhat represent the habitat quality in the study area indicates that over 87% of the area is dedicated to agricultural quality. Following that, with a significant difference, about 10% of the area is assigned to maritime waters. For the remaining habitat qualities, the percentages are roughly similar, and each is less than 1%.

Land Use	Q Index
Service areas, industrial areas, quarries, etc.	1
Urban fabric	2
Agricultural areas	3
Semi-natural areas (garrigues, reforestations)	4
Areas with woodland and shrub vegetation	5
Wooded areas	6
Maritime waters	5

Tab.4 Index of environmental quality

In the Regional Energy Plan (CONSIGLIO REGIONALE DI BASILICATA PIANO DI INDIRIZZO ENERGETICO AMBIENTALE REGIONALE, n.d.) of the Basilicata region, the suitability of land for energy production is defined through a set of constraints specific to each type of renewable energy source. In this study, constraint indicators outlined in the energy plan are used, with values assigned to each category. The value scale ranges from 0 to 1 with historical and cultural heritage assigned higher values due to the extensive protection provided by various legal frameworks, although area with hydrogeological, forest, natural feature, and municipal areas have 0.5 value. Hydrogeological sensitive areas, forests, natural features, and municipal zones are attributed an intermediate value of 0.5. A value of 0.25 is attributed to urban areas and river buffer zones, reflecting their comparatively lower constraint level. Areas not falling within the mentioned categories are assigned a value of 0. The Tab.5 presents information on the assigned constraint values for each land category.

Index relating to the presence of constraints	V value
Areas with historical-archaeological constraints	1.00
Areas with hydrogeological constraints	0.5
Areas with forest constraints	0.5
Areas with protection of natural features (PTP)	0.5
Municipal areas	0.5
Areas of buffer (about 800m) from urban fabrics	0.25
Areas of buffer, buffers (rivers, sheep tracks, etc.)	0.25
Unconstrained areas	0.00

Tab.5 Index of constraints

In the study area, 21.46% of the total area is subject to restrictions for the installation of these facilities, due to the presence of historical and archaeological values in those areas. The largest percentage of the area, about 38.98%, is allocated to regions with no restrictions. Next, around 26.37% of the area is designated for protection due to the presence of natural features and municipal zones. Finally, the smallest percentage, approximately 13%, is allocated to buffer zones of urban fabrics, rivers, and ship tracks.

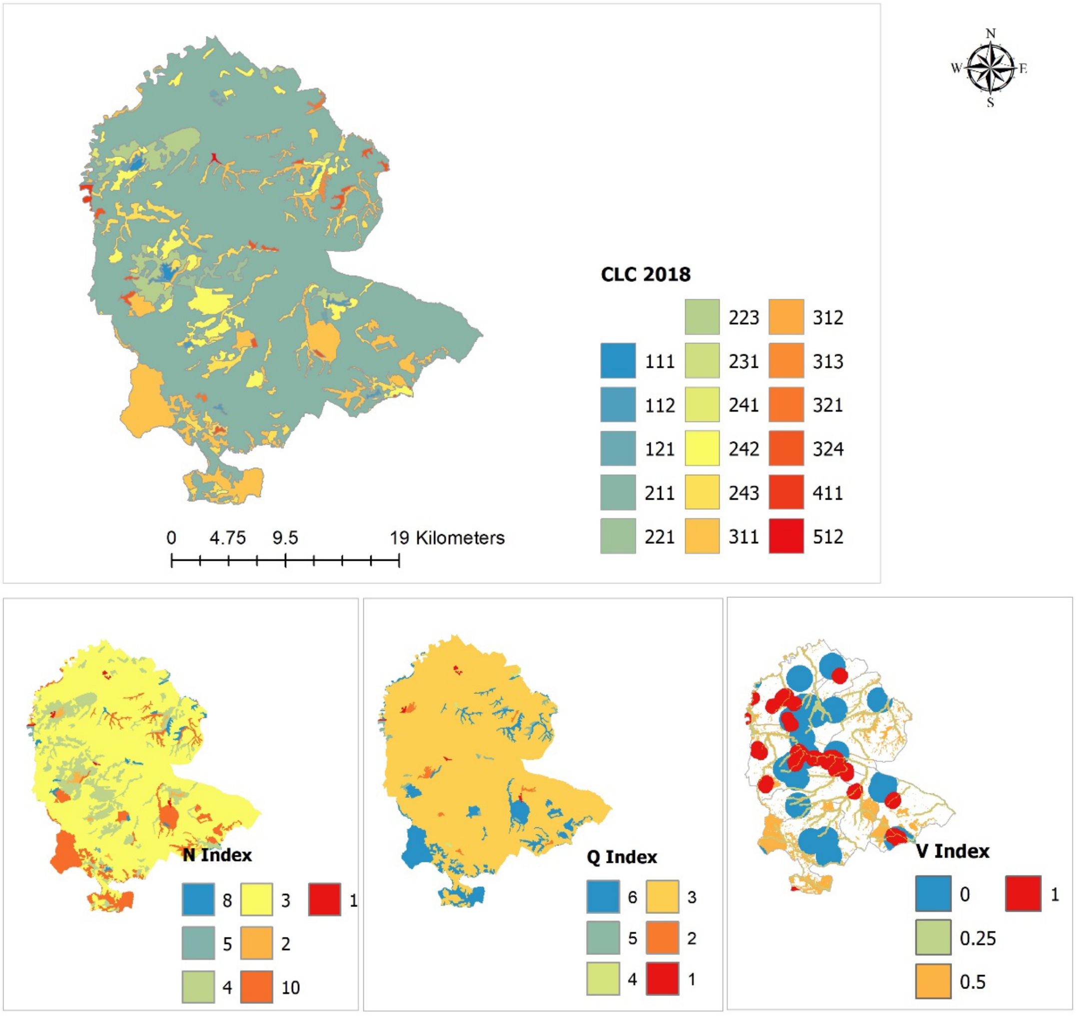

Fig.4 Transforming CLC codes to N, Q and V indexes

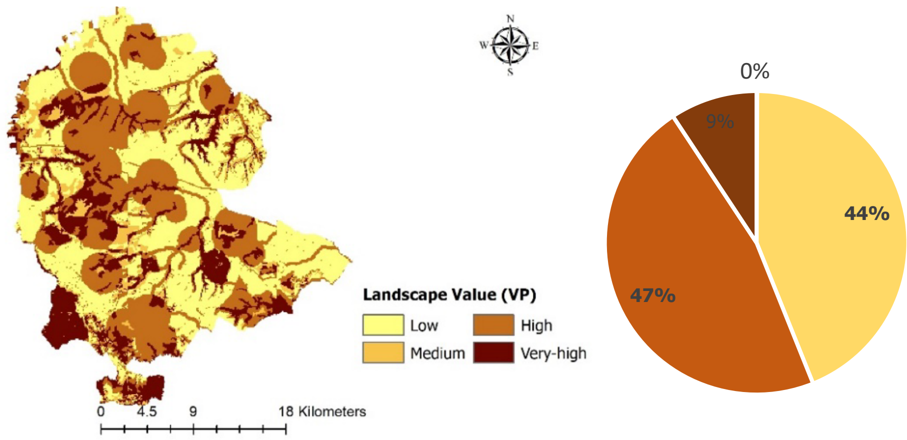

Fig.5 a) Landscape value map for study area; b) landscape value percentage for each class

In the GIS environment, the values of the N, Q, and V indices were summed and resampled on a scale between 1 and 4 according to the methodology described above to derive the landscape value map of the territory. The map algebra operation allows the result to be obtained pixel by pixel. Fig.5 shows overlaid normalized indexes.

The pie chart illustrates the proportional distribution across four categories based on absolute values. The High category constitutes the largest share at 47%, Medium at 44%, and Very High at 9%. Despite having a recorded value of 450,000, the Low category accounts for 0% of the total due to the relative magnitude of the other values.

VI calculation

The visual impact of wind turbines largely depends on their distance from the observer(Bishop & Miller, 2007). Visual impact assessments of wind turbines in Europe have been conducted since the early 1990s. The first reports published by the European Commission in 1995, focusing on the visual analysis of relatively small turbines with a height of approximately 45 meters, indicated that their maximum visibility range extends up to 20 kilometers. Thomas, based on a study conducted in Wales on wind turbines with heights ranging from 41 to 45 meters, demonstrated that the maximum range for visibility analysis should initially be limited to 15 km, later adjusting this threshold to 20 km (Wróżyński et al., 2016). At the turn of the century, increasingly taller wind turbines were constructed, and according to Bishop, their visibility could extend beyond 30 km. However, Bishop argues that beyond 20 km, the visibility of turbines becomes very limited, and their impact is minimal (Bishop, 2002).

In this study, we propose using the Scenic Quality model available within the InVEST software to assess the visual impacts of renewable energy installations. The InVEST Scenic Quality model computes the visual impact of features in the landscape in several steps, and for each structure site, calculate the visibility for each point feature viewshed algorithm. In addition to identifying visible areas, the model also estimates the amenity or disamenity value of visibility by weighting the visibility results and applying the valuation function specified by the user in the interface. By summing the individual valuation rasters, the model generates a weighted aggregate that represents the overall visual impact across the area of interest. The weighted aggregate valuation raster is divided into quartiles to produce a final. The weighted aggregate valuation raster is divided into quartiles to produce a final raster that represents visual quality across the landscape. Additionally, the visibility rasters from all structure points are weighted and summed to generate a raster that reflects the total number of visible points, accounting for their relative importance. The valuation function is computed up to a maximum valuation radius that defaults to 8.000 meters. The following section presents the model's required input data for running the analysis.

The first thing the model requires is defining the study area boundary, also known as the AOI, which is a polygon vector layer. In this study, we used the municipal boundaries downloaded from the official website of the Basilicata region, and the coordinate system has been adjusted to WGS84 / UTM Zone 32N to ensure compatibility with the DEM. furthermore a point vector representing wind turbines that negatively impact scenic quality of study area. Optionally, there are possibilities to enhance the analysis through defining more attributes such as; maximum viewing distance, which limits the extent of the viewshed for each feature, viewshed importance coefficient, which weights the visual influence of each feature, the viewpoint height, which adjusts the elevation from which visibility is assessed. These parameters enable a more precise and context-specific representation of visual impacts. height here defines the maximum length of the line of sight originating from each viewpoint. If this field is not specified, the model will consider all pixels in the DEM during the visibility analysis. For this study, we used the actual height of each wind turbine as provided in the dataset. In cases where height data was missing, we assigned the average turbine height, which is 150 meters. Additionally, a radius value was included in the attribute table, with 30 km. This distance corresponds to the typical visibility range of a 100m high turbine. Fig6. shows generated rasters that represents the visual quality of each pixel across the study area for both current situation and authorized installation as future scenario. The cells of the raster are classified based on percentile breaks, allowing for a relative assessment of visual impact.

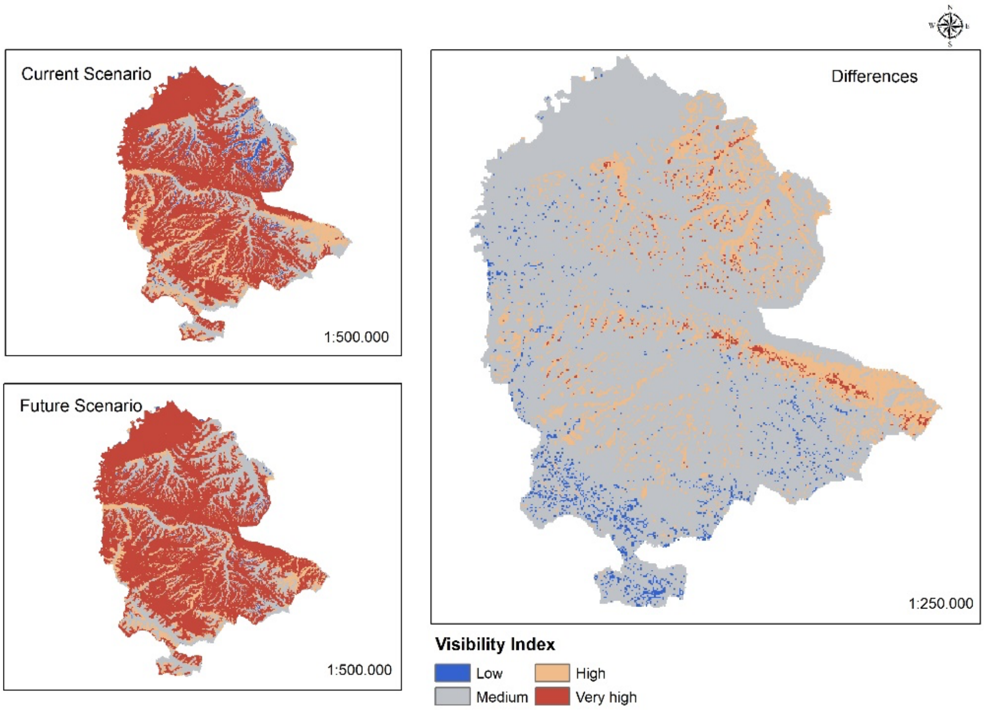

Fig.6 Comparison between current and future scenarios of the visibility index

The Fig.6 shows for both the current situation and the predicted future scenario, the impact of these wind turbines on the environmental visual quality of the study area falls primarily into category four, meaning the impact is very high. Currently, this impact is about 60.35%, and with the addition of future wind turbines, this percentage increases by 5%, reaching around 65.10%. At the same time, the current category one impact, which is about 13.14%, will decrease in the future to approximately 11.08%, and this category will then shift into category four. Meanwhile, for category two, which indicates a medium-level impact, both the current and future scenarios remain relatively stable.

Overall Impact of Visual Disturbance on the Social Value of the Landscape

Finally, considering all the analyses carried out so far, in this section we will present the results that address the main objective of this research: examining the impact of wind turbines on the visual value of the study area's landscape. Tab.4 illustrates the IP index percentages which is derived from the overlay of all the indicators we have discussed so far, along with their normalization and, ultimately, their reclassification into four classes: low, medium, high, and very high. This figure includes both the current state, the future state, and the differences between these two timeframes.

IP Value	IP Scale	Sup. ha	Sup. %	Sup. ha	Sup. %
		Current		Future	
Low	1	13,282	18.41	14,547	14.76
Medium	2	29,637	10.72	27,493	9.2
High	3	7,427	39.57	6,601	42.5
Very high	4	20,997	31.3	22,702	33.53

Tab.4 Landscape value impacted by wind turbines

The results show that, for the two timeframes analyzed both the current state and the future projections, the magnitude of changes in the high and very high categories is evident for both periods. Notably, the change in the first category representing low impact, has decreased in the future scenario, meaning the difference is about 4% smaller in the future. On the other hand, the difference has increased for the fourth category, which has the greatest impact on the visual landscape of the area.

3. Result

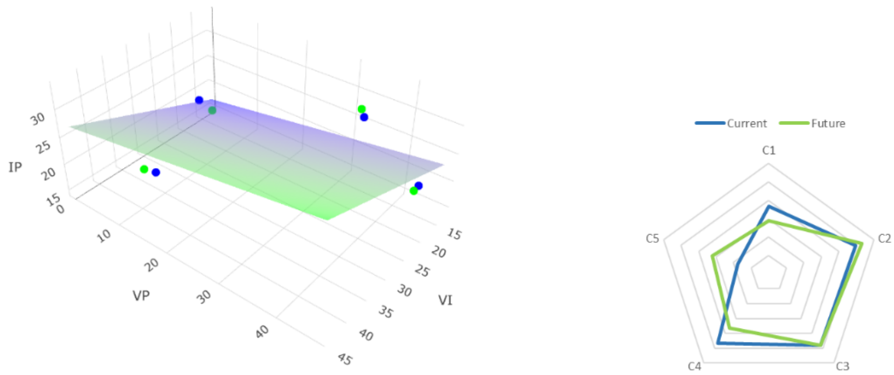

Fig.7 a) VI and VP relation con IP; b) Comparison of VI and VP impact on landscape value changes

The Fig.7b, Compare the impact of wind turbines on landscape value in the current scenario with the projected impact under future installation scenarios. The results indicate that, although the medium impact class (C3) remains constant across both scenarios, the proportion of areas falling into the C5 category, representing very high impact, is projected to increase from 9% to 16%. On the other hand, a 3D regression plot (Fig.7a) shows how two independent variables, VI and VP, together explain changes in IP. The colored surface in the 3D graph, displayed as a semi-transparent plane, represents the regression plane generated by a multiple linear regression model. This plane visualizes the fitted values of the IP as a function of the combined influence of the two explanatory variables. The green surface, corresponding to the future scenario, is positioned higher than the blue surface representing the current state. This change reflects a steeper gradient, implying a more pronounced increase in the landscape impact of wind turbine installations in the future. Although the overall landscape value remains constant between the two scenarios, the shift toward a more concentrated presence of high impact classes suggests increasing visual dominance and changing perceptions of landscape disturbance.

4. Conclusion and discussion

One of the findings of the research highlights, even with new approaches to decision-making processes, experts, especially local specialists who have been involved in environmental changes and driving factors over time, are essential and crucial. Environmental impact assessments sometimes require straightforward, practical steps rather than complex methods that can lead to confusion when many factors are not influential. Therefore, the role of these specialists should not be overlooked, and more opportunities for collaboration among stakeholders, such as academics, engineers, planners, economists, and policymakers, should be provided. It is important that, in the decision-making process, we always consider reliable plans at both the national and regional levels, and that the interests of all stakeholders take precedence over the benefits of any single group in planning and assessments. The results also show, it is possible to make a smart choice of assessment methods where needed, tailored to the type of impact. For instance, in the case of wind facilities, considering the nature of these structures and the residents' criticisms, especially regarding visual and landscape impacts, which have been a significant source of opposition goes beyond just the economic benefits and the cleanliness of the energy. If a one-dimensional harm from these technologies' increases, then, no matter how clean the energy is, it could ultimately become harmful to the environment. For this reason, we used the Scenic Quality Model through the InVEST software, which is originality of this work, because until now, most of the research conducted on the visual impact of wind facilities on the area and on the Basilicata, region has typically relied on conventional methods, such as viewshed analysis available in GIS programs. However, this model, in addition to what viewshed analysis offers, also considers dimensions and scales, which are critical and decisive factors in how these facilities affect the landscape of the studied area. Furthermore, the assessment conducted in this research has issued warnings to future projects and facilities that are planned to enter the region. Given the current state and the significant impact on the landscape and aesthetic quality of the studied area, the assessment warns that adding these facilities will further increase these impacts. This poses a serious threat to the region, which, due to its relatively low population and moderate economic situation compared to other Italian regions, could see its role at both the national and international levels weakened.

Acknowledgments

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 3.5 to improve the readability of parts of the text. After using this tool/ service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Image sources

Fig.1: Methodology framework, Author generated;

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Identifying regional green infrastructure hotspots. A comparison between the Basilicata and Campania regions, Italy

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Abstract
Assessing ecosystem services (ESs), the goods and benefits provided by ecosystems and necessary to maintain human life and well-being, is important in spatial planning. Indeed, land-use changes allowed, or even driven, by spatial plans can alter ecosystem structure and functions, thereby influencing ES supply, and, ultimately, the quality of the environment and of human life. Within this framework, this study proposes a methodological approach for the identification of ES hotspots, defined as key areas that supply high levels of ESs, to support more sustainable spatial planning. The initial phase comprises a biophysical evaluation of three key regulating ESs: habitat quality, representing the capacity of ecosystems to sustain wildlife; carbon storage and sequestration, reflecting their contribution to climate regulation; and land surface temperature, serving as an indicator of local thermal mitigation offered by ecosystems. In the second phase, multiple spatial statistical methods for hotspot detection are employed in an integrated framework. Applied to Campania and Basilicata in southern Italy, the proposed approach makes it possible to compare extent and distribution of ES hotspots in the two regions. Easily transferable to other contexts where biophysical ES assessments are available, this approach provides planners with useful information to support effective planning choices.

Keywords
Carbon sequestration and storage; Habitat quality; Landsat surface temperature; Ecosystem services; Hotspot analysis

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1. Introduction

The concept of ecosystem services (ESs) refers to the set of natural functions and processes through which ecosystems generate essential benefits to human well-being (MA, 2003). These contributions may be direct, as in the case of provisioning services, or indirect, as in the case of cultural and regulating services (Balasubramanian, 2019). Regulating ESs encompass functions such as local and global climate regulation, as well as habitat provision, which serves as a prerequisite for maintaining both geological and genetic diversity. ES protection and delivery represent a central pillar of international environmental policies. Notably, one of the core objectives outlined by the Convention on Biological Diversity is to secure the conservation of at least 17% of terrestrial areas identified as critical for safeguarding biodiversity and ensuring the continued provision of essential ESs (Aichi Target 11). In practice, ecosystems generate a wide range of interrelated and mutually influencing ESs (Turkelboom et al., 2016). Decisions to prioritize the use of specific services inevitably affect the composition, magnitude, and spatial configuration of the benefits that ecosystems can deliver (Rodríguez et al., 2006). Interactions among ESs can give rise to trade-offs, whereby the enhancement of one ES results in the reduction of another, or to synergies, defined as "a situation where the use of one ES directly increases the benefits provided by another service" (Turkelboom et al., 2016, p. 2). The functional interdependencies among ESs, encompassing both synergies and trade-offs, should be systematically incorporated into ecosystem management and policy-making, as such dynamics inherently emerge during ES provision. A human tendency to maximrize a specific service may, in fact, result in the decline or deterioration of other valuable ecosystem functions and benefits (Bennett et al., 2009). In natural ecosystems, regulating services are theoretically expected to be mutually reinforcing, as they are intimately connected to the structural elements and functional dynamics of ecosystems (Burkhard et al., 2014; Hou et al., 2018). A range of empirical studies has demonstrated the presence of synergistic interactions among regulating ESs (Haase et al., 2012; Raudsepp-Hearne et al., 2010). Raudsepp-Hearne et al. (2010) developed a framework to identify recurring bundles of ESs based on spatial patterns, by analyzing 12 ESs across 137 municipalities in Québec, Canada.

Identifying and characterizing areas that harbor high levels of biological diversity and support critical ecological functions constitutes a fundamental step toward the effective implementation of international environmental sustainability directives (Naidoo et al., 2008). From the perspective of environmental governance and decision-making support, adopting an integrated approach that accounts for the full spectrum of relevant ESs, as well as the potential synergies and trade-offs among them (Kandziora et al., 2013), is therefore essential.

Building upon these conceptual foundations, a growing corpus of scholarly research has concentrated on the spatial delineation of ES hotspots, generally characterized as zones exhibiting elevated levels of service heterogeneity, and a strong inherent capacity to generate ecosystem benefits; conversely, areas with minimal values along these dimensions are classified as coldspots (Schröter & Remme, 2016). The rising academic interest in ES hotspots can be attributed to the fact that hotspot mapping and evaluation can support the geographic targeting of high-priority zones for conservation strategies (Blumstein & Thompson, 2015), assist in assessing the performance and outcomes of biodiversity protection measures (Spanò et al., 2017), and inform decision-making regarding the spatial coordination of ES trade-offs and co-benefits (Bagstad et al., 2017). Indeed, mapping hotspots provides a valuable basis for formulating evidence-based conservation boundaries and for establishing spatial priorities in biodiversity protection, particularly under constraints of limited financial or managerial resources during ecosystem planning and governance (Reyers et al., 2009).

Although numerous efforts have been made to spatially represent hotspots, decision-makers still exhibit limited awareness of the potential of spatial planning as a tool for guiding the distribution and sustainable use of these services (Schröter et al., 2017).

Building on this conceptual framework, this study proposes a two-stage methodological approach for the spatial identification of ES hotspots, defined as areas capable of providing high levels of ESs. This approach was applied to two case studies, i.e., the Basilicata and Campania regions, in Italy. The first stage involves the spatial assessment of three regulating ESs: i., local temperature regulation, using land surface temperature (LST) as a proxy; ii., lifecycle maintenance, habitat and gene pool protection, evaluated through habitat quality (HQ), under the assumption that higher habitat quality corresponds to greater support for lifecycle functions and biodiversity conservation; and iii., global climate regulation, assessed through carbon storage and sequestration (CSS). These three ESs were mapped for both case studies using three distinct methodologies. The mapping of LST was conducted using satellite data. The mapping of HQ and CSS was conducted using two models from the InVEST suite (Integrated Valuation of Ecosystem Services), a free, open-source spatial modelling platform developed by the Natural Capital Project[1]. This versatile modelling framework supports the evaluation and cartographic representation of ESs, facilitating the comparison of alternative land-use scenarios and estimating their respective environmental consequences (Jiang et al., 2017). The second phase of the methodology focuses on the evaluation and mapping of ES hotspots, employing multiple spatial statistical techniques. These include the Local Indicator of Spatial Autocorrelation (LISA), its median variant, the Getis-Ord G* statistic, and a quantile-based approach. This phase is implemented through a structured four-step procedure.

The paper is organized into five sections. The second section describes the study areas, and the methodologies used to map the three regulating ESs and identify hotspots. The third section presents the results: the spatial distribution of the services and their hotspots in Basilicata and Campania. The fourth section discusses the findings, while the fifth section offers concluding remarks, highlights the strengths and limitations of the applied methodologies, and outlines directions for future research.

2. Materials and methods

2.1 Study areas: the regional contexts of Basilicata and Campania

Located in the southern part of Italy, the Basilicata region covers nearly 10,000 square kilometers and it is bordered by Campania, Apulia, Calabria, and the Ionian coastline (Fig.1). The territory is predominantly composed of mountainous and hilly areas, with only around 10% consisting of flatlands, mostly concentrated on the Metapontino coastal plain. The western portion includes the Lucanian Apennine, with notable mountain groups such as Pollino, Volturino, and Sirino. By contrast, the eastern hills slope down towards the Ionian shoreline. Basilicata's fluvial network primarily channels water into the Ionian Sea through rivers like Bradano, Basento, Cavone, Agri, and Sinni. Other watercourses, such as Ofanto, Platano, Melandro, and Noce, flow into either the Adriatic or the Tyrrhenian Sea. The region's hydrological framework, segmented into eight drainage basins, exhibits a typical torrential flow regime, marked by considerable seasonal variability and a tendency for flooding in the lower courses. The main settlements are Potenza, situated in the northwest, and Matera, located toward the eastern edge. About one-fifth of the regional territory benefits from environmental protection under National Law no. 1991/394, involving two national parks, three regional parks, eight state-level nature reserves, and seven regional reserves. Furthermore, Basilicata hosts 82 designated Natura 2000 sites. As of 2024, the regional population stands at 533,636 inhabitants, distributed across 131 municipalities, the latter organized into two provinces. The main settlements are Potenza and Matera, respectively home to around 67,300 and around 60,400 residents.

Campania extends over an area of about 13,700 square kilometers, bounded by Lazio, Molise, Apulia, Basilicata, and the Tyrrhenian Sea (Fig.1). The topography is predominantly made up of hills and mountains, with flatlands, mostly alluvial in origin, accounting for 14% of its surface. This geographic diversity includes the Campanian Plain and the Sele estuary, inside alluvial basins, and prominent limestone massifs rising over 2,000 meters, such as the Matese, Sannio, Irpinia, and Cilento ranges. The coastal landscape is further shaped

[1] https://naturalcapitalproject.stanford.edu/software/invest (last accessed 2025/06/25)

by volcanic features, notably the extinct Roccamonfina volcano and active volcanic systems including the Somma-Vesuvius complex and the Phlegraean Fields–Ischia area. The hydrological system is characterized by perennial rivers in the mountainous zones, episodic torrents in the uplands, and artificial or moraine channels along the coastline. Key water streams include the Volturno and Sele rivers.
As of 2024, Campania includes two national parks, four marine protected areas, nine regional parks, five state-managed nature reserves, and four regional nature reserves. The region also hosts 137 Natura 2000 sites. With a population of 5,590,076 inhabitants distributed across 553 municipalities, Campania is organized into five provinces. Major metropolitan areas include Naples, which contains 2,967,736 residents, followed by Salerno (1,057,819) and Caserta (906,080).

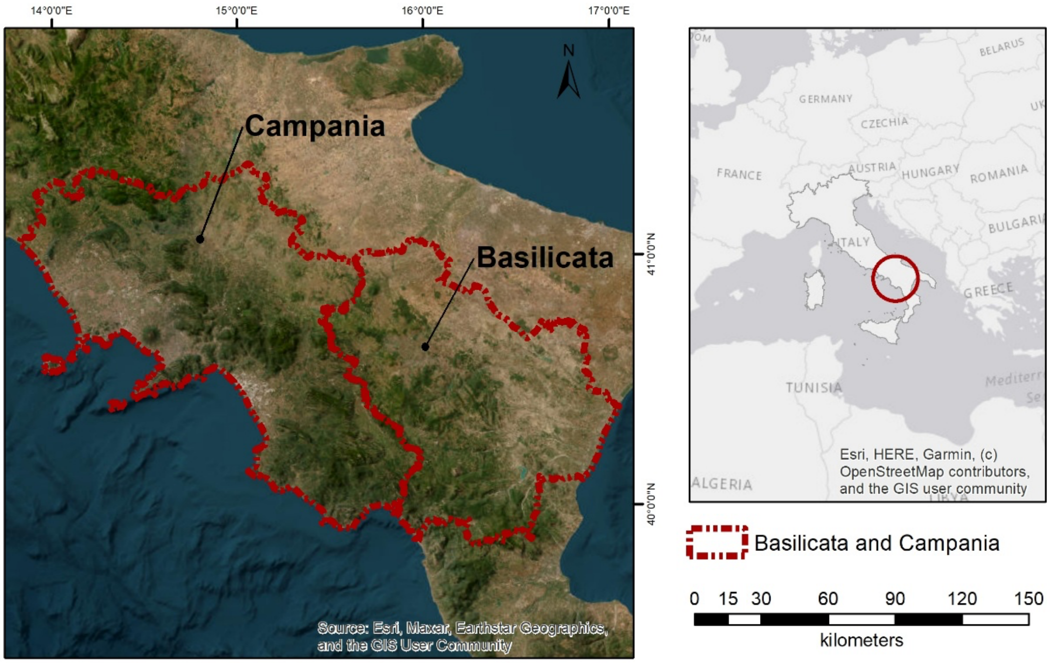

Fig.1 Study areas: Campania and Basilicata, and their location in Italy

2.2 Ecosystem service mapping

This section briefly outlines the approaches employed to assess and map the three regulating ESs, local temperature mitigation through the evaluation of LST, lifecycle maintenance, habitat, and gene pool protection where HQ is a proxy, and CSS.
LST is widely recognized as a fundamental geophysical variable for quantifying surface-atmosphere energy fluxes and assessing thermodynamic behavior at the land interface (Olivera-Guerra et al., 2025). It constitutes a key element in the investigation of climate-sensitive processes, including the characterization of urban thermal anomalies, quantification of evapo-transpirative fluxes, and analysis of surface energy balance across heterogeneous land cover types. Moreover, LST modulates near-surface air temperatures and contributes to multiscale climatic feedback operating at both local and global levels (Guillevic et al., 2018). The advent of high-resolution thermal remote sensing technologies, particularly through satellite platforms like Landsat 8–9 equipped with Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), has significantly enhanced the ability to monitor these processes across vast regions (Zhang et al., 2006; Sánchez-Aparicio, 2020).
Following the method developed by Lai et al. (2020), this study focuses on the spatial distribution of LST in Campania and Basilicata. Satellite data were retrieved from the Landsat Collection 2 Level-2 (OLI/TIRS) via the USGS Earth Explorer platform[2]. The thermal band B10, with a spatial resolution of 30 meters, was employed for extracting LST values. Data collection was limited to the summer 2023 period, from June 25 to

[2] https://earthexplorer.usgs.gov/ (last accessed 2025/06/25)

September 2, with a strict cloud cover threshold of 6%. Due to the spatial limitations of individual satellite scenes, in Campania multiple images were required to achieve full regional territory coverage.

For Basilicata, a set of images was retrieved, each covering the entire region; a total of five satellite images were available for this time period. For Campania, 21 satellite images were retrieved; these were grouped into sets of three to four images, based on scene and acquisition date, to fully cover the regional area.

Each set was mosaicked and evaluated, with those showing the highest thermal means retained for the final LST composite map. The process of selecting and analyzing the raster images entailed multiple steps. After merging image sets corresponding to the same acquisition date and scene, statistical verification of minimum and maximum values was conducted. In Campania, partial overlaps between the northwestern and northeastern image subsets were addressed through the calculation of mean LST differences within the overlapping areas. Subsequently, a clipping procedure was applied to produce the final unified LST map.

HQ was determined by employing the InVEST habitat quality model (Sharp et al., 2018), widely used because of its rapid data availability, powerful analytical capabilities, intuitive functionality, effective data processing, accurate outputs, clear result visualization, low implementation costs, and ease of adaptability to diverse contexts (Gao et al., 2017; Li et al., 2021; Yang, 2021). The model combines information on habitat suitability and threats to biodiversity to assess the overall habitat quality (Wu et al., 2021). It works on the assumption that habitat degradation intensifies depending on the sensitivity of the habitat to a set of threats (Aneseyee et al., 2020). Typically, the effect of a threat on a habitat decreases proportionally to the growing distance from the degradation source (Ibid.).

The assessment attributes numerical scores ranging from 0 to 1; rather than representing an absolute evaluation, they allow for comparison between various parts of the territory (Natural Capital Project, n.d.). The values of this relative index are finally depicted on a gradient map (Chiang et al., 2014). Required data for the model encompass a Land Use Land Cover (LULC) map, threat raster maps, a threat table, a sensitivity table, and the half-saturation constant (Natural Capital Project, n.d.). The LULC map constitutes the basis for defining the habitats; the threat raster maps provide the spatial features of the threats; the threat table specifies the characteristics of the threats, such as the impact weight, the maximum distance within which they influence a habitat, and the decay function; the sensitivity table illustrates the potential for each LULC to be a habitat and its vulnerability to the analyzed threats; and the half-saturation constant represents the point at which habitat quality is halved, meaning the habitat's ability to support biodiversity is reduced by 50% (Ibid.).

For this study, the LULC map is extracted from the CORINE Land Cover database. Following Sallustio et al. (2017), the analyzed habitats are as follows: beaches, dunes and sand; water bodies; wetlands; grasslands; shrublands; broadleaved forests; conifer forests; mixed forests; inland unvegetated or sparsely vegetated areas; intensive agriculture; extensive agriculture; buildings and other artificial areas or impervious soils; and open urban areas. The list of threats considered in this analysis includes primary, secondary, tertiary, residential, and service roads; railways; intensive and extensive agricultural areas; and buildings, other artificial surfaces, or impervious soils. The mapping of the threats relies on open-source data obtained from OpenStreetMap (OSM), while the threat and sensitivity tables are drawn from Sallustio et al. (2017). The half-saturation constant is initially set to the default value of 0.5 and subsequently to half of the maximum habitat degradation value determined by the model in the first run.

In relation to CSS, the assessment and spatial quantification is carried out using the "Carbon Storage and Sequestration" model, part of the InVEST toolkit (Natural Capital Project, n.d.). The CSS model estimates total carbon stock in relation to four carbon pools: aboveground biomass (AB), belowground biomass (BB), dead organic matter (DM), and soil organic matter (SM). AB encompasses all living plant material located above the soil surface, whereas BB refers to the root biomass associated with the AB. DM comprises decomposing vegetative material such as leaf litter and dead wood. SM, typically the largest carbon reservoir, consists of the organic fraction embedded in the soil.

This model has been employed across a wide range of geographical contexts and disciplines. For instance, García-Ontiyuelo et al. (2024) applied it to estimate carbon sequestration in coastal forest ecosystems in southern Galicia, thereby informing strategies for sustainable forest management. Similarly, Rachid et al. (2024) used the model to assess the climate regulation potential of urban green spaces in the City of Nador, aligning the findings with local climate policy objectives.

The implementation of the CSS model necessitates two primary input datasets: i., a table in .csv format that contains carbon density values (expressed in megagrams per hectare) associated with each land cover class for one or more carbon pools; ii., a land cover map.

In the present analysis, three carbon pools (AB, DM, SM) were modelled using the InVEST model. BB values were subsequently integrated by superimposing the model outputs with the global carbon dataset developed by NASA's Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), allowing for the aggregation of carbon values.

The carbon density figures used in the .csv file were derived from a range of validated sources. For AB and BB, data were obtained from the global carbon maps provided by NASA's ORNL DAAC. The National Inventory of Forests and Carbon Sinks (2015 edition) was referenced for AB and DM, and the 2005 edition for SM. Additional SM-related data were sourced from the Italian Institute for Environmental Protection and Research (ISPRA) and the Regional Agricultural Research Agency of Sardinia (Agenzia Regionale per la Ricerca in Agricoltura della Sardegna). Land cover classification was based on the 2018 Corine Land Cover (CLC) dataset, made available through the Copernicus Program.

2.3 Hotspot delineation

Following Bagstad et al. (2017), the numerous methods for detecting hotspots can be categorized into three types: approaches based on i., indices of spatial autocorrelation; ii., quantile rankings, or, iii., area. Additionally, various strategies have been proposed for delineating multi-service hotspots (Schröter & Remme, 2016). The identification of hotspots is method-dependent, with differing techniques often producing divergent results (Schröter & Remme, 2016; Bagstad et al., 2017), and "interesting locations" are those that consistently emerge as clusters regardless of the chosen approach (Anselin, 2024). Consequently, four distinct methods are here applied to delineate hotspots for individual ESs: LISA, its median variant, the Getis-Ord G* statistic, and a quantile-based approach.

LISA encompasses a class of statistical measures that assess the degree of significant spatial clustering of similar attribute values surrounding each observation (Anselin, 1995). In GeoDa (Anselin, 2024), LISA is operationalized through a localized version of Moran's I, with a moving window centered on each spatial unit; the window's dimension and shape is determined by the selected contiguity criterion. The outcome is a cluster map that classifies spatial units, at specified levels of statistical significance, into three categories: hotspots, coldspots, and spatial outliers, depending on whether the values within a given spatial unit and its neighboring units are above or below the mean value. A variant of this approach is the median LISA statistic, which substitutes the mean with the median value to mitigate the influence of outliers.

The third spatial statistic here employed is the local G* index, defined as the ratio between the sum of values within this window and the total sum of values across the entire dataset (Getis & Ord, 1992; Ord & Getis, 1995). Like LISA, the G* statistic operates through a moving window centered on the focal spatial unit; unlike LISA, the G* statistic exclusively identifies hotspots and coldspots, omitting spatial outliers (Anselin, 2024).

The fourth approach utilized is a quantile-based one, with a threshold set at the 90th percentile, thus designating as hotspots the top-richest cells.

A four-step procedure was implemented. Fists, a vector-based grid comprising 200*200-meter square cells, encompassing the two designated study areas, was developed and the average values of the three selected ESs were calculated for each cell and assigned as attributes using zonal statistics. The cell size was empirically chosen to optimize resolution and processing efficiency. Next, the four hotspot detection techniques were independently applied to each ES for both study areas, resulting in four distinct hotspot maps for each ES. The third step entailed intersecting the four hotspot maps corresponding to each ES. Finally, a further intersection was conducted to identify multi-service hotspot cores.

3. Results

3.1 The spatial distribution of ecosystem services

This section examines the spatial patterns of the three selected ESs across the Campania and Basilicata regions.

The spatial distribution of LST varies across the two regions.

In Basilicata, only one image (Landsat scene 188, row 32) suffices to cover the regional territory. Among the analyzed images, the one having the highest mean value, dating July 18, 2023, was chosen; on that day, LST values ranged from 24.42 °C to 62.54 °C, and their spatial layout is provided in Fig.2. Higher temperatures are concentrated in industrial, commercial, and agricultural zones in the northeast, notably the Bradano River basin (Alto Bradano, Venosa, Vulture Hills), and the urban area of Matera. High LST values are also found on the Metapontino Plain and Ionian coast. Cooler values are recorded along the Lucanian Apennines, particularly near Mount Vulture, Mount Volturino, and the Pollino National Park. Once the 2018 CLC map is overlaid, the highest mean LSTs (48.04–49.10 °C) occur in irrigated cropland (CLC 212), heterogeneous agriculture (CLC 241), and artificial surfaces (CLC 111, 121). The lowest (32.61–37.59 °C) are found in water bodies (CLC 512), forests (CLC 311, 313), and rocky areas (CLC 332).

Campania's LST map was generated by merging Landsat scenes 189 (west), rows 31-32, dating July 17, 2023, and 190 (east), rows 31-32, dating August 25, 2023. Regional LSTs range from 27.5 to 64.5 °C, and their spatial layout is provided in Fig. 2. Values peak in urbanized zones of the northwest, including Naples' coastal hills, the Campanian and Phlegraean plains, and around the Vesuvius crown. High temperatures also occur in agricultural zones of Avellino and Benevento (Alto Tammaro and Alto Fortore) and Salerno's Sele Plain. Cooler LSTs are observed in the mountainous Apennine belt; the highest mean LSTs (47.6–53.3 °C) occur in artificial areas (CLC 111, 112), while lower values (34.3–39.4 °C) are typical of water bodies, forests (CLC 311-313), and herbaceous vegetation (CLC 323-324).

As for HQ, the habitat quality level varies across the two regions (Fig.3). The average value for Basilicata is 0.51, while for Campania it is 0.49. Low levels characterize 44.45% of Basilicata and 40.61% of Campania, while medium values are found in 19.50% of Basilicata's territory and 27.96% of Campania's. In contrast, superior levels are found in 36.05% of Basilicata and 31.43% of Campania. The highest levels are observed in natural environments, which frequently overlap with designated protected areas. Noteworthy examples are the National Parks of Pollino and Appennino Lucano Val d'Agri Lagonegrese; the Regional Park of Gallipoli Cognato and the Piccole Dolomiti Lucane; the Vulture Regional Natural Park; and the Matera Rupestrian Churches Archaeological, Historical, and Natural Regional Park in Basilicata. Vallo di Diano e Alburni National Park, Vesuvius National Park, Valle delle Ferriere State Reserve, Picentini Mountains Regional Park, Partenio Regional Park, Taburno Camposauro Regional Park, Roccamonfina-Foce Garigliano Regional Park, and Matese Regional Park are also remarkable instances in Campania. Conversely, the lowest levels mostly concern anthropized areas including both urban zones and agricultural lands. In Basilicata, low values are identified within the urban areas of Potenza and Matera, as well as in the agricultural lands of the Metapontino, Agri, Vulture Melfese, Alto Bradano, Sauro, and Ofanto Valley regions.

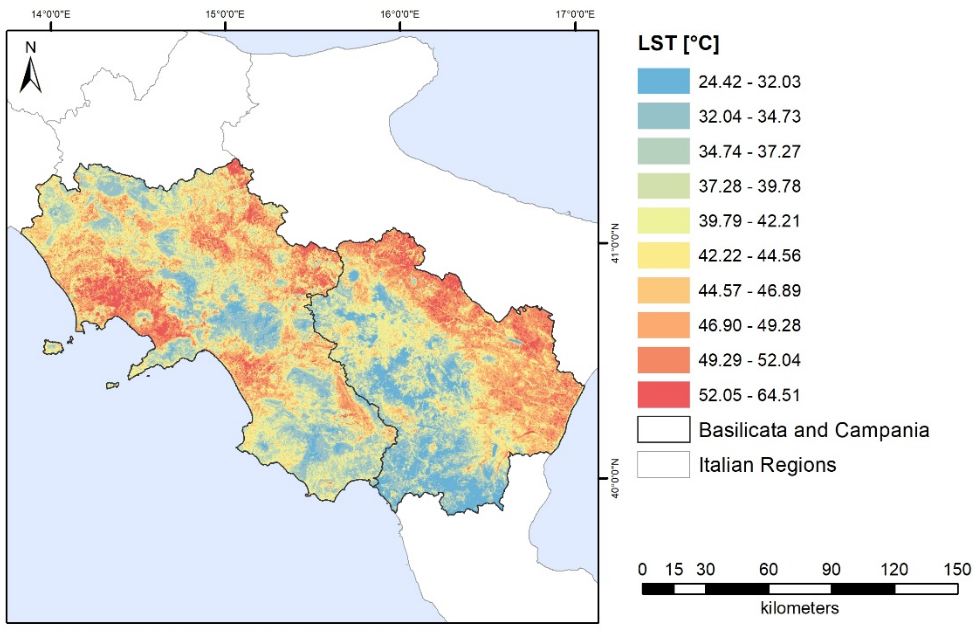

Fig.2 Spatial pattern of LST on the hottest day of Summer 2023 in Campania and Basilicata (dates vary by region)

Similarly, in Campania, poor habitats characterize the urban areas of Naples, Salerno, Caserta, Benevento, and Avellino, as well as the agricultural areas of the Sele Plain, the Acerrano-Nolano Agro, the Nocerino-Sarnese Agro, the Ufita Valley, the Coastal Cilento Hills, and the Taburno Mountain-Telesina Valley. With reference to habitat types, broadleaved forests, grasslands, and wetlands exhibit the highest levels of habitat quality, while buildings and other artificial areas or impervious soils, open urban areas, and intensive agricultural lands show the lowest levels. Meanwhile, conifer forests, water bodies, beaches, dunes, and sands, extensive agricultural land, and inland unvegetated or sparsely vegetated areas present intermediate levels of progressively lower habitat quality.

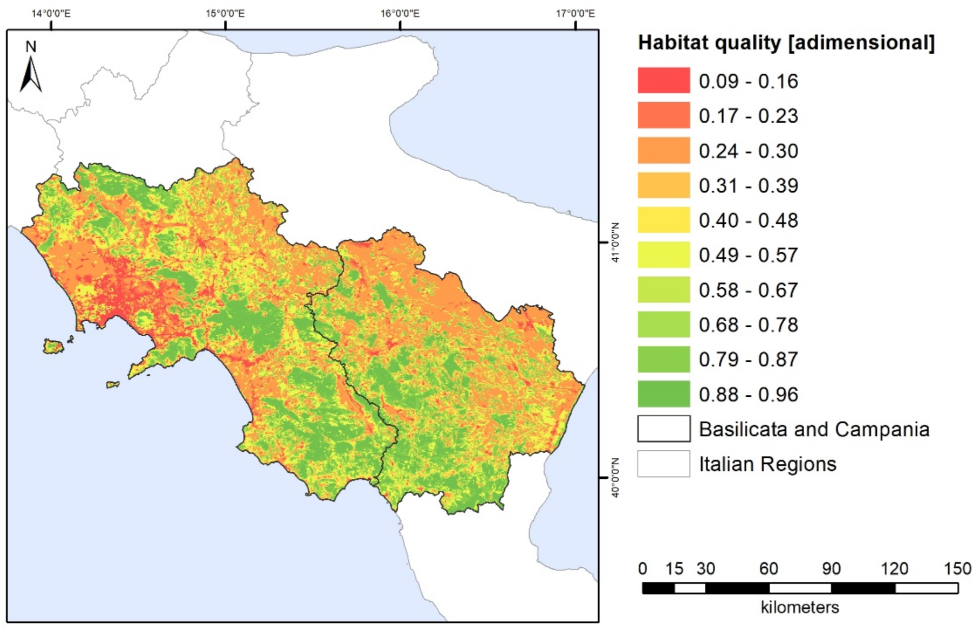

Fig.3 Spatial distribution of Habitat quality (HQ) in Campania and Basilicata

Fig.4 presents carbon storage values, expressed in megagrams per 900 square meters (Mg/900 m^2), across the Basilicata and Campania regions. In relation to Basilicata, CSS values range from 0 to 19.11 Mg/900 m^2. Three high-density clusters are located in the northeast, near Mount Santa Croce, Bosco Grande, and the protected areas of Monticchio Lake and Grotticelle. Two smaller clusters appear in central Basilicata, in proximity to the Pollino and Appennino Lucano National Parks and the Regional Parks of Gallipoli Cognato and the Lucanian Dolomites. The southwest shows moderately high values without distinct clustering, while the eastern sector displays the lowest values, especially near urban and aquatic zones. The highest average values correspond to forest classes (CLC 311, 312, 313), ranging from 13.3 to 11.6 Mg/900 m². Intermediate values (7.9–7 Mg/900 m^2) are linked to salt marshes, salines, shrubs, sparsely vegetated areas, and pastures. Agricultural lands exhibit lower values (6.8–3.4 Mg/900 m^2), while artificial areas and water bodies show the lowest carbon storage levels. In relation to Campania, carbon storage values range from 0 to 21.54 Mg/900 m^2. Two major clusters are observed in the southern and central zones, with smaller ones in the north. High carbon densities are concentrated in protected areas, including the Roccamonfina-Garigliano, Matese, Taburno-Camposauro, Trebulani Mountains, and Partenio Regional Parks in the northwest; Vesuvius National Park, Tirone Alto Vesuvius Reserve, and the Lattari, Picentini, and Eremita-Marzano Mountain parks in the center; and the Cilento and Vallo di Diano National Park in the south. The highest average values are recorded in broad-leaved, coniferous, and mixed forests (CLC 311, 312, 313), ranging from 15.82 to 13.7 Mg/900 m². Moderately high values (9.46–7.5 Mg/900 m^2) are associated with sparsely vegetated areas, burnt zones, natural grasslands, sclerophyllous vegetation, transitional woodland-shrub, pastures, and marshes. Artificial surfaces and water bodies exhibit the lowest values, typically below 1 Mg/900 m².

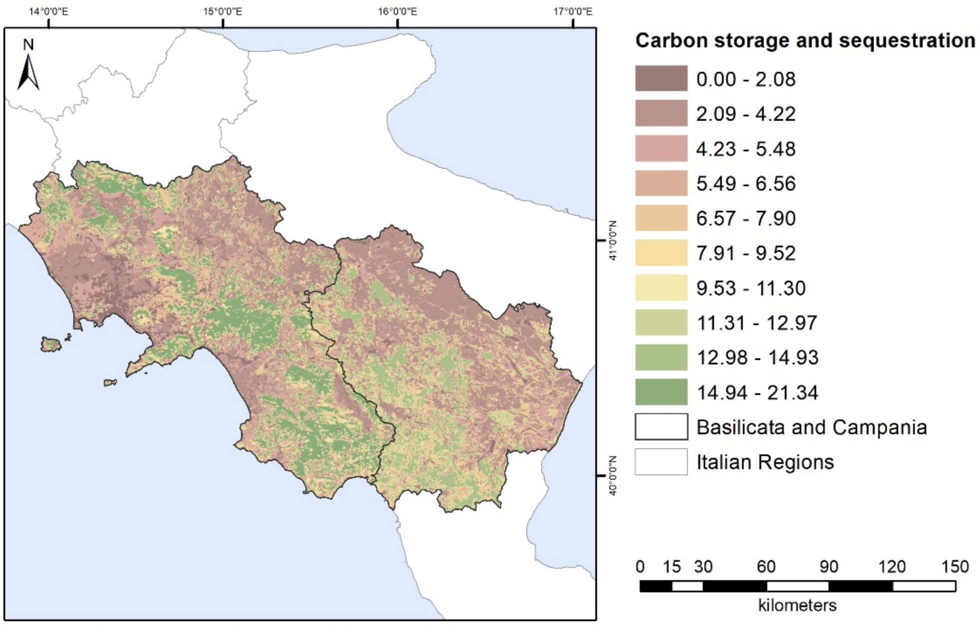

Fig.4 Spatial layout of Carbon storage and sequestration (CSS) in Campania and Basilicata

3.2 Ecosystem service hotspots

Fig.5 presents the results of the hotspot analysis, illustrating the spatial distribution of individual ESs hotspots (panels A-C) and multi-service hotspots (panel D), that is, areas simultaneously identified as hotspots for all three ESs discussed in Sections 2.2 and 3.1. In Campania, approximately 9.8% of grid cells were classified as hotspots for the three regulating ESs when considered individually. In Basilicata, 9.7% of cells were hotspots for CSS and HQ, increasing to 9.9% for local temperature mitigation. In contrast, multi-service hotspots accounted for only 4.058% in Basilicata and 4.686% in Campania.

Fig. 6 provides a more detailed view of ES hotspot interactions. Panel A distinguishes between single- and multi-service hotspots, specifying which ESs each cell supports as a hotspot core, whereas panel B offers a synthetic index, expressing the number of ESs for which each cell functions as a hotspot core. Quantitative information on categories shown in Fig.6 is provided in Tab.1.

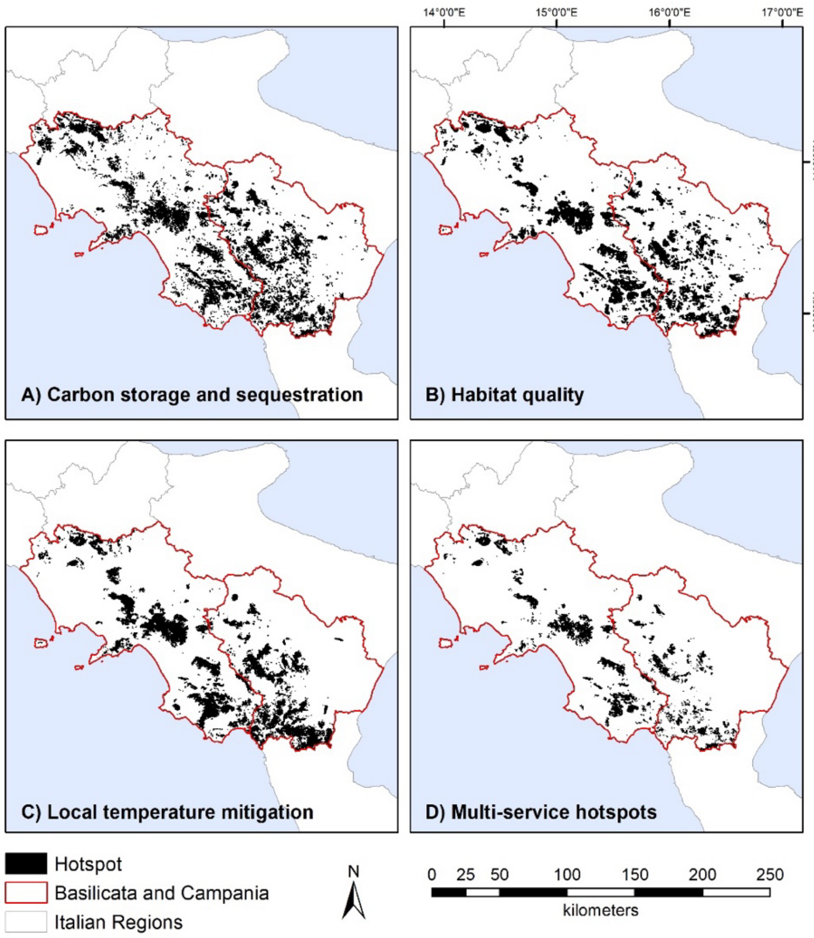

Fig.5 Spatial distribution of individual hotspots (panels A, B, and C) and of hotspot cores for the three ESs (panel D)

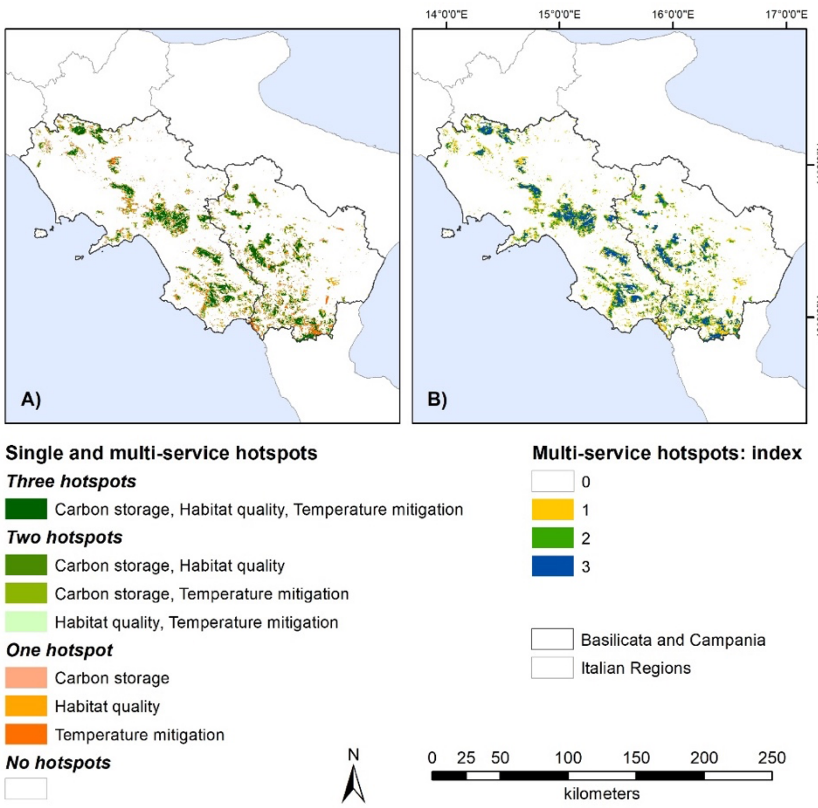

Fig.6 Single and multi-service hotspots (panel A) and a synthetic index of multi-service hotspots (panel B)

Index	Combination of ESs for which a cell performs as hotspot core	Basilicata (% of cells)	Campania (% of cells)
3	Carbon storage & Habitat quality & Local temperature mitigation	4.058 %	4.686 %
2	Carbon storage & Habitat quality	2.353 %	1.912 %
	Carbon storage & Local temperature mitigation	1.326 %	1.179 %
	Habitat quality & Local temperature mitigation	1.371 %	1.670 %
1	Carbon storage only	1.997 %	2.094 %
	Habitat quality only	2.001 %	1.689 %
	Local temperature mitigation only	3.238 %	2.451 %
0	*No significant hotspots*	83.655 %	84.318 %

Tab.1 Multi-service hotspot index and relevance of each multi-service combination in Basilicata and Campania

4. Discussion

The identification and spatial characterization of ES hotspots have become increasingly common in recent literature, as they provide a spatially explicit foundation for prioritizing conservation, land-use planning, and ecosystem-based management. This study, which reveals a relatively low co-occurrence of regulating ESs in multi-service hotspots in Campania and Basilicata (around 4–5% of the landscape), aligns with a growing body of research suggesting that multifunctionality is relatively rare in many socio-ecological systems (e.g., Fratini, 2023).

A comparable result was found by Qiu & Turner (2013), who analyzed ES bundles in the Yahara Watershed, in the US, and found limited spatial overlap of regulating services, with synergistic effects highlighted for carbon storage, regulation of water quality and of soil erosion. Similarly, Ran et al. (2020) identified trade-offs and synergies across three regulating ESs in southwestern China and observed negligible percentages of multifunctional landscapes, providing all of the three selected ESs. Studies that report higher degrees of spatial congruence among regulating ESs are often situated in ecosystems with extensive natural or semi-natural land cover. For instance, the study by Felipe-Lucia et al. (2018) found that regulating ESs frequently co-occur in forests, suggesting that ecosystem integrity plays a crucial role in enabling ES synergies.

The moderate congruence unveiled in this study is therefore consistent with previous global research. Moreover, Mediterranean landscapes, such as Basilicata's and Campania's ones, are often fragmented (Zullo et al., 2015), characterized by mosaics of forest, shrubland, farmland, and urban settlements, each contributing differently to individual ESs, which might explain the relatively low proportion of multi-service hotspots landscape as a reflection of the trade-offs between human land use and ecosystem functionality (DeFries et al., 2004), a phenomenon well documented in the European context. One factor that might be contributing to the moderate convergence across ESs in Basilicata and Campania is their sensitivity to underlying physical characteristics, as the two regions are heterogeneous in terms of topography, climate, soil characteristics, and land covers: as Crouzat et al. (2015) show, landscape heterogeneity can promote ecosystem multifunctionality at the regional scale, but such services often occur in separate patches due to specialization in land use and management. This could explain why, in the two analyzed regions, single service hotspots are distributed across the landscape, but the level of hotspot overlaps remains moderate.

A second factor to be considered is land management. In Campania, extensive urbanization and industrial agriculture have led to land-use specialization in large parts of the region, resulting in spatial concentration of regulating ESs in areas that are marginal for agriculture. Moreover, in Basilicata a strong difference between the eastern and western parts is highlighted: lower population density and prevalence of extensive pastoralism and traditional agricultural practices to the west have possibly contributed to preserving some degree of multifunctionality, leading to the western hotspot clusters. These patterns align with findings from a study by Foley et al. (2005), who observed that intensively managed landscapes tend to sacrifice regulating ESs in favor of provisioning ones.

The results of this study provide relevant implications for spatial planning and policy: since only a very small percentage of the landscape functions as multi-service hotspots, both land protection and ecosystem enhancement strategies need to be considered, depending on whether the area to be planned or managed performs as a single or multi-service hotspot, or is not identified as a hotspot at all.

From a conservation planning perspective, multi-service hotspots represent high-value targets due to their concentrated ecological benefits: to put it with Raudsepp-Hearne et al. (2010), areas that provide multiple regulating ESs are more resilient. As a result, they can provide larger long-terms returns for conservation investment (Kovacs et al., 2013) and could be therefore prioritized for public land purchasing, or for strict conservation as natural protected areas, or for protection in landscape plans (Cialdea, 2021) pursuant to the European Landscape Convention[3].

The large proportion of cells classified as non-hotspots in both Basilicata and Campania suggests a vast potential for ES enhancement through targeted interventions. Spatial planners could use hotspot maps such as the ones here produced to guide green infrastructure (GI) identification in local and regional plans, with single or multi-service hotspots serving as nodes of the GI, hence as priority zones to be connected through appropriate ecological networks. To this end, peri-urban zones or degraded rural landscapes not identified as ES hotspots could be managed to improve their ES supply by increasing tree cover, or by enhancing green connectivity through treed roads, hedgerows, or vegetative riverbanks and buffers. At the municipal scale, hotspot delineation could be integrated into local development plans to guide the siting of public green spaces, for instance to maximize the potential uptake of ESs by bridging areas rich in ES supply with demanding areas, i.e., residential zones, or within sectoral plans, as in the case of the urban greenery plan of the municipality of Trento (Comune di Trento, 2024, pp.75-80), a pioneering example of hotspot mapping integration in spatial planning. This is consistent with Lovell & Johnston (2009), who advocate for multifunctional landscapes that integrate ESs into spatial design, rather than confining them within designated conservation zones. Moreover, the findings could inform strategic environmental assessments (SEA) and environmental impact assessments (EIA) by providing a spatial baseline of ES provision: in this context, proposed development or infrastructure projects could be evaluated in relation to their interference with ES hotspot maps, thereby facilitating the integration of ecological costs into planning decisions.

5. Conclusions

This study combines established biophysical modelling with a comprehensive suite of spatial statistical techniques to define a two-phase methodological framework for the identification of regulating ES hotspots, which are areas of high ecological value due to their simultaneous provision of elevated levels of ESs. In the first phase, three key regulating ESs, CCS, HQ, and LST, are assessed using satellite data and InVEST models. In the second phase, individual and multi-service hotspots are identified through a four-step integration of four statistical methods, i.e., LISA, median LISA, the local G*, and the quantile-based segmentation. The application of the methodology to Basilicata and Campania provides important insights.

The results reveal that single-service hotspots are widely distributed across the landscape; however, the spatial overlap among them remains moderate, confined to roughly 4–5% of each region. This limited overlap is likely due to landscape fragmentation and land-use practices that foster specialization, ultimately generating trade-offs between human land use and ecosystem functionality, and causing the spatial separation of individual ESs. Since this study captures a single point in time, future research could assess how the distribution and size of hotspots change over time, ideally complemented by a longitudinal analysis of the driving factors, such as urbanization and shifts in both intensive and extensive agricultural practices. This latter aspect is particularly

[3] https://rm.coe.int/16807b6bc7 (last accessed 2025/06/25)

significant, from a policy perspective, for marginal rural areas and mountain villages affected by depopulation and farmland abandonment.

The approach here proposed offers a valuable evidence-based tool for spatial planning and decision-making. Indeed, the identification of ES hotspots allows for both the definition of conservation efforts to preserve their ecological functions, and the development of policies aimed at enhancing their functionality and increasing the services they provide. Conservation efforts should prioritize landscapes delivering multiple ESs, whereas non-hotspot zones represent strategic opportunities for ecosystem enhancement. In order to balance conservation and sustainable land use, ESs should also be incorporated into spatial plans, SEA, and EIA. As shown in Section 3, several regulating ES hotspot cores are already located within established natural protected areas, such as national and regional parks. Future research could therefore examine whether, and to what extent, the existing planning tools for these protected areas take ESs and GI into account. Analyzing the relevant planning provisions related to hotspot areas would also be valuable, as it could offer insights into their potential future evolution.

More in-depth research is required to better understand the specific drivers and spatial factors contributing to the observed low spatial overlap of regulating ESs, thus enabling more targeted and effective planning interventions. Furthermore, future research might include additional regulating ESs, as well as provisioning and cultural ESs to offer a comprehensive understanding of ES interactions.

The demonstrated applicability of the methodology across two Italian regions highlights its adaptability to other contexts where similar input datasets are available. Applying it to different contexts and integrating it with socio-economic data would further increase its role in promoting climate neutrality and adaptation to climate change while fostering development and well-being.

Authors' contributions

F.I., S.L., F.Leccis and F.Leone collaboratively designed this study. Individual contributions are as follows: F.I. wrote Section 2.1; S.L. wrote Sections 2.3, 3.2, and 4; F.Leccis wrote Section 5: F.Leone wrote Section 1. F.I., F.Leccis and F.Leone jointly wrote Sections 2.2 and 3.1.

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Image sources

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