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Regenerative Design - Climate Adaptation & Mitigation - Circular Economy - Citizen Agency - Urban Livability

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Laboratory of Land Use, Mobility and Environment
DICEA - Department of Civil, Building and Environmental Engineering
University of Naples Federico II
Piazzale Tecchio, 80
80125 Naples (Italy)

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REVIEW NOTES

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ROCCO PAPA
DICEA - Department of Civil, Building and Environmental Engineering
University of Naples Federico II, Italy
ORCID: https://orcid.org/0000-0003-3355-1418
e-mail: rpapa@unina.it

TeMA Journal was founded in 2007 with the principal objective of fostering and integrating studies on urban transformation and urban mobility in all their aspects, within a scientific context focused on adapting cities to global warming and oriented towards economic, social and environmental sustainability. The journal also addresses studies on hyper-connectivity, algorithmic governance, infrastructure durability, social equity and inclusion, and intergenerational justice. In other words, the mission of this initiative is to contribute to the development of a novel theoretical and methodological framework that transcends the boundaries separating these research domains, and to develop innovative solutions to the issues of 21st-century cities, addressing them again using methods and techniques rooted in the scientific culture of the last century.

The three issues of the 2026 volume of TeMA Journal propose articles that deal with the effects of Global warming, climate change adaptation, reduction of energy consumption, AI-driven solutions to support urban governance and transformation, immigration flows, optimisation of land use, analysis and evaluation of civil protection plans in areas especially vulnerable to natural disasters.

In this issue, the section "Focus" contains two studies. The first paper "The impact of Land Use and Land Cover (LULC) changes on coastal dynamics through landscape structure", by Makbulenur Onur (Karadeniz Technical University in Turkey), analyzes how land use and land cover (LULC) changes influence coastal landscape structure and user perception, this study compares two neighboring beach areas in Budva, Montenegro, one impacted by LULC change and the other largely maintaining its natural state.

The second contribution "Spatial and temporal evolution of urban reserve available land resources in the Karst region of North China from 1990 to 2020: a case study of Jinan city", by Shujin Wang, Shanzhong Qi (Shandong Normal University in China), investigates the spatial and temporal evolution of urban reserve available land resources in Jinan City, a representative karst region of North China, over the period 1990-2020 using integrated RS-GIS methods.

The section "LUME" includes nine studies. The first contribution of the section "Assessing urban growth and pollution through nightlight data: a case study in Thailand", by Chaichana Kulworatit, Phuvis Kerdpramote, and Saranya Saetang (King Mongkut's Institute of Technology Ladkrabang and Kasetsart University Kamphaeng Saen Campus in Thailand), aims to explore the relationship between urban development and air pollution in Thailand by analyzing remote sensing nightlight data and carbon monoxide (CO) concentrations over six years (2019-2024).

The second contribution of the section "Exploring governance challenges in coastal and marine tourism. A comparative analysis of European case studies", by Barbara Gasparini di Gaetano, Emanuel Giannotti, Vittore Negretto, and Denis Maragno (IUAV University of Venice in Italy), deals with land-sea interactions in spatial planning, particularly referring to tourism-intensive coastal areas where environmental protection and economic development collide. The paper focuses on the recently adopted Italian Maritime Spatial Plan and its application in the Friuli Venezia Giulia region also by the analysis of three coastal and marine contexts (Port-Cros National Park in France, Puck Bay in Poland, and the island of Crete in Greece) and concludes emphasizing the role of institutional coordination, participation, and administrative capacity for the implementation of maritime spatial planning.

The third contribution of the section "Dynamic map decision support systems for spatial and mobility planning" by Mara Ladu, Ginevra Balletto, Tanja Congiu, Gianfranco Fancello, and Ernesto Fontes Pupo (University of Cagliari and University of Sassari in Italy) proposes a decision support system architecture to support the Mobility as Service in Sardinia region, integrating geospatial datasets covering mainly demographic and socio-economic aspects, the supply of key services, and the provision and demand for transport, as well as the spatial distribution of tourist flows and related externalities, to offer a holistic perspective on local and regional transport needs, opportunities, and gaps.

The fourth contribution of the section "Biodiversity and ecological network: connecting ecosystem services for a sustainable future. GeoAI for Modica green city" by Celestina Fazia and Chiara Spadaro (University of Enna "Kore" in Italy) investigates the role of ecological networks and ecosystem services as strategic infrastructures for enhancing urban resilience and biodiversity. The Modica Green City Masterplan, supported by GeoAI and GIS tools, demonstrates how integrated, ecosystem-based planning can guide sustainable urban transformation. The study highlights the value of digital and participatory approaches aligned with EU cohesion policies and Agenda 2030 to support climate adaptation and territorial regeneration.

The fifth contribution of the section "Examining the temporal and spatial change of current land cover types in Demre District using machine learning" by Sibel Akten, Hüseyin Batuhan Dündar, and Atila Gül (Isparta University of Applied Sciences and Süleyman Demirel University in Italy) analyzes the temporal and spatial changes in current land use types in Demre district of Antalya Province and to establish a foundation for future land management studies, was supported by multispectral satellite images obtained from the Landsat 5- Thematic Mapper and Landsat 8- Operational Land Imager remote sensing satellites.

The sixth contribution "Evaluating urban fabric transformations using GeoAI", by Alessandro Vitale (University of Calabria in Italy) proposes a GeoAI-based framework that integrates Random Forest (RF) classification with spatial indicators to analyze urban fabric transformations in Ravenna, aiming at demonstrating how combining supervised classification with spatial metrics can provide deeper insights into urban growth, supporting more informed planning and policy.

The seventh article "CITISENSE. Enhancing urban well-being through smart design, data and AI in Italy's historic centres", by Pierfrancesco Celani, Daniel Enrique Sardo, Massimo Zupi, Margherita Tufarelli, and Adriano Bisello (University of Calabria, University of Florence and Jakala Civitas S.p.A in Italy and Universidad Jesuitica de Guadalajara in Mexico) examines how GeoAI-enabled urban analysis and participatory design methodologies can enhance urban well-being while preserving cultural heritage in small and medium-sized historic centres. The research develops a replicable methodological framework combining advanced technologies (AI, big data, wearable devices) with Living Lab participatory processes.

The eighth article "Planning for sustainable tourism in protected areas. A policy-oriented spatial evaluation framework" by Rachele Vanessa Gatto, Francesca Perrone, and Francesco Scorza (University of Basilicata and Sapienza University of Rome in Italy) introduces the Robustness Supply Tourism Index (RSTI), a robust tool to assess the infrastructural balance of tourism destinations within protected areas. The study focuses on the Appennino Lucano Val d'Agri Lagonegrese National Park in Italy, where the Specialized Tourism EcoSYstems model was implemented to define Destination Areas, and the RSTI was applied to assess the distribution of tourism infrastructure supply within these areas.

The last article "Monitoring urban dynamics using Google Earth and GeoAI", by Francesco Lamonaca (University of Calabria and National Research Council Institute of Nanotechnology in Italy), presents an innovative measurement method based on Google Earth Engine and Unsupervised K-means Clustering of multispectral satellite images to map urban and vegetation shifts. The proposed method was applied in 15 southern Italian cities, and the results were validated with the ESA Land Cover dataset. Results show 167 hectares consumed from 2005 to 2021.

The Review Notes section proposes six insights on the themes of the TeMA Journal.

The first Review Notes is entitled "Brain gain in planning academia: learning from Albania's practical approaches", authored by Irina Branko, Erida Curraj, and Dorina Pojani. The RN presents two successful "brain gain" initiatives implemented in Albania: READ, a planning research project, and GERMIN, a planning education project. Both programs represent structured efforts to mobilise diaspora expertise in order to strengthen higher education, research, and professional practice, addressing capacity gaps intensified by the prolonged emigration of skilled professionals.

The International Regulation and Legislation for the Energy Transition section of Review Notes is entitled "Digital governance of the energy transition: regulatory frameworks, data infrastructures, and spatial planning", authored by Valerio Martinelli. The RN analyzes how the EU directives are redefining the operational framework of territorial planning through binding interoperability and digital infrastructure requirements. It concludes with a reflection on the evolutionary role of the urban planner as a mediator between legislation, data ecosystems and territorial transformation.

The Urban Strategies, Programmes and Tools section of Review Notes is entitled "Governing the transformations of public space: active travel policies for people's health and well-being", authored by Annunziata D'Amico, analyzes international tools and strategies for transforming public spaces into environments geared toward active mobility. Urban design focused on daily walking and cycling promotes collective well-being by integrating public health, environmental sustainability, and the quality of the built environment

The Urban Practices section of Review Notes is entitled "Soft Adaptation Measures for Disaster Risk Reduction and Urban Resilience. Early Warning Systems", authored by Stella Pennino. The RN on Urban Practices examines the role of Soft Adaptation Measures in Disaster Risk Reduction (DRR) and Urban Resilience. It discusses the functioning of Early Warning Systems (EWS) and their relevance for Urban Planning. Three illustrative case studies are presented to highlight reproducible urban practices and potential future developments.

The Urban planning literature review section of Review Notes is entitled "Modelling microclimatic characteristics for climate change adaptation solutions: the ENVI-met simulation tool", authored by Tonia Stiuso, provides a comprehensive overview of the ENVI-met simulation tool, focusing on its methodological framework and operational potential in the field of climate change adaptation. Using a variety of scientific sources and practical resources.

The Urban planning literature review section of Review Notes is entitled "Adaptation insight: the state of climate knowledge", authored by Laura Ascione. This first contribution is dedicated to a review of reports on the state of knowledge on climate change in terms of emerging risks, observed impacts, and the conditions of vulnerability that amplify its effects in different territorial and social contexts.

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The impact of Land Use and Land Cover (LULC) changes on coastal dynamics through landscape structure

Makbulenur Onur

Department of Landscape Architecture, Forest Faculty,
Karadeniz Technical University, Trabzon, Turkiye
e-mail: mnurbekar@ktu.edu.tr
ORCID: https://orcid.org/0000-0003-4511-1284

Abstract

Coastal areas are dynamic environments shaped by the interaction between natural processes and human activities. Rapid urbanization and land use transformations increasingly threaten the ecological integrity and spatial structure of coastal landscapes. In this context, this study aims to examine the impacts of land use and land cover (LULC) changes on coastal landscape structure and user perception through a comparative analysis of two adjacent beach areas in Budva, Montenegro—one affected by LULC change and another largely preserving its natural structure. The research integrates a multi-criteria decision-making framework and perception-based analysis. The Analytic Hierarchy Process (AHP) was employed to evaluate the relative importance of ecological and functional landscape criteria, including coastal protection capacity, biodiversity contribution, aesthetic value, and public usability. In addition, user perception data were analyzed using SPSS statistical methods, including correlation analysis and one-sample t-tests. The findings reveal that coastal areas maintaining their natural characteristics perform better in terms of ecological functionality and user satisfaction. Criteria related to coastal protection and biodiversity received the highest importance in the AHP evaluation, while statistical analyses indicated strong relationships between ecological attributes and user perception variables. Overall, the results highlight the importance of integrating ecological indicators and user perception into coastal landscape planning. The study emphasizes the role of nature-based solutions and multi-criteria evaluation approaches in supporting sustainable coastal management and improving the resilience of coastal environments.

Keywords

Climate action; Sustainable development; Coastal dynamics; LULC

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1. Introduction

Throughout the twentieth century, significant urban developments have altered land use and land cover (LULC) through various human activities (Moniruzzaman et al., 2021), making LULC one of the most influential factors affecting human life (Zarin & Esraz-Ul-Zannat, 2023). LULC refers not only to how a given area is utilized for purposes such as agriculture, conservation, development, recreation, wildlife habitats, and urban uses, but also to the outcomes of human-environment interactions influenced by socioeconomic dynamics and climate change processes (Anand et al., 2024). Today, a large portion of the global population resides in urban areas, and this proportion is expected to increase further by 2050. As a result, urbanization has become a critical issue that must be addressed on a global scale (Kumar et al., 2025). Existing studies have examined the response to climate change and LULC changes (Gao & Ruan, 2018), revealing that urban expansion—particularly the rapid transformation of rural areas into commercial and residential land—is accelerating (Tariq & Shu, 2020). Changes in land use and land cover (LULC) are of vital importance for urban planning, environmental management, and sustainable development (Waleed & Sajjad, 2022; Farhan et al., 2024; Nuthammachot & Ali, 2025). A better understanding of LULC changes paves the way for analyzing the dynamics of urban growth (Gaur & Singhr, 2023). Therefore, knowledge of past, present, and future patterns of LULC significantly contributes to achieving sustainable development by informing urban planning, policy-making, and resilience-building strategies (Kumar et al., 2025). Recent studies also highlight that ecological landscape components and vegetation-based planning strategies play a critical role in improving environmental performance and ecosystem resilience in urban areas (Gulpinar Sekban, 2026). Recent research demonstrates that LULC dynamics are shaped by a diverse set of socioeconomic, institutional, and environmental drivers; for instance, studies conducted in Ethiopia and Iran reveal that land conversions from agricultural to forest or urban uses are largely governed by income expectations, land size, and local policy frameworks (Kebede et al., 2024; Ziari et al., 2025).

Today, with rapidly increasing population, urbanization trends, and evolving user needs, urban areas are under intense pressure from dense construction and functional transformation. This pressure accelerates the transformation of natural spaces and is particularly evident in sensitive ecosystems such as coastal regions. In this context, Land Use and Land Cover (LULC) changes emerge as a significant analytical technique for monitoring and evaluating these spatial transformation processes (Kumar et al., 2018). In addition to these pressures, the ecological structure of coastal environments can be significantly influenced by vegetation patterns and habitat structures, which regulate microclimatic conditions and environmental stability in urban landscapes (Onur & Gulpinar Sekban, 2026). Coastal environments are under considerable stress due to negative impacts such as climate change, infrastructure development, and human activities, which lead to coastal erosion, seawater intrusion, sea level rise, disruption of nutrient balance, and degradation of natural resources (Anand et al., 2024). In this regard, the integration of urban green spaces into spatial planning frameworks has been highlighted as a critical adaptation strategy; global city experiences indicate that green infrastructure not only mitigates urban heat but also contributes to energy savings and climate resilience (Ascione et al., 2025).

LULC (Land Use and Land Cover) analyses provide the ability to observe spatial-temporal changes, thereby offering critical data for environmental sustainability. At the root of these changes lie largely anthropogenic activities. Human-induced factors such as industrialization, tourism pressure, infrastructure investments, and urban sprawl cause significant and often irreversible physical and ecological impacts on the natural coastline. Beaches, in particular, are among the areas where this transformation is most acutely felt, due to their inherent natural structure and high level of interaction with human activities. From an ecosystem services perspective, urban green spaces and natural landscape components contribute to biodiversity conservation, climate regulation, and the overall environmental quality of cities (Gulpinar Sekban, 2025). Changes occurring along coastal routes lead to environmental problems such as erosion, habitat loss, and shoreline retreat, while simultaneously affecting the recreational, aesthetic, and social functionality of the region. Therefore, regular monitoring of LULC changes in coastal areas and analyzing the anthropogenic drivers behind these changes are of great importance for the development of sustainable coastal management policies. In this context, detailed spatial analyses will allow for the identification of current pressures and support the establishment of a balanced approach between conservation and use for the future. Evidence from urban functional areas further confirms that carbon sequestration and storage exhibit strong synergies with other regulating ecosystem services such as flood retention, local temperature regulation, and habitat quality, underscoring the value of integrating these services into coastal and urban land use planning (Lai & Zoppi, 2025).

1.2 State of research aim

Coastal landscapes are among the most dynamic environments, constantly shaped by natural processes and human interventions. In this context, understanding the implications of Land Use and Land Cover (LULC) changes on both ecological functions and social perceptions has become a central challenge for sustainable coastal management. While many studies focus separately on either the physical or social dimensions, there is still a lack of integrative approaches that combine expert knowledge, spatial analysis, and user perception within a unified framework.

The primary aim of this study is to evaluate how LULC changes affect the ecological integrity and perceptual quality of coastal areas, taking the Budva coastline in Montenegro as a representative case. The research seeks to bridge the gap between measurable landscape transformations and subjective user experiences by adopting a multidisciplinary methodology that combines spatial, environmental, and social data. Specifically, the objectives of the study are to:

1. identify and quantify spatial and temporal patterns of LULC changes along the Budva coastal zone using geospatial datasets and field observations;
2. assess expert evaluations on the environmental and visual impacts of these changes through a multi-criteria decision-making model based on the Analytic Hierarchy Process (AHP);
3. examine user perceptions regarding the aesthetic, functional, and recreational qualities of coastal areas using SPSS-supported statistical analysis of survey data;
4. determine the correlations between ecological parameters (such as coastal protection capacity, biodiversity potential, and carbon sequestration) and user-based variables (including awareness, preference, and satisfaction);
5. develop an integrated evaluation framework that combines expert judgments and user perceptions to support evidence-based coastal management and planning.

By combining the analytical precision of AHP with the interpretive depth of perception analysis, this study aims to contribute a comprehensive model for assessing coastal sustainability. The findings are expected to inform local authorities, planners, and researchers in designing strategies that balance ecological preservation with social well-being, ensuring that coastal development aligns with both environmental resilience and community values.

2. Methodology

2.1 Study area

The main material of this study is a beach located in Budva, situated along the Adriatic coast of Montenegro (Fig.1). Kotor, with its natural harbor and well-preserved medieval urban fabric, is a notable settlement both geographically and culturally. The Bay of Kotor, where Budva is located, stands out with its stunning natural landscapes, sea, and coastline. This natural allure attracts the interest of tourists (Radenovic, Tripkovic-Markovic, 2016). Budva is one of the largest and most popular holiday destinations on Montenegro's Adriatic coast. The unique geographical setting where the sea meets the mountains not only gives the city a striking natural beauty but also draws the attention of tourists. Having been under the rule of many civilizations throughout history, Budva has a rich cultural heritage as a result. It experienced significant development particularly during the Venetian period, and architectural structures from that era have survived to the present day. With its historical texture, natural beauty, and vibrant tourism scene, Budva continues to be one of the most prominent cities on the Adriatic (Hryniewicz et al., 2022).

Budva's landscape offers great visual richness through the striking contrast between exotic greenery and historical structures. The city's lively beaches, restaurants, sports facilities, and various entertainment venues blend modern living with natural beauty. Green spaces adorned with palm trees and tropical plants give the city a refreshing and vibrant Mediterranean atmosphere. These features make Budva stand out not only for its historical significance but also as a tourism destination renowned for its natural beauty (Hryniewicz et al., 2022).

The study area consists of two adjacent beaches. The first site is a beach that has not undergone any LULC (Land Use and Land Cover) changes. The second site, on the other hand, is a beach that has experienced LULC changes. These two contrasting sites form the primary material of the study. The contrasting characteristics of the areas are among the reasons for their selection as study sites. Both locations are actively functioning as beach facilities (Fig.1,2).

The classification of the two selected coastal areas as LULC-affected and non-affected was established through a rigorous combination of field observations and systematic spatial interpretation of high-resolution satellite imagery sourced from Google Earth Pro. Land use patterns, vegetation cover density, built-up surface extent, and overall landscape structure were carefully examined and comparatively evaluated across both adjacent beach sites. This dual-method approach ensured that the classification was grounded in both empirical on-site evidence and verifiable remote sensing data, thereby minimizing subjectivity in the delineation of study conditions. The two selected sites consequently represent clearly contrasting spatial conditions: one area largely retaining its natural coastal morphology, native vegetation, and ecological integrity, and another that has undergone measurable transformation through construction activities, impervious surface expansion, and land use intensification. This well-justified spatial differentiation forms the comparative foundation of the study and directly supports the validity of the subsequent AHP and SPSS analyses conducted across the two contrasting coastal landscapes.

Fig.1 Study area (Google Earth Pro)

Fig.2 Non LULC Area (1) and LULC Area

2.2 Methodology

The methodology of the study involves the use of AHP and SPSS analysis methods. The main objective of using AHP is to evaluate *which criteria and to what extent landscape elements in beaches that have not undergone LULC changes affect coastal dynamics and users*.

First stage: determination of objectives and criteria

In the first phase of the study, the main objective of the research was clearly defined. In line with this objective, a hierarchical criteria matrix was constructed in accordance with the Analytic Hierarchy Process (AHP) method. In the matrix, the top level represents the "goal," while the criteria aimed at achieving this goal are positioned at the lower levels. At this stage, the central research question of the study was defined as: *Which landscape combination contributes most positively to coastal dynamics?* To address this question, four alternatives representing different landscape forms were created for use in the AHP analysis. These alternatives are defined as follows: *Alternative 1: No LULC Change, Alternative 2: With LULC Change.*The perception survey was administered to a total of 211 participants who were visiting the study area at the time of data collection, representing a cross-section of active coastal users with direct experiential familiarity with the evaluated environments. Participants were selected through a purposive sampling approach, targeting individuals with firsthand exposure to both the LULC-affected and non-affected beach areas, thereby ensuring the contextual relevance and site-specificity of the collected perception data. The structured questionnaire comprised seven statements designed to capture respondents' environmental awareness, attitudes toward natural beach conservation, and dispositions regarding the implementation of nature-based solutions in coastal landscape management. Each statement was evaluated by participants using a five-point Likert scale, ranging from 1 — "strongly agree" to 5 — "strongly disagree", enabling the quantification of subjective perceptual responses into an ordinal measurement framework suitable for statistical analysis.

The collected data were subsequently processed and analyzed using SPSS statistical software. Pearson correlation analysis was applied to examine the strength and direction of relationships between the evaluated environmental perception variables, identifying statistically significant associations among respondents' attitudes toward ecological, aesthetic, and functional coastal attributes. In addition, a one-sample t-test was conducted to determine whether the mean perception scores of the respondents differed significantly from a predefined reference value, thereby allowing for an objective assessment of the overall direction and magnitude of user attitudes. A significance threshold of $p < 0.05$ was adopted throughout all statistical procedures. The combination of correlation analysis and hypothesis testing provides a robust and methodologically transparent basis for interpreting the quantitative dimensions of user perception within the broader analytical framework of the study.

In line with the multi-criteria decision-making structure of the AHP method, an initial pool of criteria was identified through a systematic literature review and expert consultations. Following a screening process to eliminate redundant and low-relevance criteria, 10 criteria were retained and integrated into the hierarchical AHP structure. These 10 criteria — spanning both ecological and socio-functional dimensions — were selected to ensure analytical focus and comparability across the two study sites (Fig.2, Tab.2). The relative importance of each criterion was evaluated using weights calculated through the AHP method. These weights revealed that it would be appropriate to group certain criteria under similar thematic categories (Fig.2). To more accurately analyze expert opinions, a specially designed comparison matrix was prepared for the experts. This matrix enabled the comparison of the relative importance levels between the criteria and enhanced the reliability of the study's findings (Fig.3).

A total of 20 domain experts participated in the AHP pairwise comparison process. The expert panel was composed of professionals from disciplines directly relevant to the research topic, including landscape architecture, urban planning, environmental engineering, and coastal ecology. All participants had a minimum of five years of professional or academic experience in their respective fields. The composition of the expert panel is summarized in Tab.1 below.

Expert Code	Field of Expertise	Academic/Professional Background	Years of Experience
E1	Landscape Architecture	Academic	10+
E2	Urban Planning	Practitioner	8+
E3	Coastal Ecology	Academic	12+

Tab.1 Expert panel

The Analytic Hierarchy Process (AHP) was employed as the primary multi-criteria decision-making method in this study, following the procedural framework originally established by Saaty (1980) and subsequently refined in later methodological contributions (Saaty, 2004). To determine the relative importance of each evaluated criterion, pairwise comparison matrices were systematically constructed on the basis of structured expert evaluations, in which domain specialists were asked to compare each criterion against all others with respect to its contribution to coastal landscape assessment. These comparisons were performed using Saaty's fundamental nine-point scale, where a value of 1 denotes equal importance between two criteria and a value of 9 indicates that one criterion is considered extremely more important than the other, with intermediate values representing proportional gradations of relative preference. The priority weights of the criteria were subsequently derived by computing the normalized principal eigenvector of each pairwise comparison matrix, a procedure that translates the relative judgments of experts into quantifiable and comparable weighting scores. To rigorously evaluate the internal reliability and logical consistency of the expert judgments, the Consistency Ratio (CR) was calculated for each comparison matrix.

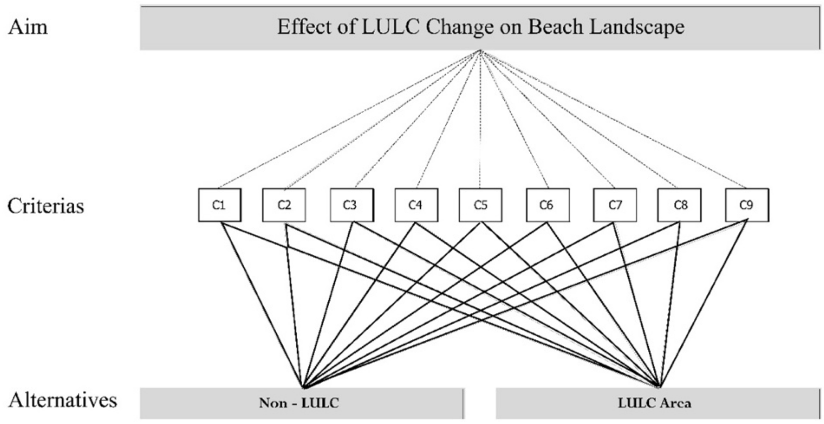


Fig.3 AHP Modelling

In accordance with the threshold established by Saaty (2004), a CR value below 0.10 is considered indicative of acceptable consistency, meaning that the expert comparisons do not contain contradictory or unreliable judgments that would compromise the validity of the derived weights. In the present study, the calculated inconsistency rate of 0.00075 falls substantially below this threshold, demonstrating an exceptionally high level of consistency among expert evaluations and thereby confirming the methodological soundness and reproducibility of the AHP-based weighting procedure applied throughout the analysis.

After determining the alternatives and objectives, the study proceeded to the next stage of the multi-criteria decision-making process. At this stage, a criteria matrix based on pairwise comparisons was developed within the framework of the Analytic Hierarchy Process (AHP) method. In the AHP analysis, comparisons of the criteria were carried out both among the criteria themselves (criterion-to-criterion comparison) and between all the defined alternatives for each criterion (alternative-to-criterion comparison) (Benítez et al., 2011; Yang et al., 2022; Chaube et al., 2024).

In the constructed comparison matrix, numerical scales were used based on expert opinions. On these scales: a value of 1 (Equal Importance) indicates that "both elements contribute equally to the objective," a value of 3 (Moderately More Important) means "one element is slightly preferred over the other," a value of 5 (Strongly More Important) indicates "one element is clearly preferred over the other," a value of 7 (Very Strongly More Important) suggests "one element is significantly more preferred," and a value of 9 (Extremely More Important) reflects "one element is overwhelmingly and indispensably preferred over the other." Intermediate values of 2, 4, 6, and 8 are used to express relative preferences between two successive fundamental values. This scaling method allows for the quantification of subjective expert evaluations, enabling systematic comparisons in the decision-making process (Saaty, 2003; Saaty, 2004) (Tab.2).

Alternative 1,2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1. Coastal protection capacity	**1**									
C2. Contribution to biodiversity		**1**								
C3. Ecological compatibility			**1**							
C4. Low maintenance requirement				**1**						
C5. Aesthetic impact					**1**					
C6. Water filtration						**1**				
C7. Ease of public use							**1**			
C8. Microclimate effect								**1**		
C9. Carbon sequestration potential									**1**	
C10. Enhancing human-nature interaction										**1**

Tab.2 Criteria matrix table

Second stage: statistical analysis

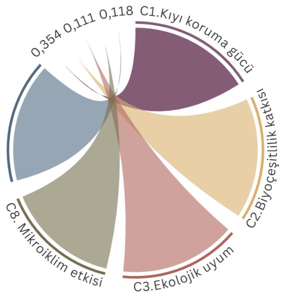
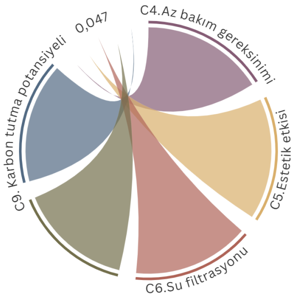
In the second phase of the study, calculations were performed using the Analytic Hierarchy Process (AHP) method with 20 experts, 10 criteria, and 2 alternatives. For these calculations, a specific area within the Budva region was selected as the study area. In this phase, a total of 7 questions were posed to the experts. These questions were designed to evaluate the criteria identified in the first phase of the method, specifically for the selected study area. Each question was structured to assess the impact of a criterion on the area. The criteria were examined through 7 different parameters, which were then transformed into survey questions for the experts. The questions in the survey were evaluated using a 5-point Likert scale: strongly agree, agree, neutral, disagree, and strongly disagree. This method allowed for the collection of quantitative data based on expert opinions, making the multi-criteria decision-making process for the study area more objective.

3. Findings

3.1. Evaluation of AHP (Analytical Hierarchy Process) results

In the AHP results for parameters classified as not undergoing LULC changes, the "Coastal protection power" (C1) criterion holds the highest priority with a weight of 35.4%, indicating that coastal protection functions are the most critical factor from the decision-makers' perspective among the criteria assessed in the context of ecosystem services. The "Biodiversity contribution" (C2) criterion ranks second with 30.7%, providing significant input for the preservation of ecological balance and habitat diversity. The "Ecological adaptation" (C3), "Microclimate effect" (C4), and "Carbon sequestration potential" (C5) criteria have weight values of 11.1%, 11.0%, and 11.8%, respectively. This shows that while these criteria are relatively lower in priority, they still make meaningful contributions to the decision-making process. Overall, it is evident that within environmental criteria, protective and biodiversity-supporting characteristics are prioritized over adaptive and climate-related features. In the case of parameters that have undergone LULC changes, the "Aesthetic effect"

(C7) criterion holds a very high weight of 51.7%, highlighting that aesthetic values are a determining factor in the planning of public spaces. Visual perception and user satisfaction are further emphasized by the "Low maintenance requirement" (C6) and "Ease of public use" (C9) criteria, which are ranked second and third with weights of 22.6% and 21.0%, respectively. These data indicate that sustainability and accessibility are taken into account in the decision-making process. On the other hand, "Water filtration" (C8) has a relatively low weight of 4.7%, suggesting that ecosystem services related to water quality are considered lower in priority compared to other socio-functional criteria, and that user satisfaction, the area's perceptibility, and social acceptance are key influencing factors.

Main criterias	Weighting score	Sub-criterias	Weighting score
NON-LULC	 0.654 - %65	C1. Coastal protection power	0.354
		C2.Biodiversity contribution	0.307
		C3.Ecological adaptation	0.111
		C4. Microclimate effect	0.110
		C5. Carbon sequestration potential	0.118
LULC Applications	 0.358 - %35	C6. Low maintenance requirement	0.226
		C7. Aesthetic effect	0.517
		C8.Water filtration	0.047
		C9. Ease of public use	0.210

Tab.3 Criterias weighting score

The obtained AHP weights show that decision-makers prioritize both ecosystem services (particularly coastal protection and biodiversity) and user-focused values (particularly aesthetic contributions) during the evaluation process. In the planning of coastal areas, physical protection and visual aesthetics emerge as the highest priority criteria. This indicates that nature-based solutions are addressed within an ecological and user-centered multi-criteria framework, aligning with sustainable planning approaches (Tab.3, Fig.4).

Throughout Section 3, all reported findings are systematically and explicitly linked to their corresponding analytical methods as established in Section 2, ensuring full methodological coherence across the manuscript. Section 3.1 presents the AHP-derived weighting scores and priority rankings for both LULC-affected and non-affected coastal parameters, revealing the relative importance assigned to ecological and user-oriented criteria by domain experts within the multi-criteria decision-making framework. Building on this foundation, Section 3.2 reports the SPSS-based statistical outputs, encompassing Pearson correlation analyses and one-sample t-test results, which rigorously quantify the interrelationships among ecological variables and user perception parameters. The integration of these two complementary analytical approaches — quantitative priority weighting through AHP and inferential statistical analysis through SPSS — not only strengthens the interpretive validity of the findings but also provides a robust, interdisciplinary evidential basis for the study's conclusions on coastal landscape dynamics.

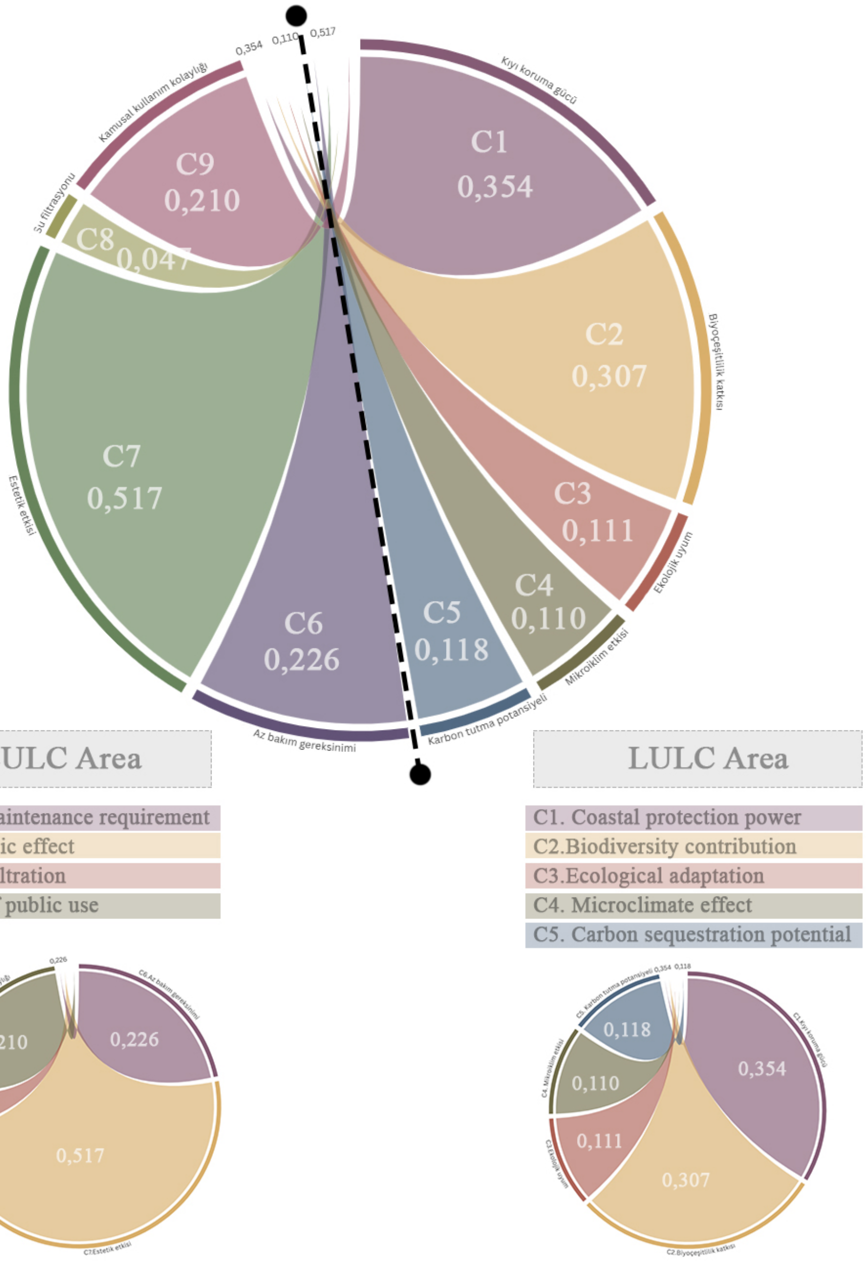


Fig.4 Distribution of criteria and scores

Within the scope of this study, the nine sub-criteria identified are grouped under two main categories: Non-LULC criteria and Land Use and Land Cover (LULC) criteria. These criterion groups were weighted 65 per cent and 35 per cent, respectively, according to the importance level of decision makers. Non-LULC Criteria Group (65% weight) This group consists of five sub-criteria focusing on ecological and environmental functions: C1. Coastal protection capacity: 0.024 C2. Contribution to biodiversity: 0.018 C3. Ecological adaptation: 0.021 C4. Microclimate impact: 0.041 C5. Carbon sequestration potential: 0.017. For example, criterion C4 has a relatively high level of importance, accounting for a significant portion of the 65 per cent weight. LULC Criteria Group (35% weight) This group includes criteria related to space utilisation such as ease of use and visual/functional value: C6. Low maintenance: 0.019 C7. Aesthetic impact: 0.017 C8. Water filtration: 0.034 C9. Suitability for public use: 0.041. Especially criterion C9 stands out as the criterion with the highest importance in this group. The score weights obtained by the alternatives for each criterion were normalised in line with the decision makers' priorities. These values reflect the relative superiority of each alternative in terms of the criterion in question. For example; C1. In terms of coastal protection capacity, the highest weight was given to Non-LULC areas with 0.354. C7. In the aesthetic impact criterion, the highest weight belongs to

LULC areas with 0.517. This shows that decision makers evaluate the aesthetic value depending on land use. According to the AHP results, factors such as microclimate effect (C4) and suitability for public use (C9) stand out with relatively higher weights among the criteria. In addition, the superiority of LULC and Non-LULC areas in terms of different criteria differs. This shows how complex and multidimensional multi-criteria decision-making processes are in areas such as land planning or landscape design (Tab.4).

Applications	**Total weights**	**Sub-criterias**	**Score weights of alternatives**		
			Score weights	Non-LULC	LULC Area
	Non-LULC %65	C1. Coastal protection power	0.024	0.354	0.646
		C2. Biodiversity contribution	0.018	0.307	0.693
		C3. Ecological adaptation	0.021	0.111	0.889
		C4. Microclimate effect	0.041	0.110	0.890
		C5. Carbon sequestration potential	0.017	0.118	0.882
	LULC Area %35	C6. Low maintenance requirement	0.019	0.774	0.226
		C7. Aesthetic effect	0.017	0.483	0.517
		C8. Water filtration	0.034	0.953	0.047
		C9. Ease of public use	0.041	0.982	0.210
Note: Inconsistency rate is calculated as 0.00075					

Tab.4 Grouping results according to AHP weights

3.2 Statistical analysis of parameters

The variable C1 - Coastal protection power shows the highest positive correlation with C2 - Contribution to biodiversity (r = 0.754). This finding indicates that landscape elements with high coastal protection capacity also tend to support biodiversity. This relationship is significant and indicates that ecosystem services are provided together. C3 - Ecological Adaptation shows very strong positive correlations with C4 - Microclimate Effect (r = 0.839) and C5 - Carbon Sequestration Potential (r = 0.760). This suggests that ecologically well-adapted areas are also effective in improving microclimate and sequestering carbon. These high correlations support the multifunctionality of ecosystem services. The relationship between C4 - Microclimate Impact and C5 - Carbon Sequestration Potential is also very strong (r = 0.828). This finding suggests that these two ecological services are often provided together and should be considered together in landscape management. C6 - Low Maintenance Requirement has strong correlations with both C4 (r = 0.693) and C5 (r = 0.724). This suggests that more ecologically sustainable sites can also be maintenance efficient. Moderate positive correlations were found between C7 - Aesthetic Impact and C8 - Water Filtration (r = 0.493) and C9 - Ease of Public Use (r = 0.461). This indicates that aesthetically pleasing areas are also functionally user-friendly and environmentally contributing areas. There is a high positive correlation (r = 0.649) between C8 - Water Filtration and C9 - Ease of Public Use. This relationship indicates that environmental services provide higher benefits when they are accessible and usable by the public. Low or weak correlations were observed between some variables (e.g. r = 0.152 between C3 and C9). This suggests that there is no direct relationship between these two attributes or that this relationship is influenced by other factors (Tab.5).

The Results section explicitly presents the numerical outcomes of both the AHP and SPSS analyses. The weighting scores derived from the Analytic Hierarchy Process (AHP) model are reported in Tab.2 and 3, including the grouping of criteria according to their priority rankings. In addition, the statistical relationships among the evaluated parameters are examined through Pearson correlation analyses (Tab. 5 and 6) and a one-sample t-test (Tab.6).

These analyses provide quantitative evidence for the relationships between ecological criteria and user perception variables, strengthening the data-driven interpretation of coastal landscape dynamics.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	0.754	0.263	0.333	0.222	0.346	0.418	0.490	0.410
C2	0.754**	1	0.232	0.244	0.226	0.353	0.266	0.470	0.443
C3	0.263	0.232	1	0.839	0.760	0.662	0.398	0.367	0.152
C4	0.333	0.244	0.839**	1	0.828	0.693	0.408	0.347	0.163
C5	0.222	0.226	0.760**	0.828**	1	0.724	0.335	0.300	0.200
C6	0.346	0.353	0.662	0.693	0.724**	1	0.323	0.399	0.387
C7	0.418	0.266	0.398	0.408	0.335	0.323	1	0.493	0.461
C8	0.490	0.470	0.367	0.347	0.300	0.399	0.493	1	0.649
C9	0.410	0.443	0.152	0.163	0.200	0.387	0.461	0.649	1

C1. Coastal protection power, C2.Biodiversity contribution, C3.Ecological adaptation, C4. Microclimate effect C5. Carbon sequestration potential, C6. Low maintenance requirement, C7. Aesthetic effect, C8.Water filtration, C9. Ease of public use

Correlation Values and Symbols

Symbol	Symbol description	Value range	
	Very strong correlation	0.600 and above	** Correlation is significant at the 0.01 level (2-tailed) * Correlation is significant at the 0.05 level (2-tailed)
	Strong correlation	0.450 – 0.600	
	Mid-level correlation	0.300 – 0.450	
	Low correlation	0.150 – 0.300	
	Very low correlation	0.000 – 0.150	

Tab.5 Correlation results

	C1	C2	C3	C4	C5	C6	C7
C1	1	0.766	0.722	0.310	0.392	0.236	0.201
C2	0.766**	1	0.793	0.275	0.252	0.197	0.133
C3	0.722**	0.793**	1	0.342	0.339	0.297	0.292
C4	0.310	0.275	0.342	1	0.329	0.445	0.323
C5	0.392	0.252	0.339	0.329	1	0.765	0.568
C6	0.236	0.197	0.297	0.445	0.765**	1	0.660
C7	0.201	0.133	0.292	0.323	0.568	0.660**	1

C1 Do you think it is important to keep the beach natural and why?
C2 Do you have information about the protection of the beach ecosystem?
C3 What threats do you think the beach ecosystem faces?
C4 What measures should be taken to protect natural beaches?
C5 What do you think about nature-based solutions in landscape design?
C6 Would it be better to preserve the beach in its natural state or to introduce certain landscaping measures?
C7 What are the aesthetic, social or ecological advantages of preserving the beach in its natural state?

Correlation Values and Symbols

Symbol	Symbol description	Value range	
	Very strong correlation	0.600 and above	**Correlation is significant at the 0.01 level (2-tailed) * Correlation is significant at the 0.05 level (2-tailed)
	Strong correlation	0.450 – 0.600	
	Mid-level correlation	0.300 – 0.450	
	Low correlation	0.150 – 0.300	
	Very low correlation	0.000 – 0.150	

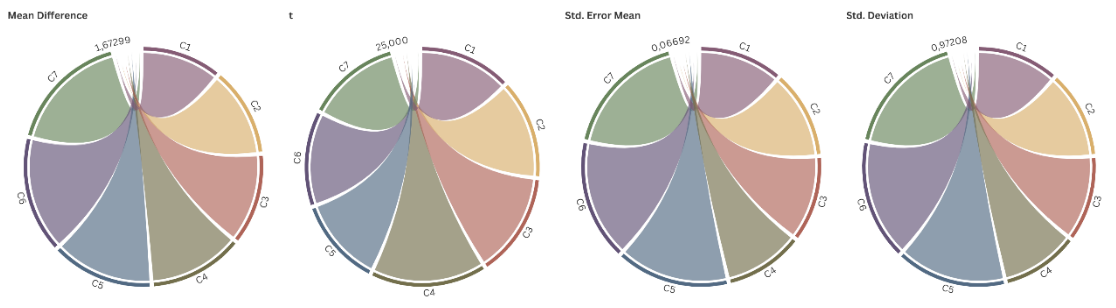
Tab.6 Correlation results

This correlation analysis reveals the relationships between attitudes, knowledge level and perceptions towards the protection of the natural structure of beaches. According to the results of the analysis, there is a high and statistically significant (**, $p < 0.01$) positive correlation at the level of 0.766 between the variables 'Do you find it important to keep the beach natural?' (C1) and 'Do you have information about the protection of the beach ecosystem?' (C2). This shows that individuals who attach importance to the protection of the natural structure of beaches are also more knowledgeable about the protection of beach ecosystems. Similarly, a very strong correlation of 0.793 was observed between C2 and the variable 'What threats does the beach ecosystem face?' (C3). This shows that as the level of knowledge increases, the threat perception also increases. Moderate positive correlations were also observed between C3 and some other variables. For example, a correlation of 0.342 was found between C3 and 'What measures should be taken to protect natural beaches?' (C4) and 0.339 with 'What do you think about nature-based solutions in landscape design?' (C5). These results show that individuals who are aware of beach threats are more inclined to produce solutions and evaluate nature-based solutions in landscape design more positively. Especially the high correlations between C5, C6 and C7 are noteworthy. There are significant correlations at the level of 0.765 between C5 and C6 and 0.660 between C6 and C7. This indicates that individuals who have a positive attitude towards nature-based solutions in landscape design are more aware of the aesthetic, social or ecological benefits of the beach and prefer the preservation of the beach in its natural state to landscaping. In general, positive and statistically significant relationships were found between the variables in the analysis.

These findings reveal that individuals' knowledge levels and environmental awareness have an impact on their attitudes and preferences towards beach protection. Such relationships emphasise the importance of environmental education programmes and awareness raising activities and can be instructive for policy makers and environmental planners (Tab.6).

The one-sample t-test conducted within the scope of this study aims to assess whether respondents' attitudes and perceptions towards the conservation of the natural structure of beaches are significantly different from a given reference value (possibly a neutral or average attitude value).

					95% Confidence Interval of the Difference			
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper	Std. Deviation	Std. Error Mean
C1	25.000	210	0.000	1.67299	1.5411	1.8049	0.97208	0.06692
C2	26.503	210	0.000	1.85782	1.7196	1.9960	1.01825	0.07010
C3	27.823	210	0.000	1.89573	1.7614	2.0301	0.98972	0.06814
C4	31.640	210	0.000	1.97630	1.8532	2.0994	0.90733	0.06246
C5	23.550	210	0.000	2.13744	1.9585	2.3164	1.31839	0.09076
C6	25.235	210	0.000	2.44550	2.2545	2.6365	1.40767	0.09691
C7	25.228	210	0.000	2.55924	2.3593	2.7592	1.47359	0.10145



Tab.7 Results of One Sample T-Test

The results of the analyses show that the p-value for all variables (C1-C7) is 0.000 and these results are statistically significant ($p < 0.05$). These findings reveal that the respondents gave significantly different and higher responses than the reference value on each relevant issue. For example, the mean of the answers to the question 'Do you find it important to keep the beach natural?' (C1) is 1.67, while the means of the questions related to knowledge and awareness such as 'Do you have information about the protection of the beach ecosystem?' (C2) and 'What threats does the beach ecosystem face?' (C3) are 1.86 and 1.89, respectively. This shows that the participants are not only sensitive to environmental issues, but also have knowledge about them.

When we move on to more practical and evaluative questions, it is seen that the mean values increase even more. For example, the mean values for the questions 'What do you think about nature-based solutions in landscape design?' (C5), 'Would it be better to preserve the beach in its natural state or to make certain landscape arrangements?' (C6) and 'What are the aesthetic, social or ecological advantages of preserving the beach in its natural state?' (C7) are 2.14, 2.44 and 2.56 respectively (Tab.6). This shows that the participants are not only limited to environmental awareness, but also find nature-based solutions more aesthetically, socially and ecologically beneficial and support these solutions.

In general, the results of the one-sample t-test scientifically support that there is a high level of social awareness and a positive attitude towards the protection of the natural structure of beaches. These data provide strong evidence to guide environmental sustainability, nature-based planning and public awareness studies.

4. Conclusion

This study aims to analyse the effects of coastal landscape elements on user perception and coastal dynamics by comparing two different coastal areas in Budva, Montenegro. Within the scope of the research, a beach with a largely preserved natural structure and a beach affected by construction and land use changes were analysed. The findings obtained using the Analytical Hierarchy Process (AHP) method and SPSS analyses showed that criteria such as biodiversity, coastal protection capacity, aesthetic value and public usability are determinant in user perception. By combining quantitative evaluation (AHP) and statistical perception analysis (SPSS), this study provides an interdisciplinary framework that bridges ecological assessment and social perception, offering a more comprehensive understanding of how users experience and evaluate coastal landscapes. The convergence of AHP-based priority weights and SPSS-derived statistical outputs across both study sites reinforces the internal consistency of the findings and validates the interdisciplinary methodological approach adopted in this study.

The results obtained reveal that the protection of natural landscape elements is important not only in terms of ecological but also social and visual quality. On the other hand, intensive construction and LULC (Land Use/Land Cover) changes in coastal areas negatively affect user satisfaction and landscape integrity. In this direction, it is emphasised that interventions should be made by considering sustainable planning and ecological balance in coastal areas. This emphasizes that the sustainability of coastal environments depends on harmonizing physical integrity with user perception — a balance that can only be maintained through integrated coastal management and the inclusion of public awareness in policy-making.

According to the results obtained from AHP analyses, coastal protection is the most important criterion for users when evaluating coastal areas. According to the AHP results, coastal protection capacity (C1) was identified as the highest priority criterion among the non-LULC parameters, with a local weight of 35.4%, followed by biodiversity contribution (C2) at 30.7%, carbon sequestration potential (C5) at 11.8%, ecological adaptation (C3) at 11.1%, and microclimate effect (C4) at 11.0%. Among the LULC-affected parameters, aesthetic effect (C7) emerged as the dominant criterion with a local weight of 51.7%, followed by low maintenance requirement (C6) at 22.6% and ease of public use (C9) at 21.0%. These distributions, as reported in Tab.2, confirm that decision-makers prioritize both ecological protection functions and user-oriented values in the assessment of coastal landscapes. This was followed by biodiversity (27.5%), aesthetic impact (22.1%) and public usability (16.2%). This distribution reveals that users primarily expect environmental protection and naturalness in coastal areas, followed by visual and social use features. This prioritization not only highlights users' sensitivity to ecological values but also suggests that public expectations align closely with scientific principles of sustainability. In this sense, the AHP framework proves to be a reliable tool for translating subjective perceptions into measurable planning criteria. It is also noteworthy that the AHP consistency ratio of 0.00075 — well below the accepted threshold of 0.10 — confirms that the expert evaluations were logically coherent and free from contradictory judgments, thereby ensuring the reliability of the derived weighting scores.

The one-sample t-test results presented in Tab.6 demonstrate statistically significant differences across all perception variables at the $p < 0.05$ level, confirming that participants expressed consistently positive attitudes toward the preservation of natural coastal structures. In particular, the coastal area that retained its natural morphology received more favorable evaluations across all ecological and aesthetic criteria.

In particular, the coastal area that preserved its natural structure received more positive evaluations by the users. This coastal area was found to be more qualified in terms of both physical preservation and landscape integrity; in terms of biodiversity, it was stated that the diversity of flora and fauna was more perceptible. This area, which visually leaves a calmer, natural and aesthetic impression, is also considered more satisfying in terms of user experience. These findings reveal that natural coastal environments contribute simultaneously to ecological stability and psychological well-being. Therefore, user perception can be considered an indirect indicator of ecological health, functioning as a social reflection of environmental quality.

According to the correlation analysis, a very strong positive relationship ($r=0.754$) was found between coastal protection capacity and biodiversity contribution. Similarly, ecological adaptation was highly correlated with microclimate effect ($r=0.839$) and carbon sequestration potential ($r=0.760$). This indicates that natural areas support each other in terms of ecological functions. Additionally, the strong relationship ($r=0.828$) between microclimate effect and carbon sequestration potential suggests that these two services should be considered together. The positive correlation of the low maintenance requirement variable with these services is also significant in terms of sustainable design. The moderate correlations between aesthetic effect and water filtration ($r=0.493$) and suitability for public use ($r=0.461$) indicate that visually appreciated areas also provide functional and environmental benefits. On the other hand, the correlation analysis regarding individual attitudes and perceptions towards the preservation of the natural structure of beaches revealed that as environmental knowledge and awareness increase, perceptions of threats and preferences for nature-based solutions also increase. In particular, the very strong relationship ($r=0.793$) between C2 (knowledge level) and C3 (threat perception) and the high correlation ($r=0.765$) between C5 (nature-based solution assessment) and C6 (preference for natural conservation) underline the connection between environmental awareness and attitudes. One-sample t-test results also showed significant differences for all variables at $p < 0.05$ level, scientifically supporting that participants demonstrated high awareness and positive attitudes towards preserving the natural state of beaches. These findings suggest that nature-based planning and environmental education efforts are well-received in society, and that there is strong public support for sustainable coastal management. This connection between awareness and perception also implies that environmental education can play a crucial role in fostering community-driven coastal conservation. Promoting knowledge-based engagement ensures that users become active participants rather than passive observers in maintaining coastal integrity. These statistically significant results, obtained from a sample of 211 coastal users, provide a sufficiently robust empirical basis for drawing conclusions about general user attitudes toward natural coastal environments and the perceived impacts of LULC-driven landscape transformation.

From a planning and management perspective, the findings of this study underscore the critical importance of integrating ecological indicators alongside user perception data into coastal landscape evaluation frameworks and evidence-based decision-making processes. The results convincingly demonstrate that preserving the natural structure and morphological integrity of coastal areas contributes simultaneously and measurably to ecological stability, visual quality, and overall user satisfaction — reinforcing the interdependence of environmental and socio-functional dimensions in coastal systems. Notably, the AHP-derived priority weights reveal that both ecosystem service criteria, particularly coastal protection and biodiversity contribution, and user-oriented criteria, particularly aesthetic value and ease of public use, are consistently ranked as high-priority determinants by domain experts, reflecting a broadly shared recognition of the multi-dimensional value of natural coastal environments.

In light of these findings, coastal planning strategies should deliberately prioritize nature-based solutions, ecological restoration practices, and soft coastal engineering approaches as primary instruments of intervention, rather than relying solely on conventional hard infrastructure measures that may compromise long-term ecological resilience. Furthermore, the systematic incorporation of user perception assessments into environmental impact evaluations and landscape performance analyses can substantially support the formulation of more balanced, inclusive, and sustainable coastal management policies. By explicitly aligning ecological protection objectives with documented social expectations, recreational needs, and aesthetic preferences, planners and policymakers can develop adaptive management frameworks that are both scientifically grounded and responsive to the evolving demands of coastal communities. Ultimately, the interdisciplinary approach adopted in this study — combining quantitative multi-criteria analysis with statistical perception evaluation — offers a transferable methodological model for sustainable coastal governance in similarly dynamic and vulnerable coastal environments.

In contrast, the coastal area affected by LULC changes has been described by users as a less preferred, less impressive, and lower-quality environment due to factors such as increased hard surface ratio, intensified urbanization, and loss of natural vegetation. This clearly demonstrates that as coastal areas deviate from natural integrity in landscape planning, both user satisfaction and ecological quality tend to decrease. These findings confirm that over-urbanization in coastal zones leads not only to ecological degradation but also to a perceptual decline that diminishes the overall landscape experience. Thus, unsustainable development practices result in both physical and cultural losses in coastal identity.

In light of all these data, it can be emphasized that for the sustainable management of coastal areas, the preservation of naturalness and the minimization of landscape interventions are essential. This multi-criteria analysis, based on users' perceptions, demonstrates that coastal areas should be addressed not only physically but also in terms of social perception and ecological functionality. Through the systematic prioritization provided by the AHP analysis and the statistical validation offered by SPSS, this study makes a significant contribution to the need for science-based decision-making in coastal planning processes. The integration of analytical hierarchy with perception-based evaluation introduces a novel methodological synthesis that strengthens the reliability of coastal assessment. It provides planners with measurable indicators grounded in both expert analysis and community experience, bridging the gap between scientific objectivity and human subjectivity.

As a result, this comparative evaluation conducted using the Budva example highlights that the preservation of the natural structure in coastal areas is indispensable in terms of user satisfaction, aesthetic quality, and ecological sustainability. Implementing nature-based solutions in coastal management, supported by multi-criteria analyses based on local user perception, is of great importance for long-term coastal protection strategies. In addition to these empirical results, this research contributes to the academic discourse on coastal sustainability by proposing an integrated methodological framework that unites expert-based evaluation and user-centered perception analysis. This dual approach advances beyond conventional spatial or visual assessments, enabling a more comprehensive understanding of how LULC dynamics influence both ecological functions and human experiences.

The study also demonstrates the applicability of multi-criteria decision-making methods such as AHP as effective tools for translating subjective user evaluations into quantifiable indicators of environmental quality. This methodological synthesis reinforces the value of combining quantitative and perceptual data in landscape research, ensuring that scientific findings remain context-sensitive and socially relevant.

From a policy perspective, the results underscore the importance of embedding participatory and perception-based indicators into coastal planning frameworks. Local governments and urban planners are encouraged to adopt evidence-driven strategies that integrate nature-based solutions, soft engineering techniques, and ecological restoration to enhance coastal resilience.

Furthermore, the Budva case study reveals that landscape perception acts as a diagnostic tool for detecting ecological degradation and urbanization pressure. As user perceptions decline, it signals an underlying loss of environmental integrity, highlighting the need for early intervention and adaptive management.

Future research should extend this analytical framework to larger spatial and temporal scales, integrating multi-temporal remote sensing, participatory GIS, and socio-ecological modeling to explore how land use dynamics interact with climate variability and cultural values in coastal systems. By incorporating both expert and community-based knowledge, future studies can help develop more inclusive, resilient, and adaptive coastal management strategies across the Mediterranean and beyond.

Taken together, the empirical evidence generated through this study contributes to the growing body of literature advocating for perception-inclusive, ecologically grounded coastal governance, and offers a replicable analytical template for assessing landscape quality in other Mediterranean and globally comparable coastal settings.The present study acknowledges several methodological limitations that should be considered when interpreting the findings. First, the criterion weighting procedure within the AHP model is inherently grounded in expert judgments, which — despite the application of consistency ratio checks to ensure reliability — may introduce a degree of subjectivity into the priority rankings. The composition and size of the expert panel, as well as the disciplinary backgrounds of its members, may influence the resulting weight distributions and should therefore be taken into account when generalizing the findings to other coastal contexts. Second, the user perception analysis is based on structured survey responses, which are susceptible to individual variability in environmental awareness, personal experience, and aesthetic sensitivity. Response biases inherent to self-reported data, including social desirability effects and varying levels of familiarity with the study area, may partially affect the representativeness of the perception outcomes. Third, the delineation of LULC-affected and non-affected conditions relied primarily on visual spatial interpretation of satellite imagery and systematic field observations, rather than on a fully automated or supervised remote sensing classification procedure, which may limit the precision and reproducibility of the spatial differentiation. Future research should address these limitations by integrating multi-temporal, high-resolution remote sensing datasets and applying rigorous land cover classification algorithms to enhance the accuracy and objectivity of LULC change detection. Additionally, expanding the expert panel diversity and increasing survey sample sizes across varied demographic groups would further strengthen the robustness, transferability, and scientific credibility of the proposed analytical framework in comparative coastal landscape studies.

Ethics statement

This study was conducted in accordance with the ethical principles of research involving human participants. Survey participants were informed about the purpose of the study and provided voluntary consent prior to participation. No personally identifiable information was collected or retained.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Author's profile

Makbulenur Onur

She graduated from the Department of Landscape Architecture at Karadeniz Technical University in 2012 and from the Department of Interior Architecture in 2013, holding two diplomas. She is currently an Assistant Professor in the Department of Landscape Architecture at Karadeniz Technical University in Trabzon, Türkiye. She received her Ph.D. from the same university, with a dissertation titled 'Development of a Method Proposal for the Biophilic Index in Space Design.' Her research interests include green infrastructure, land use/land cover (LULC), and air quality management.

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Spatial and temporal evolution of urban reserve available land resources in the Karst region of North China from 1990 to 2020: a case study of Jinan city

Shujin Wang [a], Shanzhong Qi [b]*

[a] College of Geography and Environment, Shandong Normal University, Shandong Province, China
e-mail: 1658127918@qq.com

[b] College of Geography and Environment, Shandong Normal University, Shandong Province, China
e-mail: shzhqi@sdnu.edu.cn
ORCID: https://orcid.org/0000-0001-8532-9283
* Corresponding author

Abstract

With the rapid development of urbanization, land resources are mainly converted into urban areas in most karst mountain regions of North China over the last decade, so studying available land resources would have implicational significance to regional planning and sustainability. Based on RS, GIS, DEM, slope information and the evaluation methods for reserve available land resource, this study explored the spatial and temporal evolution of urban reserve available land resources from 1990 to 2020 in Jinan city, which is located in the karst region of North China. The results reveal that the potential of the reserve available cultivated land in Jinan city is large, covering an area of 360.67 km^2, and the differences of reserve available cultivated land for each district are mainly caused by the combined effects of regional conditions, economic conditions, population, and industrial zones. The area of reserve suitable construction land in Jinan city is 292.48 km^2, which is decreasing and mostly in the southern part of the study area. Based on the overlap and differences of the two types of land, combined with regional socio-economic development and natural environmental conditions, the reserve land resources in the southern region of Tian Qiao, Chang Qing and North Huai Yin, Shi Zhong, and Li Xia within the study area can be converted into construction land, but the reserve land resources in the central and southern regions of Li Cheng and the central and southeastern regions of Chang Qing can be converted into new cultivated land.

Keywords

Reserve available land resources; Reserve available construction land; Reserve available cultivated land; Jinan city; China's North Karst

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1. Introduction

Land resources are an essential material basis for human survival and social and economic growth in the world (Yeeles, 2019; Katharine et al., 2019) and also a unique and finite economic resource with diverse uses for various land uses that cannot be separated from the urbanization process (Ziari et al., 2025; Papa, 2025). With the rapid urban expansion on a global scale, land resources are mainly converted into urban areas (Di Giacomo, 2015; Xu et al., 2012; Adam, 2020; Keith et al., 2021; Garau et al., 2023; Ziari et al., 2025). In recent decades, China has achieved rapid economic growth, large-scale industrialization, and urbanization since it initiated economic reforms and an open-door policy in 1978. At the same time, the contradiction between economic and social development and land resources is becoming increasingly serious, and the inefficient use of land resources and ecological space extrusion pose significant challenges to urban sustainable development (Feng et al., 2024; Zhou, 2025; Vishaal & Damodaran, 2026). In the context of rapid urbanization process, the prominent performance is that the expansion of urban construction land brought about a sharp decline in the amount of arable land (Deng et al., 2015; Özkan et al., 2025). Moreover, the scale of urban construction land will continue to expand, which inevitably continue to occupy arable land with the future economic and social development, thereby resulting in the reduction of the amount of arable land, and posing a threat to food security (Zhou et al., 2021; Deng et al., 2015).

Notably, China is one of mountainous and hilly countries in the world, and its karst mountainous geological area accounts for 25% of the world's carbonate rock (Jiang & Yan, 2010). Because the fragile karst ecosystems develop on carbonate rock (e.g. limestone or dolomite) and are characterized by slow-forming soils that are generally infertile, thin, and susceptible to degradation and loss by erosion (Cheng et al., 2016), the area of arable land in karst regions is limited, and the karst topography specifically complicates land reserve evaluation. The China's karst mountainous regions cover an area about 344×10^4 km^2, which consists of the China's South Karst and North Karst (Lu, 1986). Owing to the rapid development of urbanization and irrational human activities, the China's karst mountainous regions have undergone the spatial pattern change of land use in recent years, especially in the urban karst mountainous region of North China (Qi & Zhang, 2011; Xu et al., 2012; Zhang et al., 2018), thereby affecting the city's sustainable development of land resources.

In this context, in order to meet the needs of future economic and social development for new construction land, while ensuring national food security, it is an inevitable choice to develop a part of reserve usable land resources in a timely and appropriate amount (Yang et al., 2019). Reserve available land resources refer to the potential or surplus land in a region, which can be used for newly-added cultivated land or newly-added construction land. The reserve available land resources mainly include two types, namely the reserved land suitable for construction and for cultivation (Xu et al., 2010; Xu et al., 2025). Moreover, it can be used to evaluate the carrying capacity of land resources within a region for future agricultural development or population gathering, industrialization, and urbanization.

Nowadays, many case studies have been reported for the reserved land suitable for cultivation (Kim et al., 1999; Reshmidevi et al., 2009; Feizizadeh & Blaschke, 2013; Jin et al., 2013) or the reserved land suitable for construction (Xu et al., 2011; Dang et al., 2014; Xu & Xu, 2016). But most of studies have only focused on a single type of reserve available land resources potential calculation. Moreover, the contradiction and conflict between the reserve suitable land for construction and the reserve suitable land for cultivation have not been fully considered and resolved, particularly for the cities located in the China's North Karst. Therefore, it is highly required to study in-depth the reserve available land resources within the cities.

Jinan city is one of cities belonging to the China's North Karst, and well known as the City of Springs. It has undergone increasingly rapid urban expansion, especially in its urban karst mountainous area in recent years (Qi & Zhang, 2011; Xu et al., 2012), thereby profoundly resulting in the spatial pattern change of urban land resources within city. Therefore, the aim of this study is to evaluate the reserve available land resources from 1990 to 2020, further probe into Jinan city's regional orientation, thereby achieving urban sustainable development of land sources of Jinan city.

2. Materials and methods

2.2 Study area

Jinan city (116° 49'–117° 14′ E, 36° 32′ –36° 51′ N) is located in the China's North Karst, and is the capital city of Shandong Province. It exhibits a typical warm-temperate, semi-humid, continental monsoon climate, and well-defined seasons. The mean annual temperature is 14 °C, and the average mean precipitation 650–700 mm (Qi et al., 2020). The area in this study covers 3257 km^2. Administratively, the study area includes 6 districts, namely Tian Qiao, Huai Yin, Li Xia, Li Cheng, Shi Zhong, and Chang Qing (Fig.1). In recent years, Jinan city has undergone a rapid process of urban expansion, and its urbanization rate reached 72.1%. For instance, the urban area of Jinan city increased from 23.2 km^2 in 1948 to 561 km^2 in 2020, and its main types of land use within the city were cultivated land and construction land (Shandong province bureau of statistics, 2021). By 2020, the area of cultivated land and construction land was 1,373 km^2 and 922 km^2, respectively.

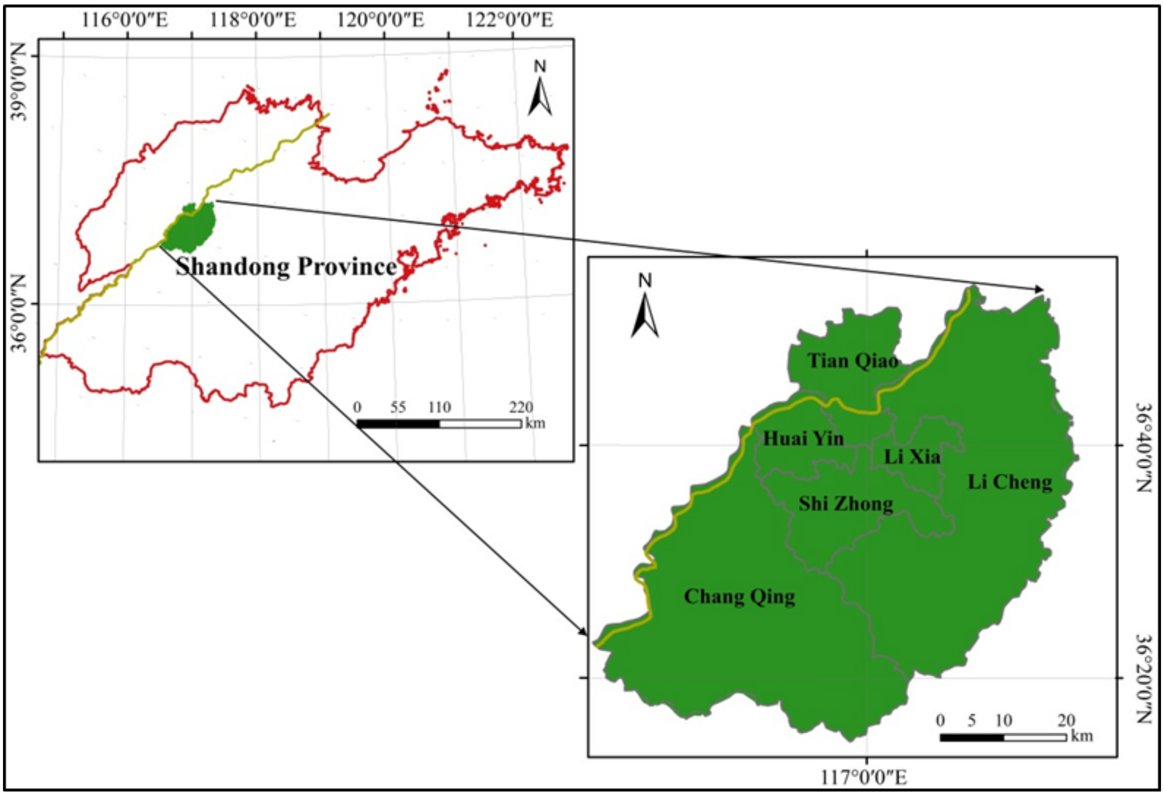

Fig.1 Location map of study area

2.2 Data sources

The land use data taken in 1990, 2000, 2010, and 2020 were obtained from remote sensing data Landsat images at 30-m spatial resolution. The land cover was classified into six types applicable to the study area, that is, cultivated land, forestland, grassland, water, construction land, and unused land listed in the Resources and Environmental Database Center of the Chinese Academy of Sciences (https://www.resdc.cn/). On the other hand, an object-based image analysis (OBIA) approach to the satellite interpretation, which was described in detail by previous studies (Congalton, 1991; Walker & Blaschke, 2008; Wang et al., 2013, 2016; Zhu et al., 2019), was used to detect land use landscape types and interpret the land cover map by eCognition software in the study area.

2.3 Methods

The reserve available land resources are mainly divided into the reserved land suitable for construction and the reserved land suitable for cultivation (Xu et al., 2010; Xu et al., 2025), whose spatial distribution has the characteristics of overlap and difference. The former belongs to the reserved suitable cultivated land when the slope of the terrain is less than 15°, that is, if the reserved available land resources can be used as new construction land in the future, it can also be used as new cultivated land. The latter lies in the value of slope, which is ⩽15° for reserve land suitable for construction and ⩽25° for arable land (National Committee on Agricultural Zoning, 1984; Xu et al. 2008). According to the connotation of reserve available land resources, followed the previous work (Feizizadeh & Blaschke, 2013; Xu & Xu, 2016; Xu et al., 2021), the evaluation methods to reserve available land resources, the reserved land suitable for construction and for cultivation were obtained, which can be calculated by the following equations:

Calculation of the available land resources:

$$L=L_{\sigma}+L_{\varphi} \quad (1)$$

where L is the area of the available land resources, L_{σ} and L_{φ} refer to the available land resources whose slope is respectively less than 15° and 15°–25° and satisfies certain elevation conditions.

Calculation of the reserved land suitable for cultivation:

$$L_{au}=L-L_{fg}-L_{wa}-L_{pz}-L_{gd}-L_{ec}-L_{cu}-L_{ga} \quad (2)$$

where L_{au} is the area of the reserved land suitable for cultivation, L_{fg} is the area of forestland contained in the regional available land resources, L_{wa} is the area of water contained in the regional available land resources, L_{pz} is the area of preserve zone contained in the regional available land resources, L_{gd} is the area of gobi and desert contained in the regional available land resources, L_{ec} is the area of existing construction land contained in the regional available land resources, L_{cu} is the area of cultivated land contained in the regional available land resources, L_{ga} is the area of garden land and basic farmland contained in the regional available land resources.

Calculation of the reserved land suitable for construction:

$$L_{sc}=L_{\sigma}-L_{fg\sigma}-L_{wa\sigma}-L_{pz\sigma}-L_{gd\sigma} \quad (3)$$

$$L_{fa\sigma}=L_{cu\sigma}\times\alpha,\ \alpha\in[0.9,1] \quad (4)$$

$$L_{ac}=L_{sc}-L_{ec\sigma}-L_{fa\sigma}-L_{ga\sigma} \quad (5)$$

where L_{sc} is the suitable area for construction, L_{ac} is the reserve suitable area for construction, $L_{fg\sigma}$ is the area of forestland contained in the available land resources whose slope is less than 15°, $L_{wa\sigma}$ is the area of water contained in the available land resources whose slope is less than 15°, $L_{pz\sigma}$ is the area of preserve zone contained in the available land resources whose slope is less than 15°, $L_{gd\sigma}$ is the area of gobi and desert contained in the available land resources whose slope is less than 15°, $L_{ec\sigma}$ is the area of existing construction land contained in the available land resources whose slope is less than 15°, $L_{cu\sigma}$ is the area of cultivated land contained in the available land resources whose slope is less than 15°, $L_{ga\sigma}$ is the area of garden land contained in the available land resources whose slope is less than 15°, $L_{fa\sigma}$ is the area of basic farmland contained in the available land resources whose slope is less than 15°, and the value of α can be determined according to the distribution pattern of the red line of cultivated land protection defined by the land department. Referring to relevant studies (Dang et al., 2014; Xu et al., 2021), the value of α for reserve suitable construction land in this study was determined to be 1, in order to ensure the balance between occupation and compensation of cultivated land in the study area.

On the other hand, a topographic map of Jinan was prepared from the obtained administrative territorial entity maps of the study area, land use maps, water system maps and elevation maps in this study; then the topographic slope was divided into five grades, namely less than 3°, 3°–8°, 8°–15°, 15°–25°, and more than 25° according to the national classification standard of topographic elevation and the characteristics of the study area. After superposition matching, the reserve available construction land area and the reserve suitable cultivated land area were obtained by the above equations (1)-(5).

In view of the differences and overlaps in the spatial distribution of the reserved suitable land for construction and the reserved suitable arable land, the geographic orientation of the two types of land use was determined based on Jinan city's natural economic and social development status and relevant planning and policies.

3. Results and discussion

3.1 Potential analysis of the reserve available cultivated land

The spatial distribution pattern of the reserve available cultivated land was relatively stable in the study area (Fig.2), whose area covered 360.67 km^2. During the period of 1990–2020, the reserve available cultivated land decreased first and then increased, reaching 360.67 km^2 in 2020, with a total decrease of 18.33 km^2. Because Jinan city has undergone increasingly rapid urban expansion from 1992, and its urbanization rate reached 30.21%, and the urban space expansion in Jinan city experienced three stages, namely medium-strength and low-speed, high-strength and medium-speed, and low-strength and high-speed from 1992 to 2018 (Wang et al., 2020). Therefore, the reserve cultivated land decreased until 2010 and then increased by 2020.

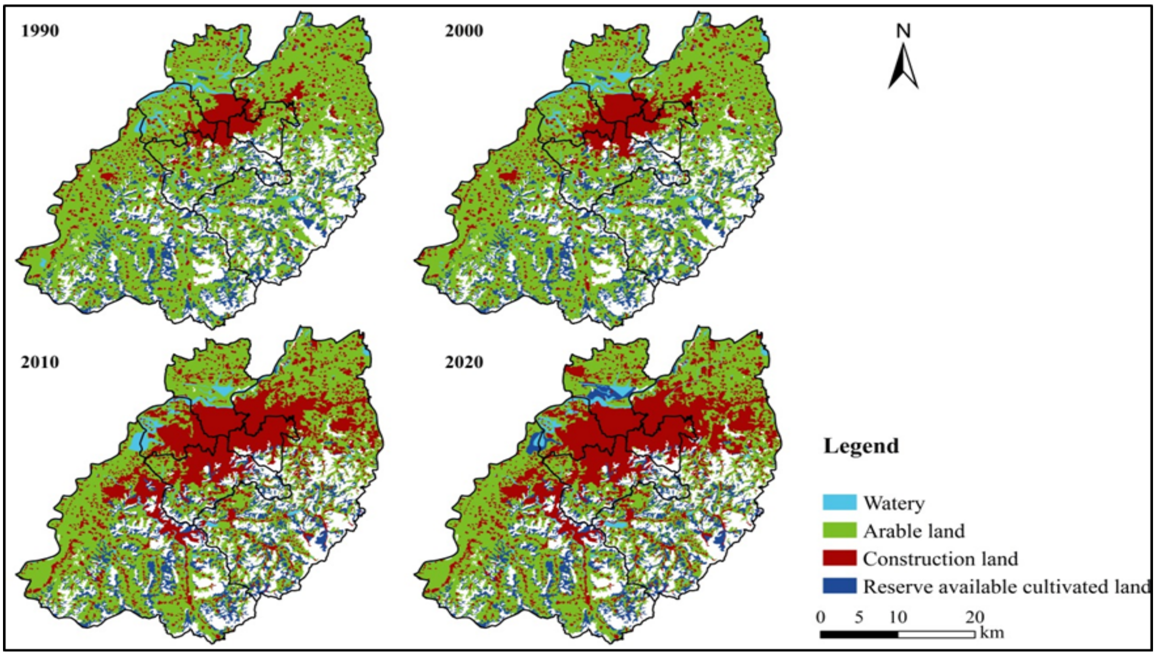

Fig.2 Spatial distribution of the reserve available cultivated land from 1990 to 2020

As shown in Tab.1, the area of reserve available cultivated land in Tian Qiao, Shi Zhong, and Huai Yin decreased first and then increased from 1990 to 2020, but continued to decrease in Li Xia and Chang Qing.

From 1990 to 2000, the area of reserve available cultivated land in Li Cheng was stable and showed a downward trend after 2000.

	Tian Qiao	Huai Yin	Li Xia	Li Cheng	Shi Zhong	Chang Qing	Jinan
1990	3.74	1.48	5.28	146.66	44.77	177.07	379.00
2000	3.50	1.48	5.28	146.66	44.67	177.09	378.68
2010	0.00	0.08	3.74	132.46	33.98	160.25	330.51
2020	17.71	4.43	3.69	132.10	34.21	168.53	360.67
1990–2020	13.97	2.95	-1.59	-14.56	-10.56	-8.54	-18.33

Tab.1 Area change of the reserve available cultivated land in each district from 1990 to 2020 (unit: km^2)

On the other hand, the area change range of reserve available cultivated land in each district was Li Cheng, Tian Qiao, Shi Zhong, Chang Qing, Huai Yin, and Li Xia in sequence, among which Tian Qiao and Huai Yin showed an overall growth trend, respectively increased by 13.97 km^2 and 2.95 km^2 during the study period. The other four districts showed a decreasing trend, which were Li Cheng, Shi Zhong, Chang Qing, and Li xia in order, with a decrease of 14.56 km^2, 10.56 km^2, 8.54 km^2, and 1.59 km^2, respectively. These area changes showed that the potential of reserve available cultivated land in Tian Qiao and Huai Yin was increasing, but in other four districts was decreasing.

On the whole, the differences of reserve available cultivated land in each district of Jinan city were mainly due to the combined effects of regional conditions, economic conditions, population, and industrial zones. Among these districts, Tian Qiao, Huai Yin, Shi Zhong, and Li Xia were the important regions for Jinan city's economic development, so the potential of reserve available cultivated land was relatively small, but the construction land was in great demand because of the relatively high population and urbanization level in the region. In addition, Li Cheng and Chang Qing possessed the following characteristics of sparse population, low levels of urbanization, and undulating terrain, so the two districts were not suitable for the development of construction land, but they could be used as cultivated land. Therefore, the potential for reserve available cultivated land in the regions was greater.

3.2 Potential analysis of the reserve available construction land

Because the arable land is the main land use type in the study area, the construction land is mainly distributed in the central-northern region of the study area, and showed a significant expansion trend. During the period of 1990–2020, the spatial distribution pattern of land suitable for construction was relatively stable and mainly distributed in the southern region of Jinan city (Fig.3). In terms of each district, the reserve land suitable for construction was mainly distributed in the southern region of Chang Qing and southwestern region of Li Cheng, and scattered in the southern region of Tian Qiao, northwestern region of Huai Yin, and southeastern region of Li Xia.

Over the past 30 years, the area of land suitable for construction in the study area showed a declining trend. From 1990 to 2010, the area of the reserve suitable construction land continued to decline, but the area increased from 2010 to 2020. By 2020, the area of reserve land suitable for construction would be reduced to 292.48 km^2, a decrease of 5.11% compared with 1990, accounting for 8.85% of the total area of the study area (Tab.2). In terms of land quantity, the potential of reserve construction land in the study area is large, which can meet the need of further development of reserve construction land resources. However, in terms of each district, the areas of land suitable for construction in Chang Qing and Li Cheng are relatively larger, which are 138.08 km^2 and 100.75 km^2 respectively, accounting for 34.45% and 47.21% of Jinan city's total reserved land suitable for construction, respectively. But in Tian Qiao, Shi Zhong, Li Xia, and Huai Yin are relatively lower, with an area of 17.71 km^2, 28.31 km^2, 3.20 km^2, and 4.43 km^2, respectively.

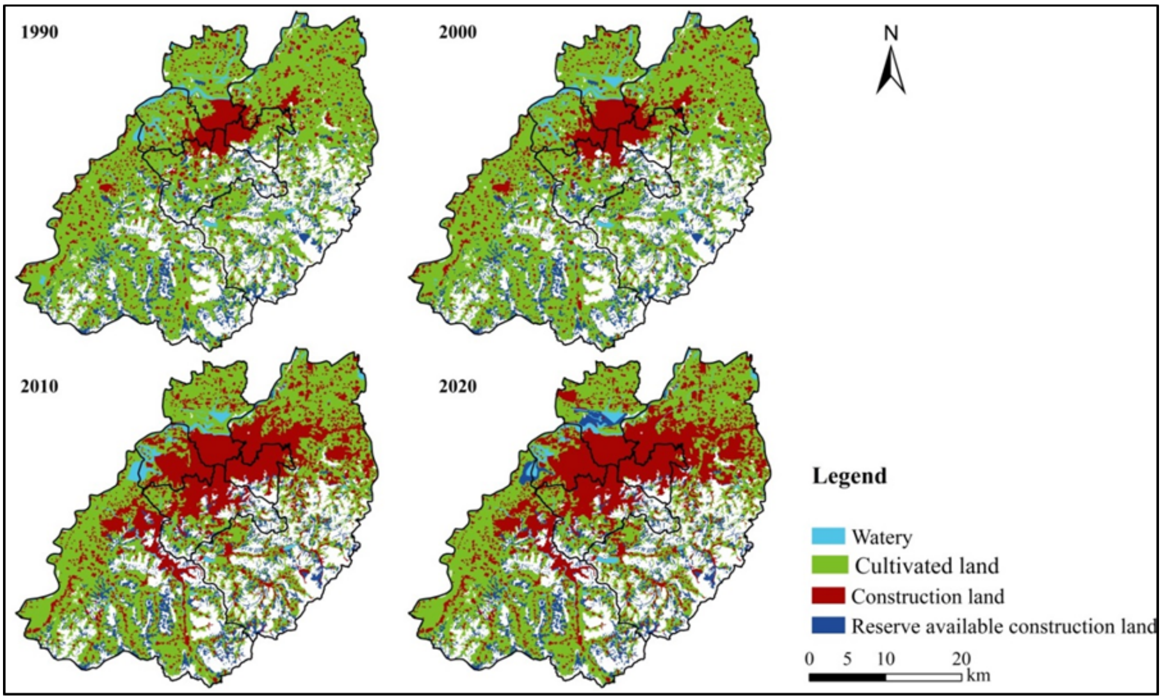

Fig.3 Spatial distribution of the reserve available construction land from 1990 to 2020

	Tian Qiao	Huai Yin	Li Xia	Li Cheng	Shi Zhong	Chang Qing	Jinan
1990	3.74	1.48	4.69	114.59	37.97	145.77	308.24
2000	3.50	1.48	4.69	114.6	37.88	145.78	307.93
2010	0.00	0.08	3.23	100.4	27.93	129.54	261.18
2020	17.71	4.43	3.20	100.75	28.31	138.08	292.48
1990–2020	13.97	2.95	-1.49	-13.84	-9.66	-7.69	-15.76

Tab.2 Area change of the reserve available construction land in each district from 1990 to 2020 (unit: km^2)

According to the results obtained from the area changes of the reserve available construction land, we could conclude that the urbanization rate of Jinan city is rising. Therefore, the construction land is expanding in recent years. Because the districts of Tian Qiao, Shi Zhong, Li Xia, and Huai Yin are mainly distributed in the more flat terrain area of North Jinan city, the potential for the reserve available construction land is lower in these districts. However, the districts of Chang Qing and Li Cheng are located in the southern part of Jinan city with the undulating terrain, so the construction area is small and the development condition is bad. Therefore, the potential for the reserve available construction land is higher in the two districts (Wang et al., 2020).

On the other hand, in terms of area change, the area of reserve construction land in Tian Qiao, Shi Zhong, Huai Yin and Chang Qing first decreased and then increased, but the area in Li Cheng and Li Xia continued to decrease. The area change range of the reserve construction land in each district is Tian Qiao, Li Cheng, Shi Zhong, Chang Qing, Huai Yin, and Li Xia in order. In the past 40 years, the total area of the reserve construction land in Tian Qiao and Huai Yin has increased by 13.97 km^2 and 2.95 km^2, respectively. The total area of the reserve construction land in Shi Zhong, Li Xia, Li Cheng, and Chang Qing has decreased, which decreased by 9.66 km^2, 1.49 km^2, 13.84 km^2 and 7.69 km^2, respectively. These indicate that the construction potential of Tian Qiao and Huai Yin has been rising, leading to a trend of counter-urbanization, while the other four districts, such as Li Cheng, are developing and building, and the potential of reserve construction has decreased slightly owing to the macroeconomic regulation and control of government policy (Li, 2017). Based on the above analysis, the changes of reserve available construction land in the study area also correspond to 3 periods of the urban space expansion, namely high-strength and medium-speed, low-strength and high-speed, and medium-strength and low-speed, (Wang et al., 2020).

3.3 Region-oriented analysis of the reserve available land resources

The total area of reserve available land resources in Jinan city is 360.66 km^2, which mostly distributed in the central and southern regions of study area (Fig.4). According to the dividing standard of terrain slope less than 8°, 8°–15°, and 15°–25°, the reserve suitable cultivated land resources in the study area are divided into three grades, namely suitable, more suitable, and conditional suitable. Meanwhile, the reserve suitable construction land resources are divided into three grades, that is, suitable, more suitable, and conditional suitable according to the dividing standard of terrain slope less than 3°, 3°–8°, and 8°–15° (Xu et al., 2008). According to the overlap between the standard of reserve land suitable for construction and reserve land suitable for cultivation in the concept of reserve available land resources, the reserve land resources with a slope between 15°–25° in the study area are classified as reserve arable land, but with the slope between 0°–15° can be used as the reserve suitable cultivated land and the reserve suitable construction land.

Based on the above mentioned, this study analyzes the regional development orientation combined with the regional natural and social economic conditions of Jinan city. On the one hand, the area of the conditional suitable reserve land resources in the study area is 229.53 km^2, and is distributed sporadically and mainly located in the central and southeastern regions of Chang Qing and the southern region of Li Cheng, but scattered in the districts of Li Xia and Shi Zhong (Fig.4). According to the classification criteria, these reserve land resources can be converted into new cultivated land resources in future planning and development, and serve as a reserve resource for maintaining Jinan city's arable land redlines and food security.

	Orientation of the reserve available land resources in each district
Tian Qiao	Most of the reserve land resources are suitable grade, which is suitable for reserve cultivated land or reserve construction land.
Huai Yin	The reserve available land resources are mostly suitable grade, and can be used as the reserve suitable cultivated land or construction land.
Li Xia	The reserve land resources are scattered, and will be suitable for the development of new construction land.
Li Cheng	The reserve available land resources are scattered, which mostly belong to the suitable grade and the conditional suitable grade, and are suitable for the reserve suitable cultivated land.
Shi Zhong	The distribution of reserve land resources is scattered, so the reserve land resources will be suitable for the development of new construction land.
Chang Qing	The suitable, more suitable, and conditional suitable grades of reserve available land resources are relatively uniform, so near the urban construction area can be planned as construction land, but the south-eastern part of the district can be used as the reserve arable land.

Tab.3 Orientation of the reserve available land resources in each district

Type of the reserve suitable land	**Reserve available land**	**Suitable grade**		**More suitable grade**		**Conditional suitable grade**	
		Cultivated land	**Constructi on land**	**Cultivated land**	**Constructi on land**	**Cultivated land**	**Constructi on land**
Tian Qiao	17.71	17.71	17.71	0.00	0.00	0.00	0.00
Huai Yin	4.43	4.41	4.35	0.02	0.06	0.00	0.02
Li Xia	3.68	1.16	0.09	2.04	1.10	0.49	2.04
Li Cheng	132.10	34.09	4.50	66.67	29.58	31.35	66.67
Shi Zhong	34.21	10.83	1.14	17.48	9.69	5.90	17.48
Chang Qing	168.53	63.08	14.52	75.01	48.56	30.44	75.01
Jinan city	360.66	131.28	42.31	161.22	88.99	68.18	161.40

Tab.4 Classification area of the reserve suitable land in each district from 1990 to 2020 (unit: km^2)

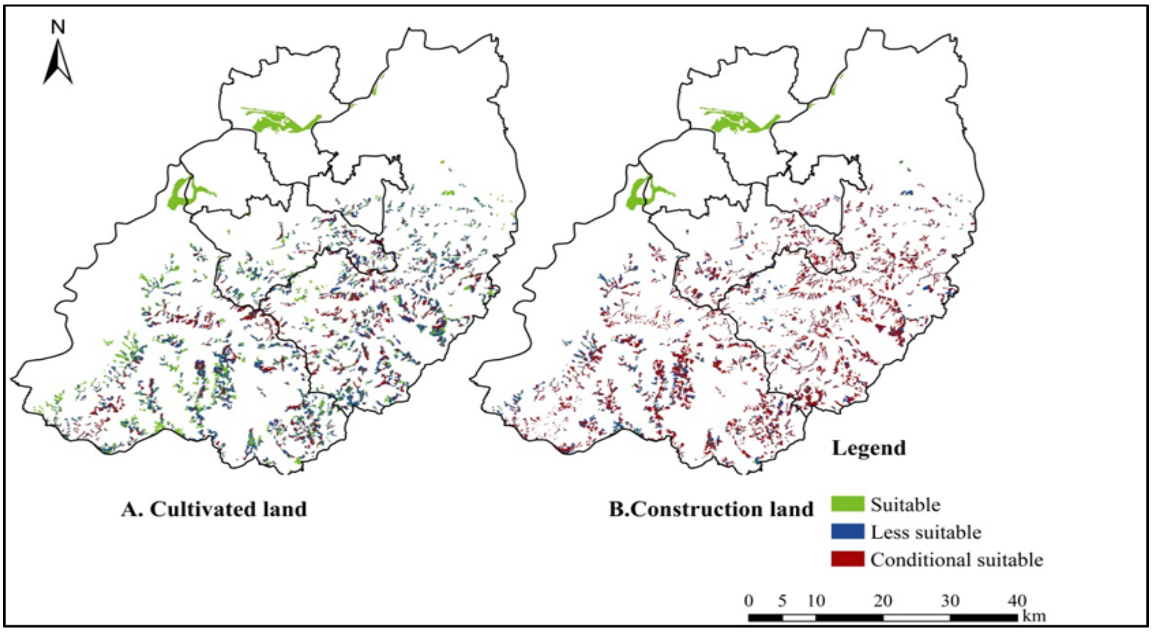

Fig.4 Spatial distribution of the reserve available construction land from 1990 to 2020

Considering the geographical environment, population gathering, land use status, and urban development planning, the orientation of reserve land use resources in each district is different in the study area (Tab.3). The distribution of reserve land resources with a total area of 17.71 km^2 in Tian Qiao is relatively concentrated, and most of the reserve land resources are suitable grade, which is suitable for reserve cultivated land or reserve construction land (Tab.4).

Furthermore, considering the high level of economic development, the large number of transport hubs (e.g. station), the dense population, the concentration of economic activities, the obvious resource advantages, and the combination of urban development planning within Tian Qiao, this district belongs to the industrial agglomeration area on the north bank of Jinan city, and many new and high-tech industrial parks have been built. Therefore, the reserve land resources can be used as the reserve suitable construction land in order to meet the needs of urban development and industrial agglomeration, promote the urban industrial function, and promote the industrial integration development (Yang & Zheng, 2006).

In Huai Yin district, the reserve available land resources are mostly suitable land resources, with an area of 4.43 km^2, which can be used as the reserve suitable cultivated land or construction land. Meanwhile, this district has a number of stations (e.g. the Jinan West station) which can bring a large number of people, and is one of Jinan city's important transport hubs, so the land resources in this region can be planned for construction land.

On the other hand, the area of reserve land resources in Chang Qing is 168.53 km^2, and the 3 suitable types (suitable, more suitable, and conditional suitable grades) are relatively uniform. Moreover, this district has built the College Town to promote economic development, and has a number of Science and Technology Innovation Industrial Parks, which are planned as an industrial cluster zone in the western region of Jinan city (Yan et al., 2005). Therefore, the reserve land resources near the urban construction area can be planned as construction land; but the south-eastern part of Chang Qing can be used as the reserve arable land owing to the rugged terrain.

In addition, the suitable reserve land resources are distributed in succession in the contiguous part of the Southwest Huai Yin and the North Chang Qing. Combining the characteristics and geographical location of the two regions, so the reserve land resources are suitable for reserve construction land in order to better integrate with the surrounding areas and meet the needs of further industrial expansion. However, the distribution of reserve land resources in the districts of Li Xia and Shi Zhong are scattered, with an area of 34.21 km^2 and 3.68 km^2, respectively. Because the two districts are the main urban area of Jinan city with densely populated and economically developed, where is home to many government departments and has a high degree of urbanization, the reserve land resources will be suitable for the development of new construction land to meet its development momentum.

In addition, the distribution of reserve available land resources in Li Cheng is scattered, with a total area of 132.10 km^2. These land resources mostly belong to the suitable grade and the conditional suitable grade. Combined with its topographical conditions, most of the reserve land resources in the central and southern parts of Li Cheng are located in the southern mountainous areas whose terrain is undulating; meanwhile, the carrying capacity of the reserve land resources is relatively insufficient and the concentration trend of reserve land resources is not obvious (Zhang & Zheng, 2001; Zheng et al., 2016; Liu et al., 2021), which is not conducive to centralized development and construction. Meanwhile, the Jinan city plans to designate the southern mountainous areas as the ecological recreation zone, giving priority to the protection and restoration of the ecological environment. Therefore, this part of the reserve land resources is suitable for the reserve suitable cultivated land in order to make up for the problem of cultivated land occupation in the process of urbanization, and to maintain the balance of cultivated land occupation and compensation.

4. Conclusions

Owing to the mass construction of the market housing and excessive real estate investment in the karst area of North China, land resources in Jinan city are mainly converted into urban areas, which result in the increasingly improving dwelling conditions. But both human interaction with karst environments and modern development could cause widespread the disturbance of karst environment in the study area. Based on the above analysis, the spatial and temporal evolution of urban reserve available land resources were explored in Jinan city from 1990 to 2020 in the present study. The results indicated that (1) the reserve construction land was mainly distributed in the southeastern region of the study area and has the lower potential. By 2020, the total area of the reserve construction land was 292.48 km^2. The potential of the reserve construction land was different to each district. Owing to the constraints of terrain and development conditions, the development of construction land in the districts of Li Cheng and Chang Qing was relatively low but the potential of reserve construction land was higher. However, the potential in other districts was lower.

During the past 40 years, the construction land in Jinan city had been expanding with the acceleration of urbanization, and the area of reserve construction land had been decreasing, shrinking by a total of 15.76 km^2. Under the macroeconomic regulation and control of government policy, the quantity of reserve construction land varied within districts. The area of reserve construction land in Li Cheng, Shi Zhong, Chang Qing, and Li Xia was on a downward trend, which decreased by 13.84 km^2, 9.66 km^2, 7.69 km^2 and 1.49 km^2, respectively. But the area of reserve construction land in Tian Qiao and Huai Yin showed an upward trend, increasing by 13.97 km^2 and 2.95 km^2, respectively.

(2) The spatial distribution characteristic of reserve cultivated land was similar with the reserve construction land in the study area, and the potential was higher. With the expansion of construction land, the area of reserve cultivated land showed a downward trend, which decreased from 379.00 km^2 in 1990 to 360.67 km^2 in 2020. During the study period, in accordance with the requirements of the social development plan, the area of reserve cultivated land in Li Cheng, Shi Zhong, Chang Qing, and Li Xia decreased by 14.56 km^2, 10.56 km^2, 8.54 km^2, and 1.59 km^2, respectively, but the area of reserve cultivated land in Tian Qiao and Huai Yin increased by 13.97 km^2 and 2.95 km^2, respectively. The potential of reserve cultivated land in Chang Qing, Li Cheng, and Shi Zhong was relatively higher owing to the impacts of the distribution of industrial parks and the topography. By 2020, the area of reserve cultivated land in the 3 districts was 168.53 km^2, 132.20 km^2, and 34.21 km^2, respectively.

(3) According to the spatial distribution characteristics of land use and regional natural economic situation, the regional use orientation of each district was different. On the one hand, the reserve land resources in Tian Qiao could be used for the reserve construction land and cultivated land. Because the regional economic development level of Tian Qiao was higher, the urbanization process was faster, and the flow of people was large. Therefore the regional direction of reserve land resources was more inclined to construction land.

On the other hand, the reserve land resources in Huai Yin, Shi Zhong, Li Xia, and the northern part of Chang Qing could be divided into construction land. Because the reserve land resources in Li Cheng and the southeastern region of Chang Qing were limited by natural factors (e.g. topography), so could be divided into the cultivated land in order to make up for the balance of arable land.

In addition, this study also revealed that the reserve land use resources were significantly affected by natural, economic and social factors. It was difficult to quantify the impact of government policy macroeconomic regulation and control and economic development policies on regional orientation in a complex reserve land planning system. Moreover, the existing evaluation methods regarded the slope and elevation of terrain as the important constraint conditions for the evaluation of reserve usable land resources according to the evaluation methods of reserve usable land resources. For example, in some regions, such as Jinan city, it was applicable, but in other regions, it was necessary to construct new constraints based on regional characteristics. Therefore, in the process of reserve land use evaluation in the karst region of North China, how to build a reasonable index system to evaluate reserve land use resources and analyze the direction of regional use was an important worth considering problem in the future.

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Image Sources

All figures are original produced by the Authors for this paper.

Fig.1: Location map of study area;

Fig.2: Spatial distribution of the reserve available cultivated land from 1990 to 2020;

Fig.3: Spatial distribution of the reserve available construction land from 1990 to 2020;

Fig.4: Spatial distribution of the reserve available construction land from 1990 to 2020.

Author's profile

Shujin Wang

He is a M.S. Student at the College of Geography and Environment, Shandong Normal University. His research interest is utilization of water and soil resources as well as ecological restoration.

Shanzhong Qi

He is a professor at the College of Geography and Environment, Shandong Normal University. Professor Shanzhong Qi received the Ph.D. degree in Physical Geography from Chinese Academy of Sciences in 2004. His research field is focused on the teaching and scientific research of environmental hazards and land use change as well as resources and environmental management, and he has undertaken many important scientific research projects. As the first author and corresponding author, he has published more than 80 SCI and EI academic papers and one monograph. He has respectively won one the 12th National Young Geoscience and Technology Award, second Prize of Science and Technology Progress of Shandong Province, and first Prize of Excellent Scientific Research Achievements of Shandong Colleges and Universities.

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Assessing urban growth and pollution through nightlight data: a case study in Thailand

Linking urban growth and CO concentrations via nightlights

Chaichana Kulworatit [a]*, Phuvis Kerdpramote [b], Saranya Saetang [c]

[a] Department of Computer Science, School of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
e-mail: chaichana.kul@kmitl.ac.th
ORCID: https://orcid.org/0000-0001-9959-4264
* Corresponding author

[b] Department of Computer Science, School of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
e-mail: poom2425@gmail.com
ORCID: https://orcid.org/0009-0001-5345-8037

[c] Department of Computational Science and Digital Technology, Faculty of Liberal Arts and Science, Kasetsart University Kamphaeng Saen Campus, Nakhon Pathom, Thailand
e-mail: saranya.sa@ku.ac.th
ORCID: https://orcid.org/0009-0003-2156-4024

Abstract

This study explores the relationship between urban development and air pollution in Thailand by analyzing remote sensing nightlight data and carbon monoxide (CO) concentrations over six years (2019-2024). Using data from VIIRS Day/Night Band (DNB) satellite imagery, CO levels, electricity consumption, and lignite production, the study finds a significant positive correlation (Pearson coefficient = 0.586) between nightlight intensity and CO concentrations. This suggests that nightlight data can be an effective tool for monitoring urban-related pollution. Seasonal and regression analyses show that urban growth contributes to pollution, but this is influenced by seasonal patterns and energy consumption. Multiple regression models highlight nightlight intensity as the strongest predictor of CO levels, with energy factors adding significant explanatory power. Regional analysis identifies the Bangkok Metropolitan Region as having the highest nightlight intensity and CO levels (correlation = 0.598). Lag correlation analysis suggests that changes in CO and nightlight intensity are most strongly correlated at zero lag, with CO changes slightly leading in some areas. These findings have implications for urban planning, environmental policy, and public health in Southeast Asia.

Keywords

Nightlight remote sensing; Seasonal patterns; Urban air pollution; Urban planning; VIIRS data

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1. Introduction

Rapid urbanization across Southeast Asia has led to significant environmental challenges, particularly regarding air quality and public health. Thailand, as one of the region's most dynamic economies, represents an ideal case study for examining the complex relationship between urban development and environmental quality. As cities expand, the demand for energy and transportation grows, often outpacing the development of sustainable infrastructure.

To monitor these dynamics, the scientific community has increasingly turned to remote sensing technologies. Traditional monitoring methods often rely on ground-based data that may be inconsistent, delayed, or insufficient in temporal and spatial resolution. In contrast, satellite-derived nightlight data has emerged as a robust proxy for anthropogenic activity, establishing a continuity of research that links luminous intensity to various socioeconomic indicators. Since the pioneering work of Elvidge et al. (2017), nightlight imagery has been extensively validated for estimating economic activity (Chen & Nordhaus, 2011), population distribution, and energy consumption (Li et al., 2020).

More recently, the application of nightlight data has expanded to environmental monitoring. Previous studies have demonstrated strong correlations between nightlights and various pollutants. For instance, Wang et al. (2019) utilized VIIRS data to predict air pollutants such as Nitrogen Dioxide (NO_2) and particulate matter (PM2.5) in urban environments. Similarly, Zuo et al. (2022) investigated the relationship between nightlights and Carbon Dioxide (CO_2) emissions, highlighting how industrial structures influence these correlations. However, despite these advancements, there remains a significant gap in the literature. Few studies have explored the specific spatiotemporal dynamics of Carbon Monoxide (CO) in developing tropical economies, particularly when analyzing the mediating role of specific fuel types like lignite.

This study addresses this gap by proposing an integrated analytical framework that links human activity indicators, atmospheric observations, and energy-system indicators. We use the VIIRS Stray Light Corrected Nighttime Day/Night Band Composites Version 1 (VCMSLCFG) and focus on the monthly mean radiance variable avg_rad, which represents average nighttime top-of-atmosphere radiance derived from cloud-free observations at a spatial resolution of 463.83 m. Although stray-light correction improves data usability, particularly at higher latitudes, avg_rad may still reflect transient illumination and background signals and therefore is interpreted as an indirect reflection of aggregate human activity rather than a direct measure of urban lighting intensity.

We integrate these nightlight-derived indicators with Sentinel-5P TROPOMI Carbon Monoxide (CO) observations to examine how the spatial and temporal rhythms of human activity drive atmospheric pollution. To disentangle these emission drivers, we combine remote-sensing metrics with ground-based energy statistics, including electricity consumption and lignite production. Within this framework, nightlights represent the demand side of urban and economic activity, while energy production and consumption capture the supply side of emissions, enabling a more comprehensive assessment of how urban development and pollution are fundamentally intertwined.

Therefore, the primary objective of this research is to quantify the relationship between urban development and CO concentration.

This research addresses several key questions:

- What is the relationship between nightlight intensity and CO concentrations in Thailand?
- How do seasonal and annual patterns affect this relationship?
- To what extent do electricity consumption and lignite production influence both nightlight intensity and CO levels?
- Can nightlight data serve as an effective proxy for monitoring urban-related pollution?
- How do regional and provincial differences affect the relationship between nightlight intensity and CO concentrations?

By addressing these questions, this study contributes to a growing body of literature on remote sensing applications for environmental monitoring and provides valuable insights for urban planners and policymakers in Thailand and comparable developing economies.

2. Data and methodology

2.1 Data sources

This study utilizes monthly data from January 2019 to December 2024 for Thailand, covering all 77 provinces, and comprising four primary variables:

Nightlight intensity

Mean nightlight values were derived from the VIIRS Stray Light Corrected Nighttime Day/Night Band Composites Version 1 (VCMSLCFG), accessed through Google Earth Engine (Hankey & Marshall, 2017). This product provides a monthly cloud-free composite of nighttime lights at 463.83 m spatial resolution with improved calibration and stray light correction, making it superior to earlier DMSP/OLS data for quantitative analysis of nighttime light emissions (Elvidge et al., 2017).

Our processing workflow consisted of the following steps:

1. Data Acquisition: Monthly nightlight composites were obtained for Thailand using the official administrative boundary from the USDOS/LSIB database, ensuring precise spatial delineation of the study area. Fig.1 presents VIIRS-derived nightlight intensity across Thailand (2022). The bright yellow-white area in the central region corresponds to the Bangkok Metropolitan Region, with smaller urban centers visible as blue points throughout the country. White boundary lines indicate provincial borders. Nightlight intensity serves as a proxy for urban development and human activity.

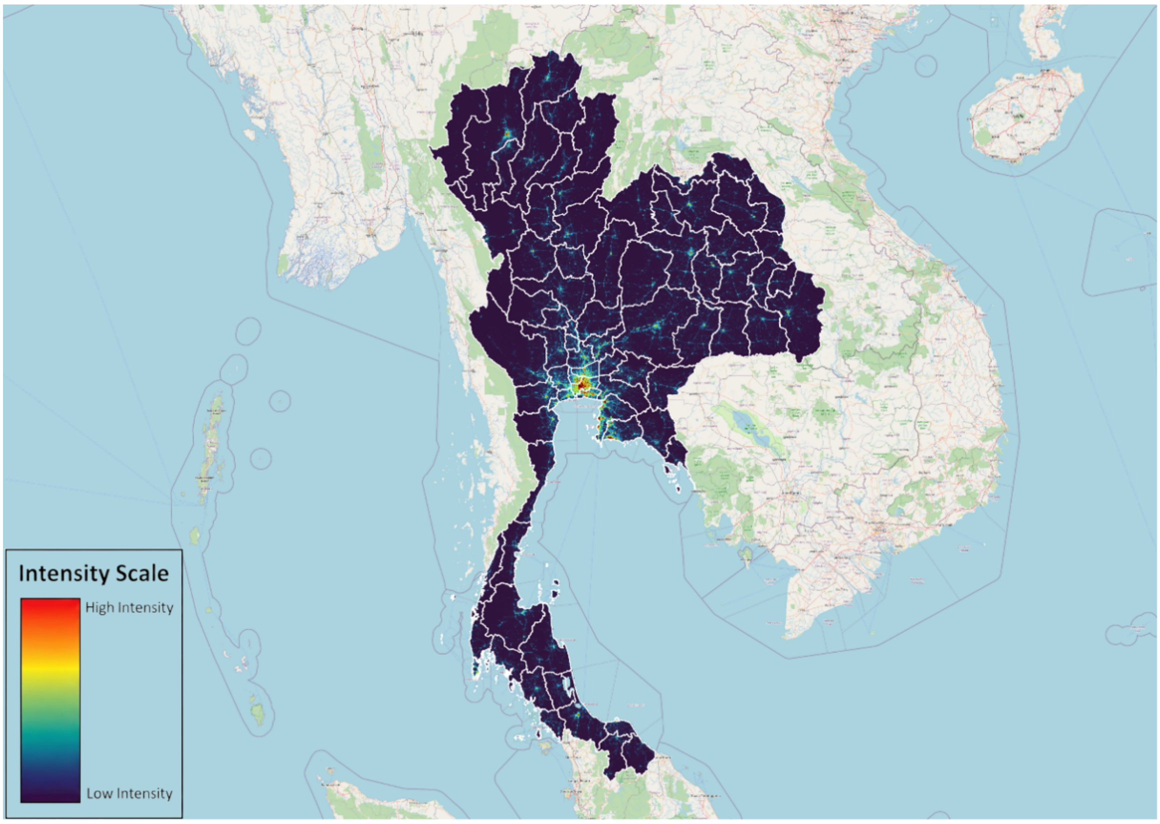

Fig.1 VIIRS-derived nightlight intensity across Thailand (2022)

2. Quality Filtering: To ensure data quality, we applied a pixel-level quality control filter using the QF_Cloud_Mask band. Only pixels flagged as "confident clear" (bitmask value 0) were retained, while cloudy or degraded pixels were masked out;
3. Radiance Selection: We extracted the "avg_rad" band, which represents the average radiance values measured in nanoWatts/sr/cm2, providing a consistent metric of nighttime light intensity;
4. Temporal Aggregation: For each month in the study period from January 2019 to December 2024, we calculated the median value to reduce the influence of outliers and short-lived illumination. The median was preferred over the mean because it is less sensitive to transient extreme values and residual stray light effects;
5. Spatial Aggregation: The final monthly nightlight value for each province was calculated as the spatially weighted mean of all valid pixels within the provincial boundary, automatically handling missing data by excluding masked pixels from the calculation;
6. National Averaging: The final monthly nightlight value for Thailand was calculated as the area-weighted mean radiance across all valid pixels within the country's boundary.

The resulting nightlight intensity metric serves as a proxy for urban development and human activity, capturing both the spatial extent and intensity of artificial lighting. This approach enables consistent monitoring of urbanization patterns throughout our study period, with values ranging from 0.318 to 1.347 nanoWatts/sr/cm^2 for national monthly averages.

CO concentrations

Mean atmospheric carbon monoxide measurements were derived from the Sentinel-5P NRTI CO: Near Real-Time Carbon Monoxide product. To ensure high data fidelity, we filtered the TROPOMI data using the provided qa_value (quality assurance value). Following product recommendations, we excluded all pixels with a qa_value < 0.5, which effectively removes data degraded by thick clouds or retrieval errors (Borsdorff et al., 2019).

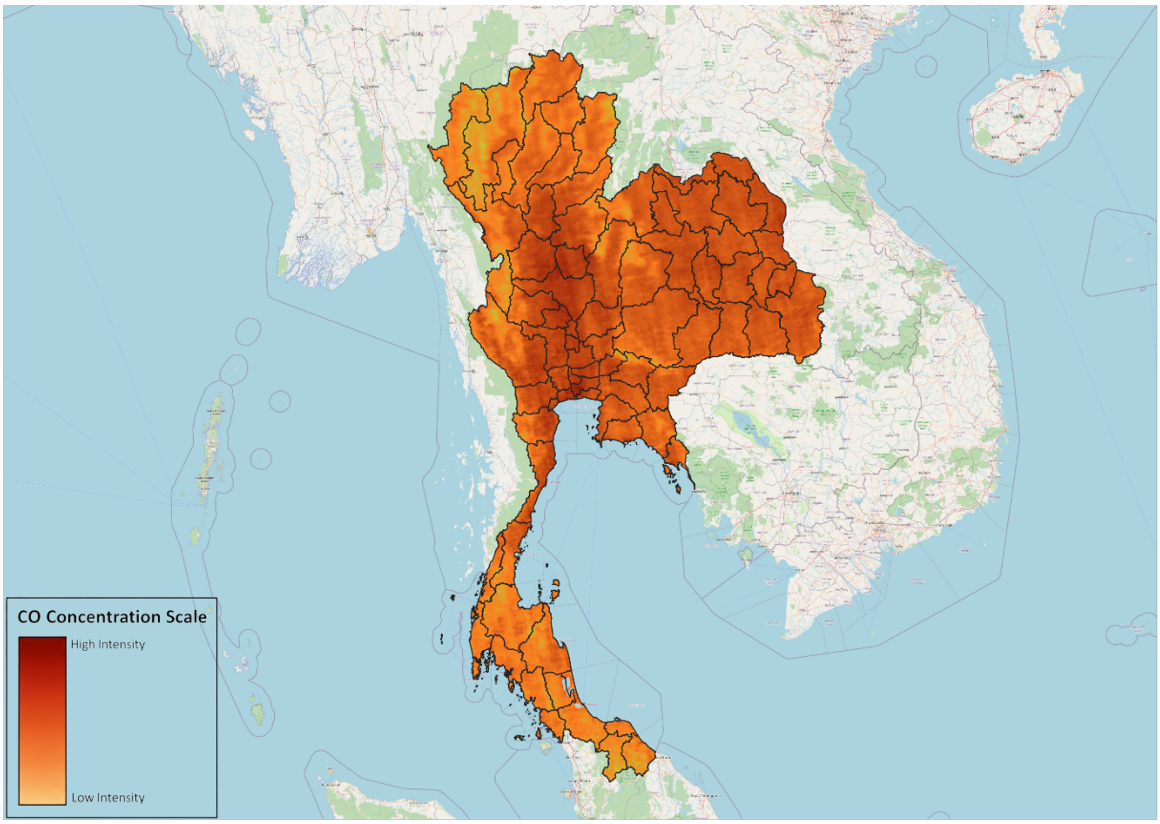

Fig.2 Carbon monoxide (CO) concentrations across Thailand derived from Sentinel-5P TROPOMI data (2022)

Spatially, we aggregated the valid 1 × 1 km pixels to the provincial level using a mean reduction method. In cases where pixels partially overlapped provincial borders, an area-weighted average was applied to assign values to the respective administrative units. The product measures the total column of CO (mol/cm^2). The satellite-based approach provides consistent spatial coverage across Thailand and captures CO from all sources, including transportation, industrial processes, biomass burning, and residential fuel combustion (Landgraf et al., 2016).

Fig.2 presents Carbon monoxide (CO) concentrations across Thailand derived from Sentinel-5P TROPOMI data (2022). Orange-red areas indicate higher CO concentrations, with darker red showing the highest levels. The distribution pattern shows correlation with urban centers and transportation corridors, with particularly elevated levels in the northern region during the dry season.

Electricity consumption

Monthly electricity consumption data for Thailand were obtained from the Electricity Generating Authority of Thailand (EGAT). These data represent total national consumption measured in gigawatt-hours (GWh), providing an indicator of energy usage patterns that may correlate with both urban activity and pollution generation.

Lignite production and consumption

Monthly data on the production and consumption of lignite, a primary fossil fuel used in Thailand's electricity generation, were sourced from the Department of Mineral Resources. Lignite is a low-grade coal that, when burned, can be a significant source of various pollutants, including carbon monoxide, particularly if combustion processes are inefficient.

2.2 Analytical methods

The analytical approach employed in this study consists of several complementary methods designed to explore the relationship between nightlight intensity and CO concentrations, while accounting for potential mediating factors and temporal dynamics.

Correlation analysis

Pearson correlation coefficients were calculated to quantify the strength and direction of relationships between key variables, with particular focus on the association between nightlight intensity and CO concentrations. The Pearson correlation coefficient (r) between two variables X and Y is calculated as shown in Equation (1).

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}} \quad (1)$$

Where:

- r is the Pearson correlation coefficient;
- X_i is the i-th observation of variable X;
- Y_i is the i-th observation of variable Y;
- $\bar{X}$ is the mean value of variable X;
- $\bar{Y}$ is the mean value of variable Y;
- n is the total number of paired observations.

Additional correlations between these primary variables and electricity consumption and lignite production were also analyzed to identify potential mediating relationships. A correlation matrix was generated to visualize the network of relationships among all variables in the dataset.

Time series analysis

Time series decomposition was applied to both nightlight intensity and CO concentration data to separate the underlying trend, seasonal patterns, and residual components. We employed the additive decomposition model, as shown in Equation (2).

$$Y_t = T_t + S_t + R_t \tag{2}$$

Where:

- Y_t is the observed value of the time series at time t;
- T_t is the trend component of the time series at time t, representing the long-term progression;
- S_t is the seasonal component at time t, capturing periodic fluctuations;
- R_t is the residual component at time t, representing irregular variations not explained by the trend or seasonal structure.

This approach enables a clearer understanding of long-term trajectories versus seasonal variations in both urban development and pollution levels. The seasonal component S_t was modeled using month-specific coefficients that capture the cyclical nature of both variables. Additionally, we analyzed annual trends by calculating yearly averages for each variable and examined monthly patterns by aggregating data across years for each month.
To measure the proportion of variance explained by seasonality for each variable, we used the variance ratio, as shown in Equation (3).

$$VR_{seasonal} = \frac{\sum_{t=1}^{T}(S_t)^2}{\sum_{t=1}^{T}(Y_t)^2} \tag{3}$$

Where:

- $VR_{seasonal}$ is the variance ratio representing the proportion of total variance in the time series;
- S_t is the seasonal component at time t, capturing periodic fluctuations;
- Y_t is the observed value of the time series at time t;
- T is the total number of time steps in the time series.

This ratio quantifies the relative contribution of seasonal patterns to the overall variability in the time series data.

Regression analysis

Two regression models were developed to quantify the relationship between nightlight intensity and CO concentrations:

1. Simple Linear Regression: Modeling CO concentrations as a function of nightlight intensity alone to establish the baseline relationship, as shown in Equation (4).

$$CO_t = \beta_0 + \beta_1 \cdot Nightlight_t + \epsilon_t \tag{4}$$

Where:

- CO_t is the carbon monoxide concentration at time t;

- β_0 is the intercept term of the regression model;
- β_1 is the regression coefficient representing the effect of nightlight intensity on CO concentration;
- $Nightlight_t$ is the nightlight intensity at time t;
- t is the error term at time t capturing unexplained variation in CO concentration.

2. Multiple Regression: Incorporating electricity consumption and lignite production as additional predictors to assess their mediating influence, as shown in Equation (5).

$$CO_t = \beta_0 + \beta_1 \cdot Nightlight_t + \beta_2 \cdot Electricity_t + \beta_3 \cdot Lignite_t + \epsilon_t \quad (5)$$

Where:

- CO_t is the carbon monoxide concentration at time t;
- β_0 is the intercept term of the regression model;
- β_1 is the regression coefficient associated with nightlight intensity;
- β_2 is the regression coefficient associated with electricity consumption;
- β_3 is the regression coefficient associated with lignite production;
- $Nightlight_t$ is the nightlight intensity at time t;
- $Electricity_t$ is the electricity consumption at time t;
- $Lignite_t$ is the lignite production at time t;
- ϵ_t is the error term at time t capturing unexplained variation in CO concentration.

For both models, we calculated standard regression diagnostics including R-squared values, adjusted R-squared, coefficient significances, and standardized coefficients to facilitate comparison of the relative importance of different predictors.

Lag correlation analysis

Lag correlation analysis was conducted to examine the potential temporal relationships between nightlight intensity and CO concentrations. This approach tests how past values of one variable relate to current values of another, helping to understand lead-lag relationships between variables. For a lag k, the correlation between X_{t-k} and Y_t was calculated to determine if changes in one variable tend to precede changes in another, as shown in Equation (6).

$$r_k = \frac{\sum_{t=k+1}^{T}(X_{t-k} - \bar{X})(Y_t - \bar{Y})}{\sqrt{\sum_{t=k+1}^{T}(X_{t-k} - \bar{X})^2}\sqrt{\sum_{t=k+1}^{T}(Y_t - \bar{Y})^2}} \quad (6)$$

Where:

- r_k is the Pearson correlation coefficient at lag k;
- X_{t-k} is the value of variable X at time $t-k$;
- Y_t is the value of variable Y at time t;
- $\bar{X}$ is the mean of variable X over the analysis period;
- $\bar{Y}$ is the mean of variable Y over the analysis period;
- k is the lag length expressed in time steps;
- T is the total number of time steps in the time series.

We calculated lag correlations for lag k ranging from 0 to 6 months in both directions (nightlight leading CO and vice versa). The statistical significance of the lag correlation coefficients (r_k) was assessed using a t-test. The null hypothesis (H_0: r_k = 0) was tested with T - k - 2 degrees of freedom, where T is the total number of time periods, as shown in Equation (7).

$$t = \frac{r_k \sqrt{T - k - 2}}{\sqrt{1 - r_k^2}} \tag{7}$$

Where:

- t is the test statistic used to assess the statistical significance of the lag correlation coefficient;
- r_k is the lagged Pearson correlation coefficient at lag k;
- k is the lag length expressed in time steps;
- T is the total number of time periods in the time series.

Regional and provincial analysis

To account for spatial heterogeneity, we conducted analyses at both regional and provincial levels using a hierarchical spatial modeling approach:

1. Regional Analysis: Thailand was divided into five regions (Bangkok Metro, Northern, Northeastern, Central, and Southern), and correlations between nightlight intensity and CO were calculated for each region (Uttamang et al., 2018). To account for spatial autocorrelation within regions, we employed a spatial autoregressive model with the following form, as shown in Equation (8).

$$CO_i = \beta_0 + \beta_1 \cdot Nightlight_i + \rho \sum_{j=1}^{n} w_{ij} CO_j + \epsilon_t \tag{8}$$

Where:

- CO_i is the carbon monoxide concentration in spatial unit i;
- CO_j is the carbon monoxide concentration in neighboring spatial unit j;
- β_0 is the intercept term of the regression model;
- β_1 is the regression coefficient associated with nightlight intensity;
- $Nightlight_i$ is the nightlight intensity in spatial unit i;
- ρ is the spatial autoregressive parameter;
- w_{ij} is the spatial weight reflecting the spatial relationship between spatial units i and j;
- n is the total number of spatial units included in the analysis;
- ϵ_t is the error term associated with spatial unit t, capturing unexplained variation.

2. Provincial Analysis: In-depth analysis was conducted for key provinces, including Bangkok, Samut Prakan, Nonthaburi, Pathum Thani, Nakhon Ratchasima, Chiang Mai, and Songkhla, representing different regions and levels of urbanization. For each province, we constructed time series models that account for both temporal autocorrelation and seasonal effects.

3. Results

3.1 Descriptive statistics

Tab.1 presents descriptive statistics for the four primary variables analyzed in this study, covering the period from January 2019 to December 2024. The data show considerable variation in all variables over the study period, reflecting both seasonal cycles and longer-term trends.

CO concentrations show significant variability, with values ranging from 0.023581 to 0.051766 mol/m^2. This range represents an approximately twofold difference between minimum and maximum observed concentrations, underscoring the dynamic nature of this pollutant.

The mean concentration is 0.037535 mol/m^2.

Variable	Mean	Std Dev	Min	Max	Range
CO Mean (mol/m^2)	0.038	0.008	0.024	0.052	0.028
Nightlight Mean*	1.003	0.254	0.318	1.347	1.028
Electricity Cons. (GWh)	15,840	1,093	13,619	18,621	5,002
Lignite Production (thousand tons)	1,125	109	942	1,341	399

Tab.1 Descriptive Statistics of Key Variables (January 2019 - December 2024) *Measured in nanoWatts/sr/cm^2

3.2 Correlation analysis

The weighted Pearson correlation coefficient between monthly mean CO concentration and nightlight intensity was 0.586 ($p < 0.001$), indicating a strong positive relationship between these variables. This finding suggests that areas with higher nightlight intensity—representing greater urbanization and human activity—tend to exhibit higher levels of CO in the atmosphere. The correlation remains robust when controlling for spatial autocorrelation using Moran's I test ($I = 0.428$, $p < 0.001$), confirming that the relationship is not merely an artifact of spatial clustering.

The correlation matrix for all variables is presented in Table 2, revealing additional relationships:

Variable	CO	Nightlight	Electricity	Lignite
CO Mean	1.000	0.586	0.475	0.382
Nightlight Mean	0.586	1.000	0.535	0.318
Electricity Cons.	0.475	0.535	1.000	0.430
Lignite Production	0.382	0.318	0.430	1.000

Tab.2 Correlation Matrix of Key Variables

These findings suggest that energy consumption patterns play a role in mediating the relationship between urban development and air pollution. The stronger correlation between nightlight intensity and CO concentrations (0.586) compared to the correlations between energy variables and CO (0.475 for electricity, 0.382 for lignite) suggests that nightlight intensity captures aspects of urban development beyond energy consumption that contribute to pollution, such as transportation and industrial activities.

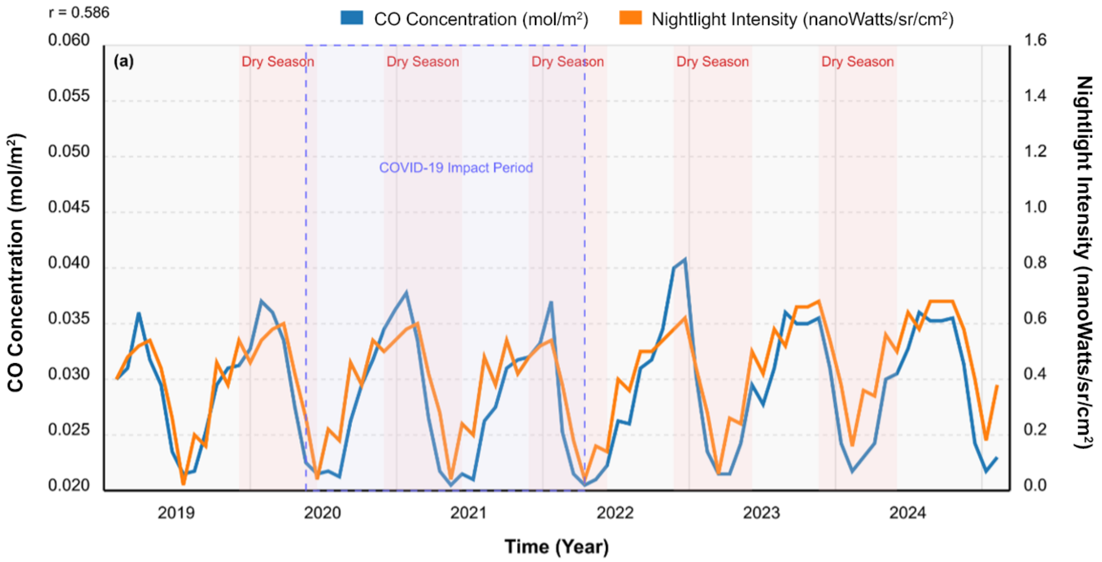

Fig.3 Time series of CO concentrations and nightlight intensity in Thailand from January 2019 to December 2024

Fig.3 presents the time series of CO concentrations and nightlight intensity in Thailand from January 2019 to December 2024. Both variables show pronounced seasonal patterns, with CO peaking during dry season months (January-April) and nightlight intensity showing peaks during December-January and April, visually illustrating their relationship over the study period. The correlation is evident in the general alignment of peaks and troughs, though not all fluctuations coincide precisely.

3.3 Temporal patterns

Seasonal variations

Both CO concentrations and nightlight intensity displayed clear seasonal patterns, but with notable differences in their cycles. Fig.4 shows the average values for each variable by month, aggregated across the six-year study period.

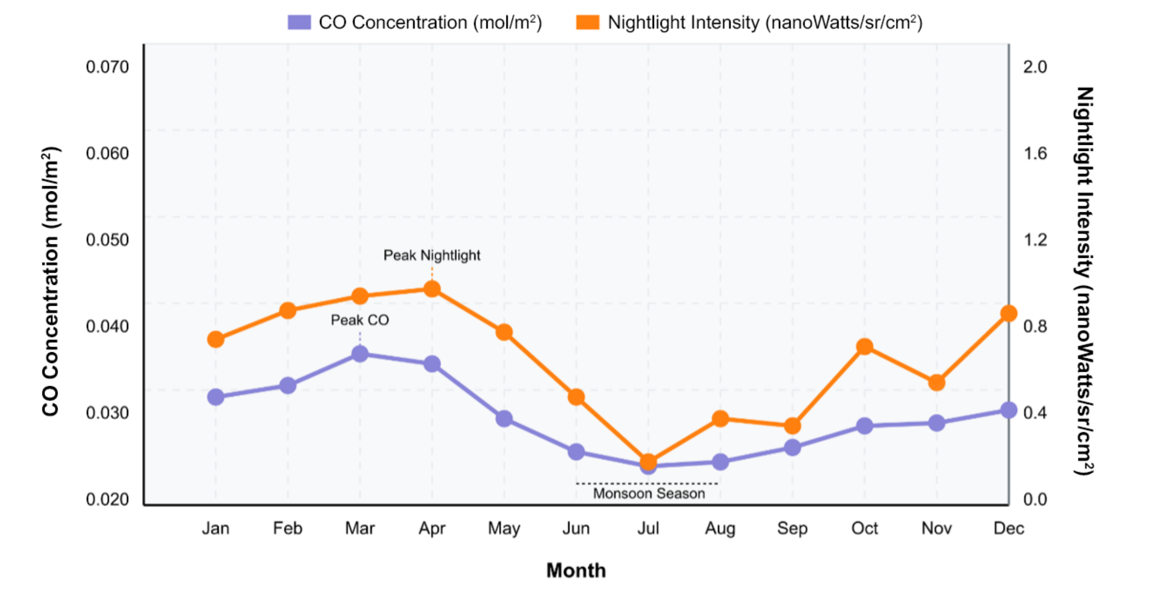

Fig.4 Monthly seasonal patterns of CO concentrations and nightlight intensity in Thailand (2019-2024 average)

Fig.4 presents the monthly seasonal patterns of CO concentrations and nightlight intensity in Thailand (2019-2024 average). Both variables show distinct seasonality with peaks in the dry season (December-April) and troughs during the wet season (May-October).

The seasonal patterns reveal that:

- CO concentrations peaked during the dry season (January-April), with the highest average value in March (0.051766 mol/m^2), and reached their lowest levels during the wet season (June-September), with the minimum in July (0.025583 mol/m^2). This pattern is consistent with established knowledge about carbon monoxide in Thailand, where dry season conditions favor pollutant accumulation due to reduced atmospheric mixing and increased biomass burning in surrounding rural areas;
- Nightlight intensity showed maximum values during December-April (peaking at 1.346730 nanoWatts/sr/cm^2 in April), coinciding with holiday celebrations, tourist season, and Thai New Year, and minimum values in July (0.531941 nanoWatts/sr/cm^2) during the monsoon season when cloud cover is most prevalent;
- Electricity consumption exhibited less pronounced seasonality but tended to be higher during the hot season (March-June) when air conditioning usage increases;
- Lignite production showed relatively modest seasonal variation, with slightly higher values in the first half of the year.

The seasonal decomposition revealed that approximately 26% of the variation in CO concentrations and 19% of the variation in nightlight intensity could be attributed to seasonal factors.

Annual trends

Over the six-year period studied (2019-2024), both variables showed overall increasing trends with some year-to-year variations. Table 3 presents the annual averages for each variable.

Variable	CO Mean (mol/m^2)	Nightlight Mean	Electricity Cons.	Lignite Production
2019	0.038993	0.898589	15,713	1,161
2020	0.037513	0.960358	15,246	1,133
2021	0.036304	1.001512	15,730	1,184
2022	0.034153	0.929382	16,080	1,145
2023	0.038068	1.215768	16,671	1,066
2024	0.036678	1.097661	16,005	958

Tab.3 Annual Average Values of Key Variables (2019-2024)

The annual trends indicate that:

- CO concentrations showed fluctuating patterns, with a notable decrease during 2021-2022 (possibly attributable to reduced activity during the COVID-19 pandemic recovery period) followed by an increase in 2023;
- Nightlight intensity increased by approximately 22% over the six-year period, with the highest values recorded in 2023, suggesting continuous urbanization even during periods of economic disruption.
- Electricity consumption showed a steady increasing trend, with a slight decrease in 2020 during the COVID-19 pandemic;
- Lignite production exhibited a declining trend, particularly pronounced in 2023-2024, potentially reflecting Thailand's energy transition policies.

The divergence between trends during 2020-2022 highlights the complex relationship between human activity, economic development, and environmental impacts, with pollution potentially responding more directly to economic slowdowns than does urbanization as measured by nightlight intensity.

3.4 Regression analysis

Simple linear regression

The simple linear regression model using nightlight intensity to predict CO concentrations yielded the following equation, as shown in Equation (9).

$$CO_t = 0.022641 + 0.014070 \cdot Nightlight_t \qquad (9)$$

Where:

- CO_t is the carbon monoxide concentration at time t;
- $Nightlight_t$ is the nightlight intensity at time t;
- 0.022641 is the estimated intercept of the regression model;
- 0.014070 is the estimated regression coefficient.

This model produced an R^2 value of 0.343, indicating that nightlight intensity alone explains approximately 34.3% of the variation in CO levels. The coefficient for nightlight intensity was positive and statistically significant (p < 0.001), confirming the strong relationship identified in the correlation analysis.

Multiple regression

The incorporation of electricity consumption and lignite production into a multiple regression model produced the following equation, as shown in Equation (10).

$$CO_t = -0.019 + 0.012 \cdot Nightlight_t + 1.38 \times 10^{-6} \cdot Electricity_t + 1.62 \times 10^{-5} \cdot Lignite_t \quad (10)$$

Where:

- CO_t is the carbon monoxide concentration at time t;
- $Nightlight_t$ is the nightlight intensity at time t;
- $Electricity_t$ is the electricity consumption at time t;
- $Lignite_t$ is the lignite production at time t;
- -0.019 is the estimated intercept of the regression model;
- 0.012 is the estimated regression coefficient associated with nightlight intensity;
- 1.38×10^{-6} is the estimated regression coefficient associated with electricity consumption;
- 1.62×10^{-5} is the estimated regression coefficient associated with lignite production.

This model increased the R^2 value to 0.527, suggesting that these energy-related factors explain an additional 18.4% of the variation in CO concentrations beyond what is captured by nightlight intensity alone. Table 4 summarizes the results of both regression models.

Model	Variable	Coefficient	p-value	Std. Coef
Simple	Constant	0.023	< 0.001	-
	Nightlight Mean	0.014	< 0.001	0.586
Multiple	Constant	-0.019	0.018	-
	Nightlight Mean	0.012	< 0.001	0.498
	Electricity Cons.	1.38×10^{-6}	0.006	0.254
	Lignite Production	1.62×10^{-5}	0.015	0.196

Tab.4 Regression Results for CO Concentration Models

All three predictors remained statistically significant in the multiple regression model, with standardized coefficients indicating that nightlight intensity is the strongest predictor of CO concentrations, followed by electricity consumption and then lignite production.

3.5 Regional analysis

Regional analysis revealed significant spatial heterogeneity in the relationship between nightlight intensity and CO concentrations across Thailand. Table 5 summarizes the key findings for each region.

Region	Corr.	R^2	CO*	NL*	Regression Equation
Bangkok Metro	0.598	0.358	0.038	3.812	0.025 + 0.002·NL
Northern	0.548	0.300	0.034	0.461	0.023 + 0.024·NL
Northeastern	0.472	0.223	0.036	0.568	0.026 + 0.017·NL
Central	0.571	0.326	0.037	0.648	0.025 + 0.019·NL
Southern	0.334	0.112	0.032	1.163	0.026 + 0.005·NL

Tab.5 Regional Analysis of Nightlight-CO Relationship *CO Mean (mol/m^2), NL = Nightlight Mean (nanoWatts/sr/cm^2)

The regional analysis indicates that:

- The Bangkok Metropolitan Region shows both the highest CO levels (0.038381 mol/m^2) and by far the highest nightlight intensity (3.812006 nanoWatts/sr/cm^2), reflecting intense urbanization and associated pollution;

- The correlation between nightlight intensity and CO is strongest in the Bangkok Metro region (r = 0.598) and weakest in the Southern region (r = 0.334), suggesting that the relationship between urbanization and pollution varies by regional context;
- The slope of the regression line (coefficient for nightlight) varies significantly across regions, with the Northern region showing the steepest slope (0.024286), indicating that a unit increase in nightlight intensity is associated with a larger increase in CO concentrations in this region compared to others;
- The Southern region shows a relatively high nightlight intensity (1.162583 nanoWatts/sr/cm^2) but the lowest CO levels (0.031675 mol/m^2) and weakest correlation, suggesting that nightlight in this region may be associated with activities that produce less CO pollution, possibly related to tourism and coastal development.

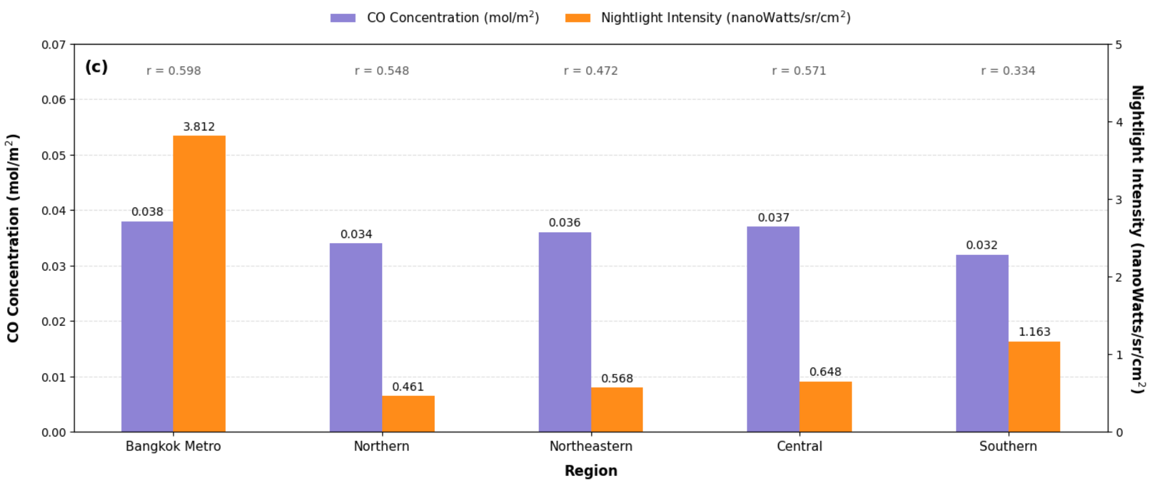

Fig.5 Regional comparison of CO concentrations and nightlight intensity across Thailand's five regions, averaged over 2019-2024

Fig.5 presents a regional comparison of mean CO Concentration and Nightlight Intensity in Thailand. Data labels above bars represent mean values; r values indicate the Pearson correlation coefficient between the two variables for each specific region.

3.6 Provincial analysis

The provincial analysis focused on key provinces representing different regions and levels of urbanization. Tab.6 presents the correlation coefficients and regression results for these provinces.

Province	Corr.	R^2	CO*	NL*	Region
Bangkok	0.547	0.299	0.039	5.025	Bangkok Metro
Samut Prakan	0.627	0.394	0.039	3.750	Bangkok Metro
Nonthaburi	0.486	0.236	0.038	3.523	Bangkok Metro
Pathum Thani	0.564	0.319	0.037	2.952	Bangkok Metro
Nakhon Ratchasima	0.501	0.251	0.035	0.530	Northeastern
Chiang Mai	0.491	0.241	0.035	0.422	Northern
Songkhla	0.195	0.038	0.030	0.844	Southern

Tab.6 Provincial Analysis of Nightlight-CO Relationship for Key Provinces *CO Mean (mol/m^2), NL = Nightlight Mean (nanoWatts/sr/cm^2)

The provincial analysis shows that:

- Bangkok has the highest nightlight intensity (5.024764 nanoWatts/sr/cm^2) among all provinces, followed by other provinces in the Bangkok Metropolitan Region;

- Samut Prakan shows the strongest correlation between nightlight and CO (r = 0.627), possibly due to its mix of industrial activities, residential areas, and transportation infrastructure;
- Songkhla in the Southern region shows a notably weak correlation (r = 0.195), confirming the regional pattern that nightlight intensity in the Southern region may be associated with activities that produce less CO pollution;
- The provinces in the Bangkok Metropolitan Region show similar CO levels despite varying nightlight intensities, suggesting potential saturation effects or differences in the types of urban activities and infrastructure generating nighttime light.

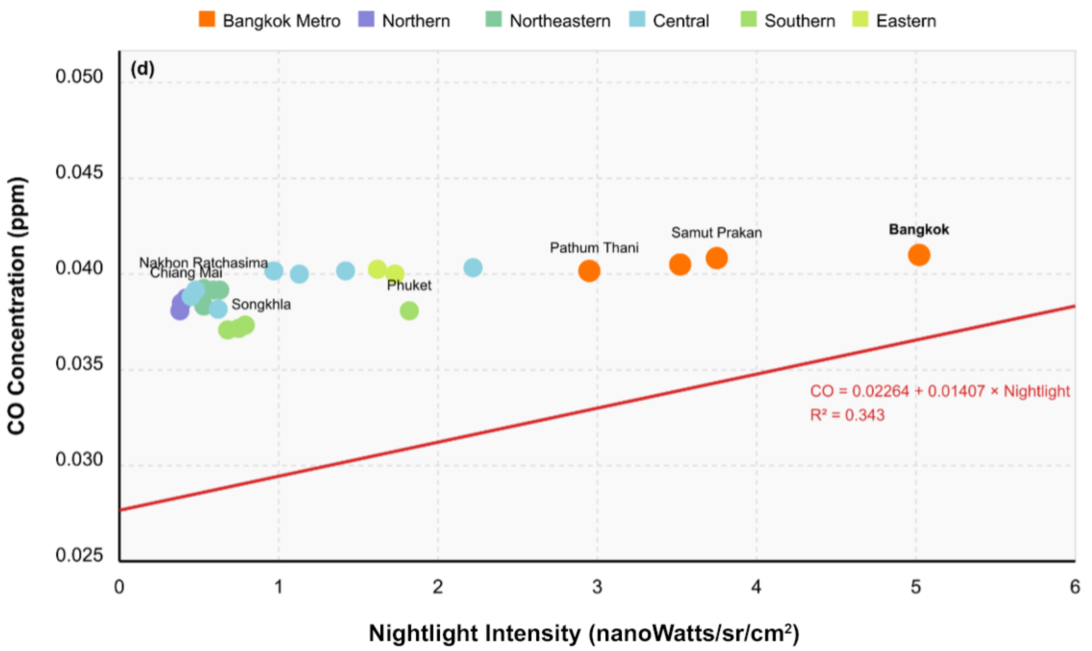

Fig.6 Scatter plot of CO concentrations versus nightlight intensity for all provinces in Thailand, with key provinces highlighted

Fig.6 presents a scatter plot of CO concentrations versus nightlight intensity for all provinces, highlighting the positive relationship between these variables and the position of key provinces. The red line represents the linear regression model.

3.7 Lag correlation analysis

Lag correlation analysis was performed to explore potential temporal relationships between nightlight intensity and CO concentrations. Tab.7 presents the correlation coefficients for different lag periods at the national level.

Lag (months)	Nightlight leading CO	CO leading Nightlight
0	0.5855	0.5855
1	0.3961	0.5029
2	0.1869	0.2056
3	-0.0587	-0.1037
4	-0.1689	-0.4125
5	-0.3237	-0.4514
6	-0.4926	-0.4989

Tab.7 Lag Correlation Analysis of Nightlight and CO Relationship

The lag correlation results indicate that:

- The strongest correlation between nightlight intensity and CO concentrations occurs at lag 0 (contemporaneous relationship), suggesting that the two variables generally change together;
- The correlation between lagged nightlight and current CO declines rapidly as the lag increases, becoming negative at lag 3, which suggests that nightlight changes do not strongly predict future CO changes beyond a month or two;
- The correlation between lagged CO and current nightlight also declines with increasing lag but remains stronger than in the opposite direction at lag 1, suggesting that CO changes might slightly lead nightlight changes in some contexts;
- The negative correlations at longer lags likely reflect the strong seasonal patterns in both variables, as periods of high values are followed by periods of low values approximately 6 months later.

This temporal analysis provides a more nuanced understanding of the relationship between urban development and pollution, suggesting that while they generally change together, there may be complex feedback mechanisms at work with slight temporal offsets.

4. Discussion

4.1 Interpreting the nightlight-pollution relationship

The strong positive correlation (r = 0.586) between nightlight intensity and CO concentrations confirms our primary hypothesis that nightlight data can serve as an effective proxy for monitoring urban-related pollution. This finding is consistent with the nature of carbon monoxide as a pollutant directly linked to combustion processes associated with human activities, particularly transportation and industrial operations.

However, the observed strength of this relationship is influenced by several factors, as discussed in the following subsections.

Seasonal variations

The differing seasonal patterns of the two variables suggest that while urbanization (nightlight intensity) contributes to pollution, meteorological and other factors also play significant roles in determining CO concentrations.

The stronger seasonal component in CO concentrations (26% of variation) compared to nightlight intensity (19% of variation) reflects these additional influences.

Thailand’s distinct monsoon climate creates pronounced seasonal variations in both variables. The peak in CO concentrations during the dry season (January-April) likely reflects a combination of:

- Reduced atmospheric mixing and dispersion due to temperature inversions common during this period;
- Increased biomass burning in agricultural areas surrounding urban centers;
- Reduced rainfall that would otherwise remove pollutants from the atmosphere;
- Possible changes in transportation patterns associated with tourism and dry season activities.

The peak in nightlight intensity during December-April coincides with:

- Holiday periods (Christmas, New Year, Thai New Year), when decorative lighting increases;
- Peak tourist season when commercial activities intensify;
- Clearer atmospheric conditions that allow for better satellite detection of lights.

These different drivers of seasonality partially explain why the correlation between the two variables, while strong, is not stronger.

Understanding these seasonal patterns has important implications for interpreting the relationship between urban development and pollution, as well as for designing effective monitoring and mitigation strategies.

Energy consumption patterns

The multiple regression results indicate that energy usage—particularly electricity consumption and fossil fuel production—mediates the relationship between urban development and pollution.

The standardized coefficients from our multiple regression model (Tab.4) provide important insights into the relative importance of different factors:

- Nightlight intensity (Standardized coefficient = 0.498) remains the strongest predictor of CO concentrations, suggesting that urban development and human activity have direct effects on pollution beyond energy consumption;
- Electricity consumption (Standardized coefficient = 0.254) emerges as the second most important factor, reflecting the contribution of power generation to atmospheric CO, particularly from older plants with less efficient combustion systems;
- Lignite production (Standardized coefficient = 0.196), while statistically significant, has a smaller effect, potentially reflecting the gradual improvement in combustion efficiency and pollution control technologies in Thailand's power sector.

The finding that nightlight intensity remains significant even after controlling for energy consumption suggests that it captures aspects of urban development and human activity that affect pollution through mechanisms beyond stationary energy use, with transportation likely being the primary factor. This aligns with established knowledge that in most urban areas, particularly in developing economies, vehicle emissions represent the dominant source of carbon monoxide.

Spatial heterogeneity

The regional and provincial analyses reveal substantial spatial differences in both the levels of and the relationship between nightlight intensity and CO concentrations. These differences can be attributed to several factors:

- Varying urban forms and development patterns, particularly the contrast between the dense Bangkok Metropolitan Region and more dispersed provincial cities, may also contribute to these spatial differences.
- Different economic activities in each region may also contribute to these differences, with the Southern region's tourism economy potentially producing less CO per unit of nightlight than the industrial activities in the Central and Bangkok Metropolitan regions;
- Geographical factors, such as topography and meteorological conditions that affect pollutant dispersion, are particularly relevant in the mountainous Northern region;
- Different transportation systems and vehicle fleets, with older vehicles more common in some regions. Moreover, these spatial disparities highlight the importance of understanding accessibility and inclusivity in urban planning, as barriers to access can vary significantly across different urban forms (Cutini & Mara, 2025; Ercetin, 2024).

The strongest correlation in the Bangkok Metro region (r = 0.598) likely reflects the dominance of transportation as both a source of CO emissions and a driver of urban lighting, while the weaker correlation in the Southern region (r = 0.334) may indicate a decoupling between lighting and pollution sources in coastal tourist areas.

4.2 Public health implications

The demonstrated relationship between nightlight intensity and CO concentrations has important public health implications. Carbon monoxide is a toxic pollutant that binds to hemoglobin in the blood with an affinity approximately 250 times that of oxygen, forming carboxyhemoglobin (COHb) and reducing the oxygen-carrying capacity of blood (Raub et al., 2000). Even at the relatively low concentrations observed in this study

(Maximum monthly average of 0.051766 mol/m^2), chronic exposure may have subtle health effects, particularly for vulnerable populations such as those with cardiovascular disease, pregnant women, and young children.
Our findings support the use of nightlight data as a proxy indicator for potential CO exposure in urban areas, which could be particularly valuable for public health monitoring in areas where direct pollution measurements are limited. The seasonal and spatial patterns identified could inform targeted interventions during high-risk periods and in high-risk areas.
Moreover, the connection between urban development, as measured by nightlight intensity, and CO pollution underscores the importance of integrating public health considerations into urban planning and development policies. As Thailand continues to urbanize, strategies that mitigate the pollution impacts of development—such as improved transportation systems, cleaner energy technologies, and urban design that reduces traffic congestion—will be crucial for protecting public health.

4.3 Implications for environmental monitoring

Our study demonstrates that satellite-derived nightlight data can serve as a useful proxy for monitoring urban-related air pollution, particularly CO concentrations (Cauwels et al., 2014). This approach offers several advantages:

- Global coverage and consistency, allowing for monitoring in areas where ground-based measurements are sparse;
- High spatiotemporal resolution, enabling detailed analysis of patterns and trends;
- Cost-effectiveness compared to establishing and maintaining extensive ground-based monitoring networks;
- Ability to observe rapid urban development and associated environmental impacts in near-real time.

However, our results also highlight the limitations of using nightlight data alone for pollution monitoring:

- Moderate R^2 value (0.343) in the simple regression model indicates that nightlight intensity explains only about one-third of the variation in CO concentrations;
- Substantial regional and seasonal variations in the relationship suggest that calibration factors would need to be developed for different contexts;
- The influence of energy-related factors indicates that complementary data sources should be integrated for more accurate pollution estimation.

A hybrid approach that combines satellite-derived nightlight data with other remotely sensed parameters (such as land use, vegetation indices, and meteorological data) and limited ground-based measurements could provide a more robust framework for urban pollution monitoring in rapidly developing regions.

4.4 Comparison with previous studies

Our findings both support and extend previous research on the relationship between nightlight data and air pollution indicators. The positive correlation we observed between nightlight intensity and CO concentrations in Thailand aligns with the findings of (Wang et al., 2019), who demonstrated the utility of VIIRS data in predicting various air pollutants, including CO, in urban environments.
Our methodological approach is similar to that of (Zuo et al., 2022), who investigated the correlation between Carbon dioxide concentrations and nightlight intensity using integrated DMSP - OLS and NPP - VIIRS data. While their study focused on China and found varying relationships between nightlight data and carbon metrics due to different urban industrial structures across regions, our work in Thailand reveals similar spatial heterogeneity in the nightlight-pollution relationship. Their findings reinforce the importance of considering regional industrial development patterns when interpreting remote sensing data correlations (Zhuo et al., 2009).

The relationship between nightlight intensity as a proxy for economic activity and environmental impacts is further supported by (Chen & Nordhaus, 2011), who validated the use of luminosity data for estimating socioeconomic statistics across different regional contexts. Similarly, developed methodologies for creating harmonized nightlight datasets (Li et al., 2020) that improve the reliability of such data for long-term environmental monitoring applications.

The observed seasonal patterns in CO concentrations are consistent with previous Thailand-specific research by (Pochanart et al., 2003), who identified significant seasonal variations in Bangkok's air quality linked to both meteorological conditions and changes in emission patterns. Our finding that CO peaks during the dry season (January-April) aligns with their results and extends the analysis to a national scale over a more recent time period.

The regional and provincial analysis extends the work of (Patarasuk et al., 2016), who investigated the carbon footprint of Thailand's urban centers using a combination of remote sensing and ground-based measurements, by providing a more detailed understanding of the spatial patterns and drivers of CO pollution across the country.

4.5 Policy implications

Our findings have several implications for urban development, environmental management, and public health policies in Thailand:

- Integrated Planning: The strong relationship between nightlight intensity and CO concentrations suggests that urban development and air quality management should be addressed in an integrated manner. Policies aimed at sustainable urban development should explicitly consider potential impacts on air quality and public health;
- Seasonal Targeting: The pronounced seasonal patterns in CO concentrations indicate that pollution control measures should be intensified during the dry season (January-April), particularly in regions prone to elevated pollution levels;
- Energy Transition: The influence of lignite production and electricity consumption on CO levels supports Thailand's ongoing energy transition toward cleaner sources. Accelerating this transition, particularly in the power sector, could help mitigate the pollution impacts of continued urbanization. Furthermore, adopting sustainable logistics and optimizing urban transport through new technological methods is essential for reducing the environmental footprint of growing cities (Oguz & Tanyas, 2024; Valentini et al., 2023);
- Regional Differentiation: The significant spatial heterogeneity in the nightlight-CO relationship suggests that a one-size-fits-all approach to urban environmental management may be ineffective. Policies should be tailored to the specific characteristics and challenges of each region, with particular attention to the Bangkok Metropolitan Region, where both nightlight intensity and CO levels are highest;
- Monitoring Enhancement: The utility of nightlight data for pollution monitoring suggests that integrating satellite-derived indicators into Thailand's environmental monitoring framework could enhance coverage and cost-effectiveness, particularly for rapidly developing areas where ground-based monitoring is limited.

Implementing these policy recommendations would require coordination across multiple government agencies, including those responsible for urban planning, transportation, energy, environment, and public health, as well as engagement with local communities and the private sector.

4.6 Limitations and future research

While this study provides valuable insights into the relationship between urban development and pollution in Thailand, several limitations should be acknowledged:

Spatial resolution

The provincial-level analysis may obscure important local variations within provinces. Future research could employ higher spatial resolution data to examine city-level or sub-district patterns, potentially revealing different relationships in urban cores compared to suburban or peri-urban areas.

Applying the same methodological approach at different spatial scales could also help identify scale-dependent effects and determine the optimal resolution for monitoring the urbanization-pollution relationship.

Additional pollutants

This study focused exclusively on CO concentrations as a measure of pollution. Future research could incorporate additional pollutants such as Particulate Matter (PM2.5, PM10), Nitrogen Oxides (NO_x), and Volatile Organic Compounds (VOCs) to develop a more comprehensive understanding of urban environmental impacts. The relationship between nightlight intensity and these other pollutants may differ from what we observed for CO, potentially revealing more complex patterns of urban environmental quality. Furthermore, analyzing multiple pollutants simultaneously could help identify common sources and inform more integrated control strategies.

Socioeconomic factors

While nightlight intensity serves as a proxy for urban development, incorporating additional socioeconomic indicators such as GDP, population density, and transportation statistics could provide more nuanced insights into the drivers of pollution.

Future research could develop more comprehensive models that include these socioeconomic variables, potentially increasing explanatory power and identifying specific aspects of development that contribute most significantly to CO pollution (Hu et al., 2017).

Long-term trends and climate change

Our six-year study period provides insights into recent patterns but may not capture longer-term trends or the potential impacts of climate change on the relationship between urban development and air pollution (Longato et al., 2025). Extended time series analysis over multiple decades could help identify how this relationship has evolved and might continue to evolve in response to changing climate conditions and urban development patterns. As Pennino (2024) emphasizes, global warming poses increasing risks to urban territories, necessitating that environmental monitoring frameworks evolve to support not just pollution mitigation, but also specific adaptation practices for challenges like extreme heat.

5. Conclusions

This study has demonstrated a strong positive correlation between nightlight intensity and carbon monoxide concentrations in Thailand, suggesting that satellite-derived nightlight data can serve as an effective proxy for monitoring urban-related pollution. The relationship is moderated by seasonal patterns, energy consumption behaviors, and spatial factors, with significant variations across regions and provinces.

The multiple regression results indicate that while nightlight intensity remains the strongest predictor of CO concentrations, energy-related factors provide significant additional explanatory power. This suggests that while the correlation between urban activity and pollution is strong, the actual causal mechanisms are complex and mediated by energy systems and consumption patterns.

Regional and provincial analyses reveal substantial spatial heterogeneity, with the Bangkok Metropolitan Region showing both the highest nightlight intensity and CO levels, and the strongest correlation between these variables. This spatial differentiation highlights the importance of context-specific approaches to urban environmental management.

The lag correlation analysis indicates that the strongest relationship between nightlight intensity and CO concentrations occurs contemporaneously, suggesting that these variables generally change together. However, there is some evidence that changes in CO concentrations might slightly lead to changes in nightlight intensity in certain contexts, pointing to potential feedback mechanisms between environmental conditions and urban activity patterns.

Given the public health significance of CO as a toxic pollutant, our findings have direct relevance for environmental management and public health protection in Thailand. The demonstrated relationship between nightlight intensity and CO concentrations provides a foundation for more targeted and effective pollution monitoring strategies.

As Thailand continues its path of economic development and urbanization, understanding these complex relationships between urban development, energy consumption, and environmental conditions will be crucial for balancing growth objectives with environmental sustainability and public health protection. Future research should focus on higher-resolution spatial analysis, incorporation of additional pollutants, source attribution, and detailed investigation of the mechanisms linking urban development patterns to environmental outcomes.

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Image Sources

All the figures have been elaborated by the authors.

Author's profile

Chaichana Kulworatit

He is a lecturer in the Department of Computer Science, School of Science, King Mongkut's Institute of Technology Ladkrabang, Thailand. His teaching areas include Geographic Information Systems Analysis, Web Mining, and Calculus for Computer Science. His research interests focus on Computer Architecture, Data Science, and Geographic Information Systems, with particular emphasis on spatial analysis, geospatial data processing, and the integration of remote sensing data within GIS frameworks. He has contributed to peer-reviewed international publications involving the application of GIS-based methods to analyze urban and environmental spatial phenomena.

Phuvis Kerdpramote

He is a student in the Department of Computer Science, School of Science, King Mongkut's Institute of Technology Ladkrabang, Thailand. His interests lie in data science and geographic information systems (GIS), with a focus on data-driven analysis and the application of computational methods to real-world problems. His academic experience includes contributing to peer-reviewed research involving machine learning and computer vision techniques for robust data analysis in applied domains. In addition to his academic work, he works as a data science trainer for both government and private sector organizations.

Saranya Saetang

She is a lecturer in the Department of Computational Science and Digital Technology, Faculty of Liberal Arts and Science, Kasetsart University Kamphaeng Saen Campus, Nakhon Pathom, Thailand. Her expertise lies in data analysis and natural language processing, with research interests encompassing knowledge management, information technology, and computational approaches to educational and user-centered systems. Her academic contributions include peer-reviewed publications that apply data-driven methods to investigate human-technology interaction and information systems in applied contexts.

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Exploring governance challenges in coastal and marine tourism. A comparative analysis of European case studies

Barbara Gasparini di Gaetano [a]*, Emanuel Giannotti [b], Vittore Negretto [c], Denis Maragno [d]

[a] Department of Architecture and Arts
IUAV University of Venice, Venice, Italy
e-mail: bgasparinidigaetano@Iuav.it
ORCID: https://orcid.org/0009-0008-3920-463X
* Corresponding author

[b] Department of Architecture and Arts
IUAV University of Venice, Venice, Italy
e-mail: egiannotti@Iuav.it
ORCID: https://orcid.org/0000-0002-4855-9116

[c] Department of Architecture and Arts
IUAV University of Venice, Venice, Italy
e-mail: vnegretto@Iuav.it
ORCID: https://orcid.org/0000-0002-5024-9221

[d] Department of Architecture and Arts
IUAV University of Venice, Venice, Italy
e-mail: dmaragno@Iuav.it
ORCID: https://orcid.org/0000-0002-9489-7538

Abstract

The increasing attention to land–sea interactions in spatial planning highlights persistent difficulties in integrating terrestrial and maritime governance, particularly in tourism-intensive coastal areas where environmental protection and economic development collide. This article investigates how such tensions are addressed through maritime spatial planning, focusing on the recently adopted Italian Maritime Spatial Plan and its application in the Friuli Venezia Giulia region. The study adopts a qualitative research design combining thematic analysis of policy documents with a comparative examination of three coastal and marine contexts: Port-Cros National Park in France, Puck Bay in Poland, and the island of Crete in Greece. These cases are used to explore how different institutional arrangements manage tourism–environment trade-offs across the land–sea interface. The findings show that integrated and participatory governance arrangements, as observed in Port-Cros, support adaptive management of tourism pressures, while fragmented institutional settings, as in Puck Bay, hinder coordination and enforcement. The case of Crete highlights the limitations of sectoral planning in the absence of a fully operational maritime spatial planning framework. The article concludes by discussing implications for the implementation of maritime spatial planning in Friuli Venezia Giulia, emphasizing the role of institutional coordination, participation, and administrative capacity.

Keywords

Land-sea interactions; Maritime spatial planning; Coastal and marine tourism; Environmental protection; Friuli Venezia Giulia

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1. Introduction

The growing competition for maritime and coastal spaces, driven by sectors such as navigation, fisheries, tourism, energy production, and ecosystem conservation, highlights the need for an integrated and cross-sectoral planning framework (Kidd et al., 2019). In this context, Maritime Spatial Planning (MSP) has been developed as a governance tool to balance competing interests while advancing sustainable development objectives (Kidd et al., 2020). Nevertheless, the multi-sectoral and dynamic nature of marine environments often generates spatial, political, and administrative tensions (Flannery et al., 2020). Moreover, there is increasing recognition of the need to coordinate terrestrial and marine planning efforts, particularly through Integrated Coastal Zone Management (ICZM), Land-Sea Interactions (LSI) and MSP (Portman, 2011). Despite extensive policy development, comparative evidence on how these instruments jointly govern tourism–environment trade-offs remain limited (Balestracci et al., 2025).
ICZM represents one of the first approaches to coastal and marine governance. However, ICZM approach has traditionally prioritized land-based pressures over marine (DG MARE, 2020; Kidd et al., 2019).
MSP emerged later as a response to increasing demands for marine space and the need to organize maritime activities in a sustainable way (Douvere, 2008; Ehler & Douvere, 2009). As a spatial governance instrument, MSP seeks to allocate maritime areas to different uses while balancing environmental, economic, and social objectives (Ehler & Douvere, 2009; Kidd et al., 2020). In contrast to ICZM, MSP focuses primarily on optimize the marine environment and minimize sectoral conflict (Pyć, 2022). The European MSP Directive (2014/89/EU) has formalized MSP as a mandatory planning tool (Innocenti & Musco, 2023; Tocco et al., 2024). In recent years, Member States have developed marine plans, but given their recent adoption remains limited (Jones et al., 2016; Morf et al., 2022; Papageorgiou, 2016).
In this context, LSI has gained increasing attention for its focus on land–sea interconnections, serving as a bridge between ICZM, MSP, and terrestrial spatial planning (DG MARE, 2020; Pikner et al., 2022; Bassan et al., 2020). LSI generally refers to the natural processes and socio-economic relationships that occur across the land-sea interface. Natural interactions include bio-geo-chemical processes meanwhile the socio-economic interactions involve dependencies between marine activities and land-based infrastructures (Kidd et al., 2019; Bassan et al., 2020). These socio-economic dimensions are particularly evident in maritime transport corridors and port–city systems, where infrastructure choices and accessibility patterns progressively reshape coastal regions and their land–sea connections (La Rocca, 2009). Thus, LSI encompasses complex, interconnected dynamics that interdisciplinary and cross-sectoral collaboration (Innocenti & Musco, 2023; Morf et al., 2022; Tocco et al., 2024).
Coastal zones are key areas for the integration of MSP and terrestrial spatial planning (Glavovic, 2013; Pikner et al., 2022, Singh et al., 2021). As development hotspots, they concentrate tourism, commerce and industry, intensifying spatial competition and generating strong urban identities and complex land–sea dynamics (Bassan et al., 2020; Innocenti & Musco, 2023; Tocco et al., 2024). Among these, tourism is a major driver shaping land–sea interactions, yet its rapid and often weakly regulated expansion has produced significant environmental impacts. In particular, nautical tourism materializes these land–sea interactions through small marinas, which operate as contact points between coastal settlements and marine space (Bove & Mazzola, 2023). This creates a paradox: tourism sustains local economies but simultaneously strains natural resources, while depending on high environmental quality for its own viability (Buckley, 2012).
The present article reflects on the Italian Maritime Spatial Plan (MSP-ITA) adopted in 2024. It focuses on the Northern-East areas of the Adriatic Sea which are included within the Unit Planning Area 01 (MIT, 2024) and the Marano-Grado Lagoon in Friuli Venezia Giulia (FVG). The FVG region combines valuable lagoon and coastal ecosystems with tourism activities in the Marano–Grado area, making it a case for examining these dynamics (Silvestri et al., 2013). The comparison with other European coastal and marine areas is used to identify governance solutions that can be adapted and applied to the Marano–Grado Lagoon, particularly in terms of

managing tourism–environment trade-offs. This research is part of the iNEST (Spoke 8, RT4: integrated land-sea maritime and spatial planning). This Italian case is embedded in a broader European discussion on how to integrate terrestrial and marine planning.

There is growing recognition that such integration is needed to address cumulative pressures, competing uses, and cross-scale dynamics at the land–sea interface (Kidd et al., 2019). Against this background, the research asks: (1) how different governance arrangements in European coastal and marine areas address the tensions between tourism development and environmental conservation across the LSI; and (2) what lessons can support the implementation of MSP-ITA in Friuli Venezia Giulia, with a specific focus on the Marano-Grado Lagoon.

The article is structured in three main parts. Firstly, the methodology section. Secondly, the results section examines the guidelines and objectives set out in the MSP framework for the FVG region, followed by the presentation of the three selected case studies. In conclusion, the main findings are discussed, identifying common challenges and proposing recommendations for enhancing the integration of terrestrial and maritime planning.

2. Methodology

2.1 Research design

This study adopts a qualitative multiple-case study design, combining thematic literature analysis to explore how LSI are governed at the intersection of maritime governance, environmental protection and tourism. The research follows a three-step process.

First, a broad literature screening identifies studies addressing MSP, ICZM, protected areas, coastal tourism and land–sea interactions. Second, only contributions with explicit case studies are retained.

Third, the analysis focuses on sites where tourism and environmental protection are drivers of pressure or conflict, prioritizing those with more extensive literature to enable in-depth reconstruction and comparison of governance arrangements, including with the FVG context.

2.2 Thematic literature analysis and case selection

The literature review began with a Scopus search of peer-reviewed studies, using three keyword combinations: (i) "maritime spatial planning" AND tourism AND conflict; (ii) "land-sea interactions" AND tourism AND marine protected area; (iii) "Natura 2000" AND coastal AND tourism AND conflicts. Only documents published after 2014 were kept, in order to work in the period opened by the EU Directive on MSP (2014/89/EU).

Only European coastal and marine contexts were included, to ensure comparability with the Italian case. This first screening yielded 67 papers, which were narrowed down through title and abstract review to 23 case-based studies with clearly defined empirical sites. These were read in full and further filtered by applying two criteria: the site had to have a formal conservation status in a coastal or marine context; tourism or recreation had to be clearly identified as a primary source of pressure or conflict. This led to five papers which are summarised in Tab.1.

Out of the five papers, three were retained as core comparative cases, while two were used as supporting examples, as one (Luján Climent et al., 2025) deals with multiple pressures and governance innovation in a dispersed wetland system, and the other (Tubío et al., 2021) provides a state-of-the-art review, with limited detail on concrete tourism–protection conflicts.

This first stage was followed by a targeted search of grey literature through Google Scholar, including EU directives and guidelines, national and regional plans, and park and Natura 2000 management documents, linked to the selected cases.

Reference	Focus	Context	Main findings	Conflict type
Tsilimigkas & Rempis (2017)	EU MSP–terrestrial planning interaction; synergies and mismatches	Crete (Greece); five coastal sub-areas.	Tourism, ports, aquaculture and energy generate governance conflicts due to overlapping mandates; need for integrated land–sea planning	Sectoral conflicts (tourism/ports/aquacultu re/energy vs protection); policy overlap
Luján Climent et al. (2025)	Governance innovations in coastal-wetland management	Valencia (Spain); six protected coastal wetlands	Conservation–production tensions under climate stress, exacerbated by fragmented governance, rigid regulation and unstable funding	Conservation vs agriculture/urbanisation/ tourism; coordination failures
Cadoret (2021)	Conflict histories and acceptability of visitor management	France; Porquerolle (Port-Cros NP)	Visitor pressure fuels conflict; acceptance linked to trust, tolerance thresholds and legitimate enforcement	Visitor pressure vs conservation; distributive and procedural justice conflicts
Tubío et al. (2021)	Ecosystem services to link conservation and sustainable business	Galicia (Spain); Rías Baixas Natura 2000 marine area	Natura 2000 enables green business models but requires coordinated governance and strong stakeholder engagement	Conservation vs intensive use; extractive vs green transition pathways
Piwowarczyk & Wróbel (2016)	Legitimacy of Natura 2000 marine governance	Puck Bay (Poland); two marine Natura 2000 sites	Overlapping responsibilities, low trust and formalistic participation undermine legitimacy; need for accountability and MSP integration	Fisheries–tourism–conservation conflicts; local vs central authority tensions

Tab.1 Subset of key studies

2.3 Comparative framework

The three case studies represent (Fig.1) contrasting land–sea governance configurations which enables a structured comparison of how tourism–conservation tensions are managed under different institutional arrangements.

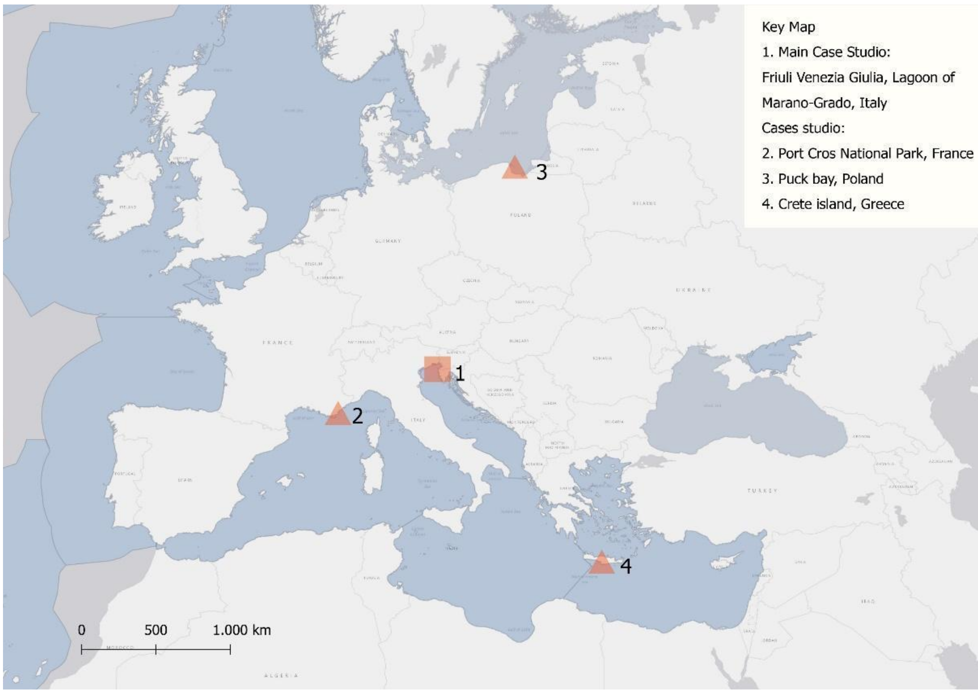

Fig.1 Keymap of the selected case studies

The comparison is based on coastal and marine governance research (Partelow et al., 2020; Stojanovic & Gee, 2020; Tocco et al., 2024; Schlüter et al., 2020). We use "modes of governance" as a shared vocabulary to describe the main steering logics found in each case, considering: (1) collaborative/networked governance; (2) market-based governance; (3) adaptive governance; and (4) transformative governance. They help interpreting steering mechanisms without forcing cases into a single category. We focus on four simple questions: which rules exist, who is involved, how coordination works, and how decisions are implemented and enforced over time (Stojanovic & Gee, 2020). These questions are operationalized through an analytical grid applied to each case and to MSP-ITA for the FVG maritime area.

3. Italian maritime spatial planning and the Friuli Venezia Giulia's tourism-environment LSIs

The Italian Maritime Spatial Plan follows an ecosystem-based approach, balancing environmental, economic, social and security objectives through strategic guidance rather than prescriptive zoning (MIT, 2024). A technical committee, comprising representatives from relevant national ministries and delegates from each participating region, was established to oversee the plan's development (Ramieri et al., 2024).

Environmental protection, landscape preservation, and cultural heritage conservation fall under the central government's broad legislative authority. In contrast, the regional governments hold joint legislative powers concerning ports, maritime transport, energy production and distribution, spatial planning, and the promotion of cultural and environmental resources. Moreover, regions possess exclusive legislative jurisdiction over fishing, aquaculture, coastal defense, and tourism (Ramieri et al., 2024). Regarding Natura 2000 areas, regional authorities directly influence the management of protected areas (MATTM, n.d.).

Planning Unit 01 (A/1_01 P) of the MSP covers the maritime and coastal zone between the mouths of the Tagliamento and Isonzo rivers, including the Marano-Grado Lagoon (Fig.2). The area is characterized by high geomorphological and ecological significance, hosting several Natura 2000 sites. From an administrative standpoint, governance is highly fragmented: most of the lagoon falls within the municipalities of Marano Lagunare and Grado, while smaller portions lie within neighboring municipalities or are classified as maritime state property (Silvestri et al., 2012). These transitional environments are subject to fragile ecological balances and considerable anthropogenic pressures, where seasonal tourism exerts substantial strain on the ecosystem (ISPRA, 2018). Lignano Sabbiadoro and Grado attract large volumes of visitors, resulting in over one million tourist stays annually despite their modest resident populations (ISTAT, 2024). This incoming tourist flux intensifies pressures on local infrastructures and fragile ecosystems. Tourism, while providing essential economic benefits, has prompted environmental repercussions. On land, increased tourism demand has led to the expansion of accommodation facilities and second homes, intensifying urbanization (FVG, 2012). At sea, activities such as recreational boating contribute to habitat disturbance (Silvestri et al, 2013). Additionally, the construction of stone protective structures to mitigate erosion has led to substantial landscape alterations (FVG, 2012).

In response to these challenges, the plan designates the UPA1_01 primarily for coastal and maritime tourism, alongside environmental protection and natural resource management (MIT, 2024). The MSP-ITA acknowledges the socio-economic relevance of seaside tourism hubs like Lignano Sabbiadoro and Grado and seeks to support complementary activities such as sustainable fishing.

While comprehensive, the MSP-ITA acts more as strategic guidance than binding regulation. Its decentralized structure assigns implementation to regions like FVG, raising key planning challenges tied to local environmental and socio-economic conditions.

In addition to tourism pressures, FVG faces climate-related threats such as sea level rise, erosion, and land subsidence (ARPA FVG, 2024), as well as cumulative impacts on biodiversity and habitats from overfishing, port development, and coastal urbanization (Barbanti et al., 2015). Ultimately, the success of MSP-ITA strategies depends on effective regional action.

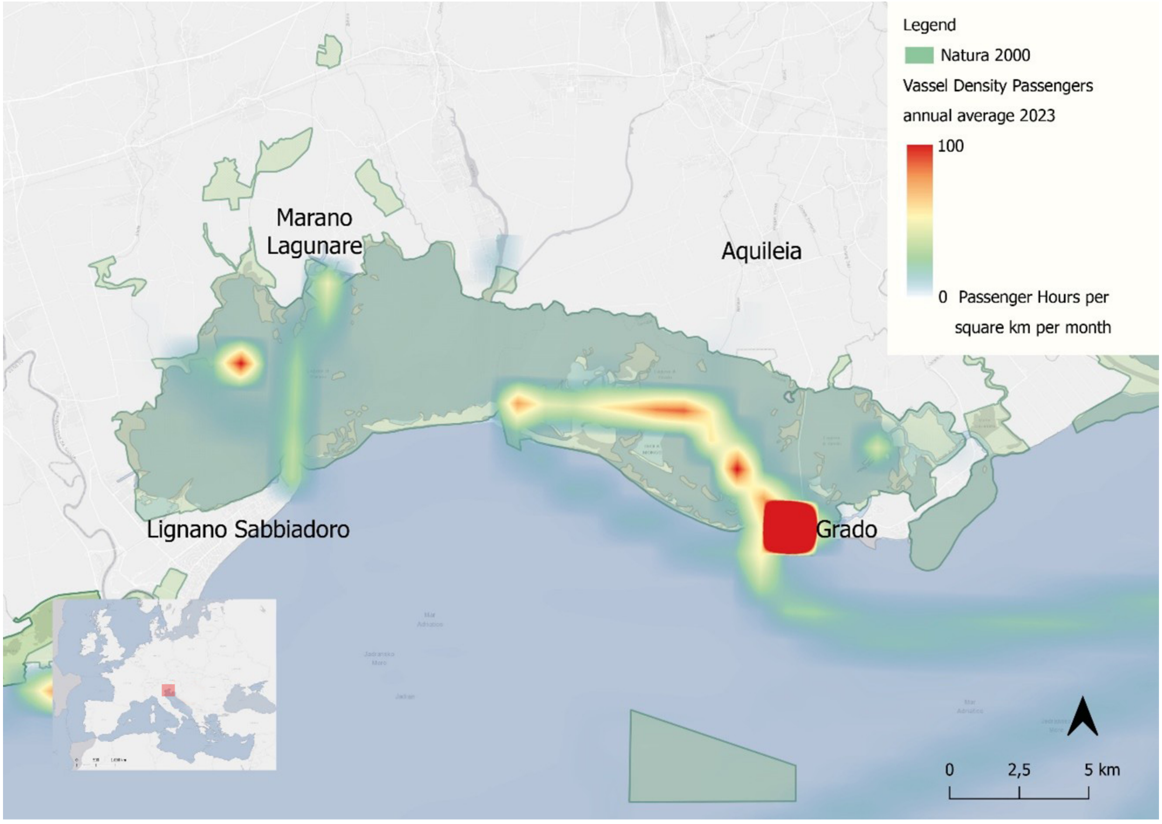

Fig.2 Study area: Marano-Grado Lagoon, Friuli Venezia Giulia, Italy

4. Management approaches to LSI: case studies on integrating maritime, coastal, and terrestrial planning with tourism development

4.1 Case study 1: France, Port-Cros National Park, Balearic Sea

Port-Cros National Park (PCNP) is located off the southern coast of France, and includes an archipelago that forms part of the Natura 2000 network (Fig.3). This protected area combines terrestrial and marine ecosystems and creates a characteristic Mediterranean land–sea landscape, where coastal reliefs, islands and underwater habitats are strongly interconnected (Barcelo et al., 2018; Port-Cros National Park, n.d.). The ecosystem hosts key species such as *Posidonia oceanica*, which is essential for marine biodiversity and coastal protection (Cadoret, 2021).

The governance framework of PCNP has progressively evolved since the mid-20th century, with its official creation in 1963 encompassing the islands of Port-Cros, Bagaud, La Gabinière, and Le Rascas, along with part of the Provençal coastline (Deldrève & Michel, 2019; Boudouresque et al., 2013; Barcelo et al., 2018). In 1964, a Scientific Council (SC) was established to define research priorities necessary for evaluating actual and potential human impacts and to guide management (Boudouresque et al., 2013). The governance framework expanded in 1971 when Porquerolles was incorporated into PCNP following state acquisition (Barcelo et al., 2018). Between 1996 and 2001, PCNP became part of the European Natura 2000 network, strengthening its biodiversity preservation objectives (Parc National de Port-Cros, n.d.).

During this period, the first visitor flow studies were conducted to develop strategies balancing environmental conservation with public accessibility (Deldrève & Michel, 2019; Le Berre et al., 2013).

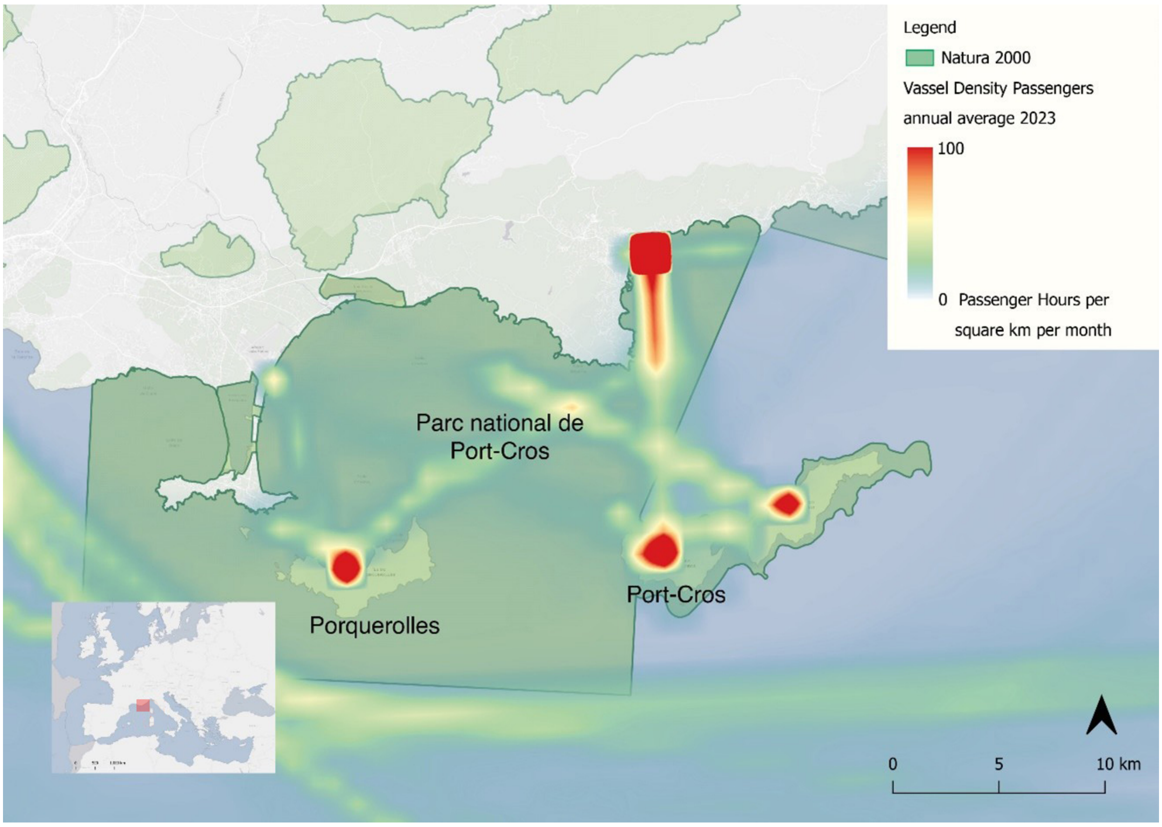

Fig.3 Map depicting the case of Port-Cros National Park, Provence-Alpes-Côte d'Azur, France

These early studies already framed tourism as a direct pressure on the coupled land–sea system. To address tourism issues, PCNP adopted several governance measures. In 2002, two tourism flow observatories were established to gather data on visitor numbers, with data collected between 2002 and 2010 indicating stable maritime arrivals, averaging 4,000 daily landings in Porquerolles during the summer, surging at 6,400 on peak days (Le Berre et al., 2013). The expansion of tourism has exceeded the ecological and social carrying capacity of the islands (Cadoret, 2021). Morever, improved infrastructure, such as passenger ferries and widespread bicycle rental services, has increased accessibility, but has also intensified crowding, pressure on coastal paths and beaches (Cadoret, 2021). Additionally, regulatory interventions have been introduced, such as the designation of a "resource zone," where anchoring, artisanal and recreational fishing, mooring, and diving are strictly prohibited (Deldrève & Michel, 2019).

The governance framework shifted significantly in 2006 with the enactment of Law N° 2006-436, transferring maritime management authority from PCNP to state marine authorities, such as the *Délégation à la Mer et au Littoral* (DML) and the *Direction Départementale des Territoires et de la Mer* (DDTM), while PCNP assumed a facilitating role (Barcelo et al., 2018). The law reinforced the role of the SC in decision-making processes and introduced an informal *Self-Organized Governance Committee* (SOGC) composed of stakeholders to sustain participatory governance mechanisms (Barcelo et al., 2018). In 2012, the official integration of Porquerolles into PCNP further consolidated the park's administrative structure, expanding its protected area to include both terrestrial and marine core zones (Boudouresque, 2020).

Solutions adopted to manage the tourism pressure are based on a combination of collaborative governance and spatial management measures. Participatory, bottom-up mechanisms foster trust and enable concerted decision-making, integrating broader social (Barcelo et al., 2018; Deldrève, 2019). Spatial measures include regulating activities to protect marine habitats, such as Posidonia meadows, by prohibiting anchoring in sensitive zones and providing ecological moorings (Boudouresque et al., 2021). Fishing activities, both amateur and professional, are managed through specific charters and authorization systems, supported by monitoring efforts (Barcelo et al., 2018; Boudouresque et al., 2021). Visitor pressure is managed through carrying-capacity approaches and observatory-based monitoring (Deldrève, 2019; Le Berre et al., 2013).

4.2 Case study 2: Poland, Puck bay, Baltic sea

Puck Bay, located within the Gulf of Gdańsk in northern Poland along the Baltic Sea (Fig.4), is an enclosed basin and a hotspot of Polish marine biodiversity (Węsławski et al., 2010; Zaborska et al., 2019). Within Puck Bay, two marine Natura 2000 sites have been designated as part of the European network for nature conservation (Piwowarczyk & Wróbel, 2016). In parallel, Puck Bay is a major tourist destination, with growing visitor numbers that stimulate the expansion of tourism-related infrastructure, encouraged by local investments and regulatory approvals (Wendt & Wiskulski, 2017). This growth generates multiple pressures both on land and at sea, including disturbance of wildlife due to unrestricted access to marine areas (Kistowski & Śleszyński, 2010) and increasing pressure on sensitive coastal habitats (Zaborska et al., 2019). Before the approval of the national MSP (2022), marine management was guided by the 1991 "Act on Marine Areas of the Republic of Poland and the Maritime Administration", while this act provided general guidelines, it lacked detailed spatial planning measures for conflict-prone areas (Pikner et al., 2022).

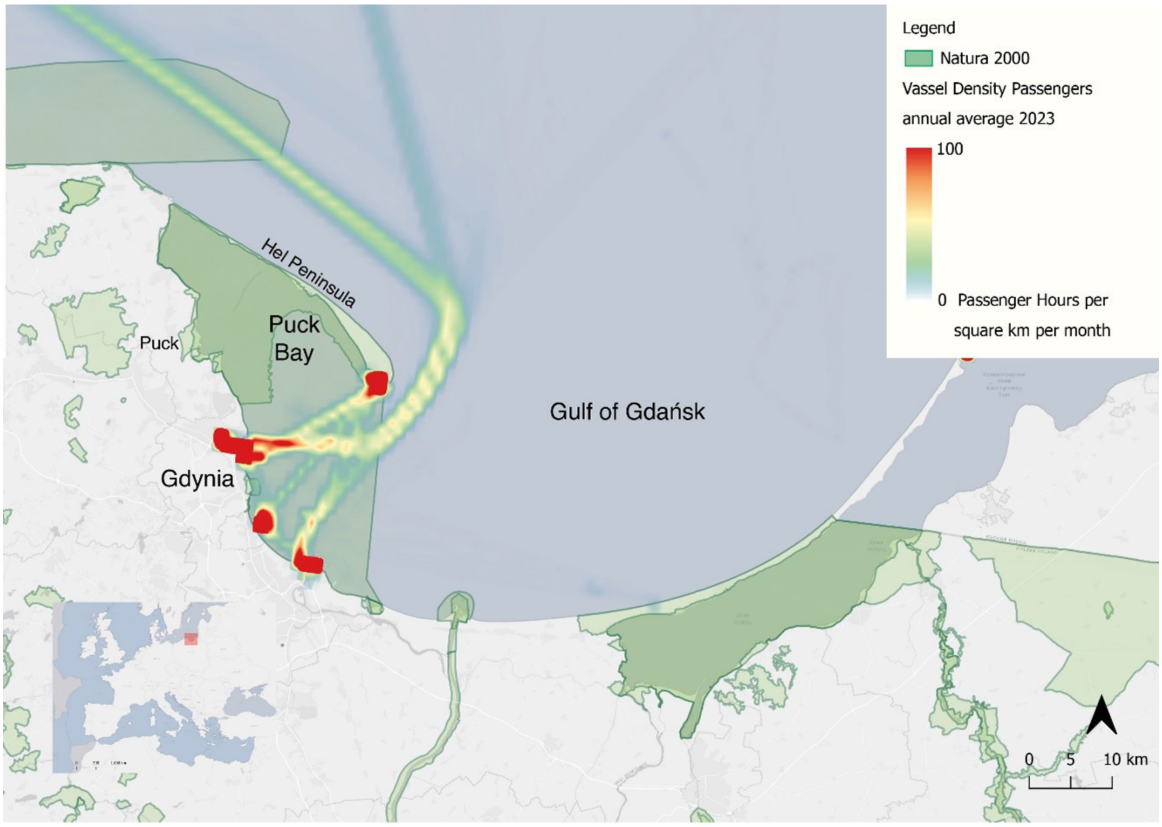

Fig.4 Map depicting the case of Puck Bay, Poland

Governance over the two marine Natura 2000 sites remains fragmented among multiple authorities, creating challenges in management, policy integration, and coordination between sectoral policies and conservation objectives across land and sea domains (Piwowarczyk & Wróbel, 2016). Unlike terrestrial Natura 2000 sites, which fall under the Minister of Environment and the General Directorate for Environmental Protection, marine Natura 2000 sites are under the jurisdiction of the maritime administration, which is subordinate to the Minister of Infrastructure and Development (Piwowarczyk & Wróbel, 2016). This fragmentation has consequently generated overlapping competencies between different state institutions (Morf et al., 2022). The Maritime Office in Gdynia, responsible for managing these marine areas, has developed spatial planning initiatives, including a draft maritime spatial plan, though its effectiveness has been limited by regulatory delays. Meanwhile, the Regional Directorate for Environmental Protection and the Coastal Landscape Park influence marine conservation policies but lack authority over marine waters (Piwowarczyk & Wróbel, 2016). Despite the formal cooperation agreement between the Maritime Office and the Regional Directorate, marine and terrestrial planning in Poland remains disconnected, governed by distinct legislative frameworks. The current marine management policy follows a sectoral approach with case-based decision-making rather than an integrated strategy (Piwowarczyk & Wróbel, 2016). As a result, tourism–conservation conflicts are managed case by case, with limited capacity to address cumulative impacts In this context, conflicts between tourism development, mobility pressures and conservation become difficult to manage, for example where recreational boating adds pressure on habitats and municipalities continue to enable tourism expansion in already constrained coastal areas (Wendt & Wiskulski, 2017; Kistowski & Śleszyński, 2010; Zaborska et al., 2019).

At the same time, local municipalities actively support tourism, often framing it as environmentally friendly and avoiding strong restrictions, which further reduces the effectiveness of conservation measures even within designated Natura 2000 sites such as Puck Bay (Piwowarczyk & Wróbel, 2016).

Ultimately, this institutional fragmentation and lack of full integration impact the legitimacy and effectiveness of Natura 2000 management in the region (Piwowarczyk & Wróbel, 2016).

4.3 Case Study 3: Crete, Greece, Aegean Sea

Greece has yet to implement a fully approved MSP, resulting in a fragmented legislative framework. However, sectoral plans for tourism, aquaculture, and other industries have been developed, incorporating strategies that address land-based, coastal, and marine considerations.

The Ministry of Environment and Energy oversees MSP at the national level, while regional and local authorities are responsible for implementing strategic and municipal-level plans to regulate spatial development and land use (Rempis & Tsilimigkas, 2021). In general, the Greek legislative system is divided into a strategic planning component, which takes place at the national and regional levels, while regulatory planning is assigned to the local level (Rempis & Tsilimigkas, 2021).

In this framework, Crete is among the largest islands in Greece (Fig.5), with a coastline of approximately 1,300 km and accounting for 6.3% of the national territory (Rempis & Tsilimigkas, 2021). The island shows strong north–south polarization: the northern coast concentrates population and development, while the south is more rural and agriculture-oriented (Rempis & Tsilimigkas, 2021).

Tourism is the main economic sector, dominated by seasonal, coastal tourism concentrated along the northern coast (Rempis & Tsilimigkas, 2021; Terkenli et al., 2007).

In Crete, the Regional Spatial Framework (RSF), initially adopted in 2003 and revised in 2017, addresses challenges such as urban expansion, coastal saturation, and environmental degradation (Rempis & Tsilimigkas, 2021). Tourism is concentrated in dense coastal hubs, land-use conflicts and impacts on fragile coastal ecosystems are especially acute (Rempis & Tsilimigkas, 2021; Rempis et al., 2018). So the RSF calls for more localized planning and frames MSP as a key lever for sustainable development (Rempis & Tsilimigkas, 2021).

Additionally, the Special Framework for Spatial Planning and Sustainable Development for Tourism provides guidelines for tourism development while promoting alternative maritime tourism activities such as cruising, yachting, diving, and fishing (Rempis et al., 2018). Nevertheless, the legislative system is characterized by fragmentation, inconsistency, and a lack of strong, binding connections (Rempis & Tsilimigkas, 2021). As a result, interventions—primarily in coastal areas—are often carried out using ad-hoc methods that lead to considerable spatial impacts, along with significant environmental, social, and economic costs, as well as negative land-sea interactions (Rempis & Tsilimigkas, 2021). These weaknesses are particularly problematic in high-pressure coastal contexts such as Crete, where the combination of intensive tourism, uneven spatial development, and climate-related risks makes coherent land–sea governance essential (Rempis & Tsilimigkas, 2021; Vourdoubas, 2025). Implementation gaps persist, especially in translating national/regional aims into enforceable local and marine zoning measures (Tsilimigkas et al., 2020).

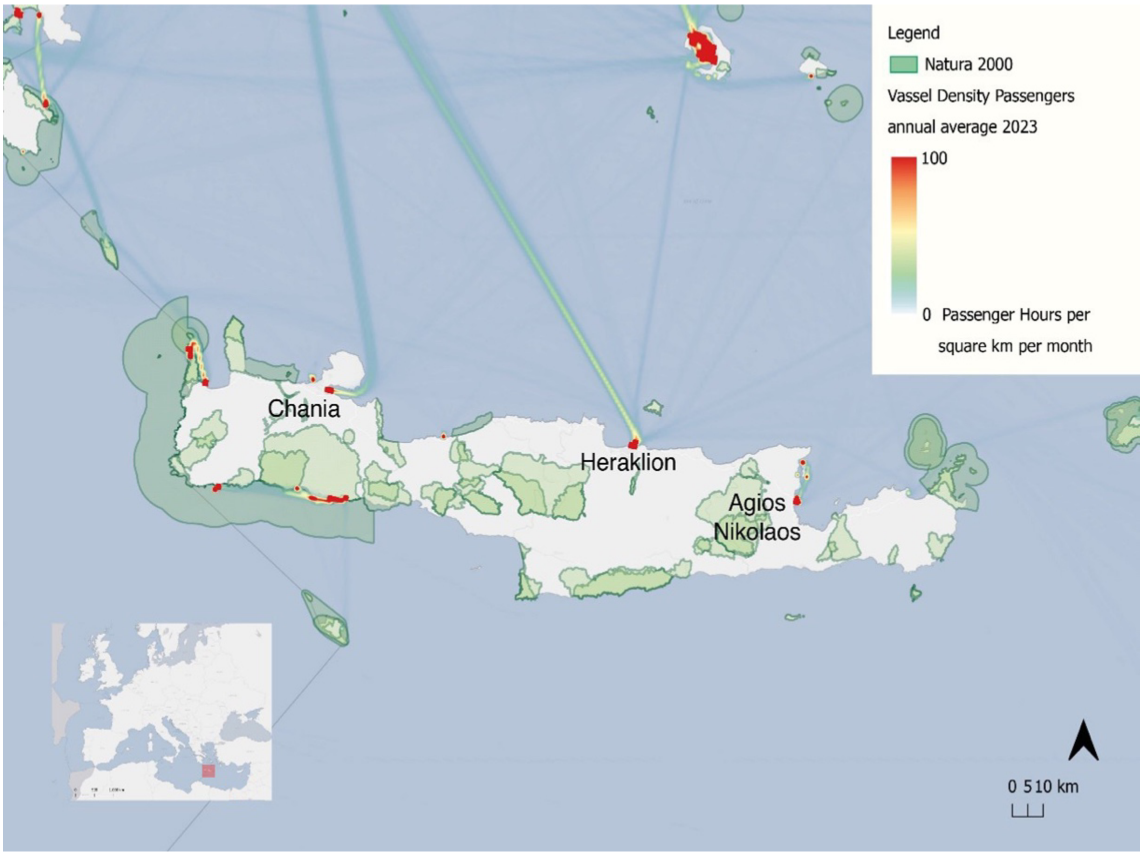

Fig.5 Map depicting the case of Crete, Greece

5. Discussion and conclusion

5.1 Comparative insights on governance models

The analysis of the selected case studies highlights how different governance approaches can either facilitate or hinder the integration of tourism development and environmental conservation in coastal and marine areas. The cases were analysed using a governance-mode framework, operationalised through Tab.2.

The case of PCNP shows strong collaborative/networked signals (a stable negotiation arena and co-produced rules) and clear adaptive signals (monitoring and iterative adjustment). The literature associates this model with negotiated rule-making and adaptive refinement (Barcelo et al., 2018; Deldrève & Michel, 2019; Boudouresque et al., 2021). Conversely, the Puck Bay case study points to governance difficulties linked to institutional fragmentation within and around Natura 2000 sites. Overlapping mandates across maritime and environmental frameworks hinder coordinated decision-making and enforcement (Piwowarczyk & Wróbel, 2016). The case is useful because it shows how "having plans" may coexist with weak interoperability between instruments and unclear responsibility for cumulative impacts along the coast.

Crete exemplifies pressures generated by large-scale coastal tourism. Studies describe an uneven spatial pattern, with tourism concentration in the north, which contributes to strong and localised land-use and infrastructure pressures (Rempis & Tsilimigkas, 2021). Sectoral planning and weak coordination exacerbate coastal saturation and environmental pressure (Rempis & Tsilimigkas, 2021). Reading through the model frames, Crete could be read as a market-driven steering context (tourism-led priorities) operating under weak enforcement and limited land–sea coupling.

	Port-Cros NP (France)	Puck Bay (Poland)	Crete – coastal area (Greece)
Institutional / legal setting	National park since 1963; Natura 2000 sites; Law 2006-436 reshapes maritime competences	Marine Natura 2000 sites; 1991 Marine Act; national MSP adopted 2022; split marine/terrestrial regimes	No fully approved MSP; strategic planning at national/regional level;
Main actors	Park Authority; Scientific Council; state marine authorities (DML, DDTM); municipalities; tourism and fisheries operators; residents	Maritime Office in Gdynia; Regional Directorate for Environmental Protection; Coastal Landscape Park; coastal municipalities;	Ministry of Environment and Energy; Region of Crete; municipalities; port authorities; tourism sector; other sectoral agencies
Main planning / management tools	Park management plan; zoning with "resource zone"; Natura 2000 measures; tourism flow observatories;	MSP for Polish marine areas; sectoral plans (fisheries, ports, conservation); local land-use plans; Natura 2000 management plan	Regional Spatial Framework (2003/2017); Sectoral plans (e.g. aquaculture); municipal land-use plans;
Participation and conflict management	Self-Organised Governance Committee; participatory mechanisms; negotiated solutions between conservation, tourism and locals	Limited structured participation; formal cooperation but weak stakeholder engagement; conflicts managed case by case	Mainly top-down procedures; ad-hoc negotiations in coastal hotspots;
Cross-sector / multi-level coordination	Park facilitates between marine authorities, municipalities and users; land–sea issues integrated in park planning	Strong institutional fragmentation; weak horizontal and vertical coordination; marine and terrestrial planning largely disconnected	Weak links between strategic and regulatory plans; poor integration of spatial, tourism and environmental policies;
Main land–sea conflicts / trade-offs	Tourism flows vs. ecological and social carrying capacity; beach and path crowding vs. habitat protection	Tourism growth and infrastructure vs. dunes and coastal habitats; recreational boating vs. wildlife and noise; congestion	Mass coastal tourism vs. fragile ecosystems; port and urban expansion vs. landscape and habitat protection;
Implementation, enforcement, revision of rules	Prohibition zones enforced (anchoring, fishing, diving); regulations adjusted using monitoring; governance framework revised after legal reforms and park extension	Regulations unevenly enforced; illegal or tolerated developments; MSP and Natura 2000 rules difficult to apply;	Plans revised slowly; frequent ad-hoc interventions in coastal areas; weak enforcement of spatial and environmental rules;
Key weaknesses / innovations in governance	weakness: high tourism pressure still near or beyond carrying capacity. Innovation: science-based, adaptive and participatory governance.	Weakness: institutional fragmentation, sectoral decision-making, poor land–sea integration; formal cooperation exists but remains insufficient for Natura 2000 governance	Weakness: fragmented legal system, ad-hoc coastal decisions, limited land–sea integration.

Tab.2 Comparative overview of the three case studies, structured according to the case-selection and analytical criteria described in the methodology

In conclusion, tourism–conservation tensions at the land–sea interface can be read in relation to how governance works in practice (Saunders et al., 2019; Partelow et al., 2020). Across the three cases, three patterns emerge. A first pattern concerns authority and decision boundaries. In PCNP, the protected perimeter is described as a relatively bounded decision arena. Here, the park authority combines spatial regulation with a stable negotiation arena (Barcelo et al., 2018; Deldrève & Michel, 2019; Le Berre et al., 2013). In Puck Bay and Crete, pressures concentrate along the coastal strip, but authority is more dispersed across agencies or split between strategic and regulatory tiers. This dispersal can produce governance "gaps" in steering cumulative impacts across land and sea (Piwowarczyk & Wróbel, 2016; Rempis & Tsilimigkas, 2021). From a polycentric perspective, the issue is less the number of actors and more whether interacting decision centres can align mandates and effects across levels (Partelow et al., 2020; Ostrom, 2010).

A second pattern concerns participation and legitimacy. PCNP approximates deeper participation through a relatively stable arena where users and local actors repeatedly engage in rule-making and trade-offs. This arrangement is presented as supporting the acceptance of restrictive measures (Barcelo et al., 2018; Deldrève & Michel, 2019; Le Berre et al., 2013), but it also has limitations, as participation is uneven, demanding, and exposed to fatigue and power asymmetries (Barcelo et al., 2018). This aligns with critical MSP scholarship, which suggests that participation can improve transparency and reduce conflict, but can also reproduce exclusion when it remains shallow, procedural, or under-resourced (Gökmen, 2025). In Puck Bay and Crete, where decision-making is more fragmented and often channelled through sectoral or multi-tier procedures, participation tends to be less continuous and therefore less able to stabilise legitimacy over time (Piwowarczyk & Wróbel, 2016; Rempis & Tsilimigkas, 2021)

A third pattern concerns enforcement and administrative capacity. In PCNP, effectiveness is repeatedly associated with the combination of negotiated rules, monitoring, and credible sanctions (Barcelo et al., 2018; Deldrève & Michel, 2019; Boudouresque et al., 2021). In Puck Bay and Crete, enforcement problems appear more tightly linked to governance structure: fragmentation and unclear mandates complicate the coordination of inspection, data, and compliance across jurisdictions (Piwowarczyk & Wróbel, 2016; Rempis & Tsilimigkas, 2021). Overall, legitimacy alone is insufficient without administrative capacity (resources, staff, procedures, and coordination) (Gökmen, 2025). Across the cases, the key explanatory factor is the configuration of interacting decision centres across land and sea, and their ability to coordinate, learn, and enforce over time (Partelow et al., 2020; Ostrom, 2010). What ultimately matters is whether governance arrangements can clarify decision boundaries, sustain legitimacy through meaningful inclusion, and support enforcement through administrative capacity (Giovinazzi & Moretti, 2010; Pirlone et al., 2022).

5.2 From plans to practice: implications for MSP-ITA and FVG

Read through these governance patterns, the FVG case can be approached less as a question of "adopting MSP" and more as a question of institutional coupling at the land–sea interface. The first implication is that any pathway from MSP-ITA to local implementation may benefit from mapping decision-making centres and their influence on tourism–conservation trade-offs, including informal practices and "rules-in-use" (Partelow et al., 2020). This step can help reveal where authority is clear, where it overlaps, and where it may be absent. A second implication is to treat interoperability as a design problem. Rather than adding new plans, governance efforts could focus on the interfaces between MSP provisions, Natura 2000 management, and municipal land-use rules, so that spatial restrictions, licensing, and monitoring are mutually consistent. A third implication concerns legitimacy. If governance arenas remain episodic or purely consultative, participation risks becoming procedural and exclusionary, with predictable conflicts around access, restrictions, and uneven distribution of costs and benefits (Gökmen, 2025).

A fourth implication is to connect legitimacy to enforcement capacity early. Implementable outcomes require not only acceptance, but also resources and coordination across inspection, data collection, and compliance routines (Gökmen, 2025).

In practical terms, one enabling step could be to treat monitoring outputs as "boundary objects" that different actors can use to align decisions. For instance, GIS-based vulnerability and pressure mapping can help identify critical areas and support more transparent trade-offs, but its governance value depends on shared interpretation and updating, not on technocratic closure (Pagano et al., 2023). Finally, Trouillet's critique suggests a caution for FVG: strengthening governance may require attention to the gap between planning narratives and institutional anchoring. Without clear mandates, interfaces, and capacity, MSP risks remaining a discourse of integration while sectoral dynamics continue to drive cumulative impacts (Trouillet, 2020).

5.3 Limits and future development of the research

This study has limitations that should be considered when interpreting the findings. First, it relies on a small, purposively selected set of cases, which supports analytical rather than statistical generalisation. Second, evidence is primarily drawn from secondary sources (legal texts, plans, policy documents, and scientific/grey literature). Third, several planning and governance instruments discussed in the paper -including MSP-ITA- remain in evolving stages of implementation. Future research could strengthen and test the proposed governance patterns by triangulating document analysis with interviews and by extending the comparison to additional European regions.

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Author's profile

Barbara Gasparini di Gaetano

She is an architect and research fellow at the Department of Architecture and Arts at IUAV University of Venice. Her research focuses on project-based approaches to land-sea interaction, with particular attention to coastal territories exposed to sea-level rise and to adaptive and amphibious settlement strategies at the land-water interface.

Emanuel Giannotti

He is an urbanist, researcher, and lecturer at the Department of Architecture and Arts at the IUAV University of Venice. His work focuses on climate change adaptation, Nature-based Solutions, and integrated strategies for sustainable territorial development.

Vittore Negretto

He is an architect, research manager and lecturer at the Department of Architecture and Arts at IUAV University of Venice. His research focuses on integrating resilience and climate change adaptation principles into urban planning and design, developing strategies to address complex environmental challenges and reduce risks.

Denis Maragno

He is an Assistant Professor in Urban Planning and GIScience at IUAV University of Venice, Italy. He works within the Planning and Climate Change LAB, where he coordinates and implements various scientific research projects and activities. He received a PhD in "New Information Technologies for the Territory and Environment" from IUAV University of Venice, Italy. His main research interests include the use of such technologies and spatial analyses to support climate change adaptation and mitigation, spatial resilience, and maritime spatial planning.

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Dynamic map decision support systems for spatial and mobility planning

Mara Ladu [a]*, Ginevra Balletto [a], Tanja Congiu [b], Gianfranco Fancello [a], Ernesto Fontes Pupo [a]

[a] Department of Environmental Civil Engineering and Architecture
University of Cagliari, Cagliari, Italy
* Corresponding author

[b] Department of Architecture, Design and Urban Planning
University of Sassari, Sassari, Italy

Abstract

Decision Support Systems (DSS) are widely recognized as important tools supporting decision making processes, quite little adopted yet to support sustainable spatial and mobility planning, despite a wide range of literature arising at the turn of the Millennium on Spatial Decision Support Systems (SDSS). This is the case of the e.INS project, which addresses critical challenges in spatial and mobility planning in Sardinia Region (Italy) and provides a methodological approach to develop a sustainable transport model by MaaS solutions. The objective is to propose a DSS architecture to support the Sardinia MaaS, integrating geo datasets relating mainly to demographic and socio-economic aspects, the supply of key services and the provision and demand of transport, the spatial distribution of tourist flows and related externalities to offer a holistic perspective on local and regional transport needs, opportunities, and gaps. Developed using geospatial technologies, the system's operational core is a dynamic dashboard that visualizes key data and performance metrics. The proposed methodology is functional to build a collaborative framework for the DSS, enabling users to update and manage data through a user-friendly interface, thus ensuring its continued relevance and accuracy. This allows local authorities and transport operators to monitor, analyze, and make informed decisions. The system supports the development of a more sustainable, inclusive, and efficient mobility network, ultimately contributing to a smarter future for Sardinia Region.

Keywords

Mobility as a service; Decision support system; Spatial Mobility Planning

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1. Introduction

The new millennium marked a turning point, driven by the rise of Big Data, Machine Learning (ML), and Artificial Intelligence (AI) (Narne et al., 2024) in several research and operational fields such as spatial and mobility planning (Mortaheb & Jankowski, 2023).

The Decision Support Systems (DSS), originally conceived as a "Management Decision System" (MDS) and used mainly in the business and management fields with the aim of supporting managers in strategic and operational activities, are becoming a strategic tool for the governance of cities and regions thanks to these rapid innovations in Information and Communication Technologies (ICT). As a matter of fact, DSS is an interactive computer tool designed to assist decision-makers in tackling complex problems.

Their evolution is closely tied to technological development and the growing need to manage and analyze big data.

The modern DSS manages and analyzes massive volumes of data from heterogeneous sources, including IoT sensors, social media, and mobile data, offering detailed, real-time information on observed phenomena. AI and ML have made DSS "intelligent," capable of formulating suggestions, identifying patterns, and developing predictive scenarios. Cloud Computing has made these solutions more accessible, while improved user interfaces with customizable dashboards and interactive visualizations have increased their usability in various sectors to support decisions in different public policies (Balletto et al. 2018; Ladu, 2020; Kameswari et al., 2025), including the main areas of investigation of the present study, which is part of the "e.INS – Ecosystem of Innovation for Next Generation Sardinia" research project, Spoke 8 - Sustainable Mobility.

The e.INS project addresses critical challenges in spatial and mobility planning in Sardinia Region (Italy) and provides a methodological approach to develop a sustainable transport model by a comprehensive DSS and an innovative MaaS system (Kriswardhana & Esztergár-Kiss, 2023). As a matter of fact, the Sardinia Region, the second largest island in the Mediterranean Sea, represents an interesting case study. Indeed, despite numerous attempts to guarantee territorial continuity (Fancello et al., 2021), geographical isolation still represents the greatest cost for the population of over 1,500,000 inhabitants. Regional disparities can be correlated to a weak extra and intra-regional continuity (mutually shaped), due to a significant gap in transport policies (air and maritime) (Benelli, 2023), as well as in infrastructure and supply for internal mobility, further aggravating the condition of insularity.

In this scenario, the objective of the present study is to propose a DSS architecture to support the development of a Sardinia MaaS. Various geo-datasets relating to demographics, socioeconomics, the supply of key services, transport provision and demand, the spatial distribution of tourist flows, and related externalities will converge on a unique interactive dashboard. The integration and representation of this information will provide a holistic perspective on local and regional transport needs, opportunities, and gaps.

The DSS therefore encourages a collaborative, cross-disciplinary approach to transport planning, enabling users to update and manage data via an intuitive interface, ensuring continuous monitoring, relevance and accuracy.

After this introduction, the manuscript delves into the literature review on the DSS for spatial and transport planning (Section 1.1). Section 2 is dedicated to the materials, and describes the main objective and challenges of the e.INS project to improve the transport system in Sardinia; Section 3 is dedicated to the methodology to develop the DSS architecture to inform a new Sardinia MaaS system, providing a focus on the conceptual framework adopted to develop the multi-level geodatabase (Section 3.1); Section 4 focuses on the main operative results obtained by the e.INS projects, describing in detail the activities carried out to build the multilevel geodatabase to implement the DSS (Section 4.1), the proposal for a ArcGIS DSS dashboard (Section 4.2), the analytical models and predictive capabilities (Section 4.3), and the validation and pilot testing (Section 4.4); Section 5 is dedicated to the discussions and conclusions of the study.

1.1 DSS for spatial and transport planning

The first DSS for spatial planning emerged in the 1970s and 1980s before the proper development and spreading of Geographic Information Systems (GIS). Early Decisions Support Systems in a pre-GIS era addressed spatial issues, also in planning, without relying on a proper and advanced cartographic representation. Early systems relied more on coupling with operations research and linear programming tools, particularly for predicting urban growth, retail location, and transportation impacts. While GIS was initially used to manage and display spatial databases, the need to support complex decision-making processes in spatial planning led to the creation of Spatial Decision Support Systems (SDSS), which integrated GIS functionalities with analysis and modeling components (Reed & Pettit, 2018). The 1990s and early 2000s marked a significant expansion of SDSS capabilities. Increased computational power and more robust GIS software allowed a shift from descriptive to predictive logic. Spatial planning benefitted from the development of SDSS, mainly on aspects related to "information, representation, and modelling, fusing these with more formalized processes of urban planning based on the rational decision model" (Batty and Densham, 1996; Batty et al., 1999). Therefore, DSS for urban planning began to integrate simulation models, multi-criteria analysis (MCA) to evaluate complex alternatives based on multiple criteria and stakeholder preferences (Li et al., 2020), and advanced visualization (2D and 3D) for a better understanding of spatial impacts. The concept of Planning Support Systems, which encompassed a wide range of computer-based tools to support the entire planning process, also began to spread.

The more recent DSS manages various types of Big Data, offering detailed, real-time information on urban dynamics such as vehicular traffic, the supply and demand for services, demographic trends, and more, to support sustainable planning. Within this framework, DSS have found wide applications in spatial planning, with reference to the development of the Smart City model (Papa et al., 2015; Gaglione, 2023; Silva et al., 2024) as they drive decisions on crucial aspects like traffic management, energy optimization, public safety, and the provision of services to citizens. Their ability to provide a dynamic knowledge of urban phenomena is essential for managing urban complexities, such as land-use and unforeseen events such as natural disasters and the impacts of climate change (Papa, 2025).

In the domain of transportation planning, DSS are used for a wide range of applications, from real-time traffic management to the long-term strategic planning of infrastructure, Local Public Transport (LPT) and shared mobility services (Balletto, 2022). These sophisticated tools are affecting a paradigm shift in the management of urban and rural mobility and the very concept of mobility itself, with the transition from purchasing vehicles to purchasing access to mobility services (Janzen et al., 2025). DSS can monitor real-time transport data (from sensors, GPS, mobile phone data) to identify congestion areas, optimize public transport routes, and provide information to travelers, using AI algorithms to suggest alternative routes or to optimize public transport schedules based on demand. In this sense, DSS proves to be fundamental for tackling challenges like decarbonization and reducing traffic congestion (European Parliament, 2020). DSS integrates advanced traffic simulation models to predict vehicle flows, the impact of new infrastructure or changes to the road network, and to evaluate scenarios to inform policies and infrastructure schemes (Papageorgiou et al., 2008) (highways, railways, airports) based on multi-criteria analysis (MCA) and the economic, environmental, and social cost-benefits of different alternatives (Macharis et al., 2009; Balletto et al., 2024b). DSS also finds application in the planning and optimization of logistics networks, from warehouse location to delivery route planning, reducing costs and environmental impact (Turban et al., 2015; Valentini et al., 2023). In this sense, DSSs serve as key tools in MaaS (Mobility as a Service) ecosystems, aiding public authorities and operators in designing sustainable mobility services, managing demand, and monitoring performance through integrated transportation models (Musolino et al., 2022; Concas et al., 2024). As a matter of fact, MaaS (Mobility as a Service) architecture focuses on multi-modal integration and data ecosystems enabling useful tools for trip planning, booking, and payment (D'Amico, 2023). Recent solutions emphasize the importance of considering

AI-driven fusion and public-private collaboration to overcome fragmentation, although many aspects still deserve further investigation (Eze, 2025).

In this perspective, the e.INS project - Spoke 08 - is developing its own DSS with the aim of supporting the implementation of a MaaS (Mobility as a Service) system for the Sardinia region. After Section 2, dedicated to the e.INS project, the DSS architecture is described in Section 3 (Methodology).

2. The e.INS project for sustainable mobility in Sardinia Region (Italy)

The e.INS project, Spoke 8 - Sustainable Mobility, funded by the Italian Ministry of University and Research under the Next-Generation EU Programme (National Recovery and Resilience Plan, is part of the broader scientific debate of sustainable multimodal mobility in the framework of the energy and digital transition (Ladu et al., 2025). The project aims to promote sustainable modal integration in the interconnections between Sardinia Region, Italy and the rest of Europe, and within the same region, applying the Mobility as a Service (MaaS) concept (Hensher et al., 2020; Zhang et al., 2021). The Sardinia Region is the second largest island in Italy, with a population of 1,562,381 inhabitants and a population density value of 64.81 inhabitants/km² (ISTAT, 2025). The Region has a significant deficit in relation to the provision and competitiveness of transport infrastructure (Sardinia Region, 2008). Despite several attempts to guarantee territorial continuity by Public Services Obligations (PSO), the geographical impedance still represents the greatest cost for both inhabitants and city users (Fig.1).

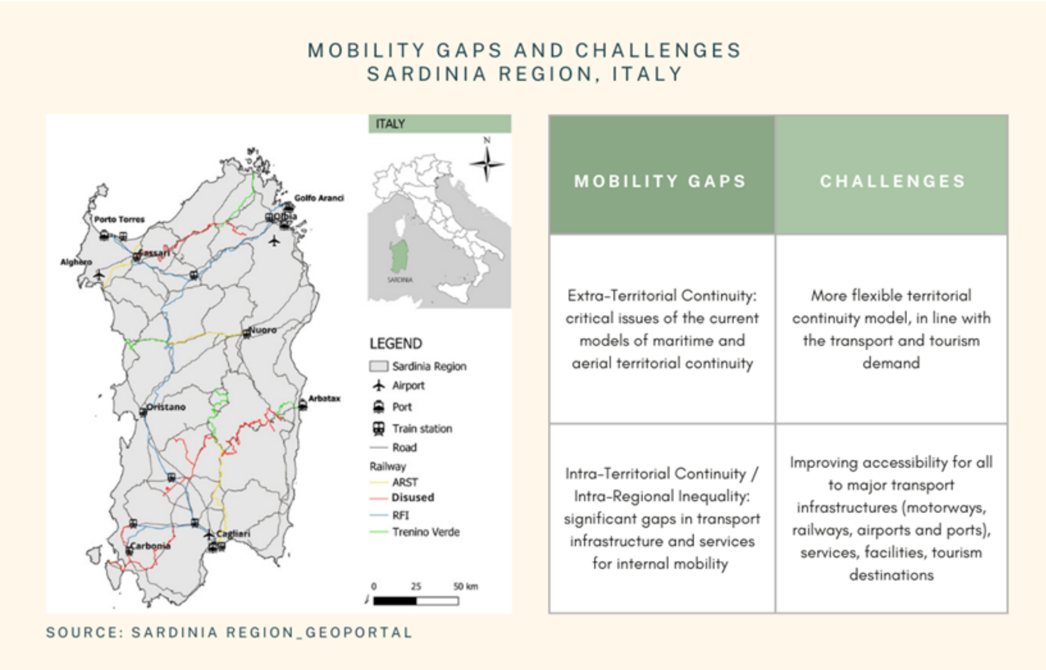

Fig.1 Mobility gaps and challenges in Sardinia (Italy). Author: Mara Ladu

Regional disparities can be correlated to a weak extra and intra-regional continuity (mutually shaped), due to a significant gap in transport policies (air and maritime), as well as in infrastructure and supply for internal mobility, further aggravating the condition of insularity (CRENoS, 2023). As a matter of fact, Transport services are limited to a few rail connections due to the limited extent of the network, as well as public transport routes on extra-urban roads operated by the regional company ARST and a few private, subsidized companies. Urban public transport is available in major cities. The island's settlement structure, characterized by smaller centers that depend heavily on main urban areas, determines the structure of transport services. These services become sparser in terms of trips and frequency further away from main attractions you go, making public transport less convenient and less competitive with private cars. In this sense, the past, present and future of the Sardinia Region are closely linked to the "transport" issue, due to the lack of continuous external connections and, above all, the lack of internal connections within the island. The transport system has significantly influenced various development opportunities (Fancello, 2022), as well as the rise of tourist destinations, which nowadays face seasonal concentration of tourist flows (Balletto, 2024a; 2025a). In this sense, the quality of transport infrastructure and services (road, rail, maritime, and air transport) is a key factor in reducing travel times and improving internal connectivity (European Parliament, 2024).

Within this framework, regional issues and regional disparity are at the core of the e.INS project. The analysis of the Sardinia transport system to encourage a modal shift from private cars to more sustainable modes of transport represents a fundamental research activity. Emphasis is placed on accessibility to Sardinia airports - the main passenger gateways to the island - to promote the integration of mobility services, supported by digital platforms for both management and use.

Within this framework, the integration between urban planning, transport systems and ICT represents a prerequisite for a multimodal transport model that combines mobility demand and supply with which to inform a MaaS system. In this perspective the research project envisages several stages, including activities and associated milestones. Among these, the present study focuses on the methodological approach adopted to create a multi-level geodatabase concerning transport supply, land use and the spatial distribution and provision of urban and territorial facilities. This structured knowledge base is essential for developing a sustainable, multimodal transport model for Sardinia's airports based on the MaaS concept that can meet the needs of residents, tourists, and city users. In this process, Decision Support Systems (DSS) are useful tools for supporting the formulation and validation of the innovative mobility system.

3. Methodology. The DSS architecture for a Sardinia MaaS system

The present study proposes an innovative DSS architecture with the aim of supporting key mobility ecosystem actors (authorities, public and private transport operators and mobility providers) in the design and implementation of a DSS for a Sardinia MaaS (Mobility as a Service) system, in line with the e.INS project - Spoke 08 – objectives.

According to the literature review (Arampatzis et al., 2004; Turban et al., 2010; Zak, 2010; Ocalir-Akunal, 2016; Sharda et al., 2019), DSS integrates data, models, and a graphic interface. The system is composed of the following subsystems: a Database Management subsystem responsible for the storage and management of large volumes of data; a model base subsystem the purpose of which is the processing of information by way of data mining techniques, algorithms, mathematical and analytical models; and a graphic user interface which provides a user-friendly, flexible, and interactive visualization of data and analytics.

Based on the way data is received and processed there are different categories of DSS (Salanova et al., 2022):

1. Communication-driven decision support systems, frequently employed to facilitate effective collaboration between internal teams within an organization via a web or client-server.
2. Data-driven decision support systems which have been proven to be beneficial in the process of querying a database or data warehouse.
3. Document-driven decision support systems utilized for the purpose of searching web pages and locating documents on a specific set of keywords or search terms via the web or a client/server system.
4. Knowledge-driven decision support systems which furnish specialized expertise and information for addressing specific problems and provide decision makers with assistance by leveraging various data mining techniques, including neural networks, fuzzy logic, evolutionary algorithms and case-based reasoning as well as artificial intelligence.
5. Model-driven decision support systems which rely on mathematical and analytical models to facilitate the analysis of decisions or the selection of different alternatives.

Fig.2 illustrates the current and prospective architecture of the Sardinia MaaS system's DSS. The proposed DSS is principally composed of two elements: the database management subsystem and the graphic user interface. This structure enables computations on data retrieved from the database management system and facilitated by the spatial analysis tools provided by Geographic Information Systems. It also allows for the inclusion of a transport model management subsystem that provides analytical and predictive functions, such as planning travel itineraries, optimization algorithms, demand forecasting, scenario analysis, evaluation, and more. Together, these subsystems form the knowledge base management system of the DSS, providing integrated, structured information to inform decisions regarding the transport system and its management.
According to this architecture and the DSS classification, our DSS is data-driven (2). With the addition of the model subsystem, it will also be classified as model-driven (5). Furthermore, the incorporation of GIS functionalities makes it a GIS-based Decision Support System.
Operationally, the DSS collects and systematizes a multi-level geodatabase functional to develop a demand and supply model for sustainable multimodal transport to and from Sardinia's airports, with the resulting knowledge base feeding into an airport MaaS system.

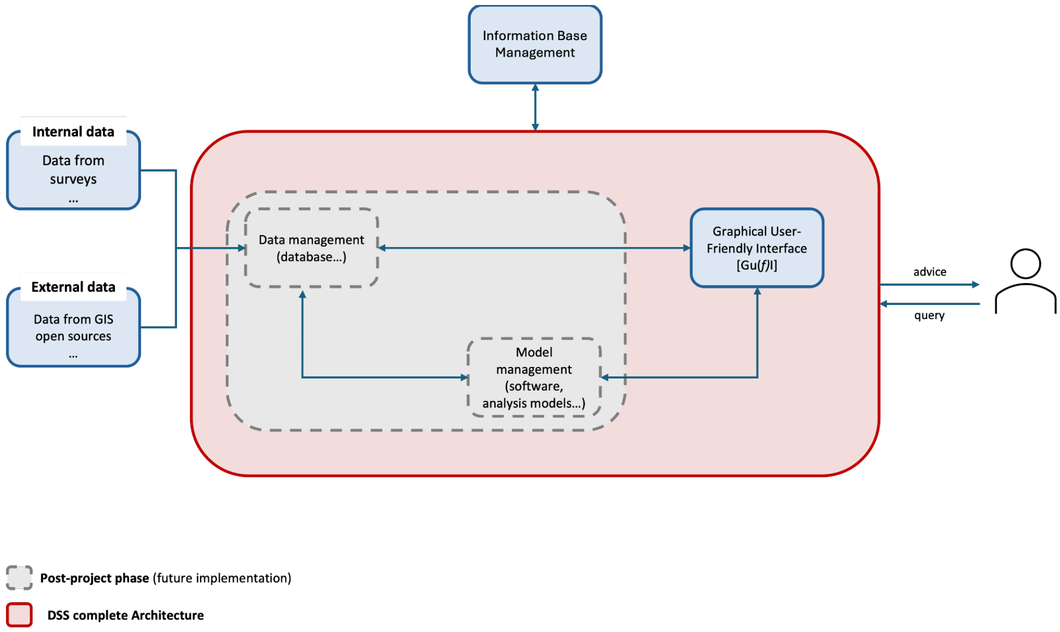

Fig.2 Current and prospective DSS architecture for a new Sardinia MaaS system. Authors: Tanja Congiu and Sara Faedda

3.1 The conceptual framework

The conceptual framework of the multi-level geodatabase is reported in Fig.3.
The construction of the database is divided into the collection and systematization of information (open data, static and real time) relating to various topics that characterize the Sardinian organization of settlement, socio-economic system (with particular attention on the spatial distribution of tourism flows), and the provision and demand of transportation services. The operational scheme is as follows: Data (code, name, source), Spatial dimension (unit and global dimension), File (format, date, and frequency update). The cartographic bases used are: Open Street map, Google Earth, MyMaps, etc. with the network of roads, railway and internal maritime routes also represented.
The multi-level database, that is preparatory for the construction of a demand (local community and city user) and supply model for sustainable multimodal transport in Sardinia, also includes the results of network analysis techniques provided by the GIS software using the data collected.
GIS-based DSS supports the holistic approach to LU&Transport planning (Geertman & Stillwell, 2009). More precisely, tools like ArcGIS are ideal for building DSS that support integrated spatial and transport planning.

Its advanced capabilities for spatial analysis, modeling, and visualization allow for the overlaying of zoning maps, transport networks, demographic data, and environmental data.
Network Analyst (for routing optimization and accessibility calculation), Spatial Analyst (for proximity and overlay analysis), and Geostatistical Analyst techniques make it possible to visualize and analyze spatial disparities (Ladu et al., 2024; Ladu & Balletto, 2024) and to accurately quantify the impacts of new infrastructure and different policies. These functionalities are testing as part of the e.INS project, Spoke 8 - Sustainable Mobility, which uses both the ArcGIS Desktop Software to create, analyze, and share multidimensional databases (social, economic, demographic, land use, transport) for the regional context of Sardinia, and the ArcGIS Dashboard web application, which allows for the development of dynamic and easy-to-understand presentations for a wider audience. In particular, the DSS is functional to the development of an airport MaaS for a more efficient, sustainable, and user-responsive transport system to and from Sardinia, promoting intramodality in internal and external connections.

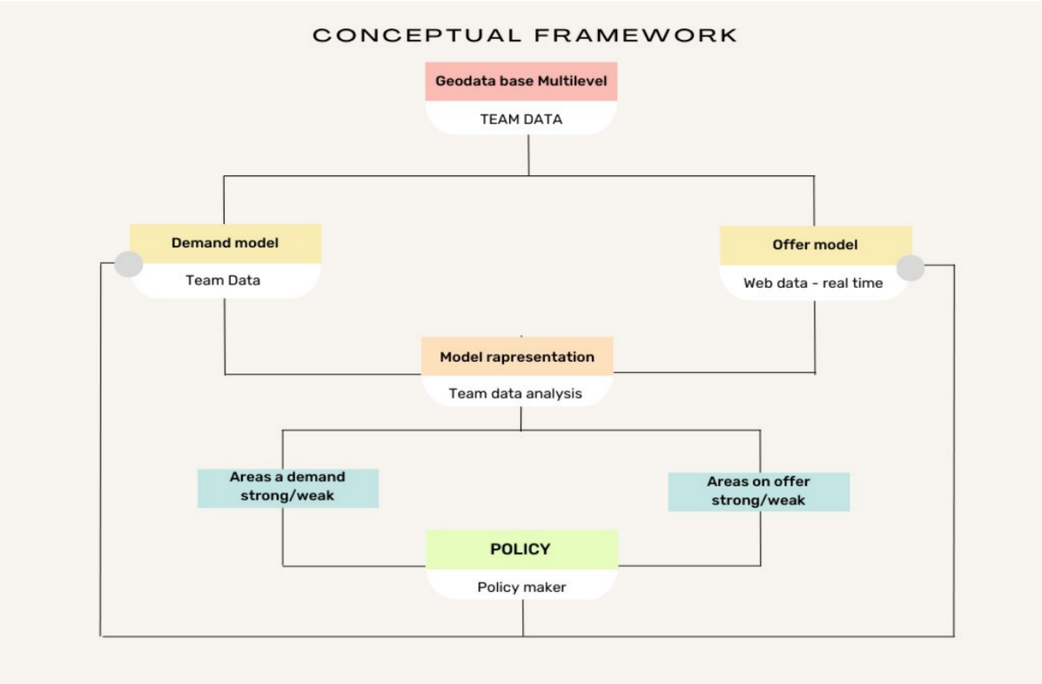

Fig.3 Dashboard framework to support MaaS system. Author: Ginevra Balletto

To enhance the clarity of the DSS development process, the system workflow can be represented using Business Process Model and Notation (BPMN 2.0) standards. The workflow follows these key steps:

1. Data Collection and Ingestion: Data from heterogeneous sources (open data portals, transport operators, IoT sensors, surveys) are collected and validated;
2. Data Processing and Cleaning: Raw data undergoes standardisation, format conversion, and quality assurance in the Database Management subsystem;
3. Storage in Multi-Level Geodatabase: Processed data is organized in the Information Base Management system, structured by topic and spatial/temporal dimensions;
4. Spatial Analysis and Modeling: GIS tools (Network Analyst, Spatial Analyst) perform analysis on the stored data, generating derived indicators and metrics;
5. Visualization and Dashboard Generation: Results are rendered in the ArcGIS Dashboard's graphic user interface as interactive maps, charts, and indicators;
6. Decision Support and Scenario Evaluation: Users interact with the dashboard to explore scenarios and generate insights for policy decisions. (Future step): Model-based predictions and optimization analyses provide recommendations.

4. The operative results. From the dataset to the dashboard

4.1 From data to DSS

A comprehensive framework of the multi-level geodatabase is provided in Fig.4. The figure illustrates the main topics selected for the achievement of project milestones and the interconnections among the following analytical dimensions:

1. Dynamics of passenger demand (temporal and spatial patterns of movement to/from Sardinia).
2. Land use (spatial distribution of services, facilities, and economic activities in Sardinia).
3. Extra-Regional Transport Connectivity (air and maritime connections connecting Sardinia to mainland Italy and Europe).
4. Intra-Regional Transport Supply (public and private transport services within Sardinia).

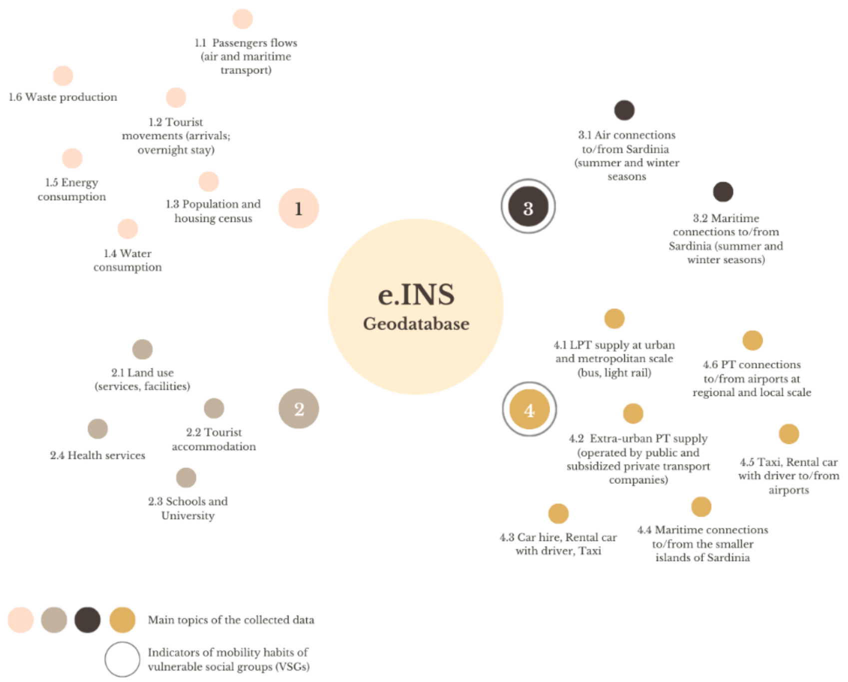

Fig.4 Framework of the multilevel geodatabase. Authors: Ginevra Balletto and Mara Ladu

More precisely, as regard 1) and 2), the list of the main topics of the collected data is reported below: Urban services and productive activities; Population and housing census; Local labor systems; Incomes; Consumption of water and electricity by sector; Urban waste production; Passenger traffic (air and maritime transport); Tourist movements (arrivals and presences); Accommodation facilities (number and type of tourist accommodation facilities); Education (schools and University); Health services (number of hospital beds; type of hospital emergency network structures).

Regarding 3) and 4), the list of the main topics concerns the depiction of the transport supply to and from Sardinia and within the island. The following data were therefore collected and processed: data on air and maritime connections to/from the main Sardinian gateways for the whole year; measurement of the infrastructural network capacity and connectivity; coverage and frequency of transport services (considering both public and private operators); accessibility of the main transport nodes (airports at first - and urban amenities). The spatial analysis of the road network and supply of mobility services (public and private) in the Sardinian regional context revealed various inequalities in access to main gateways and destinations between areas.

In addition, the analytical dimensions of the multilevel geodatabase are interconnected through cross-cutting analytical themes, including socioeconomic characteristics, accessibility patterns, and the specific needs of vulnerable social groups (Sahin et al., 2025). More precisely, a set of indicators of mobility habits of vulnerable social groups (VSGs) that represent a cross-sectional investigation element for aspects 3) and 4) of the geodatabase (Fig.4). This knowledge base supplements the travel demand database, enabling user profiling and customised mobility services. For example, depending on user preferences and needs, the DSS can provide evidence of specific transport service characteristics, such as wheelchair accessibility or assistance with changing between modes of transport. The main aim is to ensure that the needs of passengers with reduced mobility are considered when planning travel options. At the same time, the specific characteristics of the areas connected can be highlighted to identify viable, efficient solutions, such as supplementing regular transport services, in areas with low demand, with integrated, personalized mobility options that reduce isolation and contribute to territorial equity.
The DSS's graphical interface also offers advantages. For example, the provision of up-to-date information, made possible by mobility data sharing from transport operators, is particularly beneficial for all users, including planners, transport management operators and final users, especially those who are less familiar with the area, such as tourists and people with special needs.
The adoption of the "accessibility for all" approach in the design of a MaaS platform will require the incorporation of the data collected in the DSS.

4.2 Proposing a DSS dashboard

The multilevel geodatabase defined in the first phase of the project for analyzing and monitoring sustainable mobility in Sardinia, as well as to develop innovative mobility models and tools, has been essential to implement a DSS to support sustainable mobility and transport planning in Sardinia.
The DSS was initially designed as a web-based solution, developed using standard web technologies like HTML, CSS, and JavaScript. This approach offered flexibility for custom development; however, during the early phases of the project, the decision was made to transition to the ArcGIS platform to leverage mature geospatial functionality, enterprise-level infrastructure, and integration capabilities with existing systems used by regional stakeholders. This technical migration represented a significant architectural decision, balancing customization capabilities against production-readiness and stakeholder familiarity.
As a matter of fact, ArcGIS, developed by Esri, is a world-leading Geographic Information System (GIS) platform characterized by flexible approaches that enable the collection, integration, connection, connection, creation, analysis, management, and sharing of spatial data. Widely used in urban governance, among professionals and public organizations, ArcGIS supports sustainable development initiatives, including monitoring and managing natural and environmental resources, risk analysis and mitigation, transportation and logistics planning, market analysis, transparency in decision-making, and public safety. In this context, ArcGIS is a critical tool for achieving the objectives of the e.INS project.
Within the e.INS project, both ArcGIS Desktop software (Esri, ArcGIS for desktop) (Fig.5) and the ArcGIS Dashboard (Esri, ArcGIS Dashboards) web applications (Fig.6 and 7) were employed. The desktop software was used to create, analyze, and share intelligent maps and spatial data.
Moreover, ArcGIS offers free access to additional databases to implement the analyses carried out by the e.INS project such as What-if Analysis to support multi-level and cross-sectoral governance in transport planning and data-driven decisions. From a system architecture perspective, the DSS adopts a centralized geospatial data management approach based on ArcGIS services.

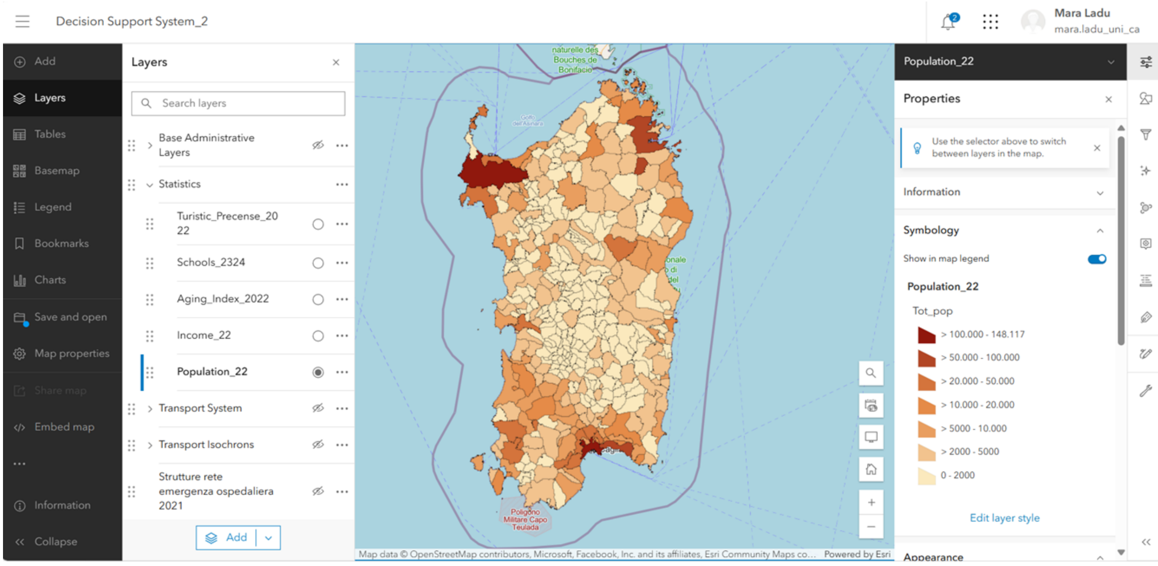

Fig.5 Spatial distribution of population in Sardinia (2022) - ArcGIS Desktop software. Authors: elaboration by all authors

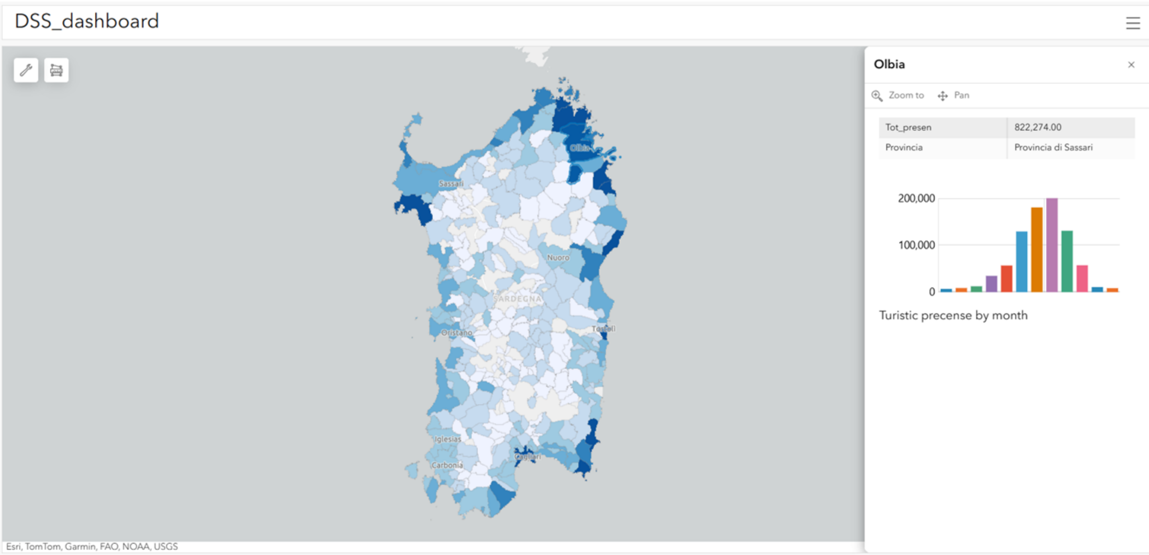

Fig.6 Tourist presences by month - ArcGIS Dashboard web application. Authors: elaboration by all authors

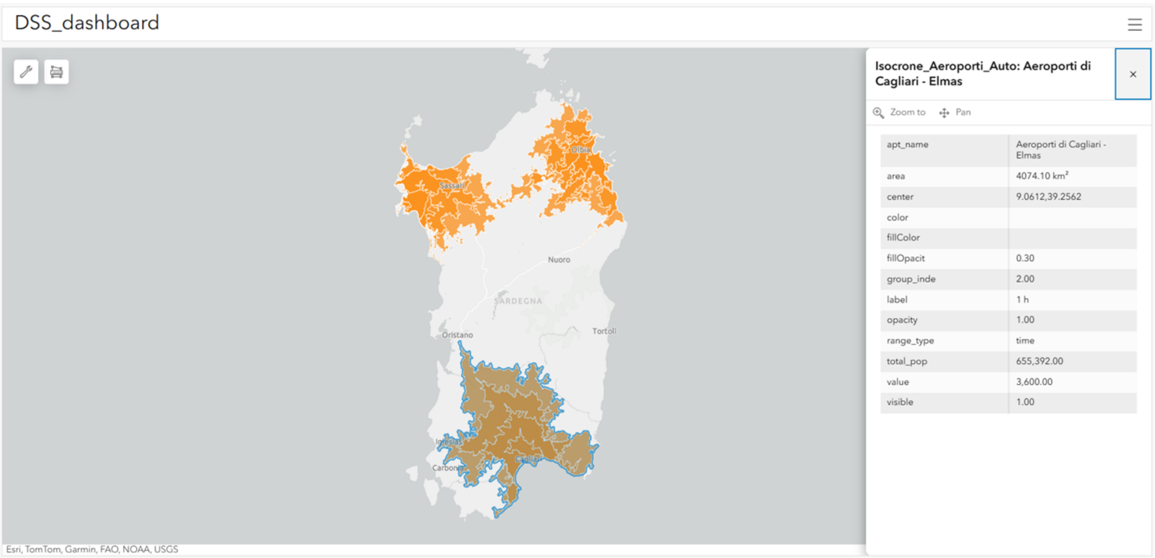

Fig.7 Sardinian Airports' isochrones by private car Travel Time: 15, 30. 45. 60 minutes - ArcGIS Dashboard web application. Authors: elaboration by all authors

Spatial datasets are processed in the ArcGIS Desktop environment and published as hosted feature services within the ArcGIS cloud, which are directly consumed by the web-based dashboards, ensuring consistency between analyses and visualizations. Data synchronization is managed through service-based updates, allowing controlled overwrite or incremental updates so that dashboards automatically reflect changes with minor reconfiguration. Data storage and security rely on ArcGIS-managed cloud infrastructure with role-based access control, ensuring differentiated user permissions, protection of sensitive information, and compliance with public administration data governance requirements. The ArcGIS Dashboard web application leverages data produced and managed in the desktop environment to create dynamic, user-friendly visual presentations for a broader audience. As a matter of fact, one of the critical success factors for the DSS is ensuring that it meets the distinct informational and decision-making needs of different stakeholder groups.

Stakeholders in the transport planning process include transport technicians, urban planners, transport operators and private mobility providers, as well as policymakers and administrators. The latter requires executive summaries, key performance indicators (KPIs), cost-benefit analyses, and scenario comparisons.

To effectively support these diverse groups, DSS implementation includes communication strategies such as multiple visualization formats for data and customizable filters and drill-down capabilities to explore data at multiple levels of detail. More precisely, the proposed dashboard offers an integrated view of geographic data through various interactive visualizations—maps, lists, charts, tables, and indicators—that allow users to monitor events, identify trends, share analyses, and develop predictive scenarios. This comprehensive overview facilitates timely and informed decision-making with a variety of analytical tools readily available. Specifically, within the ArcGIS-based phase of the project, queries constitute a fundamental component allowing easy filtering and data visualization. The users can dynamically explore the dataset by applying customized filters, selecting geographic areas of interest, or isolating particular indicators.

For example, Fig.8 shows that in the 2022 Population layer, it is possible to filter and display only those communities with at least 5,000 inhabitants.

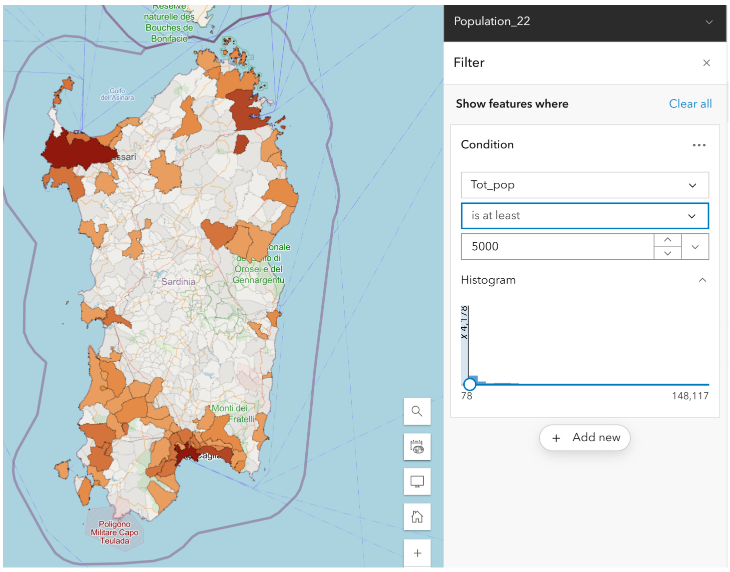

Fig.8 Sardinian Population (2022) filtered municipalities with at least 5,000 inhabitants. Authors: elaboration by all authors

Such interactive capability enables engaging navigation with insights tailored to the user's needs. As a result, decision-makers can rapidly assess the impact of various mobility strategies or environmental factors through real-time data manipulation. Moreover, the ArcGIS platform offers strong mechanisms for handling and incorporating new or updated data. The solution remains reliable without complete redevelopment or downtime, where users can efficiently update the datasets from external sources, field data collection, or periodic surveys, and automatically incorporate them into existing maps, dashboards, and analyses. Such a level of flexibility is essential for maintaining the relevance of the tool in a dynamic development environment such as sustainable mobility planning.

In terms of data sharing, ArcGIS has a complete suite of options for distributing geographic information and analytical results across multiple channels. The web-based interface ArcGIS Dashboard facilitates broad dissemination to diverse audiences, ranging from technical experts and policymakers to the general public, maximizing the DSS impact. These platforms enhance understanding and support transparent decision-making processes through intuitive, visually rich presentations of complex spatial data. Additionally, ArcGIS allows administrators to define multiple user roles, clearly define permissions, and integrate robust access control to protect sensitive information while encouraging collaboration among stakeholders.

ArcGIS is widely used in public administration, making it an ideal system to share with final users such as local governments, public transport operators at local and regional levels, and various stakeholders involved in transport planning. These end users will be able to edit and update the dataset, ensuring that the DSS remains a living tool adapted to evolving needs.

The current DSS shows the data set created during the e.INS project by the research team:

- Dataset relating to the regional socio-economic context, with particular attention on the spatial distribution of tourism flows;
- Dataset relating to the Provision and Demand of Transportation Services;
- Geospatial analysis of regional dynamics using the data collected and applying specific network analysis techniques.

4.3 Analytical models and predictive capabilities

The current implementation of the Decision Support System (DSS) integrates a diverse set of analytical tools and modeling functions designed to assess accessibility, spatial disparities, and transport demand dynamics.

A key component is the network analysis module, which evaluates accessibility through two primary approaches (Palermo et al., 2025). First, isochrone analysis employs ArcGIS Network Analyst to generate travel time polygons from key transport nodes such as airports, ports, and railway stations. These polygons, calculated for multiple travel time thresholds (15, 30, 45, and 60 minutes by private car), identify areas characterized by low accessibility under different transportation modes and scenarios. Second, service area analysis maps the spatial coverage of public transport services, detecting both underserved regions and redundant overlaps.

The spatial disparity analysis framework overlays transport infrastructure with socioeconomic and demographic indicators to highlight geographic inequities in mobility. Overlay and clustering techniques identify localities where vulnerable populations encounter limited travel options and reveal spatial patterns of service concentration or unmet demand (Di Ruocco, 2025).

In the current development phase, the DSS also provides demand characterization tools. These include a tourist flow analysis module, combining data on accommodation capacity, seasonal occupancy, and travel records to describe the spatial and temporal distribution of tourist mobility. Additionally, population and service proximity indicators measure distance-based accessibility between settlements and key facilities, healthcare, education, and employment hubs—supporting comparative analyses of service access.

A dedicated model management subsystem is being developed to enable predictive and optimization functionalities. Planned models include:

- Demand forecasting models based on machine learning regression techniques applied to historical passenger and tourist data, enabling short- and medium-term predictions of transport demand by origin-destination pair;
- Routing optimization models using integer linear programming to design efficient public transport routes that balance demand coverage, service costs, and equity objectives;

- Multi-Criteria Analysis (MCA) for evaluating policy alternatives against multiple dimensions—economic, environmental, and social—through a weighted aggregation approach.

These modeling capabilities will be operationalized in the next project phase, accompanied by full documentation of assumptions, inputs, parameter settings, and validation metrics.

4.4 Validation and pilot testing

A pilot case study was implemented focusing on airport accessibility and tourist mobility planning in Sardinia to assess the operational performance of the DSS. The test examined the region's three main international airports—Cagliari, Olbia, and Alghero—to evaluate how the DSS supports strategic planning decisions such as defining optimal shuttle routes and frequencies connecting tourist accommodation zones with airports, minimizing travel times while controlling operating costs.

The pilot integrated data on tourist accommodation, seasonal occupancy trends, and existing transport connections within the DSS. Isochrone analyses identified clusters of accommodation facilities located beyond a 30-minute travel radius from the nearest airport. These clusters were cross-referenced with tourist arrival data and public transport availability to detect service gaps.

Results indicated several poorly served areas, particularly in the Costa Smeralda region, where access to Olbia Airport exceeded 45 minutes by public transport. The DSS dashboard visualizations enable stakeholders, including the regional transport authority, tourism operators, and airport managers, to interactively explore demand concentrations and accessibility gaps. Preliminary route optimization simulations suggest that the introduction of two to three dedicated shuttle lines during peak tourist seasons could reduce average airport access times to under 30 minutes for approximately 85% of total accommodation demand, with clear implications for cost efficiency.

A DSS performance test will be performed to confirm that it meets the usability and reliability standards required for operational decision support in real-world transport planning contexts, supporting simultaneous access by multiple users and ensuring fast query response times for standard analytical operations.

5. Discussion and conclusions

As part of the e.INS project, Spoke 8 - Sustainable Mobility, the DSS and the future dashboard are intended as intelligent tools that can integrate a set of data to analyze regional development dynamics. It focuses on the accessibility of local communities to the main transport infrastructures (airports, port and railway stations) and key services to support policy makers in their decision-making processes and create predictive scenarios. As a matter of fact, based on the analyses developed within the e.INS project, which revealed inequalities between areas in terms of transport provision, together with the distribution of demand, the DSS supports planning new solutions: it could predict mobility demand in specific areas, forecast transport supply (public and private), optimize routes, thus promoting the transition to sustainable mobility models.

In this context, the identification of all possible public and private transport options plays a primary role to develop an airport MaaS system. By using the collected indicators, the DSS will be able to predict tourist flows and mobility demand, allowing operators to proactively adapt their transport offerings. The DSS will also make it possible to evaluate complex scenarios by simulating the environmental (e.g., CO_2 emissions), economic, and social impact of new policies or proposed infrastructures aimed at promoting sustainable intermodal connections.

From a social impact perspective, the e.INS project aims to ensure social inclusion by integrating data on the needs of Vulnerable Social Groups (VSGs) into the DSS to design mobility systems that reduce inequality, in line with the concept of accessibility for all. Moving from theory to practice, this involves the creation of personalized routes and services, particularly for people with reduced mobility. This design choice is a precondition for making airport MaaS a tool to promote regional equity.

Finally, the development of an interactive ArcGIS Dashboard with an intuitive user interface will make the DSS more accessible and understandable to stakeholders.

As demonstrated in Section 4.2, the DSS implementation incorporates explicit communication strategies and role-tailored visualizations to ensure that diverse stakeholder groups - from technical experts to regional administrators - can effectively engage with the tool and extract decision-relevant insights. This will facilitate public participation in decision-making processes, thereby improving governance transparency and effectiveness. Final users will be able to update or implement datasets directly through the ArcGIS Online environment or connected enterprise portals, using secure login credentials and role-based permissions. Editing can be performed via the ArcGIS Dashboard's linked web maps or dedicated ArcGIS Web AppBuilder applications, which allow point-and-click editing of geographic features, modification of attribute tables, and batch uploads of CSV, shapefile, or GeoJSON datasets. Data changes are instantly saved to the underlying hosted feature layers, ensuring that updates are immediately reflected in all connected maps and dashboards. Version control and edit tracking are enabled to log modifications and preserve data integrity, while administrators can validate updates before publishing them to the public-facing DSS. This workflow allows local authorities and transport operators to keep datasets current without requiring intervention from the development team, thus maintaining a dynamic and participatory system.

The current DSS is at Technology Readiness Level (TRL) 5-6, representing a tested and validated system in a relevant environment. The system has been prototyped using actual datasets from Sardinia's transport and territorial systems, and the ArcGIS-based implementation has been piloted with regional stakeholders. While operational for data analysis and visualization, the system is not yet deployed in full production use with continuous real-time integration from all regional transport operators. The transition to TRL 7-8 (system prototype demonstration and ready for deployment) will be achieved upon integration of the Model Management subsystem, full automation of data synchronization, and operational integration with transport operator systems for real-time data feeds. AI/ML algorithms will be considered as significant drivers for modern DSS to develop the proposed workflow.

Moreover, the DSS will include additional datasets related to the transport system supply, considering the most recent forms of Advanced Air Mobility (AAM) and drones, which are defining new transport systems. As a matter of fact, advanced mobility systems, and, more precisely, advanced aerial mobility systems, promise to adequately address the need for efficient transportation in sparsely populated areas, such as those that characterize the Sardinia region, providing efficient connections to inland and mountainous locations far from the main road network, as well as to smaller islands. The use of advanced mobility systems has the potential to become an effective solution for those areas that are otherwise challenging to reach by conventional means of transportation, especially regarding healthcare and emergency transport needs.

These aspects will be included in the DSS as key elements for supporting the implementation of new infrastructures and hubs that require strong integration with spatial planning and sustainable urban mobility plans, capable of ensuring accessibility, intramodality and integration with the territory.

More precisely, the DSS will be essential for managing the use of drones and air vehicles in urban settings, supporting the planning of vertiports (identifying optimal locations and integrating them with the existing transport network), optimizing routes, and managing interference with traditional air traffic, especially for emergency services and for connecting marginal areas, such as in the Sardinia region.

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Fig.4: Authors: Ginevra Balletto and Mara Ladu;

Fig.5-8: Authors: Elaboration by all authors.

Author’s profile

Mara Ladu

She is a Research Fellow in urban and landscape planning and design at the DICAAR, University of Cagliari, Italy. She was a Visiting Scholar at the CTS - Centre for Transport and Society (UWE Bristol) in 2024. Her research topics concern spatial and landscape planning, urban regeneration, public real estate management, accessibility and sustainable mobility, geography and spatial analysis. She is author of scientific publications and guest editor in international journals. She is involved in several research projects as a contributing team member and as the Principal Investigator.
e-mail: mara.ladu@unica.it; ORCID: https://orcid.org/0000-0002-2762-0686

Ginevra Balletto

She is Associate Professor of Sustainable urban planning at the DICAAR, University of Cagliari, Italy.
Her research topics concern sustainable spatial planning and mobility in multiple transitions: demographic, energy, ecological, and digital. She has published 250 publications and is guest editor in national and international journals.
Google Scholar profile: https://scholar.google.com/citations?hl=it&user=hMuIcA4AAAAJ
e-mail: balletto@unica.it; ORCID: https://orcid.org/0000-0003-0876-0605

Tanja Congiu

She is Associate Professor of Transport Planning at the DADU, University of Sassari, Italy. Her research focuses on the relationship between the characteristics of the built environment, mobility behavior and transport planning, as a key knowledge-base for informing policies and projects that promote more sustainable and inclusive transport systems and cities. Another research activity is urban walkability and the development of methods and tools for measuring, evaluating and guiding active transport policies. She is a scientific consultant for local authorities and author of national and international publications.
e-mail: tancon@uniss.it; ORCID: https://orcid.org/0000-0003-3791-8352

Gianfranco Fancello

He is Full Professor of "Freight Transport and Logistics" and "Transport Systems Design" at the DICAAR, University of Cagliari, Italy. He is the Director of CIREM – Interuniversity Centre for Economic & Mobility Research. His research topics concern land-transport relations, human factors related to active and passive safety, complex mobility systems, and maritime transport and logistics. He is the scientific coordinator of several national and European research projects. He is the author of five books and approximately 100 publications in national and international journals and conferences.
e-mail: fancello@unica.it; ORCID: https://orcid.org/0000-0001-5233-5126

Ernesto Fontes Pupo

He received his Ph.D. Summa Cum Laude in Electronic and Computer Engineering from the University of Cagliari, Italy in 2024. He was a Postdoctoral Researcher for one and a half years at the same university, within the EU-funded project e.INS (Ecosystem of Innovation for Next Generation Sardinia). During this period he contributed to the development of a Decision Support System (DSS) based on interactive web maps for mobility and demographic analysis. His research interests include wireless communications, radio resource management, 5G/6G network planning and orchestration, immersive multimedia applications, as well as the design and implementation of web-based decision support systems.
e-mail: efontesp90@gmail.com; ORCID: https://orcid.org/0000-0002-1715-6015

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Biodiversity and ecological network: connecting ecosystem services for a sustainable future. GeoAI for Modica green city

Celestina Fazia [a], **Chiara Spadaro** [b*]

[a] University of Enna "Kore", Enna, Italy
e-mail: celestina.fazia@unikore.it
ORCID: https://orcid.org/0009-0000-6938-0660

[b] University of Enna "Kore", Enna, Italy
e-mail: chiara.spadaro@unikorestudent.it
ORCID: https://orcid.org/0009-0004-4277-8176
* Corresponding author

Abstract

Against a backdrop of growing environmental awareness and the need to mitigate climate change impacts, urban spatial planning and management policies inspired by European sustainable development recommendations are gaining strength. These policies address environmental issues through concrete actions aligned with the 17 goals of Agenda 2030. For these strategies to be effective, it is essential to identify tools—particularly urban planning instruments—capable of ensuring the desired outcomes, making cities resilient and ready to face the energy and ecological transition according to an ecosystemic and participatory approach, in line with Policy OP5. Several urban planning instruments promote the 'resilient' upgrading of cities by assigning ecosystem services and biodiversity an active role in counteracting climate change and territorial vulnerability. In Sicily, following Regional Law no. 19/2020, the PUG introduces environmental-ecological endowments such as the Ecological Network. Effective planning and management of environmental heritage require adopting appropriate measures to protect species and preserved areas, ensuring their conservation for future generations. This enables the implementation of an 'innovative' environmental infrastructure through the reorganization of development drivers and the digital representation of its evolving forms. An example of such an 'innovative' ecosystem approach is the "Modica Green City Masterplan," developed with GeoAI support, complementary to the PUG by providing a knowledge base for planning scenarios and environmental assessment of transformation choices.

Keywords

Ecological network; Ecosystem services; Biodiversity; Sustainable infrastructure; Resilience

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1. Introduction

The term biodiversity, coined in 1988 by the American entomologist Edward O. Wilson[1], refers to the multiplicity of living beings that inhabit our planet, thus the result of the many evolutionary processes that have taken place (Wang et al., 2020). A first official definition was provided in 1991 by the World Conservation Union (IUCN) and WWF, according to which it is 'the variety of life in all its forms, levels and combinations. It includes the diversity of ecosystems, species and genetic diversity.' It is in reading this initial definition that one realises how complex the concept of biodiversity really is, welcoming within it all the varied forms of life present in a natural area, giving rise to a dense network of internal relationships and allowing them to coexist and ensure a dynamic balance over time (Ceralli, 2023). This complex process is thus schematised into three macro levels that define biodiversity: genetic diversity, taxonomic diversity and ecological diversity. Over time, intensive anthropogenic activity and economic-industrial development broke the ecosystem balance (Ahern, 2013) and put its resilience to the test; today, the effects of climate change are particularly threatening biodiversity -the most important resource for our planet- by compromising the optimal conditions of local habitats and ecosystems (Eger, 2009). It must be emphasised that biodiversity affects landscape, social, and cultural diversification processes, bringing only and only benefits to human beings. It is also true that the effects of poor environmental management, careless human activities and indiscriminate use of resources directly and indirectly affect biodiversity, and the risk of loss of 'diversity' is considerable. Diversity that is the fundamental prerequisite for ecosystem balance (Ceralli, 2023).

Species diversity includes species richness, which can be measured in terms of the quantity of the same species present in a given area, or species frequency, understood as rarity or abundance in a habitat. The third (ecological diversity) defines the variety of genetic heritage to which all organisms contribute (Reid, 2019).

The need to geo-reference and map 'diversity' at the various levels became apparent with the establishment of the Natura 2000[2] Network. The mapping of the Network is not static. On the NNB (National Biodiversity Network, of ISPRA)[3] site, it is possible to view information on the Natura 2000 network. The NNB[4] map contains data on the presence of census species and the SIC/ZPS/ZSC of the Natura 2000 network updated to December 2023.[5] NNB spreads the care of nature in the city by renewing the way of planning urban spaces and promoting virtuous actions by administrators, communities, citizens, in order to increase biodiversity in urban systems also through urban reforestation actions and the enhancement of green and blue infrastructures (Ahern, 2013). Therefore, the mapping of Natura 2000 Network of the Iblea province and especially Modica, the pilot case of this essay, is shown in (Fig.1).

Today, we have the possibility to monitor the quantity of species, threatened species, and the surface areas of habitats, but this has all happened in less than fifty years (Trusel et alii, 2018). Introducing a brief regulatory preamble, it was from the 1960s onwards that environmental issues began to gain prominence thanks to the emergence of environmental associations such as World Wildlife Found in 1961 and Greenpeace in 1971, which adopted the first regulatory measures regarding environmental protection (Wooster, 2022). Specifically, environmental and economic issues became central within the Stockholm International Agenda in 1972. It was within this document that the definition of Sustainable Development was first introduced, understood as

1 https://www.isprambiente.gov.it/it/attivita/biodiversita/le-domande-piu-frequenti-sulla-biodiversita/cose-la-biodiversita

2 With the two directives, Habitats and Birds, the network is established to all intents and purposes. The Natura 2000 network consists of Sites of Community Interest (SIC), identified by Member States in accordance with the Habitats Directive, which are subsequently designated as Special Areas of Conservation (ZSC), and also includes Special Protection Areas (ZPS) established under the Birds Directive 2009/147/EC on the conservation of wild birds.

3 https://www.nnb.isprambiente.it/it

4 NNB is a partner of the Urban Nature initiative promoted by the WWF to spread the value and care of nature in the city, renewing the way of thinking and planning urban spaces, and promoting virtuous actions by administrators, communities, citizens, to protect and increase biodiversity in urban systems.

5 EIONET, Central Data Repository, https://cdr.eionet.europa.eu/it/eu/n2000

'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs'. One of the most important events was the United Nations Conference in Rio de Janeiro in 1992[6], the results of which included Agenda 21 and the Framework Convention on Biodiversity, mentioned earlier; from these important documents came the guidelines for the Natura 2000 Ecological Networks. A next step is taken with the VI Environmental Action Plan, a programme developed from 2000 to 2010, conceived as a preparatory phase for the instruments later adopted by the European Union, to make this procedure concrete.

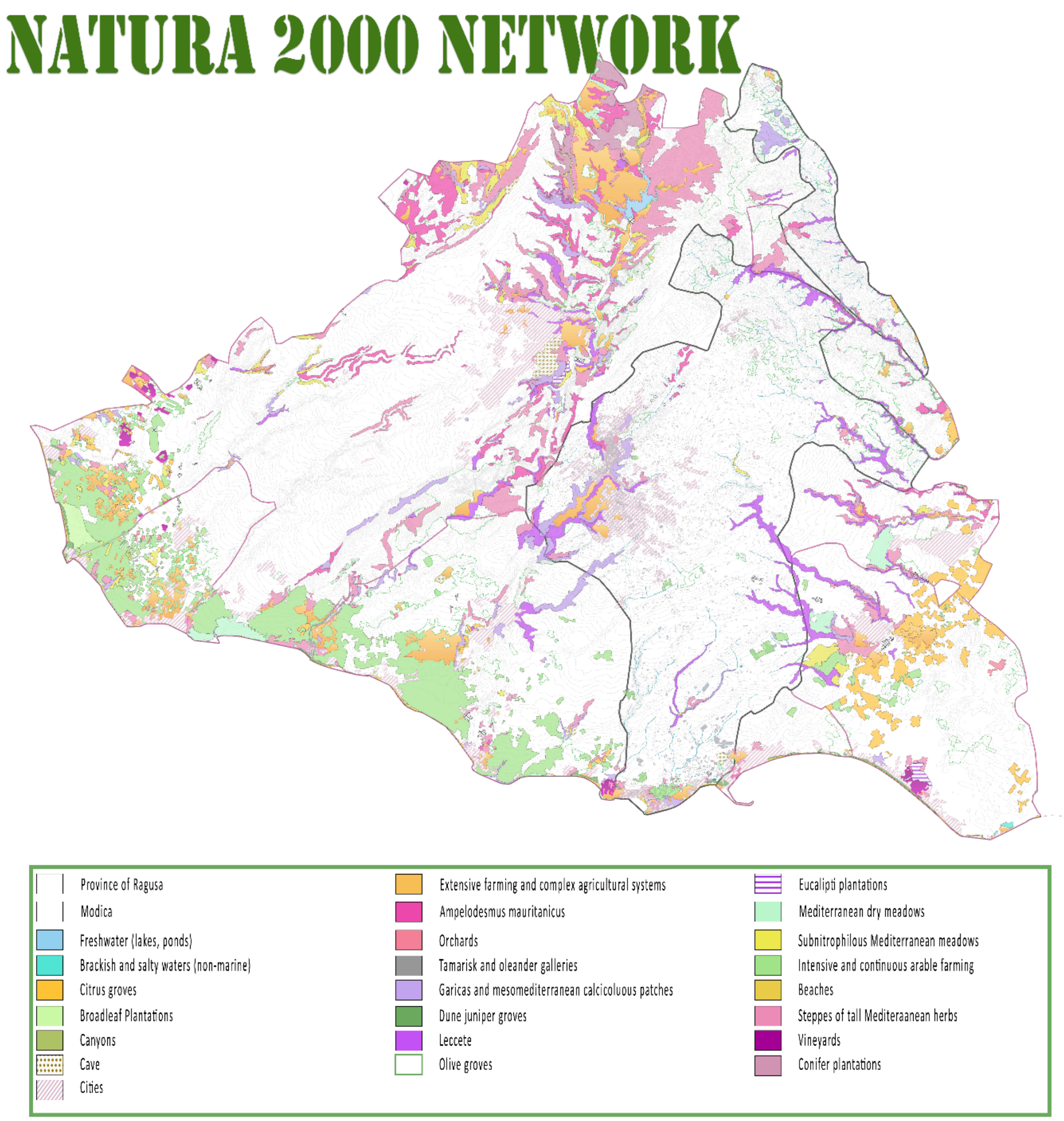

Fig.1 Mapping of the Natura 2000 Network of Modica and its province (Ragusa)

With the spread of reserves[7] -which initially had a purely aesthetic function, protecting scenic and landscape values for purely touristic purposes- and the increase in studies in the field of nature, the awareness of the importance of protected areas as 'places of conservation and protection of ecosystems and biodiversity'[8] is

[6] At this conference, global action was taken by signing two conventions and three declarations on possible strategies for sustainability and halting the negative impact of human activities on the environment.

[7] Protected areas within the dynamics of sustainability in the second half of the 19th century when parks were created only had a purely aesthetic function, as they were intended to protect scenic and landscape values for purely touristic purposes, instead they perfectly reflect the extraordinary natural diversity that surrounds us.

[8] WWF Ricerche e Progetti, Linee guida per l'interpretazione ambientale delle Aree Protette, Novembre 2008

confirmed. This new approach is the evolution of the human-environment, nature-culture binomials, and this dichotomy is being overcome precisely as a result of the socio-cultural changes that have, among other things, led to a greater awareness of environmental dynamics among communities and allowed the concept of sustainable development to take hold (Wooster, 2022). Thus, in the very early 1990s, a proposal for a European Ecological Network was put forward in accordance with the Natura 2000 programme defined by CEE Directive 92/43, mentioned above, which represented the first and official Community response to the Convention on Biodiversity introduced at the Rio Conference (Sánchez-Bayón et alii, 2020). The proposal envisages a network that can include all the protected natural habitats in the international sphere, appropriately connected to each other by means of ecological connection corridors; but the real revolution lies in the symbolic and representative value that the protected areas assume, avoiding the phenomenon of isolation, and also performing a "rhetoric of representation and socio-cultural communication, capable of activating within them models of development capable of exploring and anticipating solutions that can then be extended to the outside world, making the protected areas become a sort of points of excellence."[9] The ecological network, in these terms, translates more into a system of protected areas that relates not only habitats to each other, but also all the elements that contribute to the ecosystem balance.

In the most up-to-date approach, it is to be understood as an element of connection, use, interface and filter, aiming to overcome the fragmentation of the core natural areas by providing an international network of habitats and a programme of land management and protection, aimed at making the territory resilient. It envisages, therefore, an international network of protected natural habitats, interconnected by ecological connection corridors (typologically divided into natural areas, diffuse linear corridors, stepping stones, buffer zones, core areas), In fact, (Fig.2) shows a summary and explanatory diagram of all the components that make up this network.

The main objective is the protection but above all the improvement of biodiversity in qualitative-quantitative terms; the maintenance of this for future generations -by individually protecting the abiotic or biotic elements that make up the various ecosystems- becomes a priority (Sánchez-Bayón et alii, 2020). Recently, the protection of ecosystems and biodiversity is associated with broader strategies that include adaptation measures to manage climate change (Papa, 2024). Cities are at the forefront of the climate crisis we are experiencing[10] - extreme weather events are becoming increasingly frequent. Some cities, such as Dhaka North City Corporation and the Guadalajara Metropolitan Area, already in close contact with biodiversity, have taken tangible and positive steps to make nature, infrastructure and local communities more resilient and ready to mitigate the impacts of climate collapse, thanks to green adaptation measures and a strengthened relationship with the environment. Green adaptation measures are embodied in the system of interventions that enhance the relationship with nature, biodiversity and ecosystem benefits (Sánchez-Bayón et alii, 2020). Examples of these types of interventions are (ISPRA, 2021):[11]

- actions aimed at the hydro-morphological rehabilitation of riverbeds;
- the use and reinforcement of vegetation that can withstand high wind speeds or that can protect urban areas from direct sunlight, thus limiting overheating;
- projects for the renaturalisation of infrastructure margins and the reconstitution and enhancement of riparian greenery intercepted by watercourses in urban areas.

In relation to infrastructures, the 'climate proofing' process (articulated in two pillars, Adaptation and Mitigation, respectively) envisaged in the European Commission's guidelines (C(2021) 5430 final of 29.7.2021)

9 Gambino. R., Progetti per l'ambiente, Franco Angeli, Milano, 1996
10 C40Cities, Costruire la resilienza climatica, https://www.c40.org/it/awards/building-climate-resilience/
11 ISPRA (2021) Rapporto sulle condizioni di pericolosità da alluvione in Italia e indicatori di rischio associati, in https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-sulle-condizioni-di-pericolosita-da-alluvione-in-italia-e-indicatori-di-rischio-associati

indicates appropriate adaptation measures to climate change, with the evidence that the 'climate risk and vulnerability assessment' remains the pivot around which the identification and evaluation of the most appropriate measures to make territories resilient revolves (Sánchez-Bayón et alii, 2020).

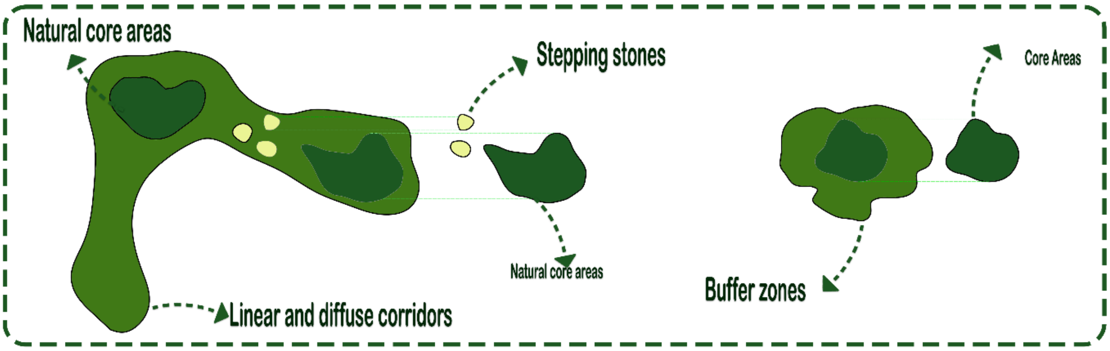

Fig.2 Explainning diagram of the ecological network

This entails both the need to manage, through sophisticated and intelligent systems, information on ecosystems and biodiversity, the dynamics of their evolution, and the use of artificial intelligence providing planners with information on the status of implementation of interventions, the identification of areas threatened or depleted as a result of incompatible anthropogenic activities.

By means of a Masterplan model linked to a QGis database, proposed within the framework of this research, it will be possible to map the different components of the ecological network, visualise and understand the planning strategies, helping decision-makers in the assessment of the sustainability of redevelopment projects, the promotion and monitoring of the actions envisaged in the Masterplan. This is aided by intelligent systems that will enable the transition from its development to future management and implementation. The implementation of the Digital Twin, i.e the development of a digital twin of the master plan, will also be useful for improving urban management and land-use planning and can enable the use of big data to optimise the delivery of new facilities and services while predicting future problems and assessing the impact of projects and their alternatives. This digital contribution -by equipping the city with sensors- allows real simulations with possible environmental, social and economic scenarios and conditions. In the European scientific sphere, some realities are moving within the Net Zero Cities programme with the help of Digital Twin technology: Amsterdam is an excellent example of a DI prototype for traffic monitoring and planning of green areas, using IoT and Big Data. Athens, still in the development phase, has implemented a model aimed at monitoring human actions in relation to the life cycle of the environment. In Florence, a model operating with the aid of software such as GIS is already operational, allowing the three-dimensional visualisation of a city environment; an interactive space where maps of heat, infrastructure, traffic flow analysis and urban development can be found.

For the case study analysed, Modica green city, propaedeutic to the construction of the master plan model was the definition of the ecosystem approach as a transversal and integrated management modality.

1.2 Materials and methods, ecosystem approach

Ecosystem management[12] is 'a strategy that promotes the conservation and sustainable and equitable use of land, water and living resources through integrated ecosystem management' in order to ensure that the ecosystem is maintained in a healthy and resilient condition and that it is productive by continuously providing humans with the goods and services they need. Compared to recurring approaches aimed at protecting a single species (humans) or specific activities and sectors, the ecosystem approach (Baldini, 2023) considers the interactions and cumulative effects of different sectors in an integrated manner.

[12] Ministero dell'ambiente e della sicurezza energetica, https://www.mase.gov.it/pagina/approccio-ecosistemico

The concept of the ecosystem approach was adopted by the Convention on Biological Diversity (CBD) in 1995 and developed by the Subsidiary Body on Scientific, Technical and Technological Advice of the Convention-SBSTTA-which identified 12 specific principles to contribute to its achievement, Malawi Principles. Through the Framework Directive 2008/56/CE, this objective became binding on Member States and was made operational through the Good Environmental Status (GES) definitions. This approach found specific application for the management of human activities affecting the marine and coastal environment, identifying a specific process for its application, the Ecosystem Approach Process (EcAp), aimed at achieving Good Environmental Status at sea.[13] Resolutive for integrated management and to guarantee an ecosystem approach to territories, are the Community cohesion policies that dictate some fundamental principles to combine biodiversity and environmental protection with strategies for ecological transition and the fight against climate change (Ceralli, 2023).

The cohesion policy for the programming period 2021-2027 envisages the pursuit of five policy objectives (OPs):

- OP1, for a smarter Europe through innovation, digitisation and economic transformation;
- OP2, for a green and carbon-free Europe;
- OP3 for a more connected Europe with strategic transport networks;
- OP4, aiming for a more social Europe, delivering on the European pillar of social rights and supporting quality employment, education, skills, social inclusion and equal access to healthcare;
- OP5, for a Europe closer to citizens through support for locally managed development strategies and sustainable urban development across the EU.

According to OP5, territorial strategies must be implemented in synergy with other policy objectives, with the primary aim of promoting the economic and social development of the areas most affected by poverty.[14]

Strategic Policy Objective 5 'A Europe closer to the citizen' (OP5) is where the programmes' support for urban and non-urban[15] Spatial Strategies (ST) is organised. Each ST articulates a project for change shared by the local community, following a deliberative process.

The ST are supported by a broad set of resources capable of activating interventions on multiple dimensions and implemented with the active involvement of local actors. Programme resources are made available for local coalitions to choose from.

Through a careful use of the formal spaces of participatory construction, the FESR and FSE Plus Programmes organise the support to the ST through the resources of OP5 and the other OP. The Programmes narrate the overall design of the ST.[16] A Territorial Strategy is the most effective tool to actively involve communities, in fact, the local stakeholders of the ecosystem thus defined, will express themselves to concentrate resources and energies on the three dimensions of sustainability, promoting the valorisation of natural, cultural and landscape resources, the revitalisation of the economic fabric, the regeneration of places and social inclusion. The address related to the participatory construction of hypothetical future scenarios was associated with the master plan, which has the task of translating the identified instances into operational and programmatic terms.

[13] The Maritime Spatial Planning Directive (2014/89/EU) also bases the pursuit of its objectives on the application of this principle. In 2007, the signatories to the Barcelona Convention adopted the ecosystem approach for the management of human activities affecting the marine and coastal environment, identifying a specific process for its application, aimed at achieving Good Marine Ecological Status.

[14] Investments, at territorial level, can be activated with reference to the following functional areas: - inland areas facing demographic challenges and poverty called upon to improve the quality of services of general interest; - metropolitan functional areas for poverty-related challenges also caused by the 'agglomeration' effect; - medium-sized urban areas to develop innovative ways of cooperation to improve their economic, social and environmental potential, taking into account the most vulnerable groups.

[15] art. 29 del Regolamento (UE) n. 1060/2021

[16] Also taking into account other resources: national resources, FEASR (rural development) and FEAMPA (fisheries)

The Laboratory dedicated to the Policy Objective -the LabOP5- involved numerous central administrations and various Italian regional realities in addressing issues related to:

- the representation of the Territorial Strategies in the formal spaces of the Programme Template in order to accompany Administrations in formulating and explicating the programme promise of multidimensional support to the Territorial Strategies;
- the definition of the system of indicators at Programme level: analysis of the fiches of the common output indicators and preliminary activities to identify possible 'meta' result indicators, measurable, significant and implementable.

Resolutive for the integrated management and to guarantee an ecosystem approach to the territories, are the community cohesion policies that dictate some fundamental principles in order to combine the protection of biodiversity and the environment with the strategies for the ecological transition and the fight against climate change, which can take place by reorganising the rules of operation of the existing city and by providing new architectural design criteria.

The research focuses on the role of the ecological network in combating climate change; the chosen case study deals specifically with the RER, Regional Ecological Network, of the municipality of Modica and the strategies to activate sustainable development drivers. The hypothesis is to implement a 'Modica Green' Masterplan model and a memorandum of understanding to incentivise the administration to adopt the measures it envisages.

2. Literature review

In the literature review, particular attention was given to ecological network projects already in place. Of these, a series of policies, methods and significant elements were analysed in order to understand the innovations in approaches and instruments. The selection criteria chosen -such as the territorial dimension, participation and social inclusion activities- returned an interesting picture of best practices (Fig.3).

The Milan Ecological Network project was particularly interesting because the Milanese territory has undergone numerous anthropisation activities and therefore in this context, the creation of a territorial planning programme that can in some way rebalance the environmental context is of particular importance for the territory. The planning strategies therefore concern the planning and implementation of an interconnected system of natural areas that can guarantee adequate levels of protection and increase in biodiversity (Baldini, 2023). In the specific case study, the components used for the realisation of the Milan ecological network are mainly natural elements called Ganglia and territorial strips characterised by good vegetation equipment. Thanks to the project's ecological corridors, genetic exchange can be guaranteed and enhanced.

An Ecological Network Project has therefore been constructed, extended to the entire provincial territory, which has become part of the PTCP (Provincial Territorial Coordination Plan) and its Implementation Regulations.

The aims of this project are in line with those of Directive 92/43/CEE 'Habitat[17] which aims to 'safeguard biodiversity through the conservation of natural habitats and of wild flora and fauna in the European territory' and to build 'a coherent European ecological network of special areas of conservation, called Natura 2000.[18]

An interesting management method for protected areas, functional to ecological connectivity, is certainly the one adopted by Trentino with the Networks of Reserves. This project is based on the participation and integration of nature conservation policies and the social and cultural development of communities.

[17] Received in Italy by DPR 357/97

[18] Città Metropolitana di Milano, in https://www.cittametropolitana.mi.it/pianificazione_territoriale/ambiente/ambiente/rete_ecologica/

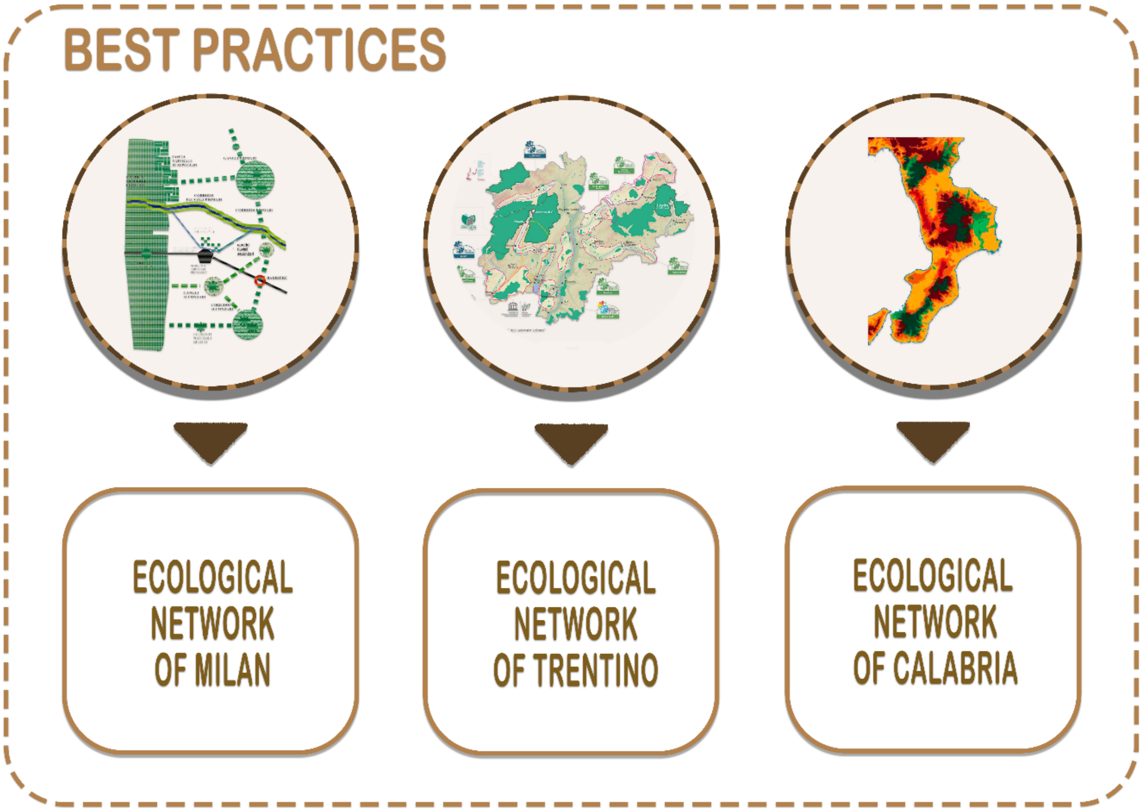

Fig.3 Best practice of Ecological Network in Italy

With the integrated 'LifeTEN' project, the drafting of the provincial ecological network was based on the Reserve Networks. The territory was subdivided into 14 homogeneous territorial areas for each of which a programme was drawn up containing protection actions and strategies for ecological connectivity; of these areas, 10 represent reserve networks that function perfectly as instruments for the innovative management of protected areas. The networks are based on the management delegation given to local authorities by the provincial administration; the direct participation of administrators, technicians, entrepreneurs is also very important in this respect. This will ensure perfect harmony between nature policies and socio-economic development instruments. The governance model used for the management of the existing protected areas has led to a series of initiatives aimed at the conservation and enjoyment of the protected areas; among the very first initiatives are the restoration of wetlands, the mowing of meagre meadows for habitats of community interest and the formation of water holes to ensure the reproduction of the yellow-bellied toad. There has also been a great deal of planning interest and territorial enhancement with the creation of equipped footpaths, the setting up of visitor centers and the establishment of information panels.

The regional ecological network of Calabria is proposed as a natural and environmental infrastructure useful to connect the different territorial areas characterised by different levels of environmental sensibility. The Region of Calabria has drawn up a project for a regional ecological network, bringing together parks, regional reserves and SIC. The RER is made up of central areas, buffer zones, continuous and discontinuous ecological corridors, areas of environmental restoration and natural development, and nodes; in all of these components, a design strategy is implemented for both development and conservation, improving the quality of the natural and cultural heritage with targeted promotional measures. Specifically, the programming completion of the Calabria POR indicates the two ways in which the RER is to be implemented:

- Protection and enhancement of natural and environmental resources, targeting local administrations and their consortia;
- Enhancement and development of non-agricultural economic activities, targeting private enterprises, associations and tourism operators.

For the efficient implementation of the Ecological Network, the Department of the Environment has promoted an operational tool: the Strategic Integrated Project approved by resolution No. 759/2003. This aims to enhance the regional territorial areas with a strong landscape value, while also guaranteeing social and economic development. Some projects were implemented immediately thanks to the stipulation of conventions with the region itself and above all thanks to the strategic action.

3. Results

At least two conditions are necessary for the existing city to dialogue with the environmental context from which it draws resources and to which it pours the pollution and waste generated by its functioning: that the overall consumption of resources is based on renewable resources; that the management of urban metabolism transforms waste into energy useful for the functioning of the built environment; and that the recycling of waste takes place in a circular process to guarantee the performance of ecosystem services (Aziz, 2021).

A pilot case capable of bringing together, according to an innovative approach, the issues of ecological network, ecosystem services, circular metabolism and cultural heritage is that of Modica Green city.[19]

Modica, located within the Ibleo territory, occupies the south-eastern part of Sicily, almost creating an island within an island. The city, belonging to the province of Ragusa, boasts a millennial history that is intertwined with the evolution of its territory. The shape that Modica takes on, typical of urbis, undoubtedly derives from the numerous influences that it has known and suffered, but above all from its geo-morphological characteristics and its characteristic orographic trend characterised by considerable elevation changes. The various influences that Modica has undergone have contributed to determining the current configuration not only of the urban fabric, but also of the rural areas linked to the typical production system and the surrounding nature. Today, Modica presents a cultural and environmental heritage of extraordinary value. (Fig.4), it explains the Modican territory, describing its environmental peculiarities on the basis of the Habitat Directive 43/92 and the Sicilian Ecological Network.mThe morphological aspect of the city of Modica is truly unique in that it develops along the eastern edge of the Ibleo territory and allows the municipal territory to be classified into macro-areas; Modica Alta, Modica Bassa and Modica Centro. Their peculiarity is their conspicuous discontinuity due to the numerous faults that make up the so-called 'Canyons', which, originating from river courses and heading towards the sea, naturally act as ecological corridors, guaranteeing the flow.

So, it is precisely the system of quarries, river valleys with V-shaped profiles and a not particularly excessive slope, that are the environmental aspect to be emphasised in enhancement strategies. Of the 'system' of valleys, the most important are Cava del Tellesimo and Cava D'Ispica; some of these host water on a perennial basis and others temporarily. Specifically, the singular Cava Ispica, six kilometres from Modica, has topographical characteristics determined by its strategic position, allowing it to act as a veritable fortress (Trombino, 2016). The Modican coast is characterised by an alternation of rocks and beaches interrupted by Falesie di Cammarana and Cava D'Aliga. These areas are also characterised by marshy areas that host a particular flora and are home to migratory avifauna that find suitable conditions for their break during their migratory routes. The Modica landscape thus gives rise to a system of ecosystems resulting from dissimilar biotic and abiotic components. The Modica territory is also characterised by numerous sites of landscape, archaeological and historical-architectural interest, which give it an extraordinary cultural value. Among the architectural assets of high cultural-historical value are the Cathedral of San Giorgio, included in the UNESCO World Heritage List, the Castle of the Counts, a visible trace of the history of the Modica County (Trombino, 2016), the Church of San Pietro together with the other 100 churches that surround Modica and enrich it with

[19] Study developed as part of Chiara Spadaro's degree thesis entitled 'Modica Greencity. Ecological Network, Ecosystem Services and Cultural Heritage' at the University of Enna Kore, supervisor prof. Celestina Fazia, discussed on 18.07.2024. Activities under the MOD_Ret Ec agreement, between the municipality of Modica and the department of engineering and architecture of Enna, kore university. Municipal Council Resolution No. 284/24

its unique Baroque character. The 7 Natura 2000 sites in the Modican territory (Cava Palombieri, Fiume Tellesimo, Torrente Prainito, Conca del Salto, Cava Ispica, Contrada Religione and Spiaggia Maganuco) create a crown within the municipal territory that can be easily connected to Modica's other historical and architectural specificities.

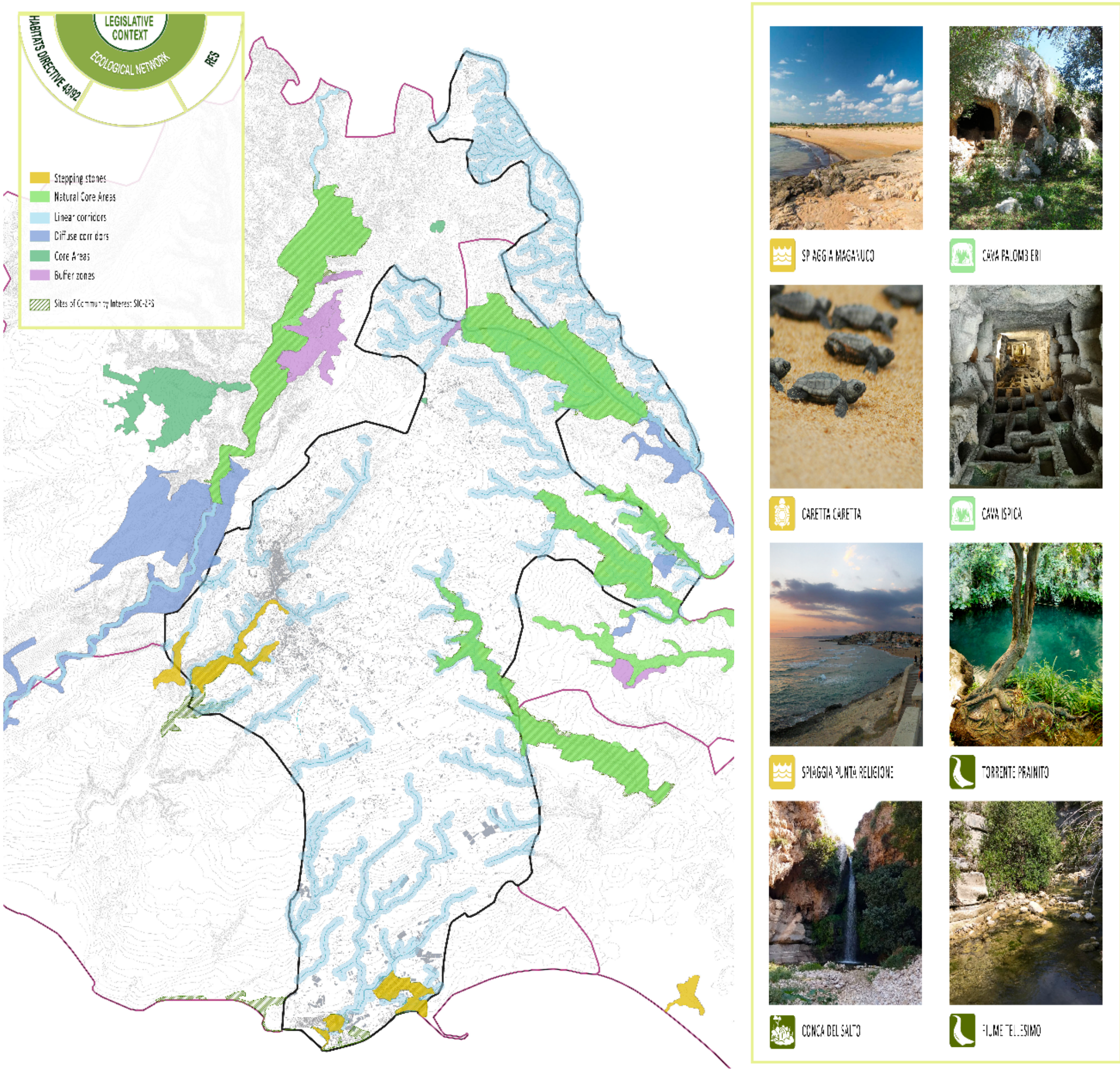

Fig.4 Cartography of Modica's spatial framework

3.1 "Modica Greencity" masterplan

The 'Modica Greencity'[20] project is aimed at the development of an ecological network intended as a sustainable environmental infrastructure capable of ensuring the resilience of the municipal territory: an interface and fruition element for the correct conservation and valorisation in qualitative-quantitative terms of biodiversity, by systemising ecosystem services and cultural heritage. The three areas of interrelation, although different, all contribute, in a coherent manner, to making the tourist-cultural experience more efficient by implementing ecosystem services in all its forms. The Network intercepts protected natural areas, SIC and ZPS zones, and ecosystem services, thus guaranteeing an interconnected system of green areas within the territory. Fig.5a,

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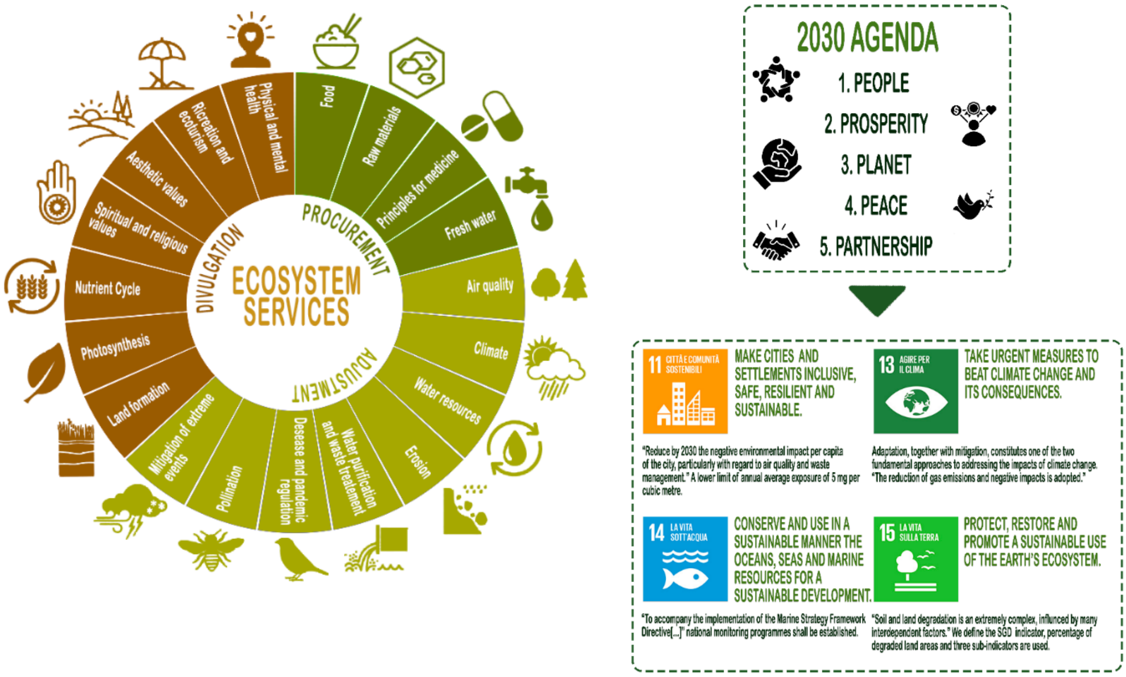
20 Study developed as part of Chiara Spadaro's degree thesis entitled 'Modica Greencity. Ecological Network, Ecosystem Services and Cultural Heritage' at the University of Enna Kore, supervisor prof. Celestina Fazia, discussed on 18.07.2024 Activities under the MOD_Ret Ec agreement, between the municipality of Modica and the department of engineering and architecture of Enna, kore university. Municipal Council Resolution No. 284/24

summarises the characteristics of ecosystem services. The proposal also proposes an innovative strategy to be implemented in order for the project to be concretely feasible and effectively implemented, consistent with Article 47 of Sicily's Lur 19/20. With the theoretical in-depth study of the ecological network and environmental components, we were able to functionally schematise the ecosystem services (Pennino, 2024) that can be included and enhanced within the project.[21]



(a) (b)

Fig.5 (a) Ecosystem Services and (b) Agenda 2030 diagram and goal selection relevant to the Modica Greencity project

It is only thanks to the careful study of the Ecological Network and its components, the ecosystem services and the regulatory-urban framework, taking into account the European and national directives, the Sicilian Regional Law 19/2020 and the recommendations of Agenda 2030, that it has been possible to think of a project that can be decidedly coherent with the notional and regulatory framework. The reference is to the punctual analysis of all the urban planning instruments, both municipal and super-ordinate, that have dictated the general guidelines and normative recommendations at different scales, including the relevant goals suggested by Agenda 2030. Therefore, consistent with the recommendations of Agenda 2030, the 4 goals relevant to the project under analysis are indicated. (Fig.5b) In order to return a precise survey of Modica's territory, an accurate photograph was taken by means of visual census, numerous surveys with remote piloting systems and monitoring of the state of health of the environmental components, as well as the identification of historical-cultural elements that are of interest for their greater valorisation and the identification of areas to complete the ecological network (ecological corridors). The analysis of all the data collected was carried out with the aid of a geographic information system such as QGIS, which made it possible to geo-reference all the completion areas of the RES, Sicilian Ecological Network (Minardo, 1998). This, identified as a starting point, was then implemented with the identification of existing ecological corridors -which due to their compromised state do not know their real function today- and new project corridors. These, identified punctually and with respect to their actual dimensions, make it possible, due to their strategic position, to intensify the connection between two nodes, areas of high naturalness, and to favour genetic exchange in better qualitative-quantitative terms. With the aid of Gis, it was also possible to draw up a very detailed synoptic picture, i.e. a

[21] These can be divided into three macro categories such as provisioning, regulation and dissemination, and are 'the multiple benefits provided by ecosystems to humankind'. Definition given by the 'Millennium Ecosystem Assessment.'

Data Bank, BD, for every single natural area that is defined as a Site of Community Interest in accordance with the regulations; the BD contains precise information on sizing, the presence of characteristic habitats, and correlated urban planning instruments in force (Fig.6).

SIC ITA080009 Conca del Salto

Area concerned	290.54 ha
Habitat	5330, 5420, 7220, 8210, 8310, 92C0, 9320, 9340
Related instruments in force	Piano paesaggistico di Ragusa PRG PAI Legge Regionale 19/96
Normative sources	Piano di Gestione dei Monti Iblei (SIC istituito dopo il piano di gestione
Objectives	Enhancing the tourist-cultural experience by implementing ecosystem services
Purpose	Creating a mature and resilient system
Actions	Gradual replacement of non-native by native species
Accompanying measures	PNRR PO.FERS FONDI STRUTTURALI

Tab.1 Synoptic Frameworks

Fig.6 Conca del Salto

Only a few examples of synoptic frameworks and their cartographic representation are given here, with a suggestion and reference to the master plan and the respective planned project action. However, all the synoptic pictures relating to the sites of community importance in the Modica's territory have been drawn up, thus serving to expand the GIS database, the software used for all the cartographic elaborations both for the state of affairs and for the project, where each ecological corridor is appropriately georeferenced.

4. Discussion

The project idea proposes to create the Network as a driver of sustainable, economic and cultural development and an opportunity to enhance the territory. In the project Masterplan[22] (Fig.8) drafted in line with the OP of Policy5, the ecological network, reorganised and connected to the historic city using three systems of spatial and functional organisation: Ecological Network, Ecosystem Services and Cultural Heritage (Livia, 2017), assumes centrality. It is a document that, on the basis of strategies fuelled by participation, envisages programmes and projects related to measurable objectives to be achieved, anticipates and outlines project ideas to be shared, implemented and then carried out. The Modica Green City Masterplan identifies the elements of considerable value, indicating for each one the actions and accompanying measures foreseen for the economic feasibility of the projects, envisaging, among the main measures, the completion of the existing green infrastructure and the replacement of allochthonous species with native ones. The project's green infrastructure is to be understood as a typical transect,[23] (Fig.7) a corridor connecting two areas of high naturalness and along which ecological studies are carried out to understand the distribution of plant and animal species along an environmental gradient (Gambino, 1996). On the other hand, with regard to the linear project corridors identified, the project action consists in the ex-novo creation of a typical green infrastructure, which allows the connection of high nature areas, characterised by native species.

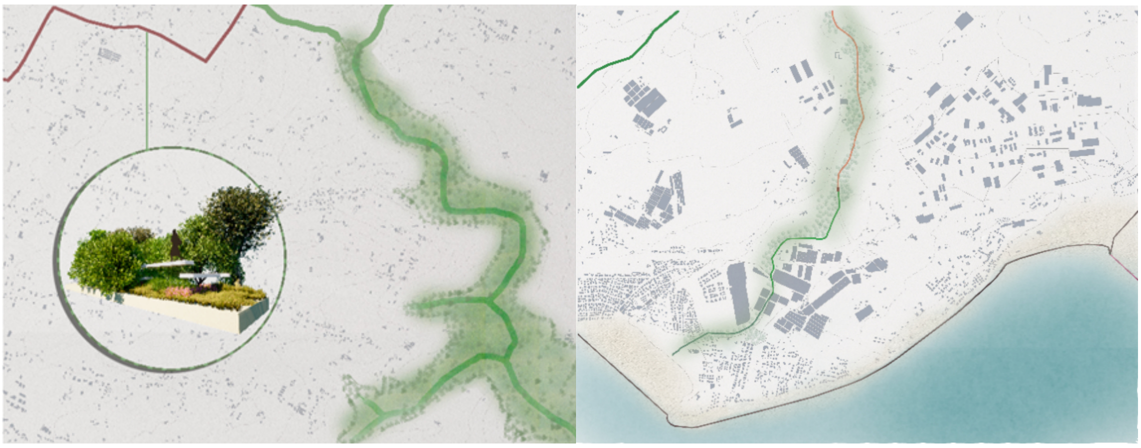


Fig.7 Project drawings for Modica, implementation of the existing ecological corridor and design of a model transect

The second aspect concerns the coastal habitat, where the project action is closely linked to increasing resilience given the numerous existing and detected fragmentations. The project action envisages naturalistic engineering activities, with the construction of embankment footbridges to preserve the naturalness of the coastal environment, windbreaks or geotextile barriers for dune stabilisation and palisades for the creation of artificial terraces that can allow the usability of coastal areas and at the same time the conservation of biodiversity and gene flow. The action planned for the Cava Ispica SIC is different; the objective is the conservation and protection of the climax, guaranteeing controlled use of the site by dictating a series of regulations and prohibitions of activities that could therefore compromise the very peculiarity of the climax. The third and final category of the Masterplan concerns cultural heritage and specifically the peri-urban park. (Fig.9) This surrounds much of Modica's layout (Raniolo, 1993), especially the historic centre of Modica Bassa and Modica Alta. This appears as a basin surrounded and framed by peri-urban forest, with considerable elevation changes and several canyons winding through the Modica territory.

22 Study developed as part of Chiara Spadaro's degree thesis entitled 'Modica Greencity. Ecological Network, Ecosystem Services and Cultural Heritage' at the University of Enna Kore, supervisor prof. Celestina Fazia, discussed on 18.07.2024 Activities under the MOD_Ret Ec agreement, between the municipality of Modica and the department of engineering and architecture of Enna, kore university. Municipal Council Resolution No. 284/24

23 This transect is obviously surrounded by plant species that must have certain environmental-naturalistic characteristics: Quercus Ilex; Pistacia Lentiscus; Olea Europaea var, sylvestris; Phillyrea Latifolia; Cistus Incanus; Rosmarinus Officinalis; Lavandula Stoechas

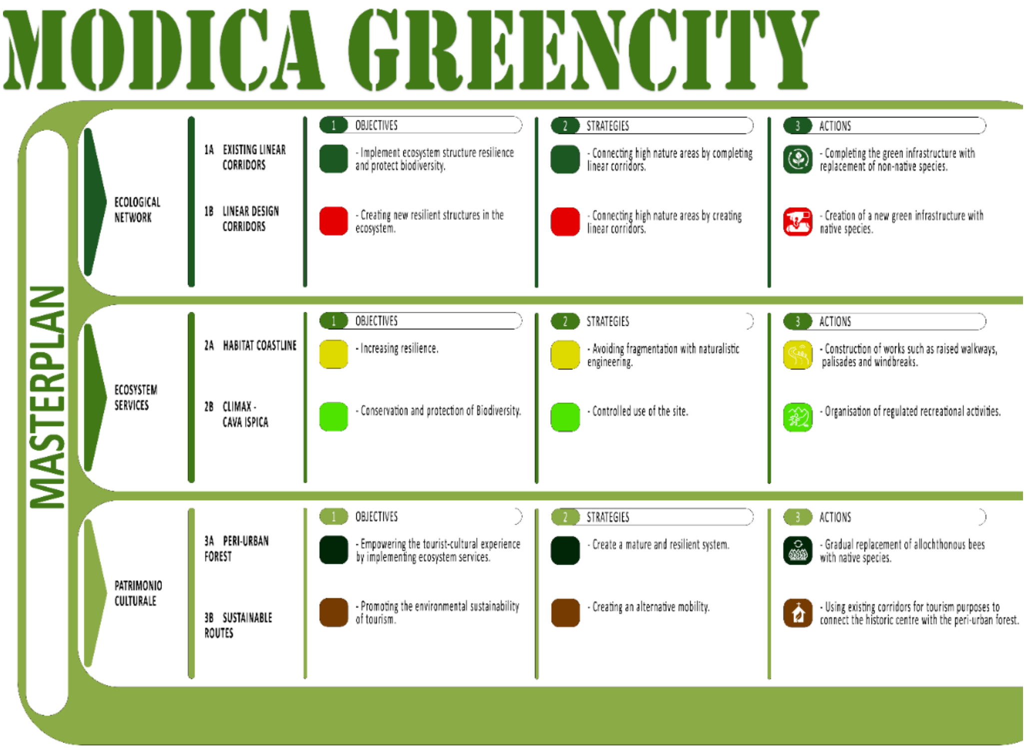


Fig.8 Modica Greencity Masterplan

4.1 IoT e Digital Twin

Urban planning is undergoing a radical transformation, making it possible, thanks to the aid of artificial intelligence, to monitor choices, spatial and environmental effects by mapping individual interventions, quantifying the areas affected, the volumes introduced and the consequent loss of natural soil and, conversely, the increase in green areas where planned. This will make it possible to calculate any loss of biodiversity and to estimate changes in ecosystem services. A further future development will be to simultaneously report, for example, the carbon stock, the contributions of (implemented) green infrastructure in terms of hydrogeological risk defence by quantifying the areas secured. In cases of particular vulnerability of territories, artificial intelligence and the digital twin are particularly useful. It is easily applied in the case of strategic/master plans. Indeed, 3D modelling can accompany the planning of planned actions and their implementation by verifying joint impacts and effects. Urban planning, by being in the vanguard of an increasingly diverse, innovative and technologically advanced range of issues, could obviate the excessively long timeframes usually envisaged for these tools of territorial government. There are numerous Net Zero Cities programmes in Europe that include Digital Twin technology. Among the most noteworthy, Florence is already operational, which with the help of software such as GIS and City4app, enables the three-dimensional visualisation of a city environment; an interactive space where heat maps, soft mobility infrastructures, traffic flow analysis and urban development can be found.

Therefore, the way of thinking and designing cities is also changing, and they are now being managed with a greater sensitivity to the unique features that are suitable for solving modern urban challenges. By now, the integration of Artificial Intelligence is becoming more and more of a necessity for urban planning, and tools such as CityEngine and UrbanistAI are becoming more and more widespread, capable of minimising environmental impact, considering socio-economic aspects, optimal use of resources, and conservation of biodiversity. Only with these technologies can we succeed in the great mission of designing cities that are truly functional and at the service of the citizen.

The implementation of the project involves, for obvious reasons, portions of municipal, state and private property. On the basis of this emerges the need to regulate the management responsibilities of privately owned areas, provide incentives and tax breaks for the non-use of the areas, useful for the creation of ecological corridors. This instrument would compensate the land owners involved in the creation of the network, ensuring a fair distribution of benefits and providing incentives for participation in its implementation.

The master plan linked to the implementable data base and the geo-referenced graphic representation, carefully drawn up on QGIS, taking on a virtual form through the use of the digital twin will be able to simulate scenarios, making it possible to explore hypotheses that would otherwise be impossible to verify for reasons of practicality and cost. However, the digital twin proposed for Modica Green City will be more than a virtual representation, providing an up-to-date and accurate representation of its state; it will be able to connect with the real system, receive data from it, conduct scenario analyses, and simulate operating processes. This is to improve urban planning, the optimal management of resources, natural capital, biodiversity and ecosystem services, and the resilience of urban systems. The model is based on the integration of data from different sources, including statistical data, sensor networks, monitoring stations and geospatial satellite data.

These data range from surface temperature to air quality and traffic flows and socio-economic information from local communities, a populable and aggregatable data framework that can aid the monitoring of SEAs, Strategic Environmental Assessments.

In recent years, thanks to advances in the field of data analysis, known as 'data analytics', and technologies related to monitoring the urban environment, satellite technologies for geospatial monitoring have been developed and low-cost sensors are frequently used to enable the development of 'Internet of Think' IoT sensor networks. These developments allow detailed information to be obtained at relatively low cost. In addition, advances in IoT allow useful information to be extracted from large amounts of data.

Among the technological tools, some already operational and others being tested, some are particularly interesting and inherent to the Digital Twin proposed for Modica. CityEngine (ArcGIS) makes it possible to visualise 2D and 3D territory; these 3D models can be useful analysis tools as well as simulation tools. The tool allows real simulations to be carried out that can simultaneously return the results of a given hypothesised strategy. Singapore has experimented with this tool and succeeded in greatly simplifying master planning processes.

UrbanistAI touches more issues close to community participation and involvement. Thus, residents are able, by consulting the platform, to visualise the urban policies implemented, evaluate the results obtained and even propose planning hypotheses. In Finland, residents themselves, with the help of the tool, have expressed their needs and shortcomings and have been able to design new parks and green spaces adapted to user demand.

Still other tools such as Cityplain and Architechtures address issues such as cloud-based analysis and socio-economic indicators of housing layouts, transforming design processes into social participation and sharing initiatives, thus reducing the timeframes for these administrative-bureaucratic activities.

Thus, alongside the 'Modica Green city' Masterplan generated on a GIS database, the Digital Twin is planned. With the use of software such as City4app or Opencities, it is possible to have a 360-degree restitution of the territory useful for mapping elements of naturalistic value such as protected natural areas, existing ecological paths and pedestrian routes; it is possible to monitor the building system, traffic flows and full-empty relationships, thanks to the integration of BIM and GIS data.

In terms of the tools needed to optimise the results and guarantee the involvement of authorities and administrations (the master plan being a voluntary document), the signing of a protocol is envisaged that would entail, in the event of adhesion by the subscribers, a series of savings (databases that can be used for the WYP) incentive benefits linked to the implementation of measures for the conservation of the ecological network (streamlining of the Vas procedure, for example) and the use of branding linked to Modica Green City.

Fig.9 Project drawings for Modica, implementation of the existing ecological corridor for periurban forest

5. Conclusions

What is proposed therefore, together with the Project Master Plan, is an innovative and immediately technically and economically feasible way of the project. It envisages the elaboration of a model protocol between municipal and private entities, in order to suggest guidelines for the regulation and use of the areas included in the Ecological Network project. The concept of the Digital Twin, or digital twin, certainly represents a digital replica of a physical entity, which can be used to simulate, analyse and optimise urban processes in real time. By integrating the Digital Twin with big data, the city can improve resource management, foresee problems and optimise services for citizens, but it also represents a resource for the territory and its residents, a dynamic snapshot of ongoing transformations and uses. The protocol would not represent a commitment that penalises municipalities or stakeholders. On the contrary, there are incentive benefits linked to the implementation of measures for the conservation of the ecological network and for the sustainable and integrated management of the intercepted areas (Trusel et alii, 2018). Getting to the heart of each measure, the protocol becomes a sort of ex-ante commitment for the assessment of plans in the territories affected by the ecological network, thus providing that when submitting environmental assessments, such as VAS and VINCA, the Proponents can sign the protocol attesting that they have complied with the principles underlying the plan, reinforcing, implementing and monitoring actions for the conservation of species and environmental protection of habitats, partly anticipating the aforementioned environmental audits. On the other hand, as far as the environmental indicator is concerned, these can be extrapolated from the Master Plan actions implemented for the conservation of the species, in this way data already collected but implementable for the purposes of species monitoring (database and GIS) would be used. Lastly, promotion and branding (Trusel et alii, 2018). After the adoption of the Memorandum of Understanding model, the municipalities involved will be able to convey the Modica Ecological Network brand as a territorial marketing tool and use it for economic-tourist purposes.

Recalling the main objective of OP 5, territorial strategies must be implemented in synergy with other strategic and environmental objectives, with the aim of promoting the economic and social development of slow development areas. Policy5 of the European Cohesion Policy stipulates that in order to promote new urban ecosystems, approaches must be operationally translated within strategic documents, in the form of Master Plans and/or guidelines on land use, fundamental resources for ecosystem balance and biodiversity recovery, to counteract phenomena of hydrogeological instability and widespread degradation, to make services, infrastructures, transport systems and urban endowments perform. In this framework, the role of urban redesign and new forms/materials, technologies for sustainable architecture becomes essential. It becomes fundamental to reconnect, following the principle of ecological connectivity, everything to the General Urban Plan, to the thresholds of transformability of the territory and the environment as better specified and foreseen by Sicily's LUR no. 19/2020. All this also in order to strengthen the territory's capacity to provide 'preventive' environmental security the Convention on Biological Diversity, mentioned earlier, defines biodiversity as including diversity at the genetic, species and ecosystem levels. The former indicates the number and abundance of habitats, living communities and ecosystems.

It will be possible to use IoT sensors to monitor and manage natural environmental resources in real time, and then to have the possibility, with the use of GIS software and 3D modelling of the city's territory, to create simulations of urban scenarios given by the city's development, planning and enhancement activities. Therefore, once this testing model has been implemented and a series of test scenarios have been carried out, it is also possible to collect interesting public comments on the actual functionality of the Masterplan once the relevant digital twin has been fielded. This digital model also acts as an immediate interface with reality, guaranteeing the monitoring and implementation of new data, always ensuring its functionality and value as an important information tool that can be consulted by all users, whether residents or tourists.

Attributions

§Abstract, by Celestina Fazia and Chiara Spadaro; §1. Introduction, by Celestina Fazia; §1.1 Materials e methods, ecosystem approach, by Celestina Fazia; §2 Literature review, by Celestina Fazia §3. Results, by Chiara Spadaro; §3.1 "Modica Greencity" Masterplan, by Chiara Spadaro; §4. Discussion, by Chiara Spadaro; §4.1 IoT e Digital twin by Celestina Fazia; §5. Conclusions, by Celestina Fazia and Chiara Spadaro

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Image Sources

Fig.1 Mapping of the Natura 2000 Network of Modica and its province (Ragusa). Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation;

Fig.2 Explainning diagram of the ecological network. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation;

Fig.3 Best practice of Ecological Network in Italy. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation.;

Fig.4 Cartography of Modica's spatial framework. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation;

Fig.5 (a) Ecosystem Services. (b) Agenda 2030 diagram and goal selection relevant to the Modica Greencity project. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity dissertation";

Fig.6 Conca del Salto. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity dissertation";

Fig.7 Project drawings for Modica, implementation of the existing ecological corridor and design of a model transect. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation;

Fig.8 Modica Greencity Masterplan. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation;

Fig.9 Project drawings for Modica, implementation of the existing ecological corridor for periurban forest. Source: Graphic design by Chiara Spadaro; part of the "Modica Greencity" degree dissertation.

Author's profile

Fazia Celestina

Architect, Ph.D. in Territorial Planning, Associate Professor ASN 08F1 CEAR 12b, Urban planning, at Kore University of Enna. Research fellow at the Mediterranea University of Reggio Calabria. Master Level II in Engineering, possesses decades of experience in the field of urban, territorial and environmental pianification both in research and professional fields. Consultant to public bodies and companies. Member of national and international research groups, also with coordination roles. Author of more than one hundred and thirty scientific publications, including monographs and essays in volumes and specialized journals.

Chiara Spadaro

Doctor in Architecture, she graduated with honours in Architecture and Building Engineering at the University of Enna "Kore" in 2024. She presented an experimental thesis entitled "Modica Greencity" focusing on current issues relating to the ecological network, ecosystem services and the role of a network of territorial opportunities to revitalise the territory. During the same year, she won a scholarship for a PhD in 'Intelligent Systems for Engineering' at Kore University. The research topics in which she is interested are innovations in integrated public freight and passenger transport systems.

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Examining the temporal and spatial change of current land cover types in Demre District using machine learning

GeoAI - Object-based controlled classification

Sibel Akten [a]*, Hüseyin Batuhan Dündar [b], Atila Gül [c]

[a] Atabey Vocational School, Isparta University of Applied Sciences, Isparta, Türkiye
e-mail: sibelakten@isparta.edu.tr
ORCID: https://orcid.org/0000-0001-6242-9687
* Corresponding author

[b] Institute of Science Department of Landscape Architecture, Süleyman Demirel University
Isparta, Türkiye
e-mail: hbatuhandundar@gmail.com
ORCID: https://orcid.org/0009-0003-7341-970X

[c] Faculty of Architecture, Department of Landscape Architecture, Süleyman Demirel University,
Isparta, Türkiye
e-mail: atilagul@sdu.edu.tr
ORCID: https://orcid.org/0000-0001-9517-5388

Abstract

The study, conducted to analyze the temporal and spatial changes in current land use types in Demre district of Antalya Province and to establish a foundation for future land management studies, was supported by multispectral satellite images obtained from the Landsat 5- Thematic Mapper (TM) and Landsat 8-Operational Land Imager (OLI) remote sensing satellites. Land use maps showing the spatial distribution of land cover changes were prepared using composite images compiled for the years 2004, 2014, and 2024. The Support Vector Machines (SVM) algorithm was used as the classifier model. High classification performance was achieved for all three images (kappa = 0.90, 0.89, 0.87, overall accuracy = 90.7%, 90.3%, 87.9%). Following the classification process, land use change maps were created for each decade, and statistical analyses related to land cover change were conducted. Over the past 20 years, according to the land use types in Demre district, quarry and mining areas (↑227.49%) and settlement and greenhouse areas (↑72.88%) have increased significantly, while scrubland (↓41.21%), agricultural land (↓9.45%), and forest areas (↓8.89%) have decreased significantly. In addition, sparse maquis areas, dune areas, and water surfaces areas have declined, indicating a situation that is detrimental to the region's natural areas. In conclusion, the study provides an overview of how land use types have changed in the region and reveals the current state of land use preferences in the district.

Keywords

Demre district (Antalya); Land cover; Land use; Machine learning; Remote sensing; Temporal and spatial change

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1. Introduction

With the increase in urban population worldwide, the demand and intensity of land use in urban areas and their surroundings have been steadily rising. Consequently, rapid changes have occurred in various land cover types, particularly in productive agricultural lands, forests, pastures, and settlement areas. Rapid population growth and the resulting uncontrolled urban expansion have intensified pressures on agricultural lands and urban ecosystems in many countries (Lambin et al., 2003; Manley et al., 2022). The goal of sustainable development is an essential priority for all nations, and it is imperative that cities are planned and managed in an environmentally, economically, and socially balanced, livable, and future-oriented manner (Murray, 2001).

Urban development is a process in which communities and cities control the emergence of a city (Bhatta, 2010). Most urban development problems in cities are indicative of land use planning and policies (Dutta, 2012). Sustainable urban development aims to strike a balance between the efficient use of resources, the protection of the natural environment, and the well-being of society. In order to establish appropriate land use policies that can promote sustainable urban development, it is necessary to determine priorities that will help identify the most suitable spatial pattern for deciding future land use, to use decision support tools, and to monitor urban growth (Meyer & Turner, 1992). On the other hand, understanding landscape dynamics and sustainable management decision-making processes requires knowledge of the current state of land cover and use (Jamal & Ahmad, 2020).

Monitoring and evaluating urban growth serves as an essential tool for the planning and efficient management of natural resources in the near future. Identifying and interpreting land use changes within a given region is crucial for understanding the relationships and interactions between human activities and natural processes, as well as for mitigating environmental and socio-economic challenges (Arfanuzzaman & Dahiya, 2019; Huang et al., 2020; Wang et al., 2021). To observe global-scale changes and maintain sustainable development, the application of change detection methods is required. In remote sensing, change detection aims to identify alterations on the Earth's surface by analyzing multi-temporal images acquired from the same geographical area at different time periods (Bolat & Doğan, 2022). These alterations are primarily referred to as land use and land cover changes.

Land use and land cover changes are an indicator representing natural and economic processes. Identifying and modeling changes in land cover and land use types facilitates the interpretation of the causes and consequences of land use dynamics and supports policymakers' decisions. Therefore, the identification of land cover types and land use changes is important for natural resource management, environmental assessment, regional and urban planning, and agricultural production management (Wang et al., 2022).

Accurate information on land cover is crucial for environmental research, monitoring the impacts of climate change, resource management, and disaster risk reduction. To assess the effects of land cover transformations on natural environments, these changes must be detected accurately and in a timely manner. Multi-year time series of land cover characteristics provide a broader perspective on land dynamics. Temporal change analysis captures both gradual and abrupt transformations (Lambin et al., 2003). Accurate and up-to-date land cover maps are of critical importance, serving both as inputs for modeling systems (e.g., flood and fire spread models) and as decision-support tools for policymakers (Feddema et al., 2005). Researchers have utilized time-series data in various applications, including forest degradation (Kennedy et al., 2010), land use change (Fallati et al., 2017; Kharazmi et al., 2018; Zhu et al., 2020), ecological alterations (Pasquarella et al., 2016), agricultural intensification (Galford et al., 2008), and forest condition assessments (Arvor et al., 2012). Therefore, conducting detailed, up-to-date, and accurate assessments of changes in urban land use is a fundamental prerequisite for sustainable management and effective urban planning.

Efficient monitoring of land use status and the accurate assessment of land cover changes primarily rely on the use of Remote Sensing (RS) and Geographic Information Systems (GIS) (Rogan & Chen, 2004). With the advancement of RS and GIS technologies, the evaluation and monitoring of natural resource management and spatial planning processes have gained a new dimension (Ghosh et al., 2017). The acquisition of high-resolution imagery through satellite data has facilitated the application of advanced algorithms for land cover monitoring (Ghosh et al., 2017; Alam et al., 2020).

Additionally, these tools are more cost-effective and less time-consuming than traditional methods, offering several advantages such as free access to satellite imagery, enhanced computational capabilities, and user-friendly interfaces. Due to their ability to map vulnerabilities on a larger scale during disaster events, they have attracted considerable attention from both governments and the public (Parthasarathy & Deka, 2019). However, certain limitations in data processing still hinder the effective monitoring of land use changes at the regional scale.

Among these limitations, intensive data processing and storage requirements are significant factors (Debella-Gilo & Gjertsen, 2021). There are a limited number of algorithms available for analysis methods such as object-based image analysis and clustering. In particular, the lack of advanced segmentation and clustering algorithms can cause accuracy and precision issues in some analyses (Tamiminia et al., 2020). Despite all these limitations, it is used as an important tool in environmental analyses and sustainable resource management processes (Pettorelli et al., 2014).

Satellite imagery is among the most commonly used sources for environmental analysis. The Earth Resources Technology Satellite (ERTS)-1, launched in 1972, was renamed "Landsat" in 1975. The Landsat program has launched eight satellites, providing nearly 50 years of continuous data. Currently, Landsat 7 and Landsat 8 remain operational. This satellite series has become one of the most important long-term and freely accessible data sources for civilian applications and has been widely used in various fields, including monitoring land cover changes in agricultural areas (Liu & Seto, 2008; Tassi & Vizzari, 2020), mapping urban expansion (Yan et al., 2021), forest cover mapping (Abijith & Saravan, 2022), vegetation analysis (Senf et al., 2017), and hydrological studies (Abijith et al., 2020). Consequently, Landsat provides a deeper understanding of land cover and land use changes, supporting improved decision-making and resource management. Its broad spectral bands and high spatial resolution enable the detection of significant variations in land cover (Abijith et al., 2020).

Demre is located in the coastal region of Antalya, which encompasses the fertile lands of the Mediterranean region. The area has undergone significant transformation in its urban land cover in recent years. Demre's urban population is growing rapidly, leading to heavy traffic and problems with basic resources. The analysis of land cover and land use types is essential for the sustainable planning and development of a new city and is influential in determining the ideal location for various purposes. Land suitability analysis for urban planning and development will reduce the destructive effects of unplanned and uncontrolled urban sprawl on the environment. Land use suitability is a measure of the suitability of a certain amount of land for specific purposes (Marull et al., 2007).

The study involves determining and examining the spatial and temporal changes in urban land cover and land use types in Demre District, Antalya Province, where tourism and agricultural production activities occur simultaneously and where land conflicts and competition exist, using machine learning. Accordingly, the aim of the study is to obtain spatial and temporal change maps of land cover and use types using satellite images from 2004, 2014, and 2024 with machine learning algorithms and various remote sensing indices, and to compare the results of the classification algorithms used and evaluate their performance.

In this context, the study sought to answer the following questions: How has the spatial distribution and change in land cover and land use types in Demre district changed over the years? How do the classification successes of algorithms vary across different land evaluation classes? Identifying and interpreting these changes will play a significant role in guiding the development of spatial planning and policies for Demre district in the future.

2. Materials and methods

2.1 Study area

The study area is the Demre District, which is part of the Antalya Province. The study area is located between 29°59′ east longitude and 36°14′ north latitude (Fig.1). The total area of the Demre District is approximately 472 km².

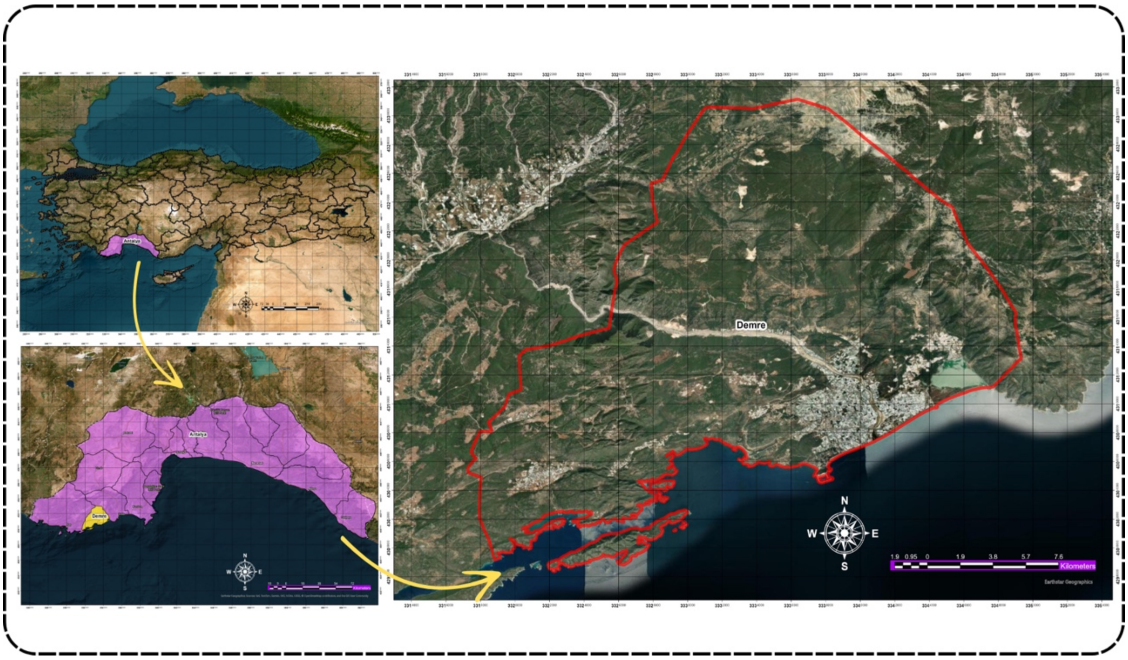

Fig.1 Location of the Demre District

Demre District is located west of Antalya Gulf, south of Teke Peninsula. The district, surrounded by mountains on three sides, was established on Demre Plain, formed by the fertile alluvial soils brought by Demre River. The northern part of the district extends to the foothills of the Taurus Mountains. A significant part of Demre is located on the coastline and has important coastal formations such as the Kekova Gulf. The district has a typical Mediterranean climate, with hot, dry summers and mild, rainy winters. This climate is quite advantageous for agricultural activities. Greenhouse cultivation and citrus production are widespread in the region. However, rapid urbanization and the growth of tourism areas have led to changes in land cover. This study will provide information on the rates of change in land cover and the land uses where these changes are most concentrated.

2.2 Methodology

In this study, land cover data obtained from Landsat satellite images with a spatial resolution of 30 meters were used specifically for Demre District. The machine learning method diagram is shown in Fig.2.

Landsat 8-OLI and Landsat 5-TM satellite images of Demre District were obtained from the United States Geological Survey (USGS) portal to determine changes in land use and land cover information for Demre District in 10-year intervals between 2004 and 2024 (USGS, 2014, and 2024, were obtained from the United States Geological Survey (USGS) portal to detect changes in ten-year intervals (USGS, 2025). The reason for selecting 10-year image intervals is that images prior to 2004 did not show reliable results for sample selection in the study area, and land use changes are more clearly observable within this period.

Additionally, the Scan Line Corrector (SLC) in the Landsat 7 ETM+ sensor malfunctioned on May 31, 2003. After this date, the satellite continued to collect data in SLC off mode, but a 22% data gap was observed in the obtained data. This situation has been another critical factor considered in the selection of satellite images within the scope of this study (USGS, 2025). Around the time the satellite images were selected, the bands of the selected satellite images were Band 7 (SWIR 2), Band 6 (SWIR 1), Band 4 (Red), and for Landsat 5-TM, Band 7 (SWIR 2), Band 5 (SWIR 1), Band 3 (Red), C2L1 level raster data (Tab.1). This is because the SWIR1, SWIR2, and RED bands have been found to provide the most effective results for urban development and vegetation change in order to detect changes in land cover (urban sprawl, vegetation change) as a result of machine learning (Butler, 2013; Kaçmaz & Döker, 2021).

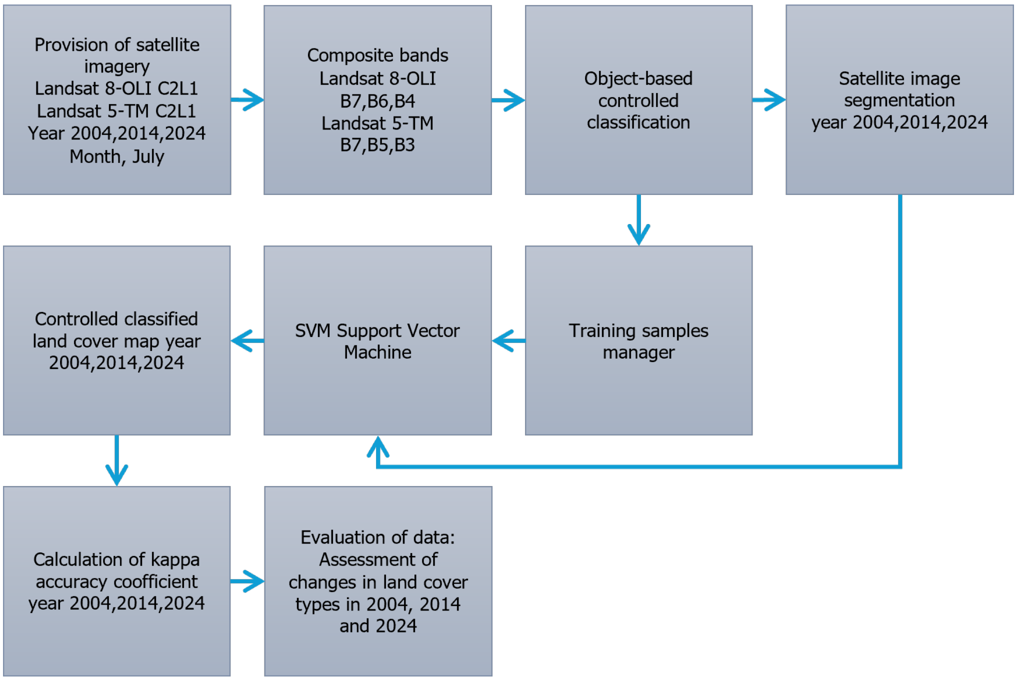

Fig.2 Study process and its application in the Demre District

Date	Sensor Type	Path	Row	Resolution	Cloud cover	Bands
23 July 2004	Landsat-5 TM	178	035	30 m	0	7,5,3 (False Color,Urban)
3 July 2014	Landsat-8 OLI-TIRS	178	035	30 m	0	7,6,4 (False Color,Urban)
30 July 2024	Landsat-8 OLI-TIRS	178	035	30 m	0	7,6,4 (False Color,Urban)

Tab.1 Satellite images used and band characteristics

C2L1 level data are suitable for time series analysis and provide the highest quality Level-1 Terrestrial Precision (L1TP) data, maintaining consistent geographic registration within a <12 m RMSE tolerance (USGS, 2020). Reflectance values for the selected bands are provided in Tab.2.

Landsat-8 OLI-TIRS	Micrometers [μm]	Landsat-5 TM	Micrometers [μm]
Band 4	0.64-0.67 μm	Band 3	0.63-0.69
Band 6	1.57-1.65 μm	Band 5	1.55-1.75
Band 7	2.11-2.29 μm	Band 7	2.08-2.35

Tab.2 Wavelength ranges of Landsat-5 TM and Landsat-8 OLI-TIRS bands used

These single-band raster data have been converted into multi-band RGB (composite) images within the working software. The resulting RGB images were cropped (extract by mask) based on the working area boundary. Following these steps, the data set was prepared for the production of result maps by proceeding to the object-based supervised classification stage for the examination of spatial and temporal change.

The process leading to the final maps consists of two stages. In the image classification process, segmentation plays an important role in object-based classification approaches using support vector machines (SVM). Using segmentation techniques, pixels with similar spectral (pixel reflectance values) and spatial characteristics (volume, shape, and proximity) are classified to obtain meaningful segments. There are three key elements in image segmentation. These are "spectral detail," "spatial detail," and "minimum segment size."

The parameters to be determined vary depending on the resolution, size, and spectral band characteristics of the image. These parameters play a decisive role in determining the classification results (Kaçmaz & Döker, 2021). Accordingly, within the main focus of the study, ten different land use classifications were performed. These classes were defined as "Forest Area," "Water Bodies," "Settlement and Greenhouse Area," "Quarry and Mining Area," "Agricultural Area," "Bare Surface (Rock and Gravel, Bedrock)", "Scrubland", "Sparse Maquis Formation," "Dune Area," and "Wetland–Reed Area".

After the classes were determined, a sufficient number of samples were collected from the study area to create the training dataset. The training data and image segmentation serve as inputs for object-based supervised classification. In this study, the SVM (Support Vector Machine) classifier was employed for object-based supervised classification. The SVM classifier is well-suited for segmented rasters and is an effective supervised classification method for multi-band imagery. The classification process was initiated using the outputs containing meaningful segments obtained through image segmentation, together with a sufficient number of training samples generated using the "Train Sample Manager."

The final outputs include controlled land cover classification maps for the years 2000, 2014, and 2024. The final process following the classification map is the calculation of the classification's accuracy. In ArcGIS Pro 3.5, a total of 1,000 validation points were generated for each year, and the software automatically distributed these points to the relevant classes in proportion to the spatial size of the classes. A total of 1,000 points were retained each year to create an error matrix; from this, overall accuracy, user/producer accuracies, and the Kappa statistic were calculated. The land cover types corresponding to these points were calculated using reference images (HGM Küre application, orthophotos obtained from Demre Municipality, Google Earth application, and Demre district forest map) to determine the Overall Accuracy (OA) and Kappa Coefficient of the results.

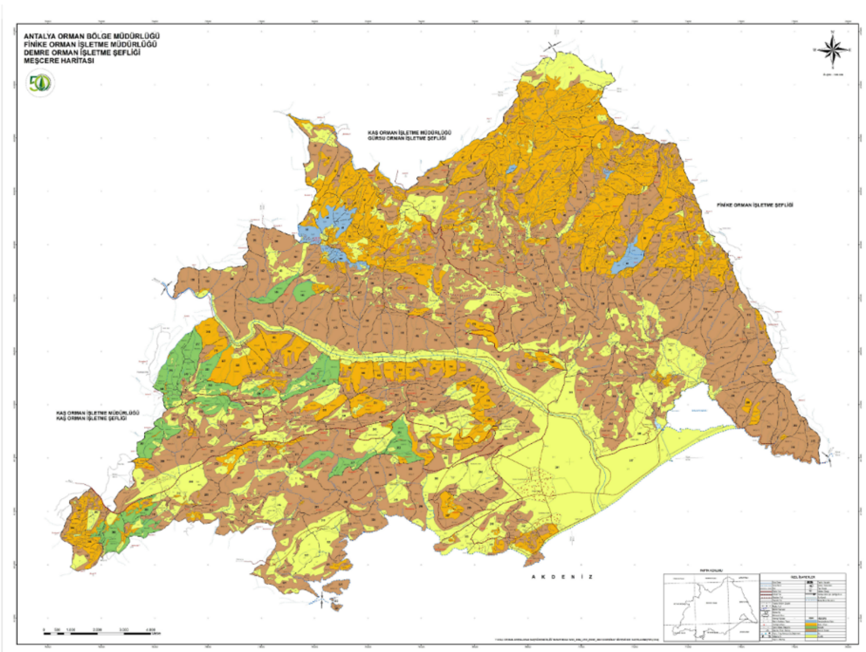

Fig.3 Forestry map of Demre District

To best observe the land cover, satellite images from July, when sunlight is high and cloud cover is low, were selected. The cloud cover ratio is zero in the satellite images selected for 2004, 2014, and 2024. Additionally, the Demre forest map obtained from the Demre Forest Management Directorate during the study was used as a reference in the area classification stage of this study (Fig.3). The systematic study process was carried out using ArcGIS Pro 3.5 software.

3. Land use classes and data set creation

The classification of images obtained from remote sensing satellites plays an important role in the context of monitoring land change. Classification is the process of assigning each element in the image to its class characteristics based on the different spectral reflectance values of the objects in the raw satellite images. It is a technique used to convert unprocessed satellite images into interpretable data. Classifying a satellite image involves separating the pixels or image fragments in the image into classes such as forest, agriculture, urban areas, water bodies, and others based on their spectral characteristics and spatial patterns (Nicolau et al., 2024).

Within the main focus of the study, ten different land use classifications were conducted. These classes were defined as "Forest Area," "Water Bodies," "Settlement and Greenhouse Area," "Quarry and Mining Area" "Agricultural Area," "Bare Surface (Rock and Gravel, Bedrock)," "Scrubland," "Sparse Maquis Formation," "Dune Area," and "Wetland–Reed Area." The Overall Accuracy (OA) and Kappa Coefficient were calculated for the classification.

The process of classifying satellite images aims to automatically assign each pixel to land use classes. However, in order to perform supervised image classification, examples related to the relevant land use classes must be provided to the classifier algorithm as training data. Marking the land use classes selected for training on the images is a prerequisite for training supervised classification algorithms (Iban & Sahin, 2022). For this reason, a total of 1000 pixels randomly distributed across the images for each year were labeled. Using these data sources and algorithms, the study created detailed land change maps of Demre and employed advanced algorithms and machine learning methods for classifying satellite images specific to the study area.

Lansat TM satellites typically cover an area approximately 170 km north-south and 183 km east-west with a sensor spatial resolution or pixel size of 30 m for spectral bands other than the sixth band, which is 120 m (Tewolde & Cabral, 2011). In remote sensing, multispectral bands are widely used for various purposes such as land use and land cover change (Chen, 2007; Koomen, 2007; Schowengerdt, 2007). From the satellite images of Demre district for the specified years, the SWIR1, SWIR2, and RED bands provide the most effective results for urban area development and vegetation change (Butler, 2013). The band order for Landsat is B7, B6, B3, while for Landsat 5-TM it is B7, B5, B3. After combining the selected bands, images of the area were obtained. The image segmentation algorithm, run with different parameters, was used to find regions of minimum heterogeneity. Satellite images and trained training examples for each year were used in this analysis. These data were processed using an algorithm called Support Vector Machines (SVM).

Support Vector Machines (SVM) are a supervised classification algorithm and are widely used in remote sensing and geographic information systems (GIS) literature due to their ability to operate with high accuracy, particularly on segmented raster images (Moeller, 2000; Mucher et al., 2000; Weih & Riggan, 2010). However, they can also be effectively applied to multispectral standard images. SVM classifiers offer significant advantages over traditional classification methods, especially when sample data is limited. The tool accepts multispectral raster data of any bit depth as input and performs pixel-based classification based on user-defined training data. This enables classification on both segmented and standard raster images. One of the key features of the DVM classifier is its ability to be used with segmented raster data. When segmented raster data is used, the tool calculates both the index image and the attribute information for each segment from the RGB segmented raster. The quality of segmentation is decisive for the outcome of subsequent classification. Due to the heterogeneous structure of urban areas, such object-based classifiers are important for urban land change studies (Hsu et al., 2003). After the segmentation process was completed, classification was performed using source-based sample collection and the standard nearest neighbor algorithm. Based on these procedures, land cover maps for 2004, 2014, and 2024 were created.

3.1 Accuracy assessment

Accuracy assessment is an important process in the classification procedure. Accuracy assessment methods are used to produce statistical outputs that can be used to control the quality of classification results. The accuracy analysis of classification has been performed by evaluating error matrices (Wulder & Franklin, 2007). Errors occur due to the misclassification of pixels. If there are a large number of unclassified pixels, the accuracy of the training data sets decreases. Through this matrix, the classes predicted by the classification results are compared with the reference (true) data. The sum of the correctly classified examples in the error matrix is used to calculate the overall accuracy rate.

Overall accuracy is calculated by dividing the total number of pixels in the error matrix by the number of correct pixels (1).

$$\text{Overall Accuracy} = \left(\frac{\sum A}{\sum B}\right) x100 \quad (1)$$

In the equation, A represents the total number of pixels assigned to the correct class, while B represents the total number of pixels that actually belong to these classes. The number of correct pixels belonging to a class divided by the total number of pixels in that column yields user accuracy; the total number of pixels in a class divided by the total number of pixels in that row yields producer accuracy (Kaya, 2020). However, since the overall accuracy rate alone is insufficient to express the classification quality, Cohen's (1960) Kappa coefficient was calculated according to the following formula (2) and taken into account to explain the differences and improvements in the classification of images (Cabral et al., 2005).

$$K = \frac{N\sum_{i=1}^{r} xii - \sum_{i=1}^{r}[(xi+)x(x+i)]}{N^2 - \sum_{i=1}^{r}(xi+)x(x+i)} \quad (2)$$

In equality; K: Kappa Coefficient, r: Number of rows in the error matrix, xii: Total sample count in row (i.) and column (i.), xi+: Total value of row i., x+i: Total value of column i., N: Total sample count in the matrix.

The Kappa coefficient is used to determine the degree to which the accuracy obtained from the classification result differs from the accuracy level that could occur by chance. If the overall accuracy rate is above 80% and the Kappa statistic value is greater than 0.8, the accuracy analysis is considered successful, meaning the classification performed is considered correct (Karayol, 2012). The Kappa coefficient accuracy assessment scale ranges from 0 to 1; 1: Perfect agreement (excellent agreement), 0: Agreement at the level of random agreement, <0: Agreement lower than random agreement (disagreement). Table 3 presents the generally accepted accuracy assessment scale for the Kappa coefficient (κ) (Landis & Koch, 1977). This coefficient allows for a more comprehensive assessment of the reliability of the classification and supports the statistical significance of the results (Sim & Wright, 2005).

Kappa Coefficient (κ)	**Interpretation**
<0	Less than chance agreement
0.0-0.20	Very low agreement
0.21-0.40	Acceptable agreement
0.41-0.60	Moderate reliability
0.61-0.80	Good accuracy
0.81-1.00	Excellent accuracy

Tab.3 Accuracy assessment scale of the Kappa coefficient

The accuracy analysis results of the study were calculated by comparing images classified according to the years of the study with the reference source, and user, producer accuracy, and Kappa ratio were calculated. Since Demre's overall Kappa ratios were 90%, 89%, and 87%, the classification is acceptable.

4. Result

Changes in land use occurring in urban areas and their surroundings, when examined and interpreted in relation to space and time, serve as an important guide for local administrators and decision-makers. Assessments of land use changes using GIS and remote sensing techniques with up-to-date and accurate data are an important tool for making environmentally sustainable decisions. To this end, satellite images from 2004, 2014, and 2024 were used to reveal changes in land cover and use over time in the Demre District.

Post-classification comparison is one of the existing change detection methods (Jensen, 1996). In this regard, the classification rules developed for each of the three images were kept the same during classification and classified independently. After the classification results were determined, the areas of change were identified through direct comparison, and the land change distributions were given as percentages. Table 4 shows the land change in 2004, Table 5 shows the land change between 2004 and 2014, and Table 6 shows the land change between 2014 and 2024. Separate maps were also created for the changes in land use classes over the years (Fig.4, Fig.5 and Fig.6).

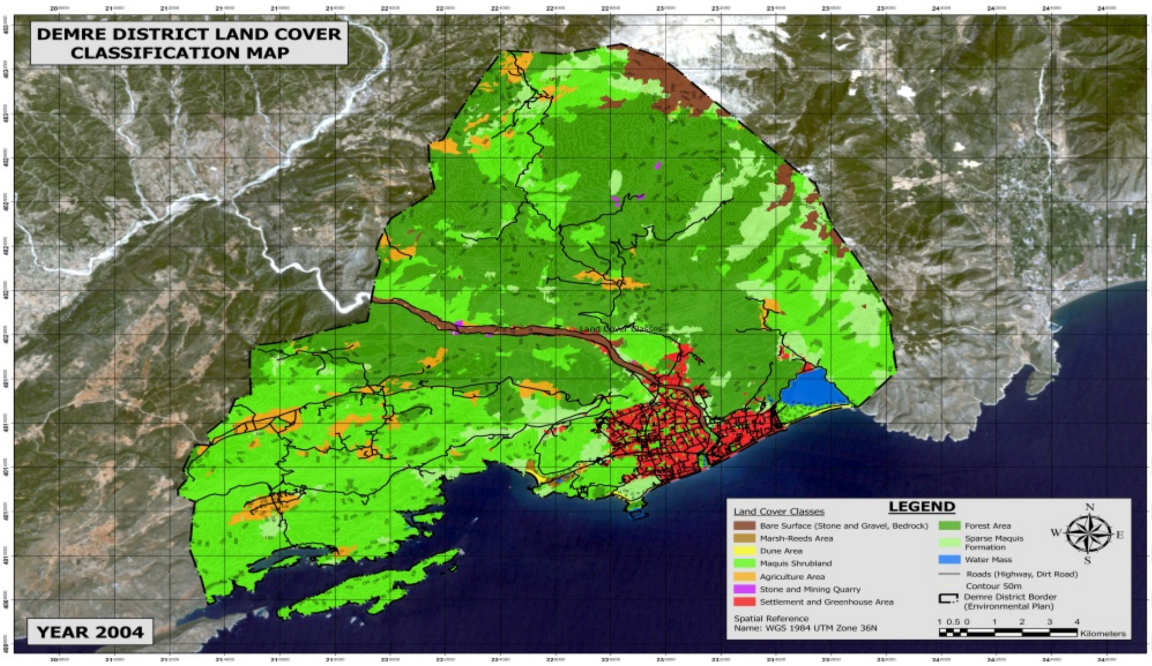

Fig.4 Land cover change map for 2004

Looking at the land use distribution of Demre district in 2004, 41.74% is forest area, 45.08% is scrubland (35.42% + 9.66%), making a total of 86% of the area natural. Settlement and greenhouse areas accounted for 4.27%, agricultural land for 4.49%, bare surface for 3.15%, water bodies for 0.85%, quarries and mines for 0.10%, and dune areas for 0.14% (Tab.4). Geodetic measurement is a three-dimensional measurement that takes into account the curvature of the Earth. This is the fundamental difference between planar measurement and geodetic measurement, as geodetic measurement is suitable for large-scale projects covering areas greater than 250 square kilometers, taking into account the spherical shape of the Earth.

The geodetic measurement method was applied to road data within the boundaries of Demre district. Accordingly, the district's road length in 2004 was 412.04 km^2, and the area it covered was 309.03 ha. The area covered by roads in the district accounts for 0.858% of the total area.

		Area [ha]	
No.	Land Use Types	2004	%
1	Forest Areas	15,030.10	41.74
2	Water Bodies	306.94	0.85
3	Settlement and Greenhouse Area	1,536.11	4.27
4	Quarry and Mining Area	36.19	0.10
5	Agricultural Area	1,617.09	4.49
6	Bare Surface (Rock and Gravel, Bedrock)	1,135.62	3.15
7	Scrubland	12,752.54	35.42
8	Sparse Maquis Formation	3,478.18	9.66
9	Dune Area	63.44	0.18
10	Wetland–Reed Area	48.65	0.14
	Total Area [ha]	36,005.28	100.00

Tab.4 Land use change distribution in 2004 [%]

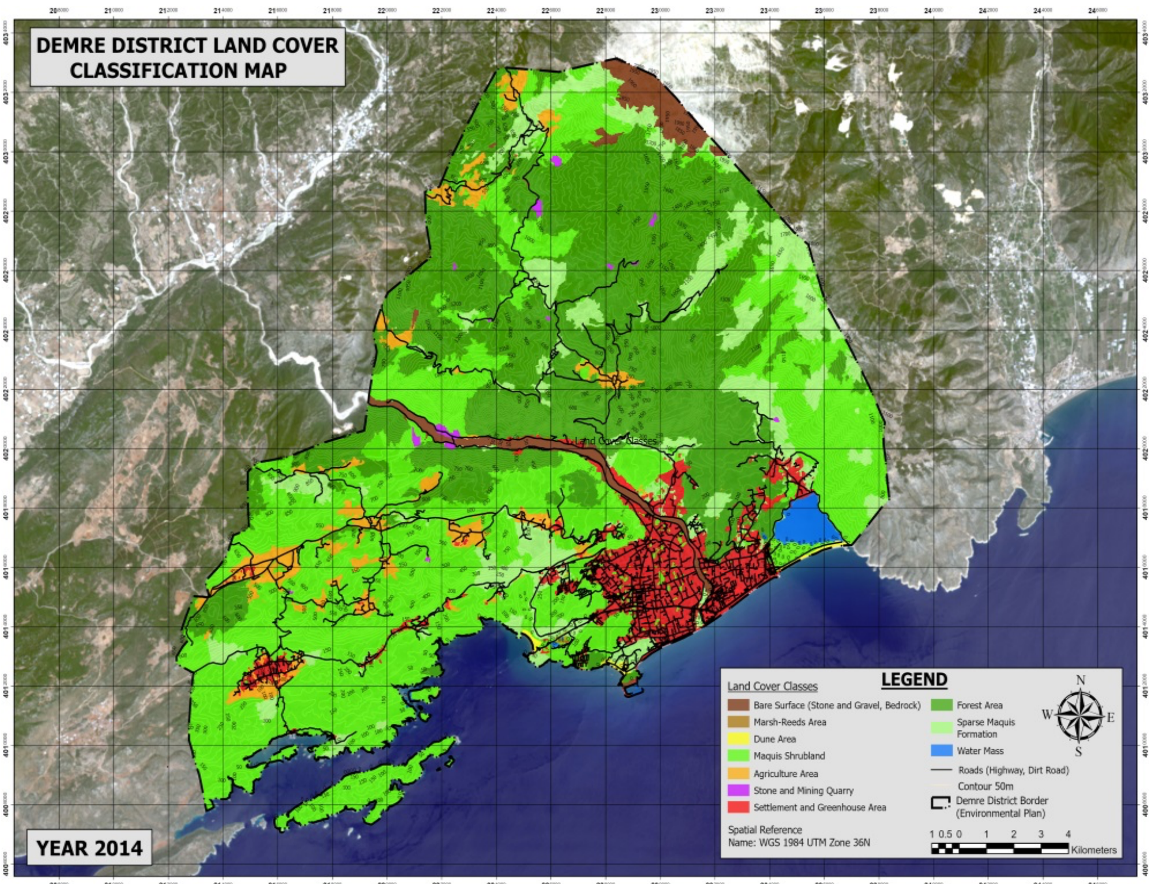

Fig.5 Land cover change map for 2014

Looking at the land use distribution of Demre district in 2014, 35.28% of the total area is forest area, 49.78% (38.86% + 10.92%) is scrubland, making a total of 85.10% natural land. Settlement and greenhouse areas accounted for 6.85%, agricultural land for 4.16%, bare surface for 2.62%, water bodies for 0.80%, quarries and mines for 0.27%, and dune areas for 0.22% (Tab.5).

Furthermore, according to the geodetic measurement method road data within the boundaries of Demre district, the road length in 2014 was 537,06 km and the area covered was 402,80 km^2. The area covered by roads in the district accounts for 1,119% of the total area.

		Area [ha]	
No.	**Land Use Types**	**2014**	**%**
1	Forest Area	12,700.91	35.28
2	Water Bodies	289.18	0.80
3	Settlement and Greenhouse Area	2,466.10	6.85
4	Quarry and Mining Area	96.05	0.27
5	Agricultural Area	1,497.43	4.16
6	Bare Surface (Rock and Gravel, Bedrock)	944.62	2.62
7	Scrubland	13,991.70	38.86
8	Sparse Maquis Formation	3,930.96	10.92
9	Dune Area	79.70	0.22
10	Wetland–Reed Area	8.62	0.02
	Total Area [ha]	**36,005.28**	**100.00**

Tab.5 Distribution of land changes between 2004 and 2014 [%]

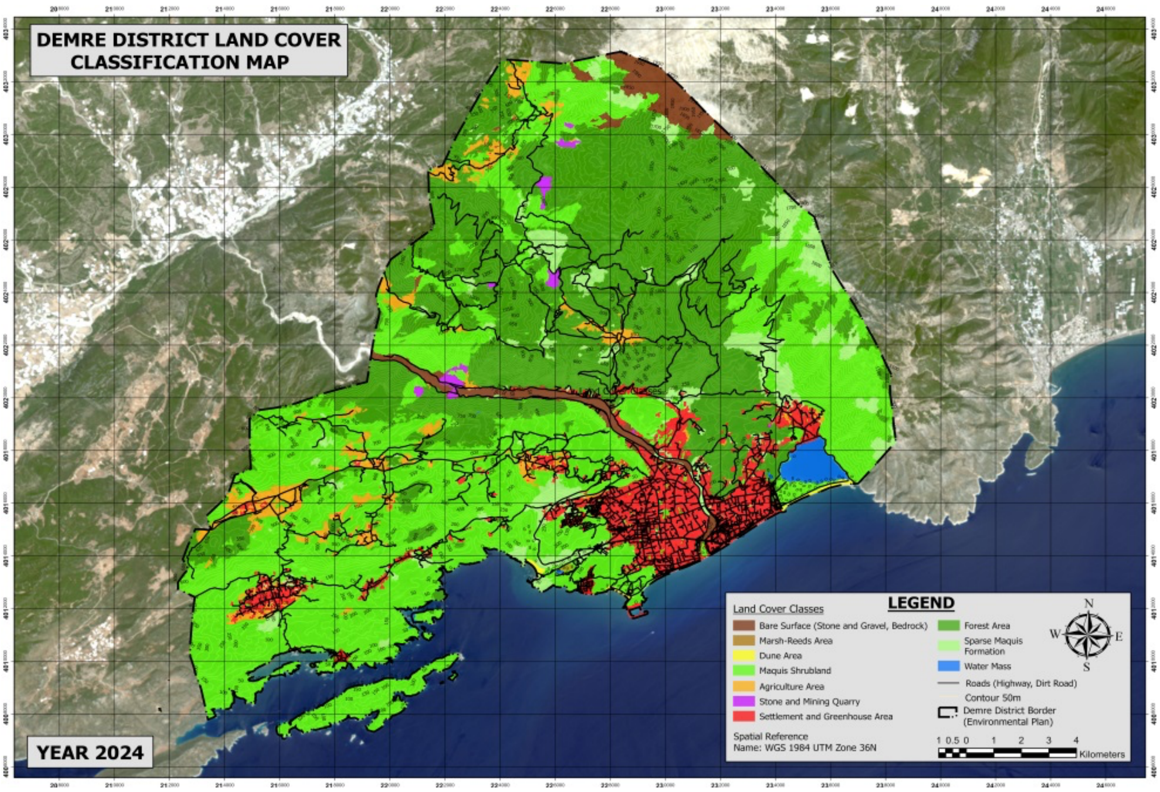

Fig.6 2024 land cover change map

Looking at the land change distribution between 2014 and 2024, 36.06% of Demre district is forest area, 46.71% (41.29% + 6.42%) is scrubland, and 82.77% of the total area is natural land. Settlement and greenhouse areas account for 7.69%, agricultural areas for 4.08%, bare surface for 3.04%, water bodies for 0.78%, quarries and mines for 0.43%, and dune areas for 0.03% (Tab.6).

Road data within the boundaries of Demre district, measured using the geodetic measurement method, shows that the road length in 2024 is 711.51 km and the area covered is 533.63 km^2. The area covered by roads in the district accounts for 1.482% of the total area.

When examining the land use types of Demre district by year, compared to 2004, in 2014, marshland decreased by 82.28%, bare surface (rock and gravel, bedrock) decreased by 16.82%, forest area decreased by 15.50%, agricultural areas decreased by 7.40%, and water bodies decreased by 5.79%. In contrast, quarry and mining areas increased by 165.39%, settlement and greenhouse areas by 0.54%, dune areas by 25.62%, and scrub and sparse maquis formations by 22.74% (Tab.7).

		Area [ha]	
No.	**Land Use Types**	**2024**	**%**
1	Forest Area	12,983.16	36.06
2	Water Bodies	280,20	0.78
3	Settlement and Greenhouse Area	2,770.31	7.69
4	Quarry and Mining Area	155.70	0.43
5	Agricultural Area	1,468.21	4.08
6	Bare Surface (Rock and Gravel, Bedrock)	1,094.98	3.04
7	Scrubland	14,865.32	41.29
8	Sparse Maquis Formation	2,310.93	6.42
9	Dune Area	66.51	0.18
10	Wetland–Reed Area	10.03	0,03
	Total Area (ha)	**36,005.28**	**100.00**

Tab.6 Distribution of land cover change (%) between 2014 and 2024

No	**Land Use Types**	**Values for 2004**	**Values for 2014**	**Difference between 2014 and 2004**	**Percentage difference between 2014 and 2004**	**Values for 2024**	**Difference between 2024 and 2014**	**Percentage difference between 2024 and 2014**
		Area [ha]	Area [ha]	Area [ha]	[%]	Area [ha]	Area [ha]	[%]
1	Forest Area	15,030.10	12,700.91	-2,329.19	-15.50	12,983.16	282.25	2.22
2	Water Bodies	306.94	289.18	-17.76	-5.79	280.20	-8.98	-3.10
3	Settlement and Greenhouse Area	1,536.11	2,466,10	929.99	**60.54**	2,770.31	304.21	12.34
4	Quarry and Mining Area	36.19	96.05	59.86	**165.39**	155.70	59.65	**62.10**
5	Agricultural Area	1,617.09	1,497.43	-119.66	-7.40	1,468.21	-29.22	-1.95
6	Bare Surface (Rock and Gravel, Bedrock)	1,135.62	944.62	-191.00	-16.82	1,094.98	150.36	15.92
7	Scrubland	12,752.54	13,991.70	1,239.16	9.72	14,865.32	873.62	6.24
8	Sparse Maquis Formation	3,478.18	3,930.96	452.79	13.02	2,310.93	-1,620.04	-41.21
9	Dune Area	63.44	79.70	16.26	25.62	66.51	-13.19	-16.56
10	Wetland–Reed Area	48.65	8.62	-40.03	-82.28	10.03	1.41	16.35
Total Area [ha]		36,005.28	36,005.28	0.00	0.00	36,005.28	0.00	0.00

Tab.7 Spatial and percentage change values of land use types in Demre District by year

The total land area of Demre district is 36,005.28 hectares. It has been determined that settlement and greenhouse areas increased by 60.54% in Demre between 2004 and 2014, and by 12.34% between 2014 and 2024, representing an approximate increase of 72.88% over a total of 20 years. Quarries and mines showed rapid growth starting in 2004, increasing by 165.39% in 2014 and 62.10% in 2024, showing a total increase of 227.49% over 20 years.

Land use is defined as the use of land and its resources by people. Change occurs due to both natural and socio-economic factors. While some researchers argue that demographic dynamics contribute to changes in land cover (Mather & Needle, 2000), others draw attention to the effectiveness of economic activities (Lambin et al., 2003; Wubie et al., 2016). Tourism in the district affects all land classes as one of the most important factors triggering urbanization and initiating change and transformation in land use. In Demre, especially in recent years, tourism-oriented accommodation and construction trends have spread and dispersed over agricultural and greenhouse areas, causing a negative impact on the urban environment.

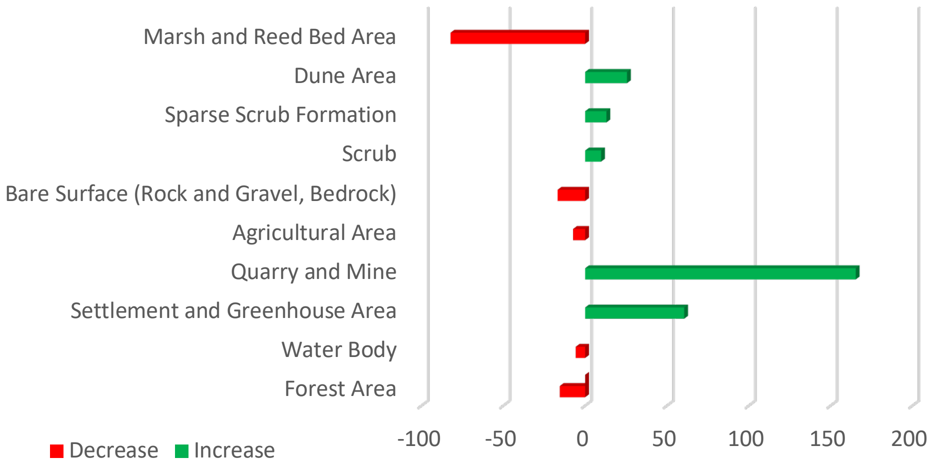

Fig.7 Percentage differences in land use types in Demre district between 2004 and 2014 [%]

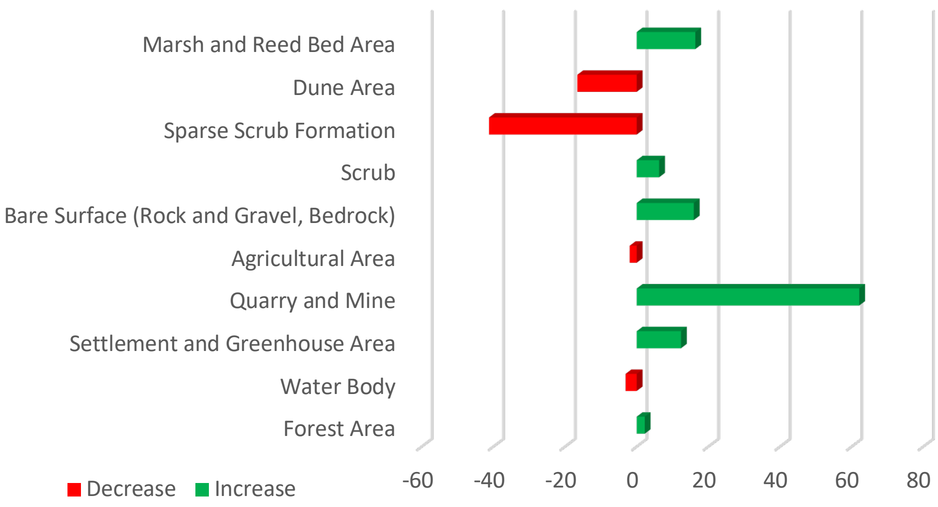

Fig.8 Percentage differences in land use types in Demre district between 2014 and 2024 [%]

The rapid increase in artificial areas and tourism facilities in Demre has led to a decrease in agricultural and forest areas. With the impact of tourism, the development of urban areas has begun to spread, particularly towards agricultural lands. Many studies in the literature addressing changes in land use have found that changes in land use types in cities are particularly associated with an increase in settlement, construction, tourism, and quarry and mine land use (Bahadır & Uzun, 2021; Potapov et al., 2020). Looking at these studies in general, it is concluded that the changes in land use are not as desired and occur in an unplanned manner. This lack of planning has irreversible consequences, especially in fertile agricultural lands, forest areas, and wetlands (Gülersoy, 2013). Therefore, planning land use and determining changes in advance is crucial in preventing improper land use and controlling urbanization.

The areas of Demre district with dense scrub and sparse maquis formations increased by a total of 22.74% between 2004 and 2014. Although there was a 6.24% increase in dense scrub areas in 2024, there was a 41.21% decrease in sparse maquis areas in particular.

Dune areas increased by 25.62% between 2004 and 2014, but decreased by 16.56% in 2024. Marshland areas decreased by 82.28% between 2004 and 2014, while an increase of 16.35% was observed in 2024.

Forest areas decreased by 15.50% between 2004 and 2014, while they increased by 2.22% in 2024. Areas with water bodies decreased by 5.79% between 2004 and 2014 and by 3.10% in 2024, showing a total decrease of 8.89%. Agricultural areas decreased by 7.40% between 2004 and 2014 and by 1.95% in 2024, showing a total decrease of 9.45%.

The results of the classified images for the period 2004-2024 are shown in Fig.7 and Fig.8.

Accuracy assessment, an integral part of the image classification process, has been calculated for the accuracy of land use types by year and is presented in Table 8. The accuracy assessment was performed using a high-resolution aerial photograph as a reference. For the three maps, 1,000 random samples were selected, labeled according to the reference data, and the kappa coefficient was calculated. The overall accuracies were determined to be 90.7% for 2004, 90.3% for 2014, and 87.9% for 2024, respectively. It is stated that a minimum accuracy value of 85% is required for effective and reliable land cover change analysis and modeling (Göncüler & Köylü, 2024). The classification obtained in this study meets the accuracy threshold at an almost perfect level of agreement according to the Tab.2 Kappa coefficient accuracy assessment scale.

Land Use Types	**2004 [ha]**	**2014 [ha]**	**2024 [ha]**
Forest Area	117	117	93
Water Bodies	99	112	107
Settlement and Greenhouse Area	95	96	115
Quarry and Mining Area	83	89	91
Agricultural Area	93	83	73
Bare Surface	110	104	90
Scrubland	124	127	151
Sparse Maquis Formation	99	86	106
Dune Area	101	84	68
Wetland–Reed Area	79	102	106
Total Sample	1,000	1,000	1,000
Correct Sample	907	903	880
Overall Accuracy	90.7	90.3	87.9
Kappa values	0.90	0.89	0.87

Tab. 8 Accuracy assessment of land use types using the Kappa coefficient

5. Discussion

The observed changes in land use types indicate a progressive loss of agricultural land and environmentally sensitive areas, accompanied by an accelerating trend of urban expansion. In particular, construction activities and tourism-related accommodation developments are expected to exert increasing pressure on agricultural production, especially greenhouse farming, which represents the primary source of livelihood in the region. This transformation largely reflects unplanned and poorly regulated land-use changes, which may undermine the long-term sustainability of local agricultural systems.

Similar socio-economic pressures have been reported in other regions. For example, Ziari et al. (2025) and Partheepan et al. (2023) documented comparable dynamics in Batticaloa, while Pultrone (2023) emphasized the role of external development pressures in accelerating urban sprawl. These findings reinforce the argument that rapid urbanization processes are often driven by socio-economic factors rather than comprehensive spatial planning frameworks. In this context, the present study also demonstrates the importance of geospatial technologies for monitoring land-use transformations and identifying environmental degradation patterns. The policy-oriented recommendations derived from the findings offer practical insights that can support local authorities in managing urban growth and promoting more sustainable land management practices.

The environmental consequences of these transformations are equally significant. The reduction of open and green spaces has eliminated an important ecological resource that previously contributed to temperature regulation, biodiversity conservation, and improved air quality. Their disappearance increases urban heat stress and dust emissions, particularly in areas already facing ecological challenges. Furthermore, the expansion of impermeable urban surfaces increases surface runoff, elevates flood risks, and intensifies pressure on limited water resources. These environmental impacts are consistent with patterns observed in many mid-sized cities located in arid and semi-arid climates, where rapid urban expansion frequently exceeds the adaptive capacity of natural ecosystems.

The dominance of socio-economic drivers over political and cultural influences suggests that Demre's land-use trajectory is currently shaped more by short-term development pressures than by long-term strategic planning. Without stronger governance mechanisms and coordinated land-use policies, continued expansion may exacerbate environmental degradation, social inequalities, and economic vulnerabilities. Therefore, integrated planning approaches are required to protect remaining open and green spaces, regulate urban expansion more effectively, and balance development needs with ecological and social sustainability. Comparable land-use transformations have also been documented in several Turkish cities. Dengiz & Demirağ Turan (2014), in their analysis of land use and land capability classes in Samsun, reported that high-quality agricultural lands (Classes I, II, and III) were increasingly converted into artificial surfaces. Similarly, Aydın & Durduran (2021) identified significant land-use changes in the Konya Ereğli–Bor Lower Basin, including the expansion of artificial surfaces and agricultural lands, alongside reductions in forest areas and wetlands. Çelik & Yakar (2023) examined urbanization pressures in Mersin and reported increases in urban areas and vegetation cover, accompanied by decreases in agricultural lands, barren areas, and water bodies. Earlier research also highlights similar trends. Sönmez (2011) demonstrated that agricultural lands in Adana have declined significantly while urban areas have expanded rapidly. According to the study, the city center and its surrounding areas have experienced intense spatial transformation, raising concerns regarding ecological sustainability and land-use efficiency. The findings emphasize the need to control the expansion of built-up areas and implement protective measures for ecologically valuable land-use types such as forests, water bodies, coastal zones, and pasture lands. In addition to controlling urban expansion, nature-based solutions play an important role in mitigating the environmental impacts of urbanization. Strategies such as soil desealing, urban afforestation, and the expansion of green infrastructure can significantly enhance carbon storage capacity, reduce urban temperatures, and mitigate the effects of heavy rainfall events. These approaches, including the utilization of residual urban spaces for green infrastructure development, have been widely recommended as effective climate adaptation strategies in urban planning (Lai & Zoppi, 2025). Urban green spaces require more than just an increase in quantity; the development of a comprehensive and systematic planning approach suitable for urban land use, a topic often overlooked in planning studies, is of greater importance (Gül et al., 2024). Climate change alters environmental conditions, and therefore, rational use of non-renewable resources, especially land, is crucial to revert to, preserve, or achieve the desired outcome. In this context, increasing green spaces and/or infrastructure, integrating them with natural and agricultural areas, will make a significant contribution to reducing vulnerability to climate change (Zucaro & Morosini, 2018).

6. Conclusion

The land change maps for Demre district for the years 2004, 2014, and 2024 were obtained using an object-oriented approach, and the resulting maps provided new information about the spatiotemporal distribution of land use types in the region. The results obtained from the classification were validated and used for further change distribution analysis. The nature of urban land cover change was addressed and quantified according to landscape metrics and urban sprawl conditions. Each map provided information about the distribution of land change.

It has been determined that over the past 20 years, there has been a significant increase in quarries and mines, as well as residential and greenhouse areas, in Demre district, based on land use types. The conversion of urban agricultural lands and vegetation cover into residential areas, along with increased construction and tourism investments accompanying urban growth, and the expansion of stone and marble quarry activities, have led to the loss of agricultural lands and a decrease in natural vegetation cover. In particular, areas with sparse maquis, dune areas, and water surfaces are experiencing a decline. This situation is detrimental to the region's natural areas. Land use change is fragmenting natural areas and increasing ecological risks. In particular, it supports the claim that tourism-oriented accommodation and urbanization trends in recent years have spread and dispersed over agricultural and greenhouse areas, causing a negative impact on the urban environment. The results suggest that urban growth will continue to expand in the future and, unless certain measures are taken, will lead to multifaceted negative impacts and risks on land resources.

The appropriate use of land according to its purpose and capacity is the most important component of urban planning and management processes. The incorrect, disorderly, and unconscious use of land leads to the destruction of natural resource values, the emergence of multifaceted environmental, social, and economic problems, the negative effects of climate change, increased carbon emissions, decreased biodiversity, and other issues. In this context, it is crucial to accurately determine the current status of land within and around cities using up-to-date inventory data and to reveal the temporal and spatial changes in land use types from the past to the present in order to ensure future sustainability.

In Demre district, strategic actions and decisions must be made with due consideration to the balance between conservation and use, in accordance with the purpose and capacity of the land. In this context, the protection and sustainability of Demre district's natural and cultural heritage values should be the primary objective. Other types of use should be planned in a manner compatible with conservation. Consequently, it is necessary to raise awareness and consciousness among local administrators, decision-makers, and city residents regarding the improvement of natural environments and ensuring their sustainability.

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Author's profile

Sibel Akten

She received his BSc in Landscape Architecture from Bolu Abant İzzet Baysal University. Also, she received his MA (The Determination of Measures, Standards and Effects Levels of Visitors of the Protected Areas (in case of Gölcük Nature Park) and Ph.D. (Strategic Action Plan Model for the Adaptation Process of School Landscape Spaces to Climate Change) in Landscape Architecture from Süleyman Demirel University, respectively. Currently, she is a Asst. Prof. of Isparta University of Applied Sciences Atabey Vocational School and his research interests include landscape design and planning, protected natural areas and planning, recreational planning and sustainable

Hüseyin Batuhan Dündar

He graduated from Süleyman Demirel University, Faculty of Architecture, Department of Landscape Architecture. He specialize in landscape planning, design, and GIS, integrating CAD and GIS software to develop sustainable solutions. As a licensed IHA-1 (drone) pilot, he utilize aerial data to enhance analysis and project efficiency.

Atila Gül

He completed his undergraduate degree at Istanbul University Faculty of Forestry in 1986, his master's degree at Yıldız University F.B.E. Landscape Planning Department in 1988, and my PhD at Ege University F.B.E. in 1998. Since 1999, I have been working as a lecturer at Süleyman Demirel University, Faculty of Architecture, Department of Landscape Architecture. Until today, I have held many administrative and academic positions as Dean, Vice Dean, Head of Department and Head of Department. I have also served in many Boards and Commissions within the University, Faculty and Department. I also the founder of the Department of Landscape Architecture and has made significant contributions and activities in education and training (undergraduate, graduate and doctoral programmed) and scientific research and projects. I have prepared and implemented many landscape design application projects within SDU and outside the institution. I have supervised 23 Master's and 13 Doctoral Thesis in the Department of Landscape Architecture. Currently, 1 PhD and 1 Master's Thesis supervision is ongoing. I have 68 scientific articles, 38 of which are International and 30 of which are National Articles. The number of papers presented in international symposiums and congresses and published in full text is 80, and the number of papers published and presented nationally is 56. There are 11 International Book Editing, 2 National Book Editing, 39 International Book Chapter Authorship, 15 National Book Chapter Authorship. The number of citations to scientific publications is more than 2007. He has participated in more than 100 Academic and Scientific Activities. He has been the Editor-in-Chief of the 'Journal of Architectural Sciences and Applications,' published in Dergipark since 2016 and indexed in the Turkish Index. He is also the Editor-in-Chief of the Journal of Protected Areas Research. He serves as a member of the Editorial Board for both journals published on Dergipark. He is also a member of the Scientific Advisory Board, Chairman of the Accreditation Board, and a member of the Indexing Committee at the Online Journal Platform and Indexing Association (OJOP). His role continues (https://www.ojop.org). Areas of specialization, Landscape Planning and Design, Protected Natural Areas and Planning, Recreational Planning, Nature Tourism, Ecotourism, Cultural Tourism, Cultural Heritage, Grasslands and Establishment, Urban Forestry, Urban Trees, Plant Materials for Landscape Purposes, Landscape Restoration (Rehabilitation and Reclamation)

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Evaluating urban fabric transformations using GeoAI

Alessandro Vitale

Department of Civil Engineering
University of Calabria, 87036, Rende (CS), Italy
e-mail: alessandro.vitale@unical.it
ORCID: https://orcid.org/0000-0001-7163-8114

Abstract

Urban growth has reshaped land use patterns globally, demanding robust and scalable methodologies to monitor its long-term dynamics. This study proposes a GeoAI-based framework that integrates Random Forest (RF) classification with spatial indicators to analyze urban fabric transformations in Ravenna, northern Italy, from 2000 to 2024. Using Landsat 5 and Landsat 9 multispectral imagery processed in the Google Earth Engine (GEE) cloud computing platform, six Land Use and Land Cover (LULC) classes were mapped with high accuracy. The RF classifier achieved an overall accuracy of 86.2% in 2024, confirming its suitability for complex urban environments. The classified maps were imported into a GIS environment to extract built-up surfaces and compute spatial indicators, including Urban Density (UD), Urban Dispersion Index (UDI), Annual Growth Rate (AGR), and Urban Expansion Index (UEI). Results reveal a moderate densification in Ravenna's urban core alongside an increase in dispersed residential nuclei, confirming a dual trend of consolidation and sprawl. The indicator values align with northern Italian urbanization trends reported in the literature. This approach demonstrates how combining supervised classification with spatial metrics can provide deeper insights into urban growth, supporting more informed planning and policy-making. The framework is scalable, reproducible, and adaptable to different urban contexts.

Keywords

GeoAI; Remote sensing; Urban fabric transformation

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1. Introduction

The impact of human activities on environmental change is a central focus of land management and geomatics research, given the spatial complexity and heterogeneity of urban evolution. Although several monitoring approaches exist, capturing the temporal and spatial dynamics of urban landscapes remains a significant challenge due to limitations in traditional field-based techniques. While effective, conventional methods, such as field surveys and participatory mapping, are time-consuming, costly, and labor-intensive. Recent advancements in data acquisition technologies and the application of artificial intelligence (AI)-based algorithms to geospatial analysis (GeoAI) have offered innovative solutions to address these challenges, enabling more efficient and accurate analyses (Chaturvedi & de Vries, 2021; Fistola & La Rocca, 2024; Gaglione, 2023; Samardžić-Petrović et al., 2017). In particular, advancements in geomatics and remotely sensed imagery have revolutionized the ability to monitor and map changes in Land Use and Land Cover processes (LULC) (Khachoo et al., 2024; Partheepan et al., 2023). These technologies provide comprehensive temporal and synoptic insights, making them well-suited for capturing transformations in natural and built environments. Their integration with Geographic Information System (GIS) tools further enhances their utility, supporting large-scale analyses of LULC changes (Francini et al., 2023; Salvo & Vitale, 2024a; Salvo & Vitale, 2024b; Vitale, 2025; Wang et al., 2022; Zafar et al., 2024).

Machine Learning (ML) algorithms, a subset of AI-based methodologies, have played a pivotal role in advancing GeoAI capabilities, particularly in automated image classification. These algorithms have significantly enhanced the accuracy and scalability of analyzing large-scale geospatial datasets, especially when coupled with powerful computational infrastructures. Indeed, despite advancements in remote sensing and data acquisition technologies, large-scale geospatial data processing remains challenging due to significant computational demands, storage requirements, and the need for advanced technological resources (Song et al., 2022). Cloud-based platforms such as Google Earth Engine (GEE) have been developed to address these limitations (Gorelick et al., 2017). GEE is an open-access platform that hosts extensive geospatial datasets, including MODIS, Landsat, and Sentinel. It facilitates high-speed processing of planetary-scale remote sensing data, particularly for tasks such as image classification. By enabling the efficient integration of machine learning algorithms and providing integrated online storage, GEE has become a powerful tool for classifying multispectral satellite imagery and analyzing LULC (Benhammou et al., 2022; Velastegui-Montoya et al., 2023; Vitale et al., 2024; Vitale & Salvo, 2024).

Among ML models, Random Forest (RF) has demonstrated consistent reliability and robustness across LULC classification tasks. RF is particularly well-suited for multispectral image classification due to its resistance to overfitting, its ability to handle high-dimensional data, and its reduced sensitivity to parameter tuning. Several studies highlight its superiority over alternative algorithms such as SVM (Le et al., 2022). For instance, RF achieved 95.2% accuracy using Landsat 9 imagery, outperforming Support Vector Machine (SVM) in multiple class-specific evaluations (Zafar et al., 2024). Furthermore, the RF classifier was successfully integrated within a transfer learning framework to map built-up dynamics in southern Italy from 2006 to 2024, achieving an overall accuracy of 0.926 in 2024 and demonstrating the method's scalability, reproducibility, and high classification performance (Vitale & Lamonaca, 2025a; Vitale & Lamonaca, 2025b).

This paper proposes a GeoAI-driven methodology focused on classifying LULC changes and spatially characterizing urban fabric transformations using the RF classification algorithm. The study aims to provide an interpretation of urban evolution over a medium- to long-term period through a set of spatial indicators derived from classified maps. Four key indicators, Urban Density (UD), Urban Dispersion Index (UDI), Annual Growth Rate (AGR), and Urban Expansion Index (UEI), are employed to measure the intensity, direction, and fragmentation of urban growth over the 2000–2024 period (Romano et al., 2017a; Romano et al., 2017b)

Accordingly, the study addresses the following research question: Can a robust and scalable automatic GeoAI-based methodology be effectively integrated with urban spatial metrics to capture long-term urban transformations? How can these indicators help planners distinguish between sprawl and consolidation patterns in urban environments?

The rest of the paper is organized as follows: Section 2 describes the study area and the datasets employed. Section 3 outlines the methodological approach, detailing the RF-based classification process and the GIS-based measurement of urban transformation through spatial metrics. Section 4 presents the results of the land cover classification and the computed urban spatial metrics. Section 5 discusses the findings about the literature and planning implications. Section 6 concludes the paper with final considerations and future research directions.

2. Study area and dataset

The study area selected by the authors to test the proposed methodology is the city of Ravenna, a small-to-medium-sized municipality with a resident population of 157,277 inhabitants, located in the Emilia-Romagna region in northern Italy (Fig.1). This urban context, covering a surface area of about 630 km², is an ideal case for analyzing urban fabric transformations due to its historical significance and contemporary urban development. The city's core is defined by a well-preserved historical area featuring numerous UNESCO World Heritage Sites, which together form a dense, distinctive urban fabric. Surrounding the historic center, Ravenna has experienced significant urban transformations over the last two decades, particularly in its peripheral areas.

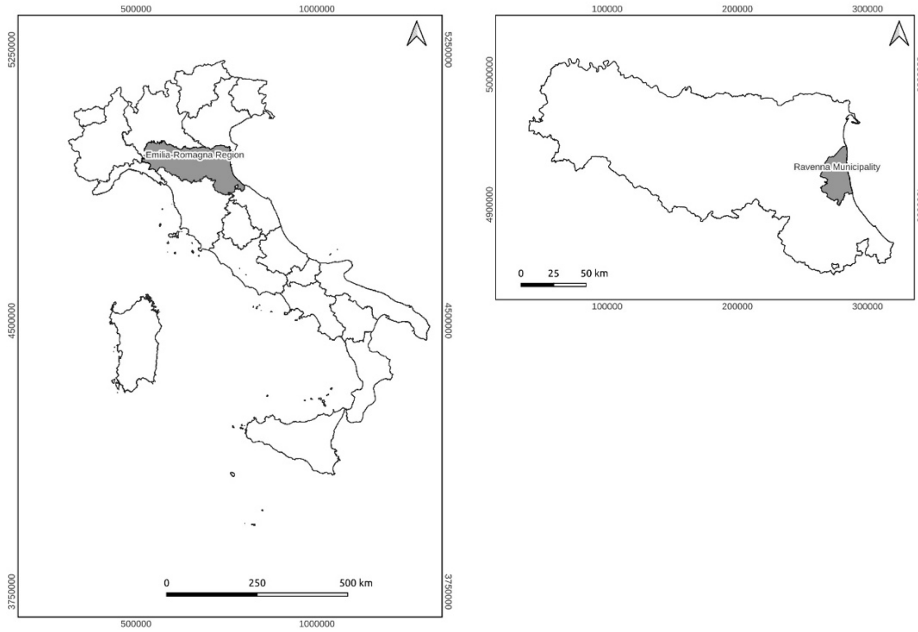

Fig.1 Study area key map

The industrial zones, in proximity to the Adriatic Sea and port facilities, have seen considerable growth, as have the adjacent residential neighborhoods. This development has resulted in a stark contrast between the compact historical urban core and the more fragmented modern urban textures elsewhere in the city.

The city's urban fabric evolution is also influenced by environmental challenges such as flood risk and coastal erosion, further reinforcing the need for long-term monitoring using advanced geospatial tools.

Urban fabric transformations in Ravenna were determined by delineating several urban morphological zones, which were identified and characterized in consideration of the Municipal Structural Plan (PSM) documents. These zones include the historical core, suburban developments, peripheral industrial zones, and isolated residential structures. The delineation and temporal comparison of these zones were achieved by automatically classifying multitemporal multispectral satellite images using a supervised RF classifier.

Landsat 5 and Landsat 9 satellite images were used to capture and analyze urban fabric transformations in Ravenna over 24 years, from 2000 to 2024. The methodology, fully implemented in GEE, utilized Level 2, Collection 2, Tier 1 Landsat 5 imagery for the historical period (2000), which features atmospherically corrected surface reflectance and land surface temperature derived from the Landsat TM sensor. With a 30-meter spatial resolution, four Visible/Near-InfraRed (VNIR) bands and two Short-Wave InfraRed (SWIR) bands, these images were orthorectified to detect and map urban fabric and land use patterns at the start of the study period. For 2024, more advanced Landsat 9 imagery was used, characterized by improved radiometric resolution and spectral coverage, including 11 spectral bands across the visible, near-infrared, and short-wave infrared regions. The higher radiometric sensitivity of Landsat 9 allowed for more accurate classification of built-up and non-built-up areas, capturing even subtle urban development.

Ground-truth data were collected directly from the multispectral images to train and validate the RF classifier, ensuring the accuracy of automatic classification and subsequent measurement of urban fabric transformations. The integration of RF classification with a GIS-based framework enables a scalable, reproducible, and interpretable approach to monitor urban expansion and morphological change.

3. Methodology

3.1 Data preprocessing

To monitor LULC changes in Ravenna from 2000 to 2024, remote sensing data (Landsat 5 in 2000 and Landsat 9 in 2024) were processed using the GEE cloud computing platform. Following an open-source paradigm, this platform was designed and implemented to meet methodological requirements.

The platform is compatible with GIS, enabling the export of classified images and change-detection maps for further analysis and visualization within GIS environments.

The Landsat 5 and Landsat 9 satellite images were processed to temporally filter scenes, selecting the periods from 1 January to 31 December for 2000 and from 1 January to 30 September for 2024.

As a critical step for comparing the images from 2000 and 2024, the imagery from both datasets was geometrically aligned to ensure consistency in spatial resolution and coordinate systems.

Once the data were preprocessed, the RF classifier was applied in GEE to map the LULC classes for both periods. The resulting classified maps served as the basis for further GIS-based spatial analysis and for the computation of indicators in QGIS (QGIS, 2025).

3.2 Multispectral satellite images classification method

Land use and land cover Class	Description
Water	Areas covered by natural or artificial water bodies, such as rivers, lakes, ponds, and reservoirs.
Tree Cover	Areas dominated by trees, typically with continuous canopy cover, including forests and plantations.
Grassland and Shrubland	Open areas covered with grasses, shrubs, or sparse vegetation, often located in transitional zones between forests and barelands.
Agricultural	Lands used for agricultural purposes, including crop production, orchards, and managed fields.
Built-up	Urban areas characterized by human-made structures, including residential, commercial, industrial, and infrastructure developments.
Bareland	Exposed soils or rocky surfaces with little to no vegetation, often associated with deserts, rocky areas, or degraded lands.

Tab.1 A brief description of predicted LULC classes

The classification process relied on six LULC classes: tree cover, grassland and shrubland, agricultural, water bodies, built-up, and bareland (Tab.1). These classes were predicted using the RF classifier, trained on a labeled sample of 1,498 elements, of which 70% were used for training and 30% for validation.
The implementation of the RF classifier in GEE enabled the generation of consistent and accurate LULC maps for 2000 and 2024, which served as the foundation for the subsequent GIS-based evaluation of urban transformations and indicator computation.

3.3 Validation and accuracy assessment

The accuracy of the RF classifier depends on the input data dimensionality, the study area, and the satellite sensor used. Several studies in the scientific literature have evaluated different classifiers for LULC classification using Landsat 5 and Landsat 9 satellite images, reporting varying accuracies in validation (Basheer et al., 2022; Krivoguz et al., 2023; Puttinaovarat et al., 2023).
The confusion matrix was used to evaluate the classifiers' accuracy by comparing their predicted land use and land cover classifications against the actual ground-truth features. Indeed, the confusion matrix provides a detailed breakdown of the classification results, showing the number of correctly and incorrectly classified pixels for each LULC class. Moreover, two other accuracy indicators were used, particularly Overall Accuracy (OA) and Producer Accuracy (PA).
OA measures the proportion of correctly classified instances out of all instances and provides a general measure of the model's performance. The equation for OA determination is equation 1:

$$OA = \frac{Correct\ Classified\ Pixels}{Total\ Pixels} * 100 \qquad (1)$$

PA or Recall is the ratio of correctly predicted positive observations to all actual positive observations (equation 2):

$$PA = \frac{True\ Positives\ (TP)}{True\ Positives\ (TP) + False\ Negatives\ (FN)} \qquad (2)$$

True Positives (TP) correspond to the number of instances correctly predicted as the positive class.
False Positives (FP) refer to the number of instances incorrectly predicted as the positive class (when they are negative).
False Negatives (FN) represent the number of instances incorrectly predicted as the negative class (actually positive).
A higher PA value indicates the model correctly classified most of the class's pixels. A lower PA value indicates that many class pixels are misclassified into other classes (higher false negatives).
Based on the accuracy metrics described, the land use and land cover classification map generated by the RF classifier was selected for subsequent GIS-based evaluation and mapping of urban fabric transformation.

3.4 GIS-based urban fabric transformations evaluation and mapping

Following the classification of LULC for 2000 and 2024, the resulting maps were imported into the QGIS environment for post-processing and spatial analysis. A preliminary assessment was conducted to quantify changes in the areal extent of each LULC category over the 24-year observation window, with particular focus on the built-up class.
In addition to examining changes within specific morphological zones, the analysis included calculating the overall urban density and additional spatial indicators to characterize the intensity and nature of urban growth.

Four metrics were computed: UD, UDI, AGR, and UEI. These indicators are commonly used in spatial planning studies to quantify urban transformation dynamics.

The selected indicators provide complementary perspectives on growth intensity, spatial fragmentation, temporal trends, and urban expansion in relation to the total municipal area. Their application helps describe the structural transformation of the urban fabric beyond mere land consumption figures.

UD is calculated as in equation 3:

$$UD = \frac{BU}{TA} \tag{3}$$

BU is the total built-up area (in km²), and TA is the total area of the municipality (in km²). This indicator provides a normalized measure of the concentration of built-up land, allowing direct comparison between different periods or territories.

UDI is defined in equation 4:

$$UDI = \frac{N}{TA} \tag{4}$$

N is the number of distinct built-up nuclei, and TA is the total area of the municipality (in km²). UDI is particularly useful for assessing the degree of spatial fragmentation in urban settlements.

AGR is calculated using equation 5:

$$AGR = \left[\left(\frac{BU_{t2}}{BU_{t1}}\right)^{\frac{1}{t2-t1}} - 1\right] \tag{5}$$

BU_{t2} and BU_{t1} are the built-up areas at the final and initial years (2024 and 2000, respectively). This indicator quantifies the average yearly growth rate of urban fabric.

UEI is computed as in equation 6:

$$UEI = \left[\left(\frac{BU_{t2} - BU_{t1}}{TA}\right) \times 100\right] \tag{6}$$

As mentioned before, BU_{t2} and BU_{t1} are the built-up areas at the final and initial years, and TA is the total municipal area. UEI helps identify the portion of land converted to urban use as a proportion of the total municipal territory.

Together, these indicators provide a robust analytical framework for measuring urban growth and its morphological patterns. By associating spatial indicators with classified remote sensing data, the methodology ensures high comparability, transferability, and planning relevance. Their integration into GIS-based workflows allows planners and policymakers to assess the direction, rate, and sustainability of urban development processes. They support decision-making by revealing whether growth has occurred through compaction or dispersion, and how intensely the territory has been consumed over time.

The analysis was further refined by delineating specific urban morphological zones to evaluate the transformation of the urban fabric. These zones were defined using reference cartographic data provided by the Emilia-Romagna Region's geoportal and aligned with the city’s PSM. The year 2000 served as the reference year for measuring spatial growth and transformation dynamics.

The city of Ravenna was subdivided into four morphological categories based on its structural and functional characteristics:

- Core Urban Zone The historical center and high-density residential and service areas;
- Suburban Zones Residential expansions developed outward from the urban core;
- Peripheral Areas Low-density, recent developments including industrial sectors, port-related infrastructure, and coastal residential settlements;
- Residential Isolated Structures Dispersed built-up forms in rural or semi-rural contexts, characterised by fragmentation and spatial discontinuity.

Built-up areas identified through classification were extracted for reference years and overlaid on these morphological zones. The spatial analysis thus provided a structured basis for evaluating how Ravenna's urban structure has evolved and identifying zones that experienced the most pronounced changes in built-up surface over the two-decade period.

4. Results

4.1 RF classification results

The classification results generated by the Random Forest (RF) model for the years 2000 and 2024 were evaluated using confusion matrices and standard accuracy metrics. In 2000, RF achieved an OA of 83.8%, indicating strong predictive reliability in distinguishing among the six LULC classes. PA values exceeded 0.90 for the water, built-up, and tree cover classes, confirming the classifier's effectiveness in detecting spectrally distinct and spatially coherent features (Tab.2).

	Water	Tree Cover	Grassland and Shrubland	Agricultural	Built-up	Bareland
Water	55	0	0	2	1	0
Tree Cover	0	37	0	0	3	1
Grass./Shrub.	0	0	51	5	3	7
Agricultural	0	0	11	95	2	9
Built-up	0	0	2	6	108	1
Bareland	0	0	6	14	2	42

Tab.2 Validation process confusion matrix for RF 2000 LULC classification prediction

The agricultural class returned a PA of 0.81, slightly lower but still robust. Some confusion was observed between agricultural and adjacent categories, such as grassland and shrubland (11 pixels), and bareland (9 pixels), possibly due to seasonal effects or spectral similarity. Grassland and shrubland recorded a PA of 0.77, with misclassification primarily involving agricultural (5 pixels) and bareland (7 pixels). The bareland class exhibited a moderate PA of 0.65, with significant confusion with agricultural (14 pixels) and grassland/shrubland (6 pixels) areas, typical of transitional or degraded land surfaces. By 2024, the RF classifier demonstrated enhanced performance, achieving an OA of 86.2%. Nearly all land cover classes experienced improvements in PA (Tab.3). Water and built-up areas retained high accuracy (PA = 0.95 and 0.92, respectively). Grassland and shrubland notably improved, with PA values of 0.94 and 0.90, respectively, and tree cover reached a PA of 0.90. Agricultural areas reached a PA of 0.88, although some confusion persisted with bareland (9 pixels) and grassland and shrubland (10 pixels). Bareland also improved, achieving a PA of 0.76, although it remained the least accurately predicted class. The RF classification outputs were selected as the definitive LULC maps for spatial analysis and the computation of urban growth indicators (Fig.2). These validated maps provided the analytical foundation for measuring the spatial distribution and temporal evolution of Ravenna's urban fabric from 2000 to 2024.

	Water	Tree Cover	Grassland and Shrubland	Agricultural	Built-up	Bareland
Water	55	2	1	0	0	0
Tree Cover	0	37	0	1	3	0
Grass./Shrub.	0	1	62	3	0	0
Agricultural	0	0	10	88	10	9
Built-up	0	2	0	4	108	3
Bareland	0	1	3	8	3	49

Tab.3 Validation process confusion matrix for RF 2024 LULC classification prediction

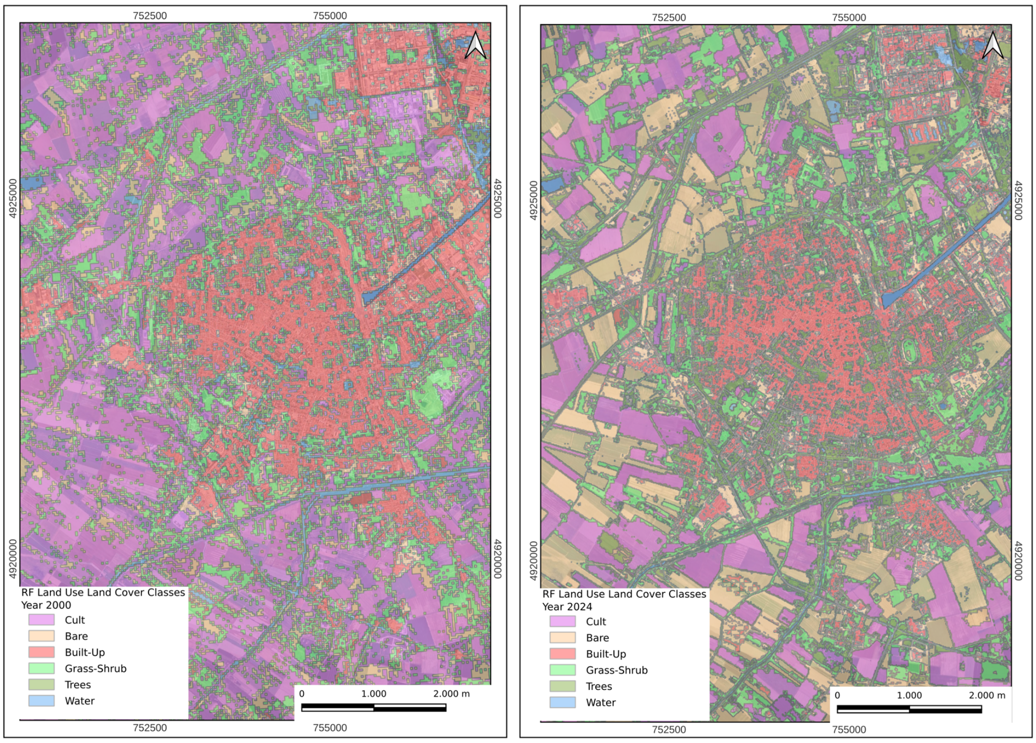

Fig.2 A sample of RF LULC classes predictions around Ravenna's historical center for 2000 and 2024

4.2 Urban fabric transformations analysis

The analysis of urban fabric transformations in Ravenna from 2000 to 2024 highlights significant changes in LULC. The spatial data and classification outputs, particularly those generated using the RF classifier, provide detailed insights into how Ravenna's urban structure has evolved.

The results reported in Tab.4, which present the surface area and percentage changes of the LULC classes from 2000 to 2024, show that the surface covered by water increased by 2.2 km² (+6.4 %), from 32.0 km² in 2000 to 34.2 km² in 2024. This increase is likely due to the expansion of water bodies and canals, or improved detection accuracy resulting from higher-resolution satellite imagery in 2024.

Tree cover decreased by 13.3 km² (-16.1 %), from 96.1 km² in 2000 to 82.8 km² in 2024. This decline indicates deforestation or urban expansion into forested areas, particularly in Ravenna's peripheral and suburban zones.

The area of grassland and shrubland increased significantly by 50.4 km² (+28.6 %), from 126.0 km² in 2000 to 176.4 km² in 2024. This increase might suggest land abandonment or a transition of agricultural land back into natural vegetation as agricultural activities decrease in some areas.

The Surface of agricultural land decreased by 12.1 km² (-4.9%), from 259.6 km² in 2000 to 247.5 km² in 2024. This reduction indicates urban encroachment on agricultural areas, particularly in the suburban and peripheral zones.

	Surface Covered in 2000 [Km²]	**Surface Covered in 2024 [Km²]**	**Surface Covered in 2000 [%]**	**Surface Covered in 2024 [%]**	**Difference 2000-2024 [Km²]**	**Difference 2000-2024 [%]**
Water	32.0	34.2	5.1	5.4	+2.2	+6.4
Tree Cover	96.1	82.8	15.2	13.1	-13.3	-16.1
Grass./Shrub.	126.0	176.4	20.0	28.0	+50.4	+28.6
Agricultural	259.6	247.5	41.2	39.4	-12.1	-4.9
Built-up	28.3	36.1	4.5	5.8	+7.8	+21.6
Bareland	87.8	52.8	14.0	8.4	-35.0	-66.3
Total	**629.8**	**629.8**	**100**	**100**	**0**	-

Tab.4 The surface of predicted LULC classes for 2000 and 2024

Bareland decreased considerably, losing 35.0 km² of surface area (-66.3 %), shrinking from 87.8 km² in 2000 to 52.8 km² in 2024. This may reflect urban development and the transformation of previously barren areas into built-up spaces or agricultural land.

Built-up areas experienced significant growth, increasing by 7.8 km² (+21.6 %), from 28.3 km² in 2000 to 36.1 km² in 2024. This reflects urban expansion, particularly in residential, commercial, and industrial developments in peripheral zones, as well as isolated residential structures.

Urban Density (UD) increased from 4.49% in 2000 to 5.73% in 2024. When compared to Romano et al. (2017a) and Romano et al. (2017b), this evolution places Ravenna above the 1950 value of 3.3% but still below the 2000 northern Italian average of 7.0%, suggesting a moderate level of urban compaction.

The Urban Dispersion Index (UDI), based on the number of built-up nuclei per square kilometer, increased from 0.0238 in 2000 to 0.0318 in 2024. These values align with the UDI range of 0.02–0.03 reported by Romano et al. for northern Italy in 2000, confirming a trend toward fragmentation consistent with that observed in the Emilia-Romagna region.

The Annual Growth Rate (AGR), which measures the average annual increase in built-up area, was calculated at +1.02%. This moderate rate reflects steady urban growth over the period.

Urban Expansion Index (UEI), which identifies the share of municipal territory converted to built-up use, aligns with the general expansion trends (1–2%) observed in Italian urban areas according to Romano et al.

In summary, Ravenna's urban transformation exhibits moderate densification, accompanied by increased dispersion. The UDI and AGR values suggest that while densification occurred within the core urban zone, growth also involved suburban and isolated areas, reinforcing the dual character of compaction and sprawl. The comparison with northern Italy further contextualizes Ravenna's evolution as a representative case of balanced urban expansion.

Considering the urban morphological zones described in the methodological section and focusing on the evolution of built-up areas, the connotation of urban fabric transformations can be outlined.

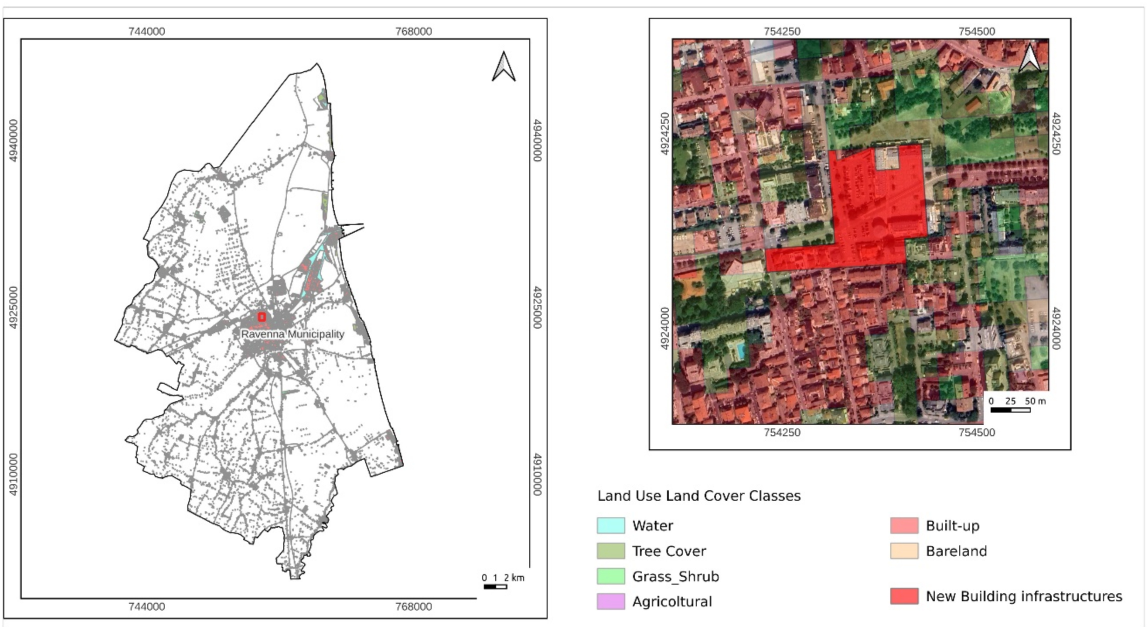

Fig.3 A sample of Built-up growth in the Core Urban Zone in the period 2000 - 2024

As can be seen from the image sample reported in Fig.3, the Core Urban Zone, which includes the historic center and the most densely populated areas, has been characterized by an increase in residential and private services. This growth has been concentrated primarily within the nucleus defined by the Municipal Structural Plan (PSM). Over the past two decades, significant urban mending has occurred within the core, focusing on intensifying the use of previously underutilized spaces. New residential buildings have replaced vacant lots and have been infilled with medium-density housing and services, reflecting the city's policy of promoting urban densification. This policy not only supports sustainable urban growth but also preserves Ravenna's historic identity by limiting outward expansion and encouraging development within the existing urban footprint.

Beyond the core, suburban and peripheral zones have seen notable urban expansion, driven by demand for new housing and commercial facilities. These zones have experienced remarkable growth in built-up areas, particularly in the residential coastal settlement developments, often characterized by detached houses and low-density residential units (Fig.4). Also, in this case, the new residential buildings have replaced vacant areas with medium-low-density housing and services, mending the urban fabric and strengthening the densification policy undertaken in the last 24 years in Ravenna.

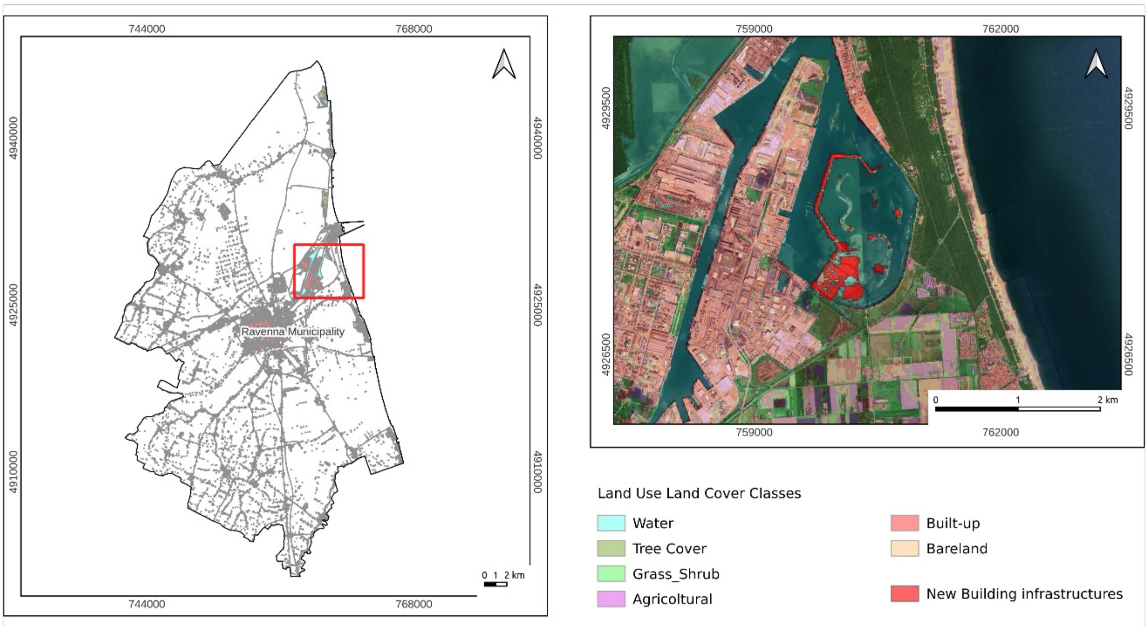

Fig.4 A sample of Built-up growth in the Suburban and Peripheral Areas in the period 2000 – 2024

The development of the commercial and industrial area near the Port of Ravenna, as depicted in Fig.4, consisted mainly of port and back-port infrastructures and services. The strategic development of these areas, hubs located near transport links and industrial hubs, within the region.

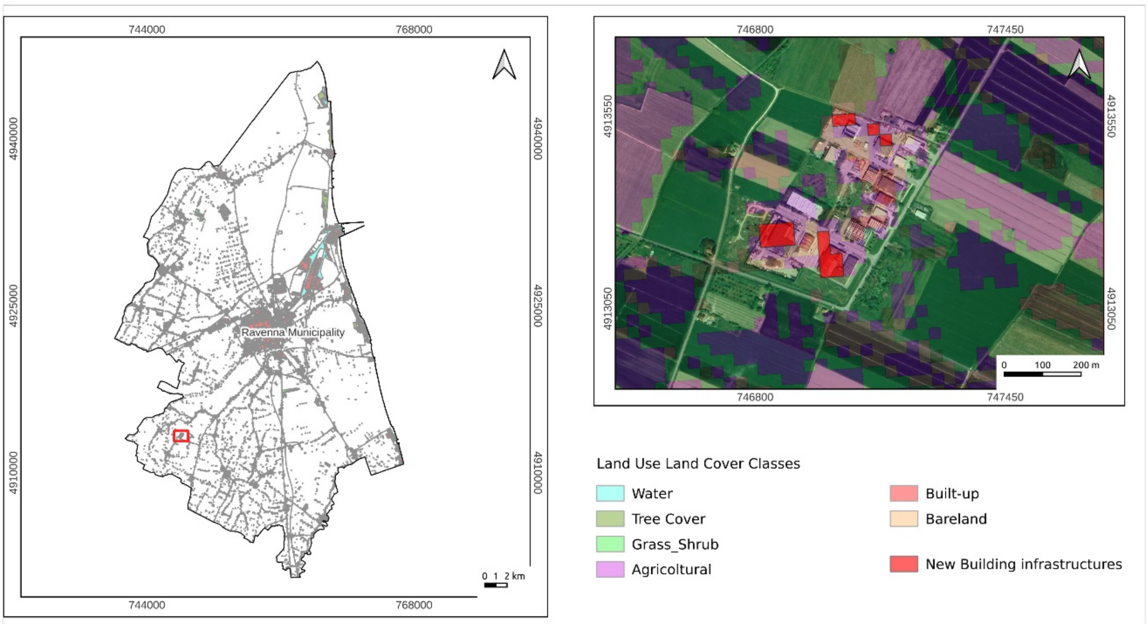

Fig.5 A sample of Built-up growth in the Isolated Residential Structures in the period 2000 – 2024

Growth in isolated residential structures has occurred primarily in the peripheral rural areas surrounding Ravenna, supporting agricultural activities. These isolated structures have contributed to a fragmented urban fabric, leading to less cohesive, more dispersed development. This development pattern is consistent with broader trends in urban sprawl, which can present challenges for infrastructure provision, transport planning, and environmental sustainability. However, these areas have become attractive for residents seeking a quieter, more suburban lifestyle while benefiting from proximity to the city center (Fig.5).

5. Discussion

The results of this study highlight the effectiveness and robustness of the proposed GeoAI-driven methodology for mapping urban fabric transformations. The RF classifier achieved an OA of 0.83 in 2000 and 0.86 in 2024, showing increased predictive performance over time. RF's ability to classify water, built-up, and tree cover classes with high accuracy (PA above 0.90) demonstrates its reliability in distinguishing these classes, especially in urban environments where rapid changes occur.

This reinforces the GeoAI-based approach as a reliable tool in geomatics for large-scale, long-term LULC monitoring, with high transferability and automation potential within GIS workflows.

The calculated spatial indicators provide strong empirical support for the classification output. Urban Density (UD) increased from 4.49% in 2000 to 5.73% in 2024, and Urban Dispersion Index (UDI) rose from 0.0238 to 0.0318, indicating a trend toward both densification and fragmentation. These results align with the spatial growth dynamics observed by Romano et al. (2017a) and Romano et al. (2017 b) in Northern Italy, confirming the relevance of the selected indicators. AGR and UEI values (1.02% and 1.24%, respectively) also align with the national trend of moderate urban expansion, validating the methodology's ability to quantify structural change.

The urban fabric transformations observed in Ravenna over the past 24 years suggest opportunities and challenges for urban and territorial planning. Consolidating the urban core, emphasizing redevelopment and densification, supports sustainable urban growth by reducing the need for outward expansion and preserving the city's historical identity. However, urban sprawl in peripheral areas poses challenges to infrastructure provision, transport planning, and environmental sustainability. This interpretation is consistent with the findings of Mazzeo and Russo (2016), who discuss land take and the territorial effects of urban expansion in Italian metropolitan contexts. The development of isolated residential structures in rural zones has contributed to a fragmented urban fabric, necessitating more strategic planning to manage growth effectively.

Methodologically, this research advances the field of geomatics by demonstrating that GeoAI-based LULC methodologies can yield multidimensional insights into urban morphology. The systematic inclusion of UD, UDI, AGR, and UEI metrics represents a significant enhancement over traditional pixel-based change detection, enabling the translation of satellite imagery into actionable urban knowledge.

While this study's results provide valuable insights into the transformations of Ravenna's urban fabric from 2000 to 2024, it is essential to highlight some limitations and potential areas for further research.

The present study relies on Landsat imagery, which, while freely accessible and valuable for long-term monitoring, has a spatial resolution of 30 meters. This resolution may not capture finer details in the urban landscape, such as small-scale residential or commercial developments. Higher-resolution imagery (e.g., from Sentinel-2 or commercial satellite providers) could provide more detailed insights into land use and cover changes in specific areas, particularly in dense urban cores or regions undergoing rapid, localized changes.

RF still encountered challenges in distinguishing between specific LULC classes, such as Bareland and Agricultural land. These challenges arise from spectral similarities between certain land cover types, which may necessitate more sophisticated classification techniques (e.g., deep learning models or object-based image analysis) to enhance accuracy, particularly in mixed-use or transition zones.

In addition, future applications could integrate ancillary data layers, such as cadastral boundaries, socio-economic indicators, or transport infrastructure datasets, to enrich the spatial interpretation of growth patterns. A multi-scalar or multi-temporal extension of this methodology would also enhance its analytical power. To overcome the limitations of traditional classifiers such as RF and SVM, deep learning models, such as Convolutional Neural Networks (CNNs), can improve land cover classification accuracy. These models are better suited to handle complex and nonlinear patterns in multispectral data. They can improve the differentiation between spectrally similar land cover types, such as Bareland and Agricultural areas.

Finally, while the methodology was validated on a single case study, its modular structure and use of open-access data and platforms make it easily replicable in other urban contexts. Future research should apply this framework to multiple cities across different regions to assess its generalizability and to contribute to a more comprehensive understanding of global urbanization processes.

6. Conclusions

This study demonstrated the effectiveness of a GeoAI-based methodology for detecting and quantifying long-term transformations in the urban fabric of Ravenna between 2000 and 2024. By integrating Random Forest (RF) classification with GIS-based spatial metrics, the approach enabled both high-accuracy land cover classification and a multi-dimensional analysis of urban growth patterns.

The RF classifier achieved an overall accuracy of 86.2% in 2024, confirming its suitability for complex land cover environments, particularly for detecting built-up areas, grassland/shrubland, and bare land. The adoption of spatial indicators, Urban Density (UD), Urban Dispersion Index (UDI), Annual Growth Rate (AGR), and Urban Expansion Index (UEI), provided a structured framework for evaluating the direction, intensity, and fragmentation of urban development.

These findings reinforce the value of geomatics-based methodologies that leverage AI and cloud computing for land monitoring. The results not only align with regional trends identified by Romano et al. (2017a) and Romano et al. (2017b) in northern Italy but also demonstrate the method's applicability to real-world urban planning challenges. Ravenna’s case illustrates how densification in the historic core coexists with a gradual increase in dispersed urban nuclei, reflecting a hybrid pattern of consolidation and sprawl.

The approach presented is scalable, reproducible, and adaptable to various urban contexts. By generating actionable, spatially explicit insights, this methodology supports more informed territorial governance, enabling policymakers to manage urban expansion while preserving environmental and cultural resources.

Future research should explore applying this framework to additional cities with different morphologies and integrating higher-resolution imagery or ancillary geospatial datasets to further enhance classification detail and planning relevance.

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Author’s profile

Alessandro Vitale

He is a Senior Researcher and Adjunct Professor at the Department of Civil Engineering, University of Calabria (Italy). His research expertise lies in geomatics, GeoAI, remote sensing, GIS-based spatial analysis, and photogrammetry, with applications to urban and territorial planning, environmental monitoring, smart agriculture, infrastructure systems, and climate impact assessment. He has authored more than 70 scientific publications indexed in Scopus and Web of Science and actively serves the international scientific community as an Editorial Board Member of the journal Geomatics (MDPI) and as a Guest Editor and reviewer for top-tier Q1 journals. His research activity is characterized by strong interdisciplinary integration between geospatial technologies, artificial intelligence, and decision-support systems.

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CITISENSE. Enhancing urban well-being through smart design, data and AI in Italy's historic centres

Pierfrancesco Celani [a]*, Daniel Enrique Sardo [b], Massimo Zupi [a], Margherita Tufarelli [c]
Adriano Bisello [d]

[a] University of Calabria, Italy
e-mail: pierfrancesco.celani@unical.it,
massimo.zupi@unical.it
ORCID: https://orcid.org/0000-0003-2102-7440
https://orcid.org/0000-0001-5648-1745
* Corresponding author

[b] ITESO Universidad Jesuitica de Guadalajara, Mexico
e-mail: danielsardo@iteso.mx
ORCID: https://orcid.org/0000-0002-3593-9865

[c] University of Florence, Italy
e-mail: margherita.tufarelli@unifi.it
ORCID: https://orcid.org/0000-0003-4824-6715

[d] Jakala Civitas S.p.A, Italy
e-mail: adriano.bisello@jakala.com
ORCID: https://orcid.org/0000-0002-4585-067X

Abstract
Italian historic centres face critical challenges balancing heritage conservation with contemporary needs, particularly in regions like Calabria where smaller settlements experience depopulation, decay, and inadequate services. Traditional smart city frameworks have inadequately addressed these contexts, focusing primarily on contemporary urban environments with adaptable infrastructure. This study examines how GeoAI-enabled urban analysis and participatory design methodologies can enhance urban well-being while preserving cultural heritage in small and medium-sized historic centres. The research develops a replicable methodological framework combining advanced technologies (AI, big data, wearable devices) with Living Lab participatory processes. The approach operationalizes "urban well-being" through three measurable dimensions: physical comfort (route optimization based on weather, terrain, facilities), cultural access (personalized itineraries considering tourist density), and perceived safety (recommendations using social media sentiment, lighting data, population density). Data governance follows GDPR protocols ensuring privacy protection and algorithmic transparency through Explainable AI (XAI). Pilot sites in Calabria represent diverse typologies: peripheral centres, high-tourism destinations, isolated villages, coastal settlements, and centres near natural parks. Expected impacts span individual (enhanced comfort, safety), community (social cohesion, participation), territorial (sustainable tourism, economic vitality), and governance (data-driven resource allocation) levels. The study demonstrates that technology, integrated within strategic vision and participatory practices, can support heritage-respectful urban regeneration oriented toward collective well-being.

Keywords
GeoAI; Living lab; Community engagement; Urban wellbeing; Italian historic centres

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1. Introduction

Rapid advances in geospatial technologies, ICT, and computational power, along with exponential growth of urban big data, have created fertile ground for collaboration between urban planning, smart cities, and GeoScience (Lazzeretti et al., 2023). Recent computational design methods and data-driven approaches fundamentally alter how designers address urban design problems, enabling more objective, evidence-based decision-making (Gün, 2023; Aidaoui et al., 2024).

Technological change plays a fundamental role in understanding and envisioning future urban scenarios. New technology adoption substantially influences city behaviours and usage patterns (Fistola & La Rocca, 2024). Digital Twin (DT), Artificial Intelligence (AI), Internet of Things (IoT), Big Data Analytics, and City Information Modeling (CIM) provide municipal authorities powerful toolsets to make cities smarter, safer, cleaner, and more inclusive (Deng et al., 2021).

As planning, designing, and managing cities undergoes profound change, a renewed cultural approach enhancing informed decision-making based on knowledge is indispensable (Pultrone, 2023). Connected and digital technologies have historically found expression in the smart city paradigm, though defining what makes a city "intelligent" remains contested (Gaglione, 2023). Some authors focus on ICT technologies, sensor networks, and Big Data analysis for efficiency (Li et al., 2020); others emphasize improving quality of life and strengthening human and social capital through IT infrastructure and information management capabilities (Caragliu et al., 2013).

However, integrating advanced technologies in historic centres presents unique challenges inadequately addressed in existing smart city frameworks. Traditional approaches, criticized for technocentric limitations (Angelidou, 2017), focus on contemporary contexts with adaptable infrastructure, while historic centres require balancing: heritage conservation with technological innovation; cultural identity preservation with modern service requirements; physical constraints with contemporary infrastructure needs; and community wellbeing with tourism management.

In Europe, approximately 75% of the population lives in urban areas, projected to reach 80% by 2050. The European landscape comprises predominantly small and medium-sized cities. In Italy, many possess historic centres of extraordinary cultural significance but face management complexity, abandonment, and decay—particularly in regions like Calabria.

Current literature reveals three critical gaps: First, while computational urban design methods have advanced significantly (Koenig et al., 2020), their application remains largely experimental, with limited participatory approach integration (Gün, 2023). GeoAI technologies offer significant potential for sustainable urban planning through machine learning and predictive modelling (Aidaoui et al., 2024), yet implementation in heritage contexts requires careful adaptation.

Second, existing smart city frameworks inadequately address historic centres' specific vulnerabilities and opportunities. Risk governance literature focuses primarily on single-hazard approaches rather than integrated, multi-risk frameworks necessary for complex historic urban systems (Ferramosca & Terracciano, 2023).

Third, insufficient theorization exists on how data-driven tools can enhance rather than replace human-centred, experience-based urban design. Gün (2023) emphasizes that technology-driven urban design must balance computational power with intuitive design thinking, moving "like a pendulum" between traditional and computational approaches.

This study[1] addresses these gaps through a specific research question: How can GeoAI-enabled urban analysis and participatory design methodologies improve urban well-being while preserving cultural heritage in small and medium-sized historic centres? Research objectives are: to develop a replicable methodological framework for GeoAI-based urban regeneration in historic centres; to operationalize "urban well-being" through

[1] The study described in this article moves from the Citisense project, a research proposal developed for participation in the 2024 FISA (Italian Fund for Applied Sciences) Call. The proposal is currently under evaluation

measurable indicators adaptable to historical contexts; to test Living Lab processes for co-creating technology-based urban solutions.

2. Facing the challenge of transitions

Contemporary urban development is shaped by three interconnected transitions: digital, ecological, and cultural. The digital transition extends beyond technological adoption, encompassing fundamental shifts in how cities collect, process, and utilize data to inform decision-making (Kitchin, 2021). The ecological transition addresses climate change mitigation and adaptation, requiring cities to reimagine their metabolic flows and resource consumption patterns (Pinson & Morel Journel, 2016). The cultural transition involves evolving social values, expectations of participatory governance, and redefined relationships between citizens and urban environments. Recognition of these interconnected challenges has catalysed new policy frameworks and conceptual models at international and European levels. The United Nations' 2030 Agenda for Sustainable Development, the European Union's Green Deal, and initiatives such as the New European Bauhaus exemplify coordinated responses across technological, environmental, and social dimensions.

Artificial intelligence's role in achieving the UN 2030 Agenda goals presents a fundamentally ambivalent picture. Recent comprehensive analyses reveal that AI can act as both enabler and inhibitor across the 17 Sustainable Development Goals (SDGs) and their 169 targets (Vinuesa et al., 2020). Positively, AI applications demonstrate significant potential for urban sustainability: predictive algorithms can optimize energy distribution and reduce consumption (SDG 7, 11, 13), machine learning models can enhance public health surveillance and personalized healthcare delivery (SDG 3), and computer vision systems can improve traffic management and reduce emissions (SDG 11, 13). However, this technological optimism must be tempered by acknowledging AI's negative externalities and potential to exacerbate existing inequalities. Algorithmic bias embedded in training data can perpetuate or amplify social discrimination, particularly affecting marginalized urban populations (Eubanks, 2018). AI-powered surveillance system deployment raises fundamental questions about privacy, autonomy, and democratic governance in urban spaces (Zuboff, 2019). Moreover, AI capability concentration in technologically advanced regions and among well-resourced actors risks widening the digital divide between and within cities (SDG 10), creating "smart" enclaves alongside digitally excluded communities. This dual nature necessitates careful, ethically-informed approaches that maximize benefits while actively mitigating risks.

The New European Bauhaus (NEB) initiative[2] represents a paradigmatic shift in conceptualizing relationships between technological innovation, environmental sustainability, and human well-being in urban contexts. Moving beyond purely technocratic approaches, the NEB integrates three inseparable core values: sustainability (addressing environmental challenges through circular economy principles and nature-based solutions), quality of experience (emphasizing aesthetics, design excellence, and cultural richness), and inclusion (ensuring accessibility, affordability, and participation across diverse social groups).

The NEB's transdisciplinary approach, bringing together architects, engineers, designers, artists, scientists, and citizens, resonates strongly with emerging perspectives on urban technology deployment. It recognizes that data-driven and AI-powered tools are not value-neutral instruments but must be consciously oriented toward human-centred outcomes that respect cultural diversity and enhance collective well-being.

The 2030 Agenda goals, combined with the New European Bauhaus vision and emerging technology potential, open new horizons for building truly smart cities, helping overcome long-standing challenges that have hindered this paradigm. The smart city concept has evolved over time, allowing us to identify at least three phases.

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[2] New European Bauhaus (NEB) is a policy and funding initiative that makes green transition in built environments and beyond enjoyable, attractive and convenient for all. https://new-european-bauhaus.europa.eu/index_en

The "smart city" notion emerged in the 1990s at the confluence of multiple technological, economic, and urban development trends. Initially, the term was closely associated with information and communication technologies (ICTs) rise and their potential application to urban management and service delivery (Hollands, 2008). Early conceptualizations emphasized digital infrastructure deployment—sensors, networks, databases, and control systems—to enhance operational efficiency in energy distribution, traffic management, and public services (Caragliu et al., 2011). This first-generation smart city model was largely technology-centric and vendor-driven, with major technology corporations promoting comprehensive urban operating systems as solutions to complex urban challenges (Söderström et al., 2014). However, this techno-deterministic perspective often overlooked social, political, and cultural dimensions of urban life, treating cities primarily as systems to be optimized rather than as complex socio-spatial formations shaped by diverse actors, interests, and values (Papa et al., 2013).

The 2010s witnessed a significant critical turn in smart city discourse. Researchers began systematically interrogating assumptions underlying technology-driven urbanism, revealing issues of corporate capture of urban governance, surveillance and privacy concerns, algorithmic bias, and potential for smart city technologies to reproduce or amplify existing social inequalities (Kitchin, 2014). First-generation smart city projects often failed to deliver promised benefits, particularly to marginalized communities, while generating new forms of digital exclusion and spatial inequality (Angelidou, 2017).

This critical scholarship catalyzed a paradigm shift toward more participatory, citizen-centric models positioning residents not as passive recipients of smart services but as active co-producers of urban intelligence. European Union policies have been particularly influential in promoting this evolution, with initiatives such as the European Innovation Partnership on Smart Cities and Communities[3] explicitly foregrounding citizen engagement, co-creation methodologies, and governance innovations alongside technological deployment.

Climate urgency and digital transformation convergence has fundamentally reshaped smart city discourse over the past decade. Contemporary smart city frameworks increasingly recognize that urban intelligence must serve not only efficiency or economic competitiveness but, fundamentally, environmental sustainability and resilience (Bibri & Krogstie, 2017). This integration of ecological imperatives with digital innovation—what scholars term the socio-ecological-digital transition—represents a third major evolution of the smart city paradigm (Yigitcanlar et al., 2019).

3. Integrating technologies into urban planning

With the advent of the new millennium, the urban data landscape has been radically transformed, shifting from small data to big data, in which data generation is continuous, system-wide, fine-grained, relational, and cross-domain (Kitchin, 2014). This production has been accompanied by new analyses for extracting information from vast dynamic datasets, grouped into four main classes: data mining and pattern recognition, data visualization, statistical analysis, and forecasting or optimization (Miller, 2010). These rely on machine learning and increased computing power, enabling a new data-driven science that generates hypotheses and insights "born from data" (Kelling et al., 2009). This has led to the rise of 'urban informatics' (Foth, 2009),a human-computer interaction approach to understanding urban processes, and 'urban science', a computational modelling discipline merging geocomputing, data science, and social physics (Batty, 2013). While urban informatics focuses on human–technology–space interactions, urban science aims to explain and simulate city processes and forecast future scenarios, providing city managers with valuable decision-making tools.

The current frontier of smart cities lies in integrating advanced computational technologies (big data analytics, digital twins, and artificial intelligence) into urban planning and governance. Big data, generated by sensors

3 The European Innovation Partnership on Smart Cities and Communities (EIP-SCC) is a major market changing undertaking supported by the European Commission bringing together cities, industries, SMEs, investors, researchers and other smart city actors. https://smart-cities-marketplace.ec.europa.eu/sites/default/files/EIP_Brochure.pdf

and mobile devices, complements traditional sources such as census and remote sensing data. Yet transforming this data flood into actionable insights requires robust analytical frameworks, awareness of data quality and bias, and attention to ethical and privacy concerns.

Digital twins, dynamic virtual replicas of physical systems enabling simulation, prediction, and scenario analysis, offer promising opportunities for evidence-based planning (Dembski et al., 2020). Deng et al. (2021) emphasize that, combined with IoT, 5G, blockchain, and AI, digital twins can foster responsive, adaptive smart cities. However, without participatory governance and explicit social and environmental aims, they risk reproducing technocentric smart city limitations.

Artificial intelligence adds new capabilities (pattern recognition, predictive modelling, optimization, and generative design) that are transforming planning practice (Batty, 2018). Machine learning detects hidden urban patterns, predicts trajectories, and generates design alternatives meeting multiple criteria. Recent work on generative AI for digital twins highlights its potential for autonomously producing urban data, scenarios, and 3D models (Xu et al., 2024).

AI has also entered spatial analysis, forming Geospatial Artificial Intelligence (GeoAI), which expands quantitative research possibilities. In spatial planning, GeoAI enhances the analysis, visualization, and simulation of how users perceive and navigate spaces; supports public engagement and collaborative planning; and informs land use, transport, and environmental policy. GeoAI employs two planning methodologies: the top-down, knowledge-based approach and the bottom-up, data-driven one, the latter grounded in ML techniques and now dominant due to its accuracy in defining smart city scenarios (Li & Hsu, 2022). Among ML methods, deep learning, particularly convolutional neural networks (CNNs), is valued for robust feature extraction and projection performance

GeoAI leverages methodological and technical tools from GIScience. In recent years, GIS-based applications have integrated statistical techniques to manage diverse territorial contexts toward smart cities. Their functional integration supports decision design and evaluation, giving rise to Spatial Decision Support Systems (SDSS) or Planning Support Systems (PSS) (Thomas, 2002).

However, incorporating AI into planning raises challenges regarding interpretability, accountability, bias mitigation, and balancing algorithmic recommendations with human judgment (Thakuriah et al., 2017). As Gün (2023) notes, technology-driven design tools reshape designers' engagement with data but cannot replace intuitive and heuristic design skills. Critical approaches are needed to combine technological potential with transparency, fairness, and democratic participation.

Terracciano and Ferramosca (2023), analyzing the Messina case, show that GIS-based risk assessments must be complemented by expert judgment and local knowledge to address urban vulnerability complexity. Their findings reveal that purely technical, optimization-oriented approaches risk neglecting non-quantifiable cultural, social, and identity values essential to historic centre regeneration.

4. The digital opportunity for historic centres. A focus on Calabria

Issues relating to historic settlements represent a shared challenge not only at the national level, but across the entire European Union. In this context, various European policies and initiatives have recognized the strategic value of urban historic heritage as a driver of sustainable development and social cohesion. The EU's New Urban Agenda[4] promotes an integrated approach to sustainable urban development that explicitly includes the enhancement of cultural heritage as a factor in quality of life and territorial attractiveness. The aforementioned New European Bauhaus links the European Green Deal to everyday living spaces, emphasizing

[4] The Urban Agenda for the EU brings together the Commission, national ministries, city authorities and other stakeholders to promote better laws, easier access to funding and more knowledge sharing on issues relevant for cities. https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/urban-agenda-eu_en#urban-agenda-for-the-eu

the importance of making the green transition accessible, beautiful, and inclusive, with a particular focus on the restoration and redevelopment of existing heritage. The Faro Convention[5] emphasizes the value of cultural heritage for society, recognizing the right of communities to actively participate in its management and enhancement. The EU's green and digital transition strategies[6] emphasize the importance of an integrated approach that combines conservation, technological innovation, and quality of life, promoting smart, sustainable, and inclusive cities and territories. These guidelines are particularly relevant for regions such as Calabria, where the restoration of historic settlements can contribute significantly to territorial resilience and the well-being of local communities. Historic settlements represent a significant heritage for Calabria, although many are unfortunately in a state of deterioration, some even in advanced decay. However, some key centres still have the potential for regeneration, which could significantly improve the territorial and landscape quality of the region, as well as its cultural and historical-artistic offerings. Particularly relevant is the heritage of smaller historic centres, a distinctive feature of Italy and Calabria, which constitute a widespread network of identity and cultural landmarks often neglected by traditional urban policies. The central challenge concerns the liveability and attractiveness of Calabrian historic centres, which require an integrated approach capable of addressing the multiple and diverse dimensions of contemporary transition. Legambiente's *Urban Ecosystem Report*[7], with the exception of the positive performance of the city of Cosenza (thirteenth and the only city in the south among the top 15), ranks the other four principals centres (Catanzaro, Crotone, Vibo Valentia, Reggio Calabria) among the worst 10 Italian cities, with a significant deficit in the field of urban services. The Sole 24 Ore *Quality of Life Survey*[8] also ranks the five Calabrian provinces in the bottom twenty positions, highlighting poor performance in terms of services for children, the elderly, and women, demonstrating the need for targeted interventions to improve social inclusion and public well-being. However, these data refer mainly to larger Calabrian settlements and do not provide a complete picture of the condition of smaller historic centres. Recent studies and research on small Calabrian villages have highlighted the complexity and multidimensionality of the challenges that characterize these contexts. Villages with fewer than 5,000 inhabitants, which represent 70% of Italian municipalities and are particularly numerous in Calabria (source: ANCI), face structural problems such as progressive abandonment, deterioration of the building stock, insufficient basic services, limited accessibility, and accelerated depopulation (Francini et al., 2012). Specific studies on the Calabrian context (Giuliani et al., 2021) have analysed the risk factors linked to the seismic vulnerability of the historical heritage of villages, highlighting how exposure to environmental risks (seismic, hydrogeological, instability) is intertwined with phenomena of socio-economic marginalization, creating conditions of systemic fragility. Research conducted on inland areas has documented the dynamics of depopulation and demographic aging that characterize the villages of inland Calabria, with some of the highest rates of demographic decline in the country (De Rossi, 2018). At the same time, these studies recognize the intrinsic value of these centres in terms of architectural, landscape, and cultural heritage. Teti's work (2017, 2022) on abandoned villages and the remaining population in inland areas of Calabria has highlighted not only the rich identity and culture of these places, but also the forms of creative resistance and local bottom-up regeneration strategies. More recent analyses (Viesti, 2021; Carrosio, 2019) emphasize how smaller villages can represent laboratories of social innovation and alternative models of development, provided that

[5] https://www.coe.int/en/web/culture-and-heritage/faro-convention

[6] https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/twin-green-digital-transition-how-sustainable-digital-technologies-could-enable-carbon-neutral-eu-2022-06-29_en

[7] Since 1994, Legambiente has published the Urban Ecosystem Report every year, produced in collaboration with Ambiente Italia and Il Sole 24 Ore, which measures the environmental performance of Italian cities. The ranking is based on twenty indicators that are normalized according to their distance from the reference threshold. The 2024 Report is available at the link: https://www.legambiente.it/wp-content/uploads/2021/11/Ecosistema-Urbano_libro2024.pdf

[8] Published annually since 1990, it examines 90 indicators relating to six macro-categories (wealth and consumption; business and work; environment and services; demography, society, and health; justice and security; culture and leisure). The 2024 ranking is available at: https://lab24.ilsole24ore.com/qualita-della-vita/tabelle/

differentiated policies and strategies are implemented that take into account the specificities of smaller contexts, their endogenous potential, and the need to strengthen essential services and physical and digital connectivity. Unlike contexts characterized by overtourism, Calabria and its smaller historic centres suffer mainly from undertourism, a condition of underutilization of tourism potential accompanied by deficiencies in essential services and quality of daily life. The primary objective must therefore be the well-being of resident communities, pursued through the improvement of services, accessibility, and economic opportunities. Restoration work must allow for the functional adaptation of heritage assets so that they can serve residential or tourist purposes, while protecting their historical and cultural character. Furthermore, in a region such as Calabria, which is highly exposed to environmental risks, conservation and enhancement objectives must also include the assessment of the causes and risk factors that threaten the integrity and survival of these historic areas. An effective protection and enhancement policy must integrate economic, social, urban, and building policies, promoting the introduction of services, accommodation, and hospitality options. This integrated approach must recognize the specific characteristics of smaller contexts and promote the liveability and attractiveness of historic centres as an essential condition for the authentic and lasting regeneration of the Calabrian territory. In this scenario, new digital and computational technologies can play a strategic role in enhancing the well-being and liveability of smaller historic centres, overcoming some of the structural limitations that characterize these contexts.

5. Methodology

From a methodological perspective, the challenges described earlier are addressed through two main approaches: integrating innovative technologies and using Living Labs for community engagement.

5.1 Technological approach

The Citisense approach aims to leverage advanced technologies, such as Artificial Intelligence (AI), big data, and wearable technologies, to facilitate the transformation of historic centres into intelligent, resilient, and citizen-centred environments. Specifically, it focuses on the following areas:

AI-Driven data analysis and integration

Complex data sets subjected to advanced AI-driven analysis come from various sources, including personal devices (such as wearables, smartphones, apps), public interfaces (QR codes, signage, access to public spaces), and databases (such as geolocation data) in an intelligent AI-powered system. Depending on the different data sources, the information collected may include:

- Personal data from wearable devices and mobile applications (e.g., fitness data, health monitoring);
- Geolocation data (public space usage patterns) to optimize the use and management of public spaces;
- Statistical data related to urban resource consumption and access of public services;
- Environmental data, such as weather conditions or dangerous situations (extreme temperatures);
- Sentiment analysis on social media to assess perceptions of safety and comfort.

This data is managed in compliance with the European Union's General Data Protection Regulation (GDPR)[9], requiring explicit and informed consent, anonymization protocols (K-anonymity and spatial and temporal data aggregation), and data retention and deletion rules. Furthermore, the application of a Data Protection Impact Assessment (DPIA) allows us to identify risks (re-identification from location trajectories; discrimination from algorithmic bias in route recommendations; invasion of privacy from continuous monitoring; data breaches; secondary uses beyond the stated purposes) and define mitigation measures (differential privacy techniques

9 https://gdpr-info.eu/

by adding calibrated noise to aggregated data; fairness audits of AI algorithms by testing for biases between demographic groups; strictly enforced data minimization and purpose limitation; end-to-end encryption for data transmission; transparent documentation of all data uses).

System integration for citizen wellbeing and urban management

Collecting and organizing the data described above allows us to provide citizens with informative feedback through dynamic maps, customized based on user preferences and real-time conditions, to improve their level of urban well-being. Urban well-being is defined as a combination of physical comfort, access to culture, and perceived safety.

- Physical comfort. Real-time maps suggest routes for pedestrians based on weather conditions (sunny or shaded areas), route difficulty (uphill or downhill), and the presence of public facilities (parks, benches, fountains, etc.). Alerts are available to highlight potentially dangerous areas to avoid temporary adverse weather events (heavy rain, flooding) or scheduled activities (construction sites, noisy activities, etc.).
- Access to culture. Urban well-being also includes the ability to access artistic and architectural heritage and urban services. To this end, the feedback provided includes information on areas that could improve the visitor experience: uncrowded squares or less frequented scenic spots, contemporary architecture or street art, traditional venues or attractive contemporary areas. Visit itineraries are customized based on user preferences.
- Perceived safety. In this case, the suggestions focus on safer and better-lit routes for nighttime mobility, reducing the perceived risk of walking alone at night, based on data collected from social media, public lighting, and population density. It uses sentiment data extracted from social media to highlight areas that might be perceived as less safe.

Citizen experience and multi-access visualization

Users access information both through immediate data visualization on personal devices and by enhancing the physical urban environment. This latter aspect draws on suggestions from community engagement initiatives, with the aim of highlighting and promoting " well-being places" located in the urban context. "Well-being places" are public spaces identified through participatory mapping (as part of Living Labs) and validated by composite scores that combine assessments of aesthetic quality and frequency of social interaction. Visualization is therefore intended as a multi-level offering tool, consisting of:

- AI-generated insights, which will be displayed through interactive dashboards accessible via smartphone;
- Physical touchpoints and visualization elements, such as totems or information points located in public spaces;
- Access to relevant information identified in places classified as "well-being places".

This system offers a user-friendly experience, allowing citizens to interact with their urban environment in ways that optimize safety, comfort, and efficiency, while also enabling local authorities to dynamically manage public resources and spaces.

5.2 Living lab: community design and engagement

The implementation of Living Labs represents a key strategy in managing urban participatory processes. These environments bring together companies, public institutions, universities, and citizens in public–private–people partnerships (4Ps) to test and develop innovations in real-world scenarios (Westerlund & Leminen, 2011).

Introduced in the 1990s and consolidated in 2006 with the European Commission’s initiative (Dutilleul et al., 2011), this model effectively bridges the gap between technological development and user needs by integrating technical expertise with creativity. Living Labs embody a philosophy of mediation between top-down institutional approaches and bottom-up citizen initiatives (Coenen et al., 2014).

In urban Living Labs, citizens can assume multiple roles, ranging from simple informants to testers, collaborators, and co-creators in the development process (Juujärvi & Pesso, 2013). Their participation often stems from a connection to the territory and a sense of belonging to the community (Horelli, 2013). Municipal administrations act as facilitators, orchestrating interactions among different stakeholders.

This approach fosters participatory innovation in smart cities by emphasizing the role of users as innovators and promoting effective multi-stakeholder collaboration. These are environments in which the openness of innovation manages to transcend the organizational infrastructures that are traditionally operating in the city and to invent new institutional figures for, or ways of, dialoguing between citizens and institutions (De Bonis et al., 2014).

At the international level, several initiatives have demonstrated the effectiveness of the Living Lab model, offering valuable lessons for its implementation. The European Network of Living Labs (ENoLL), founded in 2006, is the most significant international network of Living Labs, bringing together over 400 active initiatives worldwide (Schuurman et al., 2016). ENoLL's experience has highlighted the importance of the long-term sustainability of Living Labs, the creation of standardized methodologies for evaluating results, and the need to balance commercial interests and social benefits (Leminen et al., 2012). Other relevant experiences include the Amsterdam Living Lab, which has developed innovative solutions for urban mobility through collaboration between citizens and technology developers and the Manchester Urban Living Lab, focused on energy sustainability and community engagement (Voytenko et al., 2016).

These practices have shown that the success of Living Labs depends on the ability to maintain genuine citizen engagement beyond the initial phase, the effective integration of user data and feedback into decision-making processes, and the creation of flexible governance structures that allow for adaptation to local needs (Steen & van Bueren, 2017).

In conclusion, three main advantages can be identified from the implementation of Living Labs in cities (Veeckman & van der Graaf 2015): i) they facilitate citizen participation and collaboration; ii) they enable co-creation processes in urban settings; iii) they empower citizens.

Citisense Living Labs are conceived as dynamic spaces for real-life testing, co-design, and open innovation, where citizens and stakeholders collaborate to develop and validate smart city technologies. The focus will be on creating solutions that enhance urban safety, social wellbeing, and quality of life in Italian historic centres. The Living Lab methodology emphasizes a user-centred approach, ensuring that the technologies developed respond to real urban needs.

The methodology is based on four key phases:

Community involvement and co-design

Citizens and administrations are involved in a participatory design process, playing an active role in co-creating solutions to address urban challenges, thereby gaining a sense of ownership of the ideas developed.

Participants are recruited through different channels: institutional (government websites and social media); third sector (in collaboration with local, cultural, environmental, or neighbourhood associations); educational institutions (secondary schools to involve young people); tourist offices (to capture the perspective of visitors). The inclusion criteria provide for distribution among different categories of users: residents, visitors, key stakeholders (local entrepreneurs, cultural operators, municipal officials); with a focus on sampling strategies to achieve a uniform distribution in terms of age groups, gender, socio-economic status, mobility profiles, and levels of digital literacy.

The phases and activities of the living lab include:

- Workshops, brainstorming sessions, and focus groups to identify local needs, define objectives, and co-design smart urban solutions;
- Co-design to enable participants to collaborate on prototyping and testing technologies, providing feedback on how well they meet their needs, thus promoting mutual learning between users and designers;
- Continuous feedback cycle to ensure constant citizen involvement and make iterative improvements to technologies based on real-time data and user feedback.

Laboratory governance and citizen training

Stakeholder coordination is ensured by the presence of a Living Lab manager (responsible for day-to-day coordination, communication with participants, logistics and documentation management) and a Panel manager (responsible for participant recruitment, database management and engagement maintenance). In general, the staff responsible for managing Living Labs takes on the task of facilitating participants, ensuring that the user-centred design approach is maintained and that citizens feel comfortable adopting the technology.

To this end, citizens participating in Living Labs are trained in the use of the smart technologies being tested (e.g., accessing data via dashboards and using dynamic maps). These sessions focus on facilitating digital learning and familiarizing citizens with AI-based systems, avoiding the phenomenon of the "AI black box." This approach promotes social equity and ensures that the benefits of smart city solutions are accessible to all.

Community ICT interaction and data access

The project focuses on developing an intuitive user experience that allows citizens to easily interact with the technologies being tested and developed, ensuring a multi-channel data access system and high-quality design. The methodology guarantees:

- Data visualization tools. Interactive dashboards accessible via smartphone provide real-time information (e.g., personalized route suggestions, safety alerts, and cultural recommendations);
- Physical touchpoints. Information kiosks and public access points complement digital access, ensuring that even those less familiar with ICT tools can interact with the system. These contact points are located in strategic locations, such as libraries or tourist centres, providing real-time information for all citizens.

The user interface is designed with an inclusive approach, ensuring that the experience is accessible to users with different levels of digital literacy.

Scalability and transferability of solutions

To enable comparative analysis and assess the transferability of solutions, the pilots (described in the previous paragraph) share: common data collection protocols (standardized sensor deployment, comparable survey tools), a shared technology platform, parallel Living Lab timelines (synchronized phases for cross-site learning), and inter-pilot exchanges (for knowledge sharing).

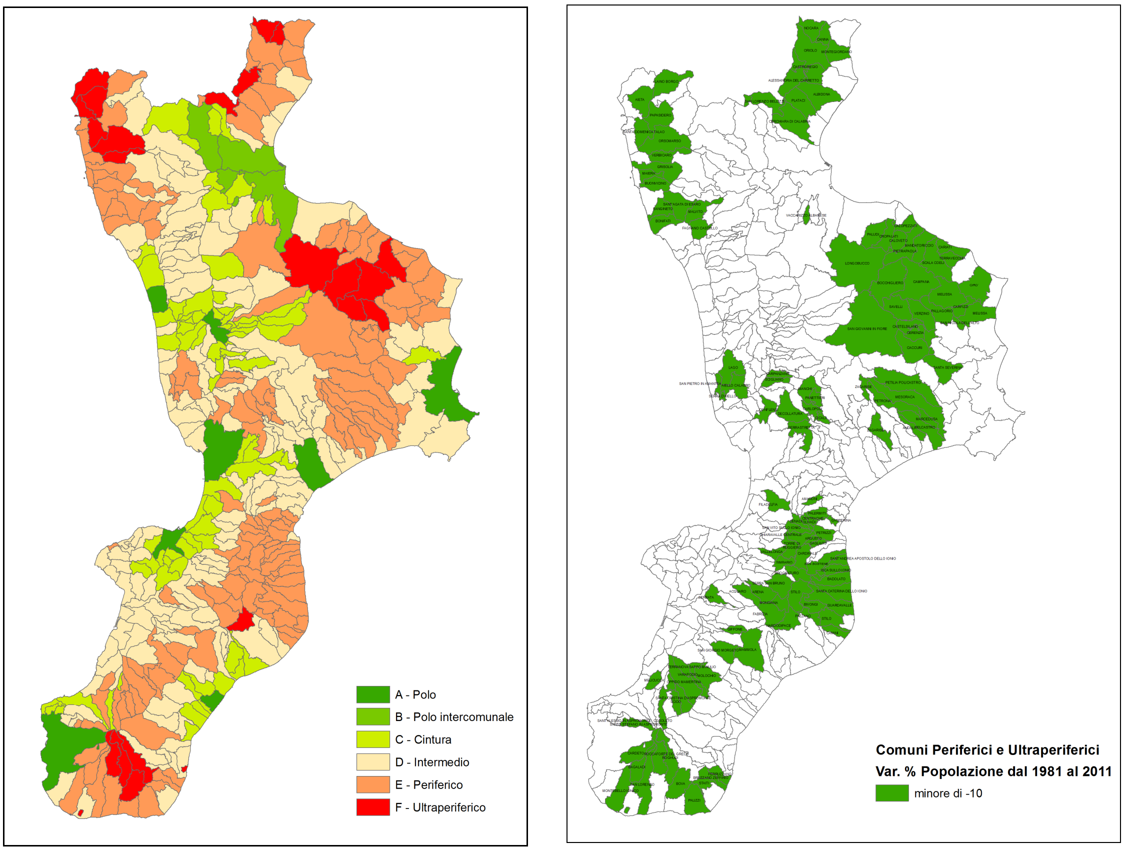
5.3 Selection of pilot

Within the Calabria region, identified as the experimentation area, criteria were established for selecting pilot municipalities to ensure they reflect a comprehensive taxonomy of the various types of historic centres in the territory. These diverse settings will allow the project to test its solutions across different urban environments, ensuring that the technologies developed are adaptable and scalable to varying challenges.

Calabria has a complex and articulated settlement pattern, characterized by 404 municipalities distributed over a predominantly mountainous territory (53.5% of municipalities are entirely mountainous) that is home to

28% of the regional population[10]. The Calabrian territory is affected by significant demographic and socioeconomic dynamics that have profoundly influenced the evolution of historic centres. Between 1951 and 2019, while the main urban centres maintained relative demographic stability, the inland areas of southern Italy lost a total of 1.2 million residents, with an average annual rate of decline of -2.5‰, and one in three municipalities has been systematically losing population since 1951 (Bianchino et al., 2022). In Calabria, this trend is reflected in a continuous demographic decline: between 2020 and 2024, the region recorded a net loss of 28,459 inhabitants, distributed across all provinces.

According to the classification of the National Strategy for Internal Areas (SNAI)[11] a significant proportion of Calabrian municipalities fall into the 'intermediate', 'peripheral' and 'ultra-peripheral', characterized by greater distance from essential services (health, education, rail transport) and by phenomena of territorial marginalization. The population of Calabria's internal areas is on average older than that of urban centres, with an old-age index that reaches over 223 elderly people per 100 young people in ultra-peripheral municipalities, compared to 178.8 in urban centres. The Calabria Region has identified seven SNAI areas for the 2021-2027 cycle, comprising a total of 58 municipalities in the initial pilot areas[12].



(a) (b)

Fig.1 (a) Classification of inner areas in Calabria (b) SNAI intervention areas in Calabria

From a socioeconomic point of view, inland areas of Calabria have higher levels of poverty risk (14.3-14.4% in peripheral and ultra-peripheral municipalities) than urban centres, although the incidence of absolute poverty is distributed in a more complex way across the territory (Bianchino et al., 2022). These dynamics are intertwined with the presence of a significant historical and cultural heritage and with diverse tourism

10 Data taken from "Rapporto Montagne Italia 2025", Rubbettino Editore.
11 https://www.agenziacoesione.gov.it/strategia-nazionale-aree-interne/
12 https://calabriaeuropa.regione.calabria.it/wp-content/uploads/2024/05/DGR-n_490-del-27.11.2015 - Approvazione-Strategia-Regionale-per-le-Aree-Interne.pdf

opportunities, ranging from isolated villages of scenic beauty to coastal centres with high tourist appeal, such as Tropea, which attracts significant national and international flows, to the peripheral historic centres of major urban areas.

In light of these general considerations on the structure of the regional territory, the selection of pilot sites was carried out using a multi-criteria framework that considers the following aspects: Demographic criteria (population size and density, demographic trends, age structure); geographical criteria (topography, accessibility, environmental risks, climate zone); socio-economic criteria (employment indices, tourist intensity, infrastructure quality); heritage/cultural criteria (presence of cultural sites, integrity of the historic centre, cultural vitality, state of the building heritage).

The application of these criteria resulted in the selection of pilot sites, which are outlined below in both qualitative and quantitative terms:

- Historic centres that have become peripheral due to subsequent urban expansions, yet still retain administrative and representational functions. These areas are affected by housing issues, such as the replacement of residents with socially disadvantaged groups, social insecurity, and the lack of adaptation to contemporary life. While they typically hold historical and architectural heritage, they attract only modest tourism flows and are often subject to selective rehabilitation efforts.
- Historic centres with intense tourism flows, representing a few cases (e.g., Tropea, Pizzo Calabro) that attract significant national and international tourist influxes. These areas often exceed their carrying capacity during certain times of the year, which is increasingly frequent and intense, leading to problems related to mobility, liveability, environmental pressure, and the overall enjoyment of these spaces.
- Isolated historic villages, among the most characteristic elements of the regional settlement system, face depopulation, ageing, and abandonment. Situated within valuable landscape or environmental settings that enhance their value, these villages are often far from essential services and are classified as ultra-peripheral centres under the taxonomy of Internal Areas. They hold historical and cultural values that could be leveraged to attract niche tourism.
- Coastal historic centres, which are of two main types: fishing villages located near the coast and mid-coastal centres that have expanded along the shoreline, forming modern settlements known as "marine". These areas experience seasonal population fluctuations due to the presence of numerous "second homes" used in the summer and return tourism from emigrants.
- Historic centres near Natural Parks. The central spine of Calabria is continuously intersected by three national parks: Pollino National Park, Sila National Park, and Aspromonte National Park. While the perimeters of these protected areas often exclude inhabited centres, these towns are still strongly influenced by their proximity to the parks and the relationships they maintain with these natural areas.

Fig.2 qualitative description of the pilot sites

Each of these urban settings provide a unique context for testing the smart city technologies developed within the four intervention domains of the project, ensuring a broad application of solutions.

6. Discussion

Through the integration of planning, regeneration and Geo-AI, the Citisense project sets a series of objectives aimed at promoting the liveability and attractiveness of historic centres, with particular attention to the heritage of smaller historic centres, which are a distinctive feature of Italy. In particular:

- Enhancing citizens' perceived wellbeing and comfort by improving individual rewarding experiences for both residents and visitors. This objective focuses on improving the individual urban experience by creating personalized journeys that take into account different preferences, such as physical comfort (shade or sun, noise levels), emotional well-being (safety and personal security), and aesthetic preferences and interests (art, architecture, or cultural heritage). By delivering dynamic, data-driven maps and recommendations based on real-time data, the project aims to tailor the experience to the specific needs of residents, tourists, and other urban users.
- Ensuring public spaces are accessible, safe, and suitable places of interaction by fostering social interaction, community engagement and inclusivity. The objective targets the creation of inclusive public spaces that foster social interaction and community cohesion. By creating accessible and liveable urban environments, cultural divides are reduced, improving the experience of both locals and visitors, ensuring that urban spaces can accommodate diverse needs. The system is also open to feedback and suggestions from city users.
- Support urban governance by enabling local governments to manage urban resources more efficiently using big data, thus anticipating urban needs and providing timely and dynamic action. Local governments face challenges in managing limited urban resources and maintaining public services in historic centres. Data-driven governance systems that provide real-time information on urban needs help city governments make informed and dynamic decisions. By anticipating demand, the system allows for more efficient urban management, reducing congestion and improving the overall quality of life for citizens and increasing sense of belonging.

All aforementioned objectives align on a wider scope with the New European Bauhaus (NEB) initiative by combining beauty, functionality, and sustainability criteria, to sustain the development of cities that are human-centred and resilient.

6.1 Potential socio-economic impacts

The socio-economic impacts resulting from the Citisense approach operate at various levels (individual, community, territorial, public administration).

Individual impact

At individual level the project ensures a consistent impact, given that access to information will be conveyed via real-time data to citizens while they carry out ordinary activities. Immediateness of access to such new data and tools significantly enhances the comfort, matching simultaneously with activities that citizens carry out as a part of their relevant interests associated with their mobility, or by enjoyment of cultural experience. The typical use of dynamic maps does not currently foresee access to a wellbeing dataset, as proposed by Citisense. A brand-new set of information can be widely perceived by citizens as a tangible effort to meet their real needs. Indeed, the population is made up of different individuals, with varying characteristics that shape individual perception, for example in relation to age, physical mobility or limitations, emotional stress, etc. As a result, increasing citizens' and tourists' confidence in using public spaces, as well as the perceived individual safety provides for more attractive cities for residents and visitors.

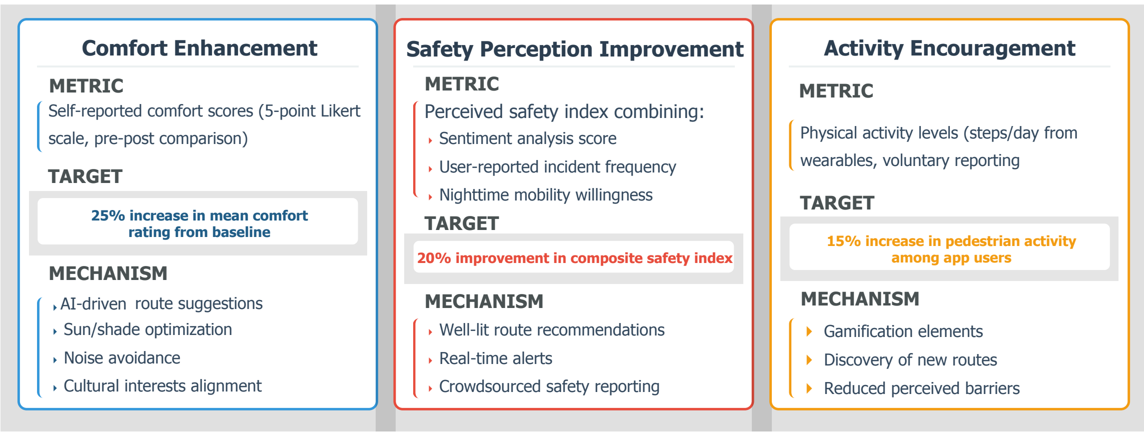


Fig.3 Individual impact assessment metric

Community impact

The activities carried out within the framework of the Living Labs help to foster a sense of belonging and responsibility among residents. As citizens collaborate with local authorities, researchers, and businesses, they develop a shared vision for the future of their cities, thereby strengthening social cohesion. This aspect is particularly important, as it contributes to creating a favourable environment in which smart city services can operate effectively.

This is a significant impact, as it relies on the relational bonds within a community and strengthens its ability to be resilient, supportive, and inclusive.

More cohesive cities are certainly a fundamental foundation that preserves the integrity and authenticity of historic centres themselves, as they help reduce depopulation and promote the inclusion of disadvantaged groups in civic initiatives.

Impact assessment metric:

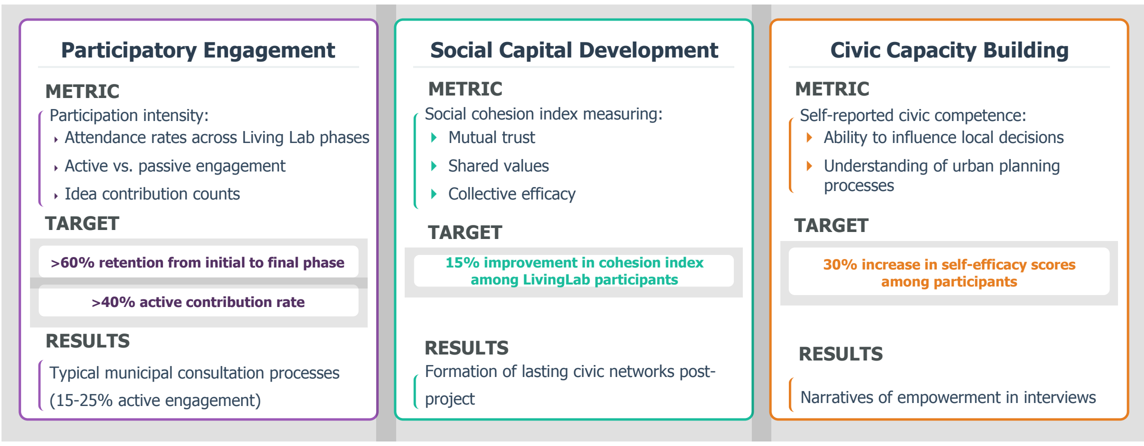


Fig.4 Community impact assessment metric

Territorial impact

The Citisense approach enhances cultural tourism experiences by enabling visitors to access personalized information and insights, such as recommendations on destinations, visiting times, and itineraries, which can be regarded as smart tourism services.

Emphasizing visitor well-being represents an advancement in both the concept and the experience of tourism, as it entails, for instance, the possibility of avoiding congestion peaks by suggesting alternative routes and visiting schedules. Ultimately, this contributes to redefining the notion of "well-being places" in relation to situational and emotional perceptions.

Such an enhanced qualitative service generates positive territorial impacts, fostering more rewarding visitor experiences and promoting economic growth for micro and small enterprises, thereby paving the way for greater economic vitality and urban regeneration.

Impact assessment metric:

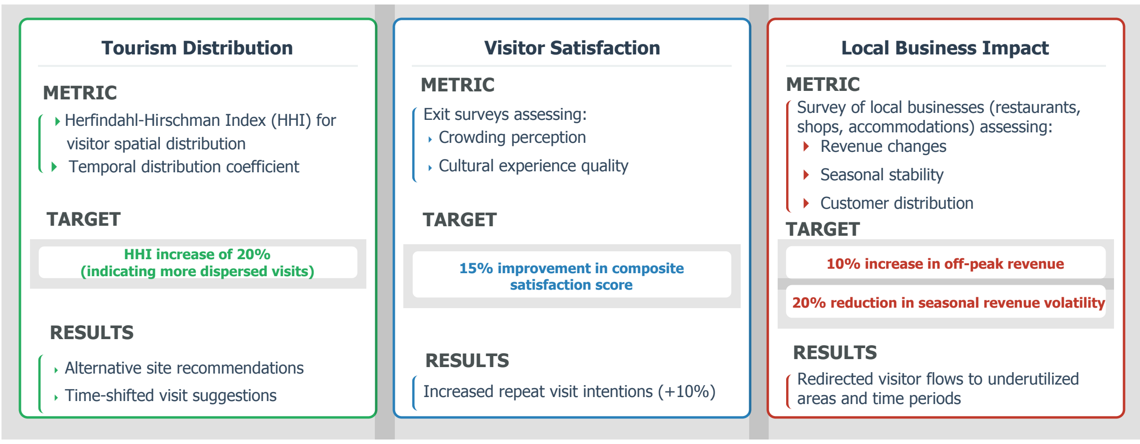


Fig.5 Territorial impact assessment metric

Public administration impact

Public authorities and stakeholders involved in the Citisense approach can derive significant benefits in terms of collective learning. First and foremost, they can obtain datasets which, when combined with an understanding of the specific characteristics, opportunities, and challenges of local territories, can effectively support the scope of public intervention.

The most crucial aspect, however, concerns resource management. Access to a comprehensive dataset serves as a key input for resource allocation, with the goal of improving the quality of smart city services and enhancing citizens' well-being. Commerce, security, public health prevention, and mobility are key dimensions of local governance. The availability of tools derived from personal devices and environmental sensors enables authorities to anticipate service demand in these areas. Consequently, this can lead to more efficient public spending and optimized resource use.

The metrics for assessing this impact should be sought in the improvement of resident and visitor satisfaction (evaluated through specific surveys) and in the wider adoption of data dashboards within public decision-making processes.

7. Conclusions and research perspectives

Technological innovation offers significant opportunities to protect, enhance, and regenerate Italy's historic centres. However, as already emerged from the expected results, the well-being of residents and the environment, as well as the quality of the landscape and cultural heritage, both tangible and intangible, cannot be the simple product of advanced technologies: these must remain tools at the service of communities, not the ultimate goal of urban policies.

The Citisense project, thanks to the combination of explainable AI (XAI), participatory design, and real-time data collection, represents a departure from the traditional Smart Cities paradigm, often criticized for its focus on technocratic and infrastructural solutions at the expense of social and cultural values. The focus on urban well-being, landscape quality, and cultural heritage enhancement is an important step towards context-sensitive and inclusive models of technological innovation.

Most national and international urban transformation/regeneration projects focus on contemporary cities with adaptable infrastructure, while greater attention should be paid to the specific challenges faced by historic centres (particularly small and medium-sized ones). These areas require a delicate balance between preserving cultural heritage and introducing cutting-edge technologies to improve urban management and citizen well-being.

The ability to collect and integrate anonymized personal data from wearable devices, smartphones, and municipal databases allows for the creation of a personalized urban experience. This user-centric approach enables dynamic real-time mapping of public spaces based on user preferences and contextual factors such as weather, safety, and crowding levels. Unlike traditional models, which focus on collecting infrastructure data via large urban sensor networks, innovative methods can be developed that use personal devices to collect information, significantly reducing the need for new sensor installations. This approach not only minimizes infrastructure costs, but also ensures that solutions are scalable and adaptable to different cities without massive investment.

Developing community-based designs with explainable AI (XAI) improves citizen trust and engagement. By involving users in the shared design process, citizens actively shape smart city solutions, ensuring that systems reflect their needs and concerns. The participatory approach of co-design encourages greater user involvement, making citizens key contributors to urban innovation and resource management.

The impacts described in the previous paragraph concern various levels: for individuals, increased perceived comfort and safety; for communities, greater social cohesion and active participation through Living Labs; for territories, more sustainable cultural tourism and new opportunities for local economies; for public administrations, innovative data-based governance tools capable of optimizing resource allocation. Although promising, these prospects also have limitations that require critical reflection:

- Local contextualization: each historic centre has physical, social, and economic characteristics that require tailor-made solutions, avoiding technological standardization that would risk compromising identity and authenticity;
- Balance between conservation and innovation: technologies must be introduced with respect for architectural and cultural heritage, avoiding invasive interventions that alter the perception of the urban landscape;
- Effective participation and transparency: the use of XAI and co-design methodologies is crucial to strengthen citizens' trust and counteract the biases inherent in algorithmic systems;
- Integrated governance and strategic vision: innovation must be part of coordinated urban plans, avoiding fragmentation and dispersion of projects that would reduce their impact.

The research perspectives emerging from Citisense include:

- The construction of conceptual frameworks that integrate cultural heritage, local identity, and digital infrastructure, overcoming the still widespread separation between Smart Cities and the protection of cultural heritage;
- The development of mixed online/offline methodologies to assess the social value of places, capable of capturing the ‘deep values’ of historic centres and guiding more inclusive decisions;
- The development of predictive and explainable AI to support urban decisions on comfort, environment, and tourism, while ensuring interpretability and social acceptability;
- The analysis of overtourism and seasonality dynamics in smaller historic centres, with models capable of suggesting visitor distribution strategies without compromising the quality of life of residents;
- The establishment of public monitoring systems for the long-term impacts of technological solutions, through shared indicators of well-being, sustainability, and heritage quality.

In conclusion, Citisense's main contribution is to show that technology, when integrated into an overall strategic vision and accompanied by participatory practices, can support urban regeneration processes that respect heritage and are oriented towards collective well-being. The biggest challenge is not only to innovate, but to do so in a coordinated manner, avoiding dispersion and fragmentation, and ensuring that innovation is always guided by the common good and long-term sustainability.

Notes

Although the paper is the result of the joint work of the authors, M. Zupi wrote sections 1, 6 and 7, D. M. Tufarelli section 2, A. Bisello section 3, P. Celani sections 4 and 5.3 and D. Sardo sections 5.1 and 5.2.

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Fig.1a and 1b are taken from Burc n. 90 of 22 December 2015, available at the link: https://calabriaeuropa.regione.calabria.it/wp-content/uploads/2024/05/DGR-n_490-del-27.11.2015.-Approvazione-Strategia-Regionale-per-le-Aree-Interne.pdf

Fig.2, 3, 4 and 5 are made by the authors.

Author's profile

Pierfrancesco Celani

Architect, Ph.D. in Psychology of Programming and Artificial Intelligence. In 2006 he specialized at IUAV University of Venice in participatory planning and urban development. In 2008 he attended The Eco-Polis International Masters in environmental and regional policies for sustainability and local development at the University of Ferrara. Since his master degree, he has been working in the fields of regional planning, urban design, valorization of historical and natural cultural heritage, and environmental monitoring of large-scale infrastructure. He focused his research working on sustainable cities and architecture, investigating the relationship between design quality and sustainability. Currently, he is a research fellow at the Department of Environmental Engineering of University of Calabria and works with smart cities and innovative technologies applied to the city.

Daniel Enrique Sardo

Architect, Ph.D. in Economics, Territorial and Urban Development from the University of Ferrara, Italy. He is currently Coordinator of the Professional Application Programs (PAP) and Professor of the Bachelor in Architecture, Master in Sustainable City and Public Space and PhD in Habitat and Sustainability at the Department of Habitat and Urban Development of Iteso, Jesuit University of Guadalajara, Mexico. He is an ad-honorem researcher and environmental policy advisor at the Catholic University of Córdoba and a contract professor at the same university. Since 2009 he has been working as an international consultant for local governments and coordinator of numerous projects for sustainable local and urban development in Italy and Latin America. He has given conferences and seminars in Argentina, Chile and Italy on sustainable local development, interdisciplinary approach to urban and territorial problems, participatory governance, collective intelligence and smart communities.

Massimo Zupi

Associate Professor in technical and urban planning at the Department of Environmental Engineering, University of Calabria. PhD in Technologies and Environmental Planning. He conducts research on the issues of territorial governance, with particular attention to urban regeneration, reading, protection and enhancement of the landscape, local development in weak contexts, intertwining educational experiences and operational experimentation in the field, through the deepening of analysis techniques and the verification of the potential of the most innovative urban instrumentation. He was research fellow from 2012 to 2018, on the following topics: Transport and territory interaction in infomobility systems; Participation and communication in the smart city; Enhancement strategies for valuable identity landscapes; Territory Regeneration's Tools and Techniques.

Margherita Tufarelli

She is a Researcher in the design field at the University of Florence (Italy) since 2021. Her research explores the opportunities and impacts of digital transformation on the design and production processes, particularly emphasising traditional local manufacturing and its tangible and intangible Heritage. Her research interests have followed an organic path from earning a Master's Degree in Design in 2014 to a PhD in Design in 2020 at the School of Doctorate at the University of Florence. Coherent research activities enrich her profile, all rooted in the digital transition of design and manufacturing systems, always considering the centrality of intangible aspects of cultural and creative productions.

Adriano Bisello

Urban Planner and Ph.D. in Real Estate Economics. He is senior researcher in the Urban and Regional Energy Systems group at Eurac Research in Bolzano (Italy) and senior Manager at Jakala Civitas. Adriano's activities range from local to European-funded projects in the field of smart cities and energy transition, with a focus on multiple-benefits and energy communities. Actually he is project manager of the smart city project EU H2020 STARDUST in the "Lighthouse city" of Trento (Italy) , in H2020 VARCITIES, and subtask co-leader in the IEA Annex 83 on Positive Energy District. Since 2015, Adriano has managed the international conferences on "Smart and Sustainable Planning forCities and Regions" —SSPCR— held by Eurac Research and his works are published in international books and journals.

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Planning for sustainable tourism in protected areas. A policy-oriented spatial evaluation framework

Rachele Vanessa Gatto [a*], Francesca Perrone [b], Francesco Scorza [c]

[a] Department of Engineering (DIING)
University of Basilicata, Potenza, Italy
e-mail: rachelevanessa.gatto@unibas.it
ORCID: https://orcid.org/0009-0007-3024-112X
* Corresponding author

[b] Department of Planning, Design and Technology of Architecture (DPTA)
Sapienza University of Rome, Rome, Italy
e-mail: francesca.perrone@uniroma1.it
ORCID: https://orcid.org/0000-0001-5240-8065

[c] Department of Engineering (DIING)
University of Basilicata, Potenza, Italy
e-mail: francesco.scorza@unibas.it
ORCID: https://orcid.org/0000-0001-6149-7346

Abstract
The governance of protected areas plays a key role in preserving biodiversity and fostering sustainable development, particularly through nature-based tourism. This paper introduces the Robustness Supply Tourism Index (RSTI), a robust tool to assess the infrastructural balance of tourism destinations within protected areas. The study focuses on the Appennino Lucano Val d'Agri Lagonegrese National Park in Italy, where the STESY model (Specialized Tourism EcoSYstems) was implemented to define Destination Areas (DAj), and the RSTI was applied to assess the distribution of tourism infrastructure supply within these areas. Results highlight significant disparities among DAj, revealing mismatches between tourist attractions and available services and accessibility. These findings provide insights into infrastructure planning, identify priority areas for investment, and support evidence-based policy-making to promote sustainable tourism models. The RSTI approach enables benchmarking across regions and contributes to the operationalization of territorial sustainability. Furthermore, the analysis expands beyond administrative boundaries, identifying a new geography of tourism supply that reveals regional dynamics and cross-jurisdictional planning needs. This study contributes to the operationalization of sustainability principles in tourism governance and spatial planning. Future research directions include expanding the model to other case studies and incorporating socio-environmental variables for a more comprehensive assessment.

Keywords
Tourism evaluation index; Sustainable development; Cluster analysis

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1. Introduction

Nature-based tourism in protected areas presents opportunities and challenges for balancing conservation and local development (Kuenzi & McNeely, 2008; McNeely, 1998). Recent studies emphasize how nature-based tourism could enhance socio-economic development in rural communities located in proximity to a natural area (Blanco-Cerradelo et al., 2022). On one hand, the presence of visitors provides support to the local economy in a territorial development perspective, also generating values contributing to the maintenance and management of protected areas (Tolkach & King, 2015). On the other hand, excessive tourist pressure leads to environmental impacts (Buckley, 2012). Finding a balance between tourism development and habitat conservation remains an open question both for public bodies entitled for planning and managing protected areas and researchers committed in sustainable spatial development (Grube, 2023).

Often, the lack of a multi-scale perspective and a systematic analysis of the Nature based tourism system within protected areas leads to a fragmented understanding of the broader landscape. As a result, infrastructure development becomes unbalanced across different parts of the park. This, in turn, causes localized uncontrolled increases in tourism pressure and potential environmental degradation. Reconstructing the geographic dynamics and systematically assessing the performance of tourist destinations within the protected areas could help to identify areas suitable for balanced tourism investments. This approach enables the effectiveness of the tourism infrastructure intended in a multidimensional view (environmental, social, economic, spatial) ensuring a more sustainable and evenly balanced development in a specific territorial system (Fistola & La Rocca, 2024). The adoption of an effective framework for the sustainable management of these areas is essential to support planning activities and, consequently, decision making. In this context, protected areas have to be considered not only as natural systems but also as spatial infrastructures with variable capacities to host and promote tourism. This study addresses the need for a robust, replicable framework to assess the infrastructure supporting nature-based tourism in protected areas. We introduce the Robustness Supply Tourism Index (RSTI) and apply it to the Appennino Lucano Val d'Agri Lagonegrese National Park to identify spatial disparities in local tourism system readiness and to support sustainable planning. The study aims to: (I) Identify the spatial elements that belong to the value chain of nature-based tourism in the specific case study area; (II) Provide a new geography that synthesizes, from a multi-scale perspective, the territorial organization of local specialized tourism system; (III) Develop the "Robustness Supply Tourism Index" to compare the level of infrastructure of each tourist destination area within the protected area; (IV) Address the analytical results for the definition of policy implication in protected area management processes, aiming for an integration between tourism development perspective and effective conservation issue. The paper is structured in four section: in the first section, we propose a literature review on the role of nature-based tourism in protected areas; In the second section the case study is described highlighting policy and weakness in managing tourism in the Appennino Lucano Val d'Agri Lagonegrese National Park; The Materials and Methods presented in the third section introduce the taxonomy adopted to identify the specialized destination areas and the spatial analysis describes territorial clusters in tourism supply. In the Results section, we show nature-based tourist supply maps at high spatial resolution in a specific case study. The last section of the paper wraps-up and discusses the work done highlighting policy implications and sets out further research development.

1.2 Nature based tourism in protected areas

According to relevant literature, it is possible to affirm that “Optimal management” of protected areas integrates conservation, restoration, safeguarding, and the identification of development strategies (Bode et al., 2015; Mackay, 2003). To balance these approaches, territorial managers (i.e. decision makers) are increasingly turning from traditional approaches in natural tourism development to multifunctional tourism and recreational activities for both educational and leisure purposes (Chen & Jim, 2012; Karanth & DeFries, 2011;

Lal et al., 2017). Nature-based tourism within protected areas represents a major economic resource for inland contexts, playing a key role in both funding local investments and tourism operators, the management efforts of public bodies within specific responsibilities and preserving ecosystems. When tourism development is approached sustainably, it not only supports local economic development but also raises visitor awareness of environmental conservation, fostering a harmonious balance between enjoyment and protection of natural heritage (Karanth & DeFries, 2011; Mukul & Rashid, 2017). While nature-based tourism helps preserve natural environments and strengthens the economic sustainability of local communities (Watson et al., 2014), it also leads to growing demands due to increasing visitors' interest (Cságoly et al., 2017). However, it can also exert significant environmental (Buckley, 2012; Leung & Marion, 2000; Newsome et al., 2012), sociocultural, and economic pressures (Esteves et al., 2011; Mason, 2020). As tourism development intensifies, the potential for conflict between maintaining a healthy natural environment and economic or recreational expansion increases (Terborgh et al., 2002). *As emphasized by the World Tourism Organization (WTO), tourism operations in protected areas need to be carefully planned, managed, and monitored to ensure their long-term sustainability* (Salerno et al., 2013). Performance evaluations of tourism in protected areas encompass various fields of investigation. The methodology used to measure the three dimensions of sustainability (social, economic, environmental) mainly consists of a framework of indicators based on quantitative and/or qualitative approaches (Canale et al., 2019). Qualitative methods, such as surveys, interviews, and informal assessments, are commonly adopted to identify stakeholders' perspectives (Saviano et al., 2018) and collect data to develop qualitative sustainable indexes (Karampela et al., 2017; Ristić et al., 2019). Quantitative approaches often rely on statistical data aggregate on administrative units and extensively to the wide extend of protected area (Luo et al., 2022; Mahar et al., 2024). We may affirm that a critical issue in measuring the performance of a protected area is the tendency to overlook the geographical dimension of the analysis, treating the entire park as a homogeneous entity without considering variations in data concentration across different sections.

According to Rahmafitria et al. (Rahmafitria et al., 2020b), adequate level of tourism supply infrastructure in protected areas depends significantly on the site's geographic location the physical, social, and cultural conditions of visitors, and the availability of services and attractions. However, achieving a balance between preserving the integrity of natural ecosystems and addressing the minimum technical requirements of an effective local tourism supply chain remains highly complex especially if the expert includes extensive concerns derived from social inclusion, tourism flow management (Juutinen et al., 2011; Rahmafitria et al., 2020a), and the development and adaptation of road and technological infrastructure (Garrod et al., 2006; Tolkach & King, 2015).

2. Case study

With national and regional parks in Basilicata Region (Italy) attracting approximately 41% of the region's total tourist arrivals in the area, the Appennino Lucano Val d'Agri Lagonegrese National Park emerges as a key destination, second only to the Murgia Materana Park, accounting for 23% of the total influx (Colangelo, 2017). Strategically located between the Pollino National Park and the Cilento, Vallo di Diano National Park, (Fig.1) it functions as an ecological corridor and a critical spatial node within the broader framework of regional development policies (Cerabona et al., 2002).

The governance of the Appennino Lucano Val d'Agri Lagonegrese National Park is addressed by the Park Authority (PA) but, actually a Park Plan is still missing. A review of the draft Park Plan reveals a SWOT analysis presented in the general report, which identifies a range of opportunities linked to high-priority interventions promoted by the PA, as well as to regional environmental planning and rural development strategies.

Among these are: *projects for widespread enhancement, trail development, and the valorisation of existing resources, already authorized and implemented with the support of the PA.* In recent years, the Appennino

Lucano Val d'Agri Lagonegrese National Park has promoted a range of policy initiatives aimed at integrating biodiversity conservation with sustainable tourism and local development.

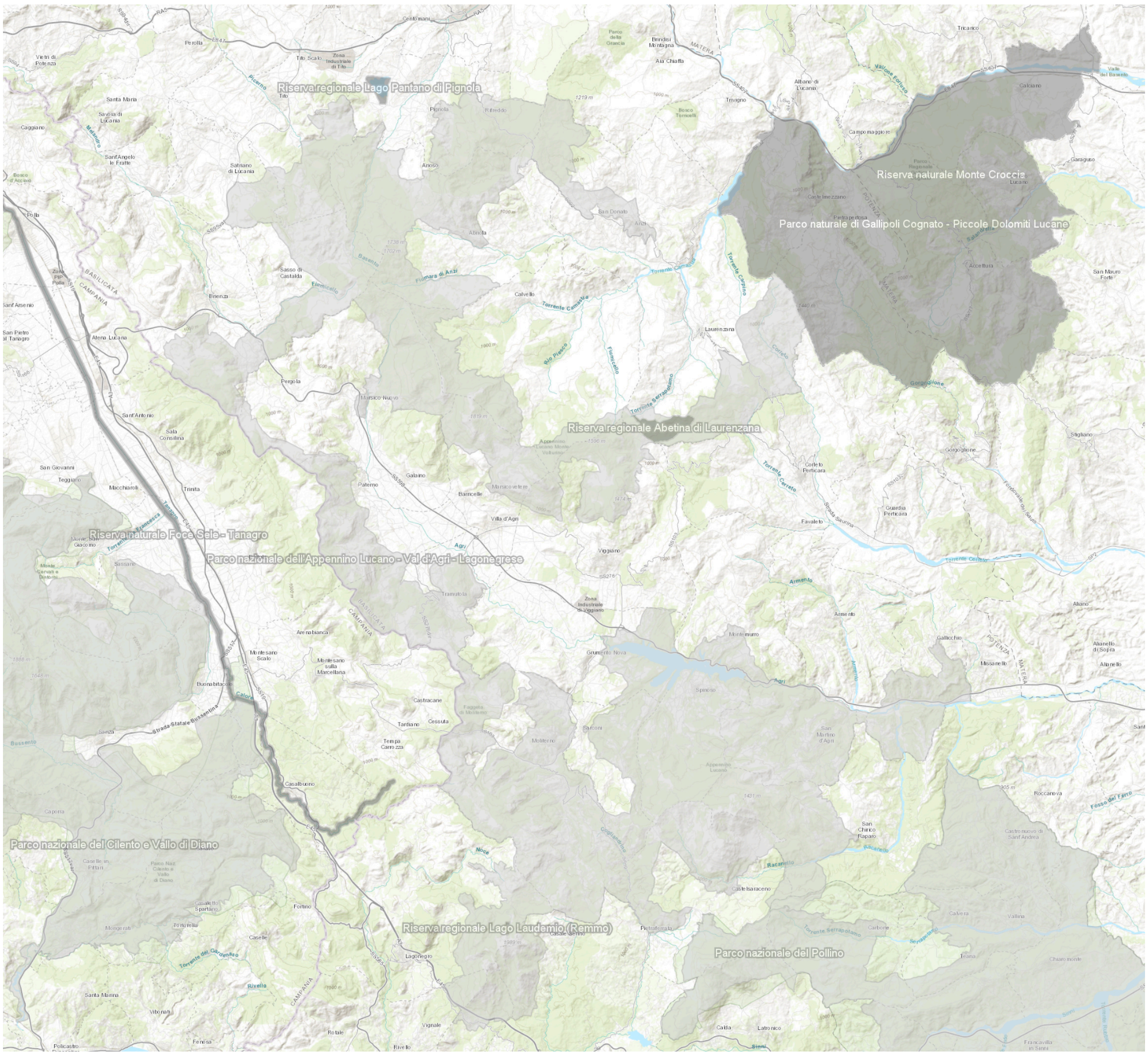


Fig.1 Study Area

Among these, a key strategic pillar is the Park's ongoing adhesion process to the European Charter for Sustainable Tourism (CETS), facilitated through a participatory approach involving institutional, economic, and social stakeholders. The goal is to co-design a five-year sustainable tourism strategy aligned with local values and environmental priorities. However, the PA planning process also revealed critical weaknesses. The Park Plan's general report highlights the territory's limited capacity to generate integrated, cross-sectoral initiatives. This lack of a holistic perspective undermines the potential for synergies among different heritage assets, resulting in initiatives that are often sectoral, disconnected, and short-sighted. Consequently, opportunities to enhance the Park's overall cultural value, to strengthen its role in regional development, and to foster a shared sense of identity among local communities are significantly diminished.

Furthering its commitment to sustainability, the PA launched the *Ambasciatori 2030* project, part of the broader *Il Parco c'è* campaign. This initiative highlights local stories and actors contributing to the achievement of the UN's 2030 Agenda, promoting a shared identity rooted in landscape stewardship and quality hospitality. Additionally, the PA has entered into inter-park cooperation agreements with neighbouring national parks (Pollino and Cilento-Vallo di Diano), aiming to develop joint tourism itineraries and cycle networks thereby enhancing connectivity between protected areas and fostering inter-regional synergies.

These actions demonstrate the PA's commitment to advancing a model of nature-based tourism that balances territorial equity, ecological resilience, and community well-being, despite ongoing challenges in institutional coordination and strategic integration. In the background of such efforts the lack of an official park plan, and a week territorial information describing local recourses, tourism infrastructures, local supply systems and a comprehensive territorial marketing undermine the success in reaching the balance between exploitation and conservation issues in tourism development governance. This critical point unveils the need of robust territorial model oriented to detect spatial relations among attractors, facilities and operators in a comprehensive *tourism ecosystem framework* (Gatto et al., 2025)

3. Methodology

3.1 Taxonomy

In order to develop the spatial model for Nature based-tourism phenomena assessment in an explicit territorial perspective we refer to the domain taxonomy STESY (Gatto et al., 2025) as a conceptual framework to organize knowledge and information. Such conceptual model represents a robust framework for the purposes of this research supporting the quantitative analysis from the early analytical stages of territorial classification to the final strategic decision-making support system. The taxonomy provides a systematic way of classifying and organizing information by classes of items in a hierarchical structure. This approach organizes complex knowledge domains into structured categories, simplifying map reading and ensuring consistent reference to the similar objects or concepts throughout the tourism system. We refer to the Specialized Destination area (DA_j) as domain of investigation to describe the territorial offer in a geographical area. Intended as a spatial statistical unit, the DA_j it is not comparable with municipal or other administrative boundaries, as it depends on the spatial and functional organization of tourism system in a specific territorial value. Conceptually we may have a DA_j aggregating parts of many municipalities or more than one DA_j inside one municipal border.
The DA_j conceptualization is formalised as:

$$\mathrm{DA}j = f(\mathrm{A}j, \mathrm{S}j, \mathrm{R}) \quad (1)$$

It is remarkable to highlight that Specialization *(j)* is the attribute describing tourism categories, it refers to a tourism supply chain. Each destination area is "specialized" on the basis of the type(s) of tourism (cultural, gastronomic, natural based etc.); thus, the tourism specializations is a comprehensive way to define the tourism supply of a specific place. The function *f* represents the spatial model thought which the configurational relations among elements structuring the DA_j is computed. It is defined according to the specific analytical purposes and it is oriented to describe tourism specialization (Corrado et al., 2024). The elements are described as follow: *Aj* Attractors are physical points of interest (POIs). Each attractor is located in spatial configuration and collects a set of activities linked to tourist demand and supply. Specifically, an attractor is an element of the territory recognized by national and/or international agencies, bodies, and organizations, and included in an accountable list (e.g. UNESCO Sites, "Italy's Most Beautiful Villages," Blue Flag, MIBACT, etc.). *Sj* are points of interest representing the services involved in the supply chain (i.e. restaurants and accommodations). Each service is represented by a specific location and attributes; and *R* represent the reachability, the points of access of each DA_j. It expresses the infrastructural and organizational territorial system ensuring that people may access to a specific place (where attractors and/or services are located) for tourism purposes according to a multi-modal classification. The point of access to a destination area are mainly representing the infrastructural transport system (including train/bus stations, parking, etc.). This taxonomy, in particular the DA_j, describes the components of the territorial supply for a specialized tourist supply chain. Applying this framework to the selected case study, we deliver a territorial network through the local representation of DA_j elements understanding in a detailed way the relations between functional spatial subregions.

3.2 Spatial analysis

According to the research purposes we defined the Robustness Supply Tourist Index (RSTI) to assess the balance between tourist attractions assets and support services infrastructure in the analysed protected area. Once the Destination Areas (DA_j) have been identified using a clustering algorithm, we apply the RSTI to evaluate each identified DA_j. This approach enables the quantification of the intrinsic level of infrastructure within each DAj and facilitates systematic comparisons across territorially homogeneous zones (protected areas) characterized by a dominant tourism value chain associated with Nature-Based Tourism. Within this framework, the RSTI operates not only as a metric for assessing services infrastructural endowment, but also as a statistical construct designed to capture variations in the robustness of tourism supply systems. Its application allows for the identification of intra- and inter-zonal disparities, the measurement of relative strengths and weaknesses, and the generation of standardized indicators that support robust comparative analyses across the study area. In fact, although the analytical focus of the study was primarily centred on the Appennino Lucano Val d'Agri Lagonegrese National Park**,** the investigation was progressively extended to the surrounding municipalities. This broader spatial perspective allowed us to delineate a coherent tourism geography that functionally connects three major protected areas: Pollino National Park**,** Dolomiti Lucane Regional Park (Basilicata Region), and Cilento, Vallo di Diano and Alburni National Park (Campania Region). We compared by RSTI index different DA_j belonging to different protected areas identifying disparities in infrastructures development and services provisioning. RSTI allowed to define a standardized approach for benchmarking among similar DA_j, facilitating the identification of best practices (more robust tourism DA_j) and areas requiring interventions in a sustainable development perspective. It may also support decision-making processes by helping policymakers and stakeholders in identifying intervention priorities and allocating resources more effectively, ensuring that tourism development aligns with sustainability requirements, enhancing visitors experience in natural tourism activities.
The methodological workflow is out-lined below in 3 analytical steps (Fig.2).

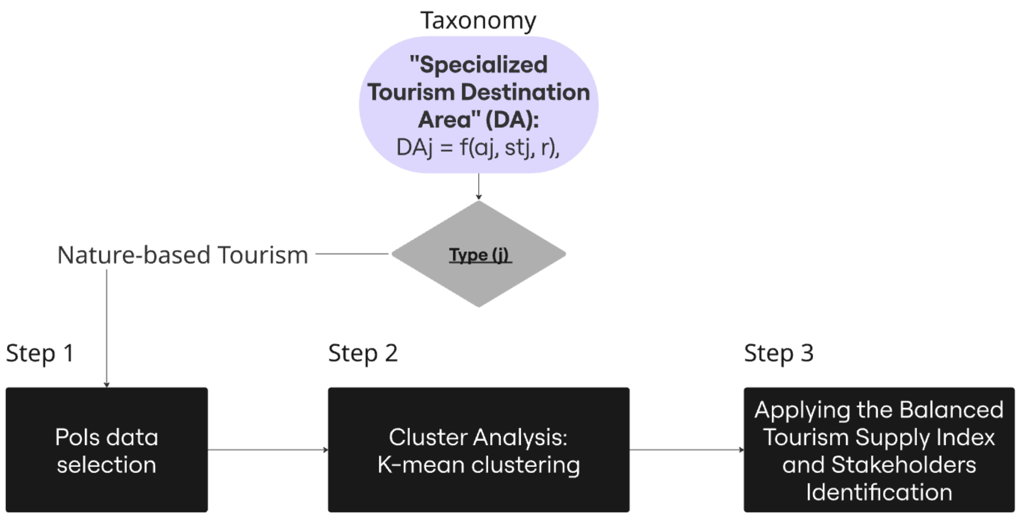


Fig.2 Scheme of Analytical steps

In order to calculate the Robustness Supply Tourist Index (RSTI) and related Tourism Supply maps, we collect POI data from different sources (ATP-Basilicata, Openstreet maps, CAI- Italy's national mountaineering and hiking association, ESRI Basilicata, Ente Parco Nazionale dell'Appennino Lucano Val d'Agri – Lagonegrese, Apennine Cycle Route, Locus map). Then, for the construction of the network of DA_j a set of operations were based on the application of spatial clustering algorithm. We employed the K-Means clustering algorithm to define Destination Areas (DA_j) in the study area. Specifically, we applied the K-Means initialization method, as proposed by Arthur and Vassilvitskii (2007)**,** to enhance the robustness and efficiency of cluster formation. We adopted the spatial statistical software Geo-Da for the cluster analysis and QGIS Geographical Information System (GIS) for the collection of data and set of them and Kepler.gl as main tools for the visualization output maps. For each identified DA_j, the RSTI index had been computed.

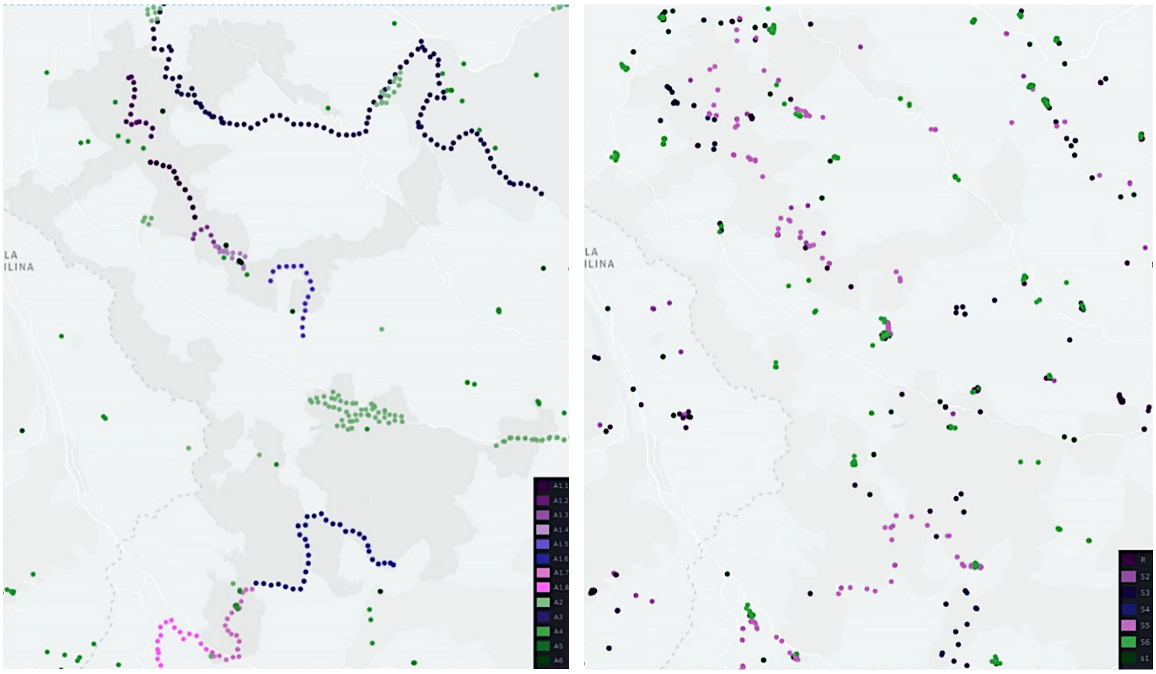
3.3 Step 1 - DAj POI data selection

The selection of the "attractors" POIs was based on the territorial objective to enhance the enjoyment of the natural and environmental heritage in the area of the Appennino Lucano Park in Basilicata (Italy). This principle was at the basis of the research in order to contribute in supporting policymaking in the specific case study area.

ID	Source	Purpose	Activity	Name	N° Pois
A1.1	https://www.parcoappenninolucano.it/	environmental heritage	trekking	S01-trail	11
A1.2	https://www.parcoappenninolucano.it/	environmental heritage	trekking	S02-trail	14
A1.3	https://www.parcoappenninolucano.it/	environmental heritage	trekking	S03-trail	8
A1.4	https://www.parcoappenninolucano.it/	environmental heritage	trekking	S04-trail	13
A1.5	https://www.parcoappenninolucano.it/	environmental heritage	trekking	S05-trail	15
A1.6	https://www.cai.it	environmental heritage	trekking	T05-trail	33
A1.7	https://www.cai.it	environmental heritage	trekking	T06-trail	19
A1.8	https://www.cai.it	environmental heritage	trekking	T07-trail	17
A2	https://dati.regione.basilicata.it/	environmental heritage	excursion	Lake,Rriver	106
A3	https://appenninobiketour.com/	environmental heritage	bicycle	route	103
A4	https://www.openstreetmap.org/	environmental heritage	view	viewpoint	60
A5	https://www.openstreetmap.org/	environmental heritage	speleology	cave	4
A6	https://www.openstreetmap.org/	environmental heritage	climbing	rock	5
S1	https://www.openstreetmap.org/	restoration	Culinary	Restaurants	91
S2	https://www.openstreetmap.org/	restoration	Relaxing	picnic site	28
S3	https://www.openstreetmap.org/	restoration	waterdrinking	spring	44
S4	https://www.openstreetmap.org/	restoration	accomodation	alpine hut	4
S5	https://www.openstreetmap.org/	restoration	info	waypoint	158
S6	https://www.aptbasilicata.it/	restoration	accomodation	Hotel, b&b	312
R	https://www.openstreetmap.org/	Access infrastructure	parking	P-area	379

Tab.1 Data selection

According to these specific categories of attractors had been selected retrieving official databases: the data sources include the official website of the Parco Appennino Lucano, the Basilicata Region's open data portal, Appennino Bike Tour and OpenStreetMap, ATP Basilicata. The attractors identified are linked to outdoor activities aimed at experiencing the natural landscape, such as trekking, excursions, cycling, viewing scenic landscapes, speleology, and climbing. Specifically, in Tab.1 The majority of POIs are related to trekking trails sourced from the official park and national organizations website. Additional POIs include also water bodies (lakes and rivers), cycling routes, viewpoints, caves, and climbing areas. The dataset provides an overview of tourism and recreational opportunities in the park, aiding in assessing the distribution and availability of different nature-based tourism activities. Reachability is key components of the nature-based tourism value chain and are directly linked to the local accessibility infrastructure system**.** The availability of essential services, such as accommodations, restaurants, parking areas, and waypoints, enhances the overall tourist experience and determines the feasibility of accessing protected areas. In the next table we describe a comprehensive picture of data, sources and typologies of information according to the taxonomic model. The maps in Fig.3 represent the spatial distribution of POIs (attractors and services and reachability on the right part of the figure).



(a) (b)

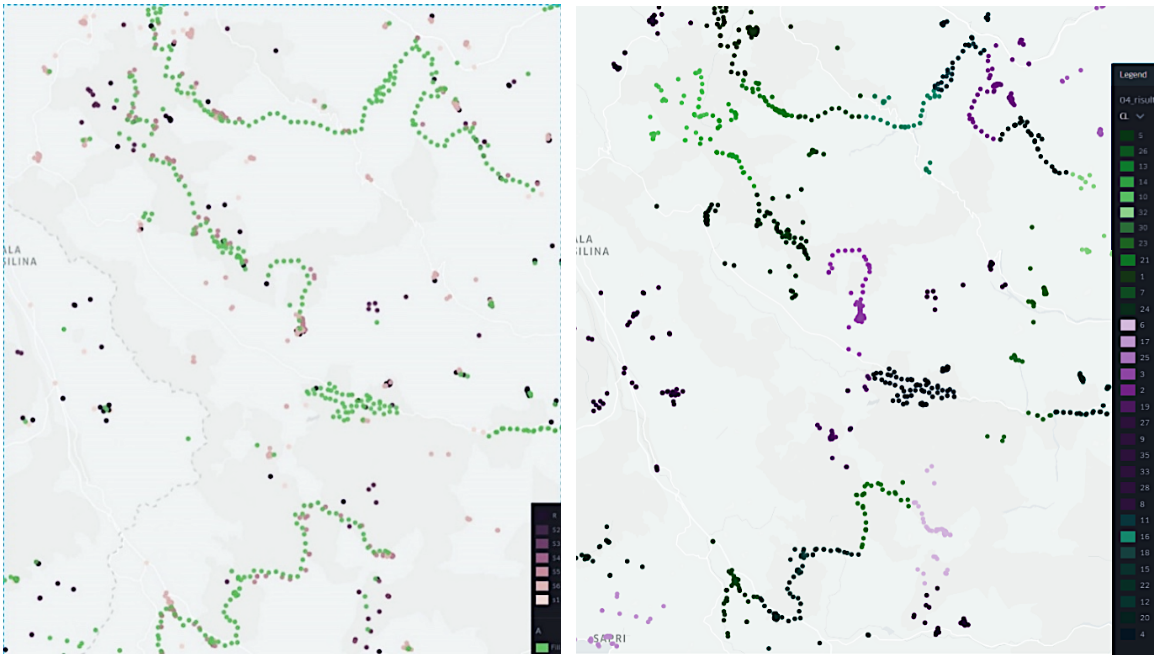
Fig.3 (a) Spatial distribution of Attractors and (b) Services and Reachability in Case study Area – 2025, visualized using Kepler.gl

3.4 Step 2 - Cluster Analysis: K-mean clustering

To delineate Destination Areas (DA_j) within the study region, we employed K-Means clustering within GeoDa (GeoDa Center for Geospatial Analysis and Computation, Tempe, AZ, USA). This method was selected due to its distance-weighted clustering approach, which ensures more stable and meaningful spatial segmentation by minimizing variance within clusters. The selection of the number of clusters (k) is a critical component of the K-Means clustering algorithm. To determine the optimal number of clusters (k), we applied the Elbow Method using GeoDa.

This approach, described by (Anselin et al., 2006), plots the objective function against increasing values of k to identify the point where the reduction in intra-cluster variance stabilizes. After testing various k values, we selected the optimal one (35 clusters) based on the change in slope of the Within-Cluster Sum of Squares (WSS) curve. In the previous figure (Fig.4) are represented in the left part the whole POIs dataset and the results of the cluster analysis in the study area.

The K-Means clustering**,** weighted by the distances between entities, allowed for a robust segmentation of DAs**,** ensuring consistency with the analyzed territorial structure. The input data for clustering consisted of spatial entities representing tourism-related features (e.g., trails, accommodation, viewpoints) and their pairwise Euclidean distances, ensuring that clusters formed around spatially coherent tourism zones**.** This methodology ensured that the resulting DAs were well-defined, spatially consistent, and optimally segmented to support further analysis on tourism infrastructure distribution and planning strategies.



(a) (b)

Fig.4 (a) PoIs and(b) Clusters k-means results, visualized using Kepler.gl

3.5 Step 3: Applying the balanced tourism supply index and stakeholders identification

The application of the RSTI provides strategic insights for targeting infrastructure investments in areas with deficiencies and for identifying zones where the tourism supply is already well-balanced relative to available resources. The index is calculated using the following formula:

$$RSTI = \frac{A}{(S + R)} \tag{2}$$

where: A represents the number of tourist attractions in the considered area; S indicates the availability of tourist services; R corresponds to the existing infrastructure resources.

The interpretation of the index allows for the identification of two distinct scenarios:

- RSTI > 1: DAs with an index greater than 1 require infrastructure improvements, as the number of attractions exceeds the availability of support services and resources.
- RSTI < 1: DAs with an index lower than 1 are considered well-equipped, indicating a sustainable balance between tourist attractions and support infrastructure.

We computed the Balanced Tourism Supply Index on the 35 DAs identified by spatial clustering. Those territorial units representing the spatial structure for the assessment of natural based tourism supply in the study area. DAs without any POIs in the category of Attractors (A) or Reachability (R) or Services (S) were also excluded according to the principle that a DA is formally defined if it includes at least one of these elements. This approach ensured the consider only those DAs representing meaningful tourism dynamics of the case study area, enhancing the reliability and the explicability of the findings. DA_j with an RSTI value close to zero (less than 0.1) were excluded from the analysis due to their lack of statistical significance in the process of territorial interpretation of results. Finally, we analysed a whole of 27 DAs according to the selection criteria previously described. Building on this methodological framework, Tab.2 illustrates the linkage between selected entities (A, S, and R categories) and the corresponding stakeholders involved in their governance and management. The classification highlights the multilevel structure of responsibilities, ranging from the Park Authority's role in environmental protection to the participation of municipalities, regional institutions, private operators, and associations. By aligning each entity with its stakeholders, the table provides an operational dimension to the statistical results, clarifying how infrastructural and service components of tourism supply are embedded within a complex network of institutional, community-based, and private actors. This cross-referencing allows for a more robust interpretation of the RSTI values, as it connects quantitative measurements with the socio-institutional processes that underpin the functionality and sustainability of tourism supply in the study area.

Entity	Involved Stakeholders	Role/Function
A2 - Lake/River	Park Authority	Enviromental Protection and Conservation
	Basilicata Region	Policies regulation
	Municipalities	Strategic actions
	EIPLI	Water Management
	WWF	Regulation of Access and Use
A3 - Routes	Park Authority	Enviromental Protection and Conservation
	Pro Loco	Promotion and sustainable use
	Environmental Guides	Outdoor and educational activities
	Local Associations	Outdoor and educational activities
S1 – Restaurants	Community cooperatives	Promotion of local products
	Local entrepreneurs	Promotion of local products
S2 – Picnic areas	Park Authority	Development and maintenance
	Municipalities	Promotion for hiking and leisure use
	Local associations	Promotion for hiking and leisure use
S3 – Springs	Park Authority	Hydrogeological protection
	EIPLI	Water Management
	Municipalities	Water Management
S5 – Waypoints	Environmental guides	Route definition
	Trekking associations	Visitor guidance
S6 – Accommodations	Local B&Bs and agritourism	Widespread hospitality
	Private operators	Services for short and long-term stays
R – Parking areas	Municipalities	Planning and maintenance
	Province	Management of tourist access and protected areas
	Park Authority	Management of tourist access and protected areas

Tab.2 Relationships between the main types of POIs and their relevant stakeholders, as well as their respective functions within the nature-based tourism ecosystem

4. Findings and discussions

The application of RTSI index allowed to identify those territorial units where we expect a formal organization of Nature-Based tourism supply. The presence of local tourism supply chains is the precondition in order to affirm that the economic value of tourism flow represents an effective driver in promoting local development options in those areas and, for the whole Appennino Lucano Park, a strategic perspective of sustainable exploitation of local tourism potential.

In a general view, values of the RTSI index greater than one identifies weaker DAs within the study area (Fig.5), it suggests that these regions may face challenges in terms of lack of infrastructures and services. This implies a need for targeted interventions to strengthen the local support systems and enhance their local tourism potential. Conversely, values of the index less than one signify stronger and more resilient communities with better infrastructures and services in place, indicating that these areas are more prepared to handle tourism growth and manage the increasing tourism demand over time.

In Fig.6, the DAs are represented. For each DAj, the BTSI value is displayed. We generally observe an absence of Attractors, services, and Accessibility in the western part of the Appennino Lucano National Park. Additionally, all the significant DAs with RTSI > 0.1 are located at the boundaries of the protected area, confirming the area's nature-based tourism vocation.

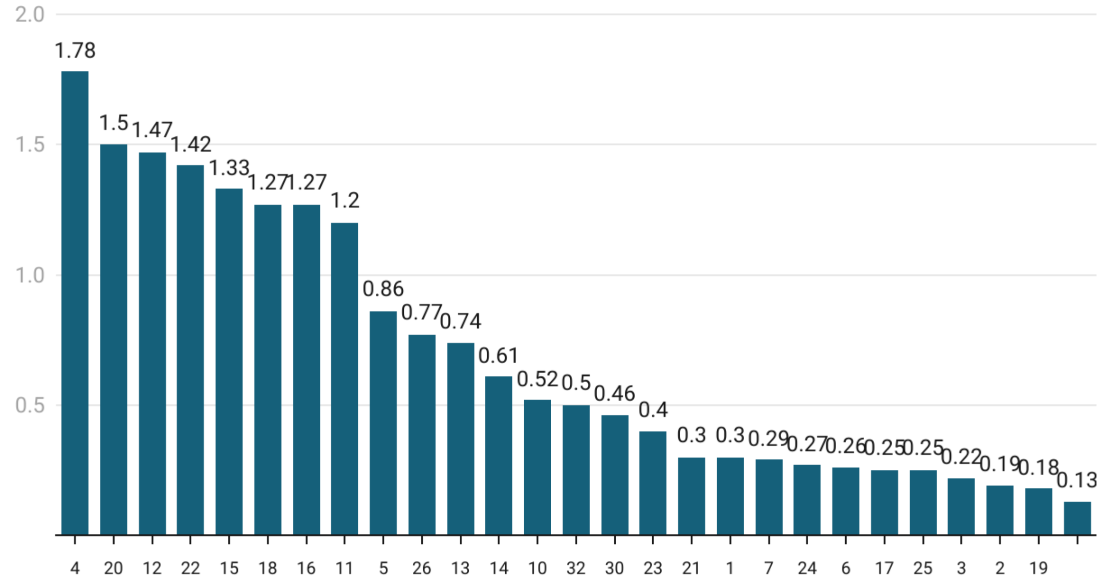


Fig.5 Map of DAs, visualized using Kepler.gl

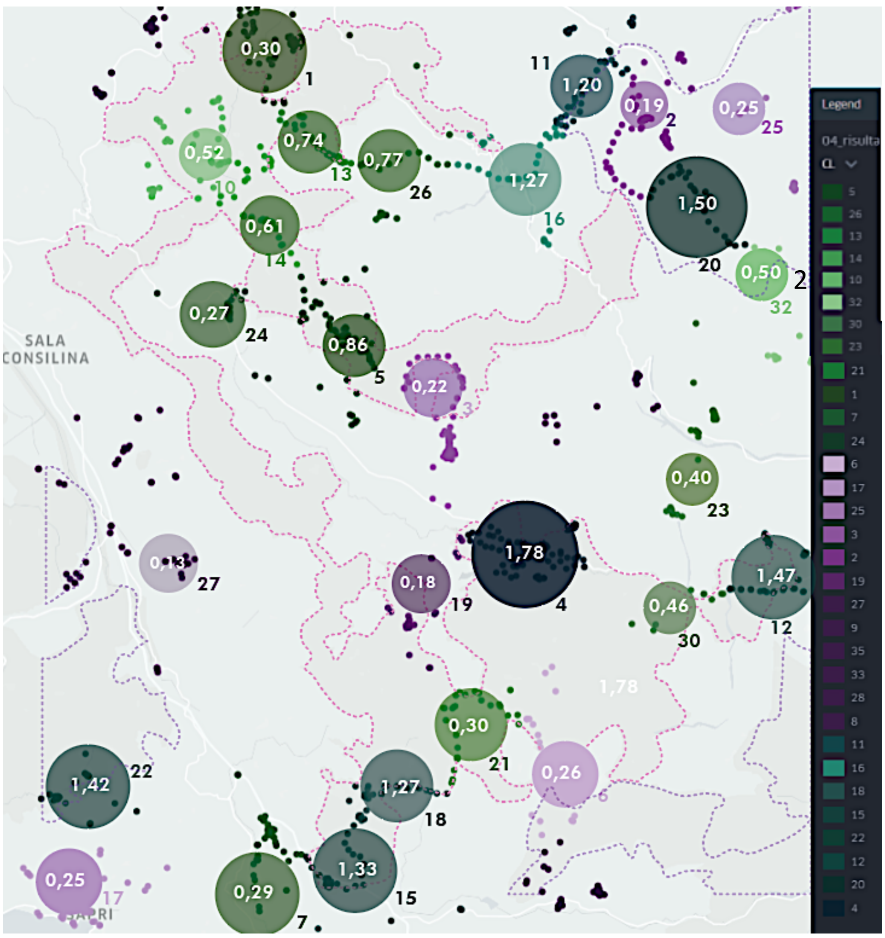


Fig.6 Map of DAs, visualized using Kepler.gl

In order to discuss the results in terms of RTSI, firstly, we compare the distribution in Appennino Lucano Val d'Agri Lagonegrese National Park: DA_j 4 (the maximum value of RTSI entailing the presence of A2 attractor – lake) and the DA_j 1 (the minimum one entailing the presence of A2 attractor – lake). The comparison between DA_j 4 and DA_j 1, as shown in Tab.3, reveals significant differences in the distribution of services and facilities across the two DAs.
In the table below (Tab.3) the two DAs are described according to the attribute's categories defined in Tab.1.

ID	**A2**	**A3**	**R**	**S1**	**S2**	**S3**	**S5**	**S6**
DA_j 4	47	0	14	4	1	1	0	7
DA_j 1	7	13	64	9	0	1	5	24

Tab.3 Comparison between POIS structure in DA 4 and DA 1

DA_j 4 is an area with a strong natural vocation**,** characterized by the presence of the Pertusillo Lake**,** a key environmental and ecological landmark. The landscape of DA4 is a mix of pristine natural environments and rural traditions, with small nearby towns like Spinoso, Montemurro, and Grumento Nova contributing to the region's cultural and historical heritage. The park is also a vital water resource, used for both hydroelectric production and irrigation, underlining its strategic environmental and economic significance. DA_j 1 corresponds to the Lago del Pantano**,** a significant wetland ecosystem characterized by its natural conservation value**.**
The values in the table show the number of Points of Interest (POIs) or services available within each DA for various categories such as restaurants (S1), picnic sites (S2), springs (S3), waypoints (S5), and accommodations (S6), and Parking areas (R). DA_j 4 has a notably number of "R" points (parking area = 14), which may suggest that this area is reachable. However, its lower score in categories like picnic sites (S2), springs (S3), and accommodations (S6) suggest that it might be lacking in essential tourist services that support extended stays or nature-based activities. DA_j 1, on the other hand, shows a more diverse distribution of services and attractors. It has more points in the "Restaurants" (S1) and "Accommodation" (S6) categories, indicating a complete and more well-rounded infrastructure for tourism. The presence of a higher number of restaurants (9) and accommodations (5) suggests that DA_j 1 is more prepared to support tourists for longer stays and provides more opportunities for restoration.
In this regard, it is essential to highlight the key stakeholders involved in the provision and management of the various entities and services in each DA. For example, local municipalities, the Park Authority, EIPLI, and community cooperatives play different but complementary roles in managing natural resources (such as lakes and springs), offering hospitality (via local agritourism and B&Bs), and maintaining infrastructure (e.g., parking and trails). Fig.7 (below) outlines the relationships between the main types of POIs and their relevant stakeholders, as well as their respective functions within the nature-based tourism ecosystem. This kind of stakeholder mapping reinforces the importance of coordinated governance in ensuring sustainable tourism development across the park area, particularly where disparities between infrastructure and service provision are evident.
Further analysis of the reasons behind this difference in infrastructure distribution would be useful and represents a perspective of this research. For example, it would be interesting to explore whether DA_j 4 is an area where investment in public services and tourism infrastructure is needed or the synergy between the nearby DAs could also create a more attractive tourism offer while maintaining the ecological integrity of the area.
Another relevant case regards the transition community's DA_j n°16 and DA_j n°11 located in an area between the Dolomites Park and the Appennino Lucano Park in the north-eastern part of the study area.
It emerges that DA_j 11 even if spatially and functionally connected with DA_j 16 in terms of nature-based attractors and routes, is less developed in terms of infrastructure as the results of differences in terms of

recent exploitation and development tourism policies targeted on the Dolomites Park. The RTSI points out a geographical and functional gap between these areas. In other terms, despite being situated within neighbor protected natural area, these communities may not yet fully capitalize their proximity both in terms of valuating natural and ecological resources and in terms of services and reachability structure. DA_j 11 shows underdeveloped infrastructure and this weakness could be limiting its ability to support sustainable tourism development.

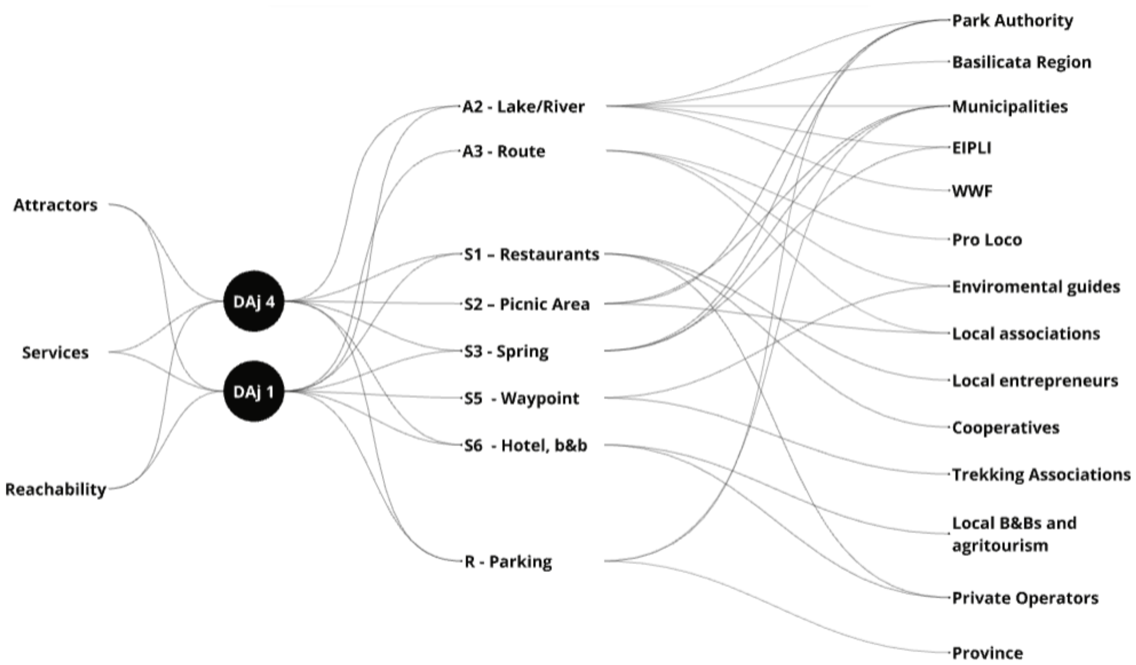


Fig.7 Summary of Stakeholders and Functions in Tourism Supply Chains

Pointing at specific natural resources: the lakes, it is remarkable to see how DA_j n°4 and DA_j n°12 appears to be poorly valorized in the whole territorial system. It evidently represents a missed opportunity in enhancing the natural resources of the area. Lakes and rivers are often major tourist attractions, particularly in nature-based tourism value chains. If these resources are not adequately promoted or integrated into tourism itineraries, the region loses the chance to attract more visitors creating advantages for local economy benefitting also from multiple options in establishing new activities and services directly related to the exploitation of lakes and water natural environment. This could indicate the need for better developing strategies targeted on this territorial specialization oriented to better marketing, improved accessibility, and investments in infrastructure.

Finally, the lack of service distribution from DA_j n°7 fitting with Lagonegro Municipality to the more inland areas DA_j n.15 and n.18 suggests an imbalance between main territorial settlement system offering essential services also in the tourism supply chain and inner areas where tourism supply is based on small number of services and operators. Such structural deficits may directly impact the experience of the tourists influencing negatively influence their preferences in choosing local tourism services. Without proper transport links, accommodations, and amenities, the more remote or rural areas may be left underdeveloped and inaccessible, causing negative effects on the region's overall tourism potential. A more comprehensive and evenly distributed service network could not only improve the tourism experience but also contribute to more balanced regional services for residents. This represents a challenging scenario for local policymaking and planning both at protected area level and intermunicipal level. Addressing these gaps is essential for creating a sustainable and attractive tourist ecosystem in the area of the Appennino Lucano Park in the long run and, according to the effective classification of local DAs, priorities and effective criteria for the selection of investments (public and private) could be reinforced in the sustainable perspective declared by PA and other local development policies.

From a broader academic perspective, the STESY analytical framework and the RSTI contribute to the literature on sustainable tourism assessment in protected areas by overcoming two recurrent limitations of existing models (Lagonigro et al., 2020; Romão & Neuts, 2017; Sarrión-Gavilán et al., 2015). First, unlike traditional indicator-based frameworks that aggregate socio-economic and environmental variables at administrative scales, STESY redefines the unit of analysis through functionally derived Destination Areas (DAj), grounded in spatial clustering and tourism supply-chain logic (Batista e Silva et al., 2018). This shift from administrative to configurational spatial units enables a finer-grained interpretation of internal disparities and avoids treating protected areas as homogeneous entities. Second, while carrying-capacity models and sustainability scorecards often focus predominantly on demand pressures or environmental thresholds, the RSTI introduces a supply-side robustness perspective, systematically balancing attractors, services, and accessibility within a replicable and benchmark-oriented index (Bridge, 1994). In doing so, the framework strengthens comparability across sub-regions and contributes methodological originality by embedding sustainability evaluation within a spatially explicit ecosystem approach.

5. Conclusions

This study proposes the STESY analytical framework and the "Robustness Supply Tourism Index" (RSTI) as an effective evaluation framework to support policymaking in balancing between tourism development potentials exploitation and conservation policies making in protected areas. By applying this index to the case study of the "Appennino Lucano Val d'Agri Lagonegrese" National Park and its neighboring protected areas, we discussed the contribution of the proposed methodological framework to better understand how tourism infrastructure distribution is structured in the specific investigation area and its implications for sustainable tourism development policies. The findings indicate a significant imbalance in tourism infrastructure among different DAs. The results highlight key challenges, including gaps in infrastructure, underutilization of natural assets, and service distribution imbalances that affects the sustainable exploitation of tourism potential in the protected areas. The identification of these disparities underscores the necessity for targeted policy interventions aimed at enhancing infrastructure in underdeveloped areas while ensuring sustainable growth for the whole region (Erçetin, 2024). Moreover, the RSTI framework offers a standardized methodology for benchmarking tourism infrastructure in protected areas, facilitating comparisons across different geographic regions and supporting decision-making processes for policymakers and stakeholders.

Concerning the specific case study, this study contributes to increase critical knowledge on the development trajectories for the park management.

The integration of the stakeholder mapping into the analysis provides a significant advancement in interpreting the spatialized performance of nature-based tourism within protected areas. By linking each type of attraction, service, and infrastructure to the relevant institutional, economic, and community actors, the map operationalizes the concept of multi-level governance and supports the implementation of sustainable development strategies aligned with the European Charter for Sustainable Tourism (CETS). In contrast to generalized evaluations that treat protected areas as homogeneous units, this stakeholder-based approach enhances territorial differentiation and facilitates a place-based reading of tourism dynamics. Furthermore, it offers a concrete framework for identifying gaps in infrastructure and service provision—particularly evident in weaker DAs such as DAj 4—and highlights opportunities for coordinated action among local municipalities, park authorities, and private actors. This framework not only improves planning and monitoring processes but also aligns with the Park's efforts to promote integrated, cross-sectoral strategies, overcoming the limitations of fragmented local knowledge. Overall, the stakeholder map contributes both as an analytical tool and as a foundation for participatory governance, making it possible to address the challenges of balancing environmental conservation with tourism development in a structured and inclusive manner.

To identify sustainable development strategies, nature-based tourism development has to be enhanced by the PA in the scope of its territorial planning responsibilities. The Park Plan serves as a regulatory tool for the general organization of territorial systems and components addressing also policies oriented to re-balance tourism infrastructures according to sustainability principles. The investigated DAs, identified also beyond the park boundaries represents a new geography highlighting priority of interventions according to the actual endowments of local tourism supply chain. In this context, the results of this work could support a renewed planning action proposing an enhancement of strategies for the valorization of natural assets according to an extensive picture of tourism system organization within the park and in a sustainable proximity surrounding the administrative boundaries. Limitations of the study depends on data availability and the lack of institutional infrastructure to provide accurate and spatialized information for territorial analysis. Additionally, a direct debate with local actors could further enhance the reliability of the input information and the interpretation of results compering the perception of the "people of the place" (Scheiber & Mifsud, 2024) in accounting new tourism geographies.

The implementation of STESY and RSTI raises critical governance challenges. Translating analytical outputs into policy requires coordinated action among heterogeneous stakeholders (park authorities, municipalities, regional agencies, private operators, and local communities) whose priorities may diverge. Infrastructure reinforcement in under-served DAs may conflict with conservation objectives aimed at limiting anthropogenic pressure, while more developed areas may face tensions related to congestion, environmental degradation, or unequal distribution of economic benefits. These potential conflicts highlight the need for adaptive, participatory governance mechanisms capable of mediating between ecological integrity and local development aspirations (Marinelli et al., 2022). Therefore, beyond its evaluative function, the proposed framework should be interpreted as a decision-support infrastructure that facilitates negotiation, prioritization, and long-term alignment between conservation strategies and sustainable tourism development goals (Faghih Abdollahi et al., 2025; Sedaghatfard & Soltani, 2025).

Future research should focus on refining the RSTI framework by incorporating additional socio-economic and environmental variables, assessing benchmarks in to a broader range of protected areas investigation, and exploring the long-term impacts of infrastructure investments on tourism sustainability.

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Image Sources

All figures were elaborated by the authors.

Author's profile

Rachele Vanessa Gatto

Architect and PhD candidate in *Engineering for Innovation and Sustainable Development* at the University of Basilicata (UNIBAS), Department of Engineering. Her research focuses on spatial planning, sustainable tourism, and data-driven decision-support systems for territorial governance.

Francesca Perrone

Researcher in urban and regional planning affiliated with the Department of Planning, Design and Architecture Technology (PDTA) at Sapienza University of Rome. Her research focuses on heritage-led urban regeneration, spatial planning, and sustainable territorial development, with particular attention to the transformation of marginal and peri-urban landscapes. She investigates how cultural heritage systems can be reinterpreted as strategic infrastructures within contemporary urban and regional networks.

Francesco Scorza

Associate Professor of Urban and Regional Planning at the University of Basilicata (UNIBAS), Department of Engineering. His research focuses on spatial planning, smart cities, and decision-support systems for territorial governance, with particular emphasis on the integration of digital technologies, spatial data, and participatory processes in planning practices.

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REVIEW NOTES

"Brain gain" in planning academia: learning from Albania's practical approaches

Irina Branko [a], Erida Curraj [b], Dorina Pojani [c*]

[a] Department of Urbanism
Polytechnic University of Tirana, Tirana, Albania
e-mail: irina.branko@fau.edu.al
ORCID: https://orcid.org/0000-0002-5925-107X

[b] Department of Engineering and Architecture
European University of Tirana, Tirana, Albania
e-mail: erida.curraj@uet.edu.al
ORCID: https://orcid.org/0000-0002-5787-3529

[c] School of Architecture, Design and Planning
The University of Queensland, Brisbane, Australia
e-mail: d.pojani@uq.edu.au
ORCID: https://orcid.org/0000-0002-2018-6338
* Corresponding author

Abstract
This Review Note presents two successful "brain gain" initiatives implemented in Albania — READ, a planning research project, and GERMIN, a planning education project. Both programs represent structured efforts to mobilize diaspora expertise in order to strengthen higher education, research, and professional practice, addressing capacity gaps intensified by the prolonged emigration of skilled professionals. In this context, "brain gain" is understood not as permanent return, but as the circulation of talent. These models emphasize knowledge exchange, research partnerships, co-teaching, and global networking, often driven by strong personal and professional ties and implemented at relatively low financial cost. The lessons drawn may provide useful insights for policymakers, educators, and researchers confronting similar issues along the Mediterranean.

Keywords
Brain drain; Brain gain; Planning diaspora

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1. Introduction

The purpose of this Review Note is to present two "brain gain" programs implemented in Albania — READ, a planning research project, and GERMIN, a planning education project — in which the three authors participated. These programs exemplify structured approaches to mobilizing diaspora expertise to strengthen higher education, research, and professional practice in Albania, addressing gaps intensified by the prolonged emigration of skilled professionals. While the focus is on Albania, the experiences documented here have broader relevance in countries across the European Sunbelt — spanning the Iberian, Italian, and Balkan Peninsulas — which face comparable challenges related to brain drain, talent circulation, and the integration of diaspora knowledge (see, for example, GRS, 2024). Accordingly, the lessons drawn from our participation in these programs may provide useful insights for policymakers, educators, and researchers confronting similar issues along the Mediterranean. Below, we provide context on Albanian brain drain challenges before proceeding to a discussion of the READ and GERMIN programs.

2. Albanian emigration trends: the 'brain drain' problem

The dramatic collapse of Albania's communist regime in 1990 catalysed one of the most intense migration episodes in post-World War II Europe. During nearly five decades of strict communist rule, emigration was prohibited and the borders were tightly sealed. With the fall of the regime, all barriers to exiting the country were removed while the economy collapsed (state industries shut down, unemployment soared, and inflation spiked.) Desperate Albanians left the country in large numbers — usually for neighbouring Greece and Italy but also other parts of Europe, North America, and Australia — often in irregular circumstances. Over the three decades following 1990, it is estimated that more than one-third of the Albanian population has left the country — reducing the resident population from around 3.3 million to approximately 2.8 million in 2023 (INSTAT, 2024).

Annual departures have been roughly 42,000 people in recent years. Surveys of potential emigrants indicate that a significant share of young Albanians still contemplate leaving, driven by perceptions of better economic prospects, quality of life and professional opportunities abroad. While emigration continues at high levels, its patterns have evolved. Early migration was heavily motivated by immediate economic survival whereas more recent emigrants seek white-collar work, university studies, and postgraduate qualifications (King & Gëdeshi, 2020).

A core component of Albania's migration dynamics is the so-called "brain drain" — the emigration of highly skilled and well-educated individuals. From the 1990s onward, Albania has lost a substantial portion of its human capital. While the early emigration was heavily motivated by economic survival, also it is estimated that approximately 40% of university professors and research scientists emigrated during the 1990s, significantly weakening the country's academic and scientific capacity (MPI, 2025). Contemporary research on Albanian students abroad shows that large numbers of degree-seeking and highly educated young people do not intend to return (King & Gëdeshi, 2020). The economic implications of this sustained brain drain include not only the loss of national investment in education and training but also reduced innovation capacity and weakened institutional development.

Brain drain also poses a challenge for Albania's governance because it systematically removes the very social groups most critical to democratic consolidation. Skilled professionals such as planners, lawyers, doctors, engineers, and academics are essential for designing, implementing, and evaluating public policy. When these individuals emigrate in large numbers, state institutions become understaffed or reliant on less experienced personnel, reducing administrative effectiveness and policy continuity. In an economically and politically fragile context, this loss of capacity limits the state's ability to deliver services to the citizenry.

Furthermore, brain drain diminishes democratic accountability and civic participation. Educated citizens are disproportionately more likely to vote, engage in civil society, monitor government performance, and demand transparency. Their departure has weakened watchdog functions and reduced pressure on the Albanian political elite to govern responsibly. This has further entrenched clientelism and patronage networks and undermined political pluralism and leadership renewal. With potential reformers gone, the likelihood of domestic institutional reform has been curtailed; the country risks turning into a "kakistocracy."[1]

Finally, brain drain has distorted the state–citizen social contract. Remittances have helped stabilise household incomes and reduce poverty, but they are also substituting for public provision and muting demands for systemic reform. When livelihoods depend more on transnational family networks than on domestic institutions, trust in the state erodes and incentives for political engagement weaken. Practically, brain drain is replacing public participation as the primary response to governance failure. This is a structural challenge — not merely a demographic issue for Albania (see Politico, 2024; Tirana Times, n.d.).

3. A variety of "brain gain" programs

Despite major challenges — including weak governance, democratic deficits, and entrenched corruption — Albania has come to recognise that attracting and retaining skilled professionals is essential for national development. Achieving this requires proactive strategies to mobilise highly qualified members of the Albanian diaspora in the country's economic, academic, and institutional life. The urgency of this effort is heightened by widespread disillusionment with decades of foreign technical assistance, which often failed to produce sustainable outcomes (Pojani & Stead, 2018). External experts frequently lacked a nuanced understanding of the local context and did not speak the language (which is notoriously difficult and unrelated to any other language). In response, Albania has increasingly emphasised diaspora-linked expertise as a mechanism to bridge global knowledge with domestic realities. A number of programs and policy efforts, led by the government, universities, and civil society, have sought to leverage "brain gain" — the return or productive engagement of diaspora talent.

One of the earliest structured efforts was the Brain Gain Programme, initiated in the mid-2000s in coordination with the Government of Albania and international partners such as the United Nations Development Programme (UNDP). The program aimed to create incentives for highly skilled emigrants to return or engage with Albania's institutions by establishing policy frameworks that would welcome and integrate diaspora expertise into academia, public administration, and research sectors. It included an online diaspora database to match expertise with institutional demand and regulatory adjustments to facilitate employment and recognition of foreign qualifications. This approach explicitly targeted academics, researchers, and professionals with overseas experience, envisioning short-term consultancies, joint research projects, and temporary or permanent return placements that could enhance capacities within Albanian universities and public institutions (Zeneli et al., 2013).

More recently, Albania's national policy frameworks — including strategic documents developed under diaspora engagement and economic development umbrellas — have incorporated digital platforms and structured return programs. Notably, the Albrain Platform and the Diaspora Return Program are designed to connect Albanian professionals worldwide with opportunities for short-term projects, consulting, workshops, and innovation collaborations with government, academia, and industry in Albania (GoA, 2025). At the institutional level, some private universities have instituted their own brain gain programs that specifically aim to bring Albanian educators and researchers back into the country's educational landscape. These programs recruit mid-career and senior academics from the diaspora to participate in teaching and research, either through physical presence in Albania or through remote collaboration. The remainder of this Review Note focuses on two programs, READ and GERMIN, in which these authors participated through a planning research project and a planning education project, respectively.

[1] A *kakistocracy* is a system of government in which the least qualified or most unscrupulous people hold power. From Greek: *kakistos* (worst) + *kratos* (rule).

4. In focus: READ and GERMIN

AADF's READ Fellowship. The Albanian-American Development Foundation (AADF) is a non-profit organisation established in 2009 with original support from the U.S. government. Its mission is to advance sustainable development in Albania through strategic investments in education, leadership, entrepreneurship, cultural heritage, and community empowerment. One of AADF's flagship initiatives in the education and research sector is the Research Expertise from the Academic Diaspora (READ) Fellowship Program, launched in 2021 in partnership with the Institute of International Education (IIE). READ is a competitive fellowship designed to connect Albanian universities and other higher education institutions with highly qualified researchers and scholars of Albanian origin based in OECD countries. The program seeks to strengthen Albania's research and teaching capacity by facilitating collaborations such as co-authored research, joint supervision of doctoral candidates, curriculum and course development, and co-teaching activities (AADF, 2025; IIE, 2025).

READ operates on a dual-application model, in which projects are proposed by resident Albanian scholars and subsequently matched with diaspora academics. Fellowships typically support engagement periods of up to one year, either in person or in a hybrid format. The program has already received strong institutional support from Albanian universities, including formal cooperation agreements. A team composed of two of the authors (Erida Curraj as the resident scholar and Dorina Pojani as the diaspora scholar) was awarded a Fellowship for 2023–2024.

The team led a research project designed to provide a more comprehensive understanding of Tirana's gendered mobility and accessibility patterns in post-industrial suburban areas and their connection to urban liveability. Issues of mobility, accessibility, and liveability are, of course, central to *TeMA: Journal of Land Use, Mobility and Environment* and its readership. The Journal was established specifically to connect urban studies with research on mobility in all its aspects, and it seeks to advance novel theoretical and methodological frameworks that move beyond approaches rooted in the scientific culture of the last century. Research on gender issues in the city, as well as within the urban and transport planning professions, is also growing — albeit slowly — within *TeMA*'s volumes (see Stiuso, 2024; Carpentieri et al., 2023; Delatte et al., 2018; Pojani, 2011).

For the READ-supported study, three types of primary data were collected: field observations, quantitative population surveys, and qualitative focus groups. The project involved planning students who assisted with data collection and junior researchers who supported the analysis. Students reported that this experience was particularly valuable for learning how to gather data in a hands-on manner and for gaining exposure to applied research methods. Overall, the project was deemed highly successful, resulting in a conference presentation and an academic research article that is currently under review in a leading planning journal.

EU4Innovation's GERMIN Fellowship - The Global Engagement and Research in Migration Network (GERMIN) is a non-governmental organisation that connects the Albanian and regional diaspora with institutions in their countries of origin (GERMIN, 2025). Its programs are implemented in partnership with the EU4Innovation program, a multi-donor initiative funded by the European Union, the German Federal Ministry for Economic Cooperation and Development (BMZ), and the Swedish International Development Cooperation Agency (SIDA), and delivered locally by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Albania.

Similar to AADF, GERMIN's mission is to facilitate knowledge transfer, professional engagement, and innovation across sectors such as education, entrepreneurship, and research. Its work, however, is more targeted: it leverages diaspora expertise to address gaps between education and labor market needs and thus accelerate Albania's transformation toward a more innovation-driven, knowledge-based economy. As with READ, GERMIN has been well received by Albanian universities (EuroNews Albania, 2025).

Like READ, GERMIN operates on a team-based model. However, in this case, projects are proposed by faculty from the diaspora and implemented in collaboration with resident academics over the course of one year, through a combination of in-person visits and online activities. In 2025–2026, one of the authors (Dorina Pojani, a member of the academic diaspora) was awarded a teaching fellowship, which she carried out in collaboration with Irina Branko (one of the authors, a lecturer in the Department of Urbanism at the Polytechnic University of Tirana).

The fellowship focused on refreshing a landscape planning course led by the resident lecturer. Normally, the course is delivered through a combination of theoretical lectures and studio-based work. Historically, this urbanism program has placed a strong emphasis on design rather than theory or policy. In this case, the key innovation was a series of guest lectures by domestic and international practitioners from the public, private, non-profit, and international assistance sectors. These lectures, complemented by visits to the lecturers' workplaces, introduced students to a range of career opportunities for planning graduates beyond the more typical employment in design studios. Although planning education and careers are not *TeMA*'s specific focus, the Journal is interested in landscape planning, particularly when it relates to environmental sustainability. While case studies from across Europe have appeared in its pages, Italian examples (Leone et al., 2020; Zullo et al., 2015) are especially relevant, as Italy often serves as a reference point for Albania on these matters.

Returning to the GERMIN initiative, student feedback on was very positive. In an anonymous survey completed by more than half of the students (20 out of 37), the course — and particularly the new elements — received an average score of 4.75 out of 5. Beyond the quantitative results, qualitative feedback gathered through a focus group attended by 15 students was especially illuminating. Students clearly expressed a desire for more than technical training. They sought greater exposure to real-world practice, including experiences outside the capital city in coastal and mountainous regions; insight into non-traditional career pathways; and stronger links between urban planning, architecture, and communities. Students highlighted the importance of learning about non-design aspects of professional practice, including coordination with institutions, financial management, budgeting, and project governance — areas they felt were largely absent from their formal training but central to real-world work. They also valued the interdisciplinary nature of several guest organisations. Importantly, students welcomed the territorial breadth of the course, which deepened their understanding of landscape, tourism, and regional challenges, and strengthened their appreciation of planning at multiple scales.

5. Success factors and lessons learned

Here the authors reflect on the factors that, in our experience, contributed to the success of these programs, as well as lessons learned and suggestions for future improvement.

<u>Funding</u> -While both fellowships are competitively awarded, they are low-cost programs. This is a positive feature, as it enables broader participation. The administrative burden is also limited, with short application forms and minimal reporting requirements. This stands in contrast to major EU-funded project applications, which typically have low rates of success but high potential rewards. These projects also involve substantial administrative burdens, often requiring researchers to spend a disproportionate amount of time preparing applications and reporting on the outcome of the project (see Dresler et al., 2022; Kooijman, 2015). In this case, the main cost was the return airfare for the diaspora scholar (who was coming from Australia), along with some project-related expenses and payments for casual research assistants. With planning being a social science discipline, project expenses were relatively low; natural science projects may involve higher costs (such as for labs, materials, and advanced software), and therefore it would be advisable to integrate diaspora scholars into university departments and/or ongoing projects for which the major infrastructure is already in place. READ provided funding for the resident participants, whereas GERMIN did not. Ideally, funding should also be available for domestic researchers and lecturers, as this represents an important incentive for participation — particularly given that academic salaries in Albania are lower than the OECD average.

Presence - While online collaboration is possible, some physical presence is essential for these fellowships to succeed. Research and teaching activities are less effective online than in-person engagement — as was clearly demonstrated during the Covid-19 pandemic. Being present allows the diaspora scholar to guide activities and provide mentorship, in line with Albania’s relational culture. During their visit, diaspora scholars often take on additional activities, such as media appearances and workshops, which also help domestic scholars expand their professional networks. This networking support aligns closely with one of the program’s key objectives and is highly valued by resident participants. In the case of *planning* academics from the diaspora, their commentary on controversial urban development projects is particularly valued in the media, as they are often freer to critique current practices than local professionals (the latter may face conflicts of interest or feel constrained by political pressures). Engaging senior diaspora academics, who are well respected in both Albania and their country of domicile, further amplifies the program’s effectiveness and impact. In Albania’s patriarchal culture, junior academics who are without international recognition — while potentially very capable — often struggle to have their voices recognized.

Collaboration - Some grant funding schemes are conservative and prefer teams with an established track record of collaboration. In this case, however, that was not necessary. While team members were acquainted prior to participating in the programs, they had not collaborated professionally before. Yet the programs were successful, driven by a strong motivation to work together. In the teaching fellowship, much of the success can be attributed to the course and resident lecturer being well liked, and to the positive rapport that already existed between students and the lecturer. This created a welcoming environment into which the diaspora academic could be effectively integrated. Both AADP and EU4Innovation have actively supported ongoing connections through formal and informal networking opportunities, including study visits, conferences, workshops, and, in the case of READ, an annual New Year’s party for all fellows. While the latter may seem trivial, such events play a meaningful role in sustaining engagement and community.

Support - Government support, even symbolic, is important for the success of these programs. While neither fellowship was directly funded by the Albanian government, the presence of officials at events demonstrates recognition and appreciation, which carries real value. Albania is fortunate to have a diaspora that is emotionally attached to the country — reflected in the old proverb, “Albanian soil is sweeter than honey” — and eager to stay connected and contribute. Many diaspora members who received part of their education in Albania feel a strong desire and/or personal obligation to give back. This represents a special circumstance, whereby diaspora academics are willing to participate for nominal compensation out of allegiance to their country of origin. It is therefore important for the government to acknowledge and value this commitment, rather than only viewing the diaspora as a source of remittances.

6. Conclusion

Some countries, like Italy, take different approaches to brain gain — for example, giving priority in academic jobs to members of the Italian diaspora. However, this type of outcome cannot realistically be expected for Albania until higher education salaries, institutional capacity, and global rankings approach those of OECD countries, where most of the academic diaspora is based. In the Balkans, Serbia is the most committed state in terms of diaspora integration, with formal programs, dedicated budgets, and an established institutional infrastructure (Brojka, 2025).

In Albania’s context, “brain gain” is often understood not as permanent repatriation of diaspora scholars and other professionals, but as circulation of talent: diaspora expertise is mobilized through temporary and sometimes virtual collaborations that support domestic development — in planning and other arenas. These models emphasize knowledge exchange, research partnerships, co-teaching, and global networking mainly propelled by human attachment at a very moderate financial cost.

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Authors’ profiles

Irina Branko

She specializes in landscape design. She teaches and conducts research on the ecological and aesthetic dimensions of urban development. Her work highlights the importance of greenery in enhancing urban livability and wellbeing.

Erida Curraj

Her work explores the transformation of design and production practices in post-socialist contexts, with particular attention to the preservation of industrial heritage and cultural landscapes.

Dorina Pojani

Her research focuses on the built environment triad of urban design, transport, and housing in both the Global North and South. She approaches her work from a feminist perspective, considering the role of gender in the city.

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Monitoring urban dynamics using Google Earth and GeoAI

Francesco Lamonaca [a,b]

[a] Department of Computer Engineering, Modeling, Electronics and Systems Engineering, University of Calabria, Rende (CS), Italy

[b] National Research Council Institute of Nanotechnology (CNR-NANOTEC), Rende (CS), Italy
e-mail: f.lamonaca@dimes.unical.it
ORCID: https://orcid.org/0000-0002-6263-8929

Abstract

Urban areas face mounting pressure from increased space demand, degrading key environmental services. Thus, understanding Land Use/Land Cover (LULC) changes is vital. In order to offer a robust decision-support framework for urban planning and environmental conservation, this study presents an innovative measurement method based on Google Earth Engine and Unsupervised K-means Clustering of multispectral satellite images to map urban and vegetation shifts. The proposed method was applied in 15 southern Italian cities and the results were validated with ESA Land Cover dataset. Results show 167 hectares consumed from 2005 to 2021. The proposed unsupervised classification achieved favorable F1-scores, with 0.64 for urban areas and 0.92 for vegetation, demonstrating strong performance despite the challenges of classifying diverse 30 m Landsat land cover types. For these reasons, these results show the potential to make the proposed method a useful tool for aiding policymakers and urban planners in making informed decisions to mitigate the adverse effects of urban growth on the environment.

Keywords

Built-up monitoring; Measurements; Artificial intelligence; Google earth engine; Unsupervised K-means clustering

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1. Introduction

Understanding the dynamics of Land Use and Land Cover (LULC) is crucial for guiding urban and territorial planning and management strategies aimed at conserving natural resources essential for sustainable development, as emphasized in both past and recent studies (Dwivedi et al., 2025; Fan et al., 2007; Esfandeh et al., 2022; Yao et al., 2022; Vitale et al., 2023; Salvo et al., 2023; Francini et al., 2023). In pursuit of this goal, researchers in recent years have extensively utilized RGB, multispectral (MSI), and hyperspectral (HSI) satellite imagery from major space agency programs, such as Landsat, Sentinel-2, and MODIS (Khachoo et al., 2022; Khachoo et al., 2023; Salvo & Vitale, 2024; Vitale & Salvo, 2024). Multispectral imaging (MSI) is a passive technique that is known to be an effective remote sensing technique for collecting earth observation (EO) data (Lim et al., 2023). MSI captures images in the visible, near-infrared (NIR), and short-wave infrared (SWIR) ranges in tens of bands. In contrast, HSI captures images in hundreds of narrow but contiguous spectral bands that extend from the visible range (0.4-0.5 μm) to the SWIR (Shaw & Burke, 2003). Although hyperspectral imaging (HSI) provides higher spectral resolution, multispectral imaging (MSI) and its enhanced versions remain widely preferred due to their balanced trade-off between spatial and spectral resolutions. This preference arises from the sensor complexity, which is determined by the product of the number of spectral bands and image resolution relative to spatial coverage. These MSI satellite images are readily accessible through cloud computing platforms, which enable efficient data storage, retrieval, and analysis on powerful servers that emulate the capabilities of supercomputers for users. Numerous cloud computing platforms have been established to date. For instance, Amazon Web Services (AWS) operates on a pay-as-you-go model, billing users for the services based on the duration of usage (Tamiminia et. al., 2020; Amani et al., 2020). This service provides access to open data from various satellites, including Landsat-8, Sentinel-1, Sentinel-2, the China–Brazil Earth Resources Satellite program, and datasets from the National Oceanographic and Atmospheric Administration (NOAA). Microsoft Azure is a cloud computing service that launched the AI for Earth initiative to tackle environmental issues in climate change, agriculture, biodiversity, and water management. Azure offers Landsat and Sentinel-2 datasets for North America from 2013 onwards, along with MODIS imagery, operating on a pay-as-you-go basis and providing virtual systems to users (Wilder, 2012). Launched in 2010, Google Earth Engine (GEE) leverages Google's advanced computing infrastructure to provide open-access remote sensing (RS) datasets (Gorelick et al., 2017). Renowned as a premier platform for large-scale geospatial data processing, GEE facilitates scientific research by offering free access to an extensive collection of remotely sensed data (Salvo & Vitale, 2024b; Vitale, 2025). It can be accessed through an internet-based Application Programming Interface (API) that requires HTML expertise.

Remote sensing data is invaluable for mapping LULC and detecting changes (Partheepan et al., 2023), offering unmatched spatial and temporal resolution. Nonetheless, accurately identifying urban and territorial features presents significant challenges due to the complex interactions and variability in spectral, spatial, and textural characteristics (Blaschke et al., 2014). A thematic LULC map featuring classified categories is a crucial instrument for visualizing changes in land use and land cover within a study area. Mapping land use and land cover (LULC) at medium spatial resolution requires a comprehensive dataset encompassing modern and historical remote sensing data. Progress in LULC mapping has been realized by integrating machine learning (ML) and artificial intelligence (AI) classifiers (Fistola & La Rocca, 2024; Gaglione, 2023). This advancement is part of a broader field known as GeoAI, Artificial Intelligence for Geospatial Data, which combines geospatial science with artificial intelligence technologies to analyze and interpret vast amounts of geographical data. GeoAI leverages the capabilities of ML and AI to automate and enhance the accuracy of spatial analysis, including the critical task of LULC mapping, by efficiently processing and learning from multi-temporal and multi-source remote sensing datasets. Numerous approaches, including unsupervised algorithms, parametric supervised techniques, and machine learning (ML) methods, have been widely applied for Land Use and Land Cover (LULC) mapping (Halder et al., 2011; Li et al., 2016; Orieschnig et al., 2021). Supervised classification techniques include methods such as the maximum likelihood classifier, Mahalanobis distance, k-nearest neighbors (kNN), support vector machine (SVM), random forest (RF), decision trees (DT), spectral angle mapper (SAM), fuzzy logic, fuzzy adaptive resonance theory-supervised predictive mapping (Fuzzy-ARTMAP), radial basis function (RBF), artificial neural networks (ANN), and naive Bayes (NB) (Ma et al., 2019; Shih et al., 2019, Vitale & Lamonaca, 2025a; Vitale & Lamonaca, 2025b). Unsupervised classification techniques encompass fuzzy c-means, the k-means algorithm, the affinity propagation clustering algorithm, and ISODATA methods (Maxwell et al., 2018).

Among these methods, ML algorithms for LULC mapping have gained considerable attention (Wang et al., 2022) due to their ability to handle input data without assuming specific distributions and their superior performance compared to traditional parametric classifiers (Jozdani et al., 2018). ML algorithms have been extensively applied to urban LULC mapping and modeling (e.g., Zhang et al., 2019; Mao et al., 2020) and evaluated in comparative studies (Camargo et al., 2019; Ouma et al., 2023). However, the accuracy of ML algorithms varies across different datasets and case studies. Among these, the unsupervised K-means classifier stands out for its computational efficiency, enabling the processing of large datasets quickly. This capability is especially valuable for analyzing the extensive remote sensing datasets used in LULC mapping. As an unsupervised algorithm, K-means does not require retraining and can be easily applied to new datasets, making it particularly useful for monitoring temporal LULC changes where new land cover classes may emerge (Lemenkova & Debeir, 2022).

This study proposes an innovative methodology that integrates advanced geospatial techniques with artificial intelligence to analyze and map LULC changes. It focuses on built-up and vegetation cover dynamics over 16 years (2005-2021) in a territorial-scale case study. The analysis emphasizes built-up area dynamics due to their significant social, economic, and environmental impacts, including increased resource demand and alterations to natural landscapes. Expanding built-up areas often results in vegetation loss, with ecological consequences such as reduced biodiversity, carbon cycle disruptions, and regional climate shifts.

Using the Google Earth Engine (GEE) cloud computing platform, implemented with JavaScript code, the study utilized a multitemporal series of multispectral satellite images from the Landsat 5 (1984-2012) and Landsat 8 (2013–present) datasets. These images were pre-processed and classified using the unsupervised K-means algorithm to assess built-up area dynamics over time. The classification accuracy for 2021 was evaluated by comparing the algorithm's results with the European Space Agency's (ESA) WorldCover 10 m product derived from Sentinel-1 and Sentinel-2 data, using the F1-Score as the accuracy metric. Following the validation of the classification process, changes in built-up and vegetation cover were analyzed in the QGIS environment by comparing the K-means algorithm outputs for 2005 and 2015 with those for 2022.

The structure of this paper is organized in the following manner: Section 2 provides a comprehensive overview of the study area and the datasets used for the study. Moreover, in the same section, the authors introduce the proposed methodology to determine study area built-up and vegetation cover changes for 2005-2021. The research outcomes are thoroughly analyzed in Section 3, while Section 4 engages in a detailed discussion and presents the findings from the case study. The paper concludes with a Section summarizing the key conclusions drawn from the research.

2. Materials and methods

2.1 Study area

The study was conducted on a territorial-scale area encompassing 15 municipalities in the Calabria region of southern Italy (see Fig.1). These municipalities include Carolei, Castiglione Cosentino, Castrolibero, Cerisano, Cosenza, Dipignano, Lappano, Marano Marchesato, Marano Principato, Mendicino, Montalto Uffugo, Rende, San Pietro in Guarano, San Vincenzo la Costa, and Zumpano.

The study area covers approximately 8,685.68 hectares and has a resident population of about 70,550 people. Cosenza and Rende are the most prominent of these municipalities, serving as central hubs for regional activities. Calabria is largely characterized by small municipalities, with most having populations of no more than 5,000 inhabitants.

Including 15 municipalities provides a representative sample of the region's typical urban and rural landscapes, offering a comprehensive perspective on land use dynamics across communities of varying sizes and characteristics. In a region where urban growth and green space changes often occur subtly, especially in smaller municipalities, examining a broader geographical area is crucial to identifying significant transformations over time.

A study area of this scale enables the observation of meaningful development and transformation patterns that might not be evident in smaller, more homogeneous areas. This broader scope ensures a nuanced understanding of regional land use and land cover dynamics.

2.2 Datasets

Landsat multispectral images are among the most widely used datasets for time-series analysis in land use and land cover (LULC) classification, largely because of the extensive historical records available in their archives (Qu et al., 2021).

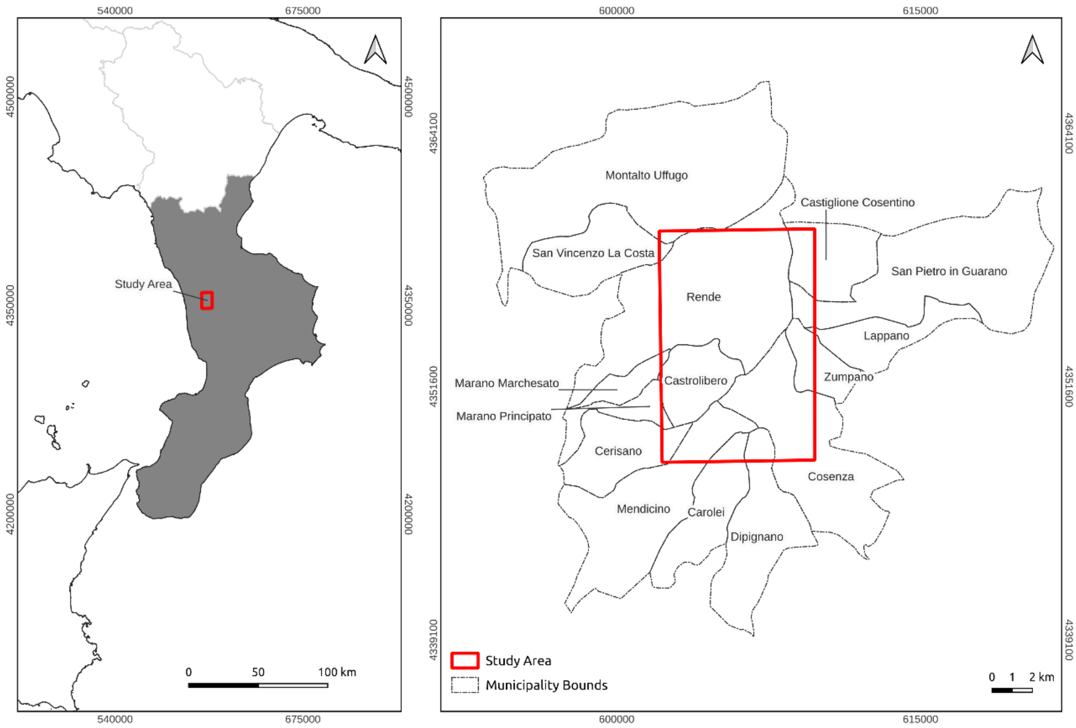

Fig.1 Study area Framework

For this analysis, Landsat imagery from multiple dates was utilized. Specifically, 2005, 2015, and 2021 satellite images were acquired from the Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) sensors. These images were obtained from the open-access Google Earth Engine (GEE) repository at a spatial resolution of 30 meters, using the World Geodetic System (WGS84) coordinate reference system.

Standard preprocessing steps were carried out within GEE prior to analysis. These steps included cloud cover removal, corrections for topographic, atmospheric, and geometric distortions, layer stacking, and image resizing. Additionally, histogram equalization was applied in ERDAS Imagine to enhance the multitemporal and multisensor Landsat imagery.

To evaluate the classification accuracy of the unsupervised k-means algorithm applied to the 2021 multispectral satellite image, the authors utilized the European Space Agency's (ESA) World Cover v200 map with a 10-meter resolution as ground truth. This map was obtained from GEE and is based on data from Sentinel-1 and Sentinel-2 satellites, part of the ESA's Earth Observation Envelope Programme. While Landsat imagery offers a longer temporal record, its operational bands have a coarser spatial resolution (30 meters). The finer resolution of the ESA map enhances accuracy by distinguishing land cover classes that might be blended in the Landsat data.

The World Cover v200 map classifies land into 11 distinct classes, including tree cover, shrubland, grassland, cropland, built-up areas, bare or sparse vegetation, snow and ice, permanent water bodies, herbaceous wetlands, mangroves, and moss and lichen. For this study, the authors focused on two layers: built-up areas and vegetation cover. The vegetation cover layer was created by merging the shrubland, grassland, cropland, bare or sparse vegetation, herbaceous wetlands, mangroves, and moss and lichen classes. This layer fusion was performed in QGIS by importing and processing the ESA World Cover map.

2.3 Landsat images classification

The authors used Landsat satellite imagery to analyze changes in built-up and vegetation cover from 2005 to 2021, and they classified the images using the unsupervised K-means clustering algorithm.

K-means clustering is a simple and widely adopted unsupervised learning method in data mining. This iterative algorithm partitions an unlabeled dataset into K predefined, distinct, and non-overlapping clusters based on similarity, ensuring that each data point is assigned to only one cluster. The main objective of K-means clustering is to minimize the distance between data points and their respective cluster centers. It is particularly effective for large datasets, ensuring the algorithm converges efficiently.

The number of clusters (K = 15) was established through an iterative process that combined visual inspection of the resulting classifications with domain knowledge of the study area, ensuring a clear separation between built-up and vegetation cover. The classification of Landsat images from the years 2005, 2015, and 2021 was carried out using ERDAS Imagine software.

2.4 Classification accuracy assessment

To assess the accuracy of the unsupervised K-means clustering algorithm's classification of built-up and vegetation cover areas, the authors used the 2021 Landsat satellite image and the 2021 ESA World Cover v200 Map as reference data. Both datasets were imported into QGIS software, enabling a direct comparison between the areas predicted by the algorithm and the ground truth provided by the ESA map.

The accuracy of the classification was assessed using Precision, Recall, and the F1-Score, which is the harmonic mean of Precision and Recall. Precision measures the proportion of correctly identified built-up and vegetation areas out of all regions predicted as such. In contrast, Recall measures the proportion of actual built-up and vegetation areas correctly identified by the model. The F1-Score provides a single balanced metric of classification performance, ranging from 0 (poor) to 1 (perfect).

These metrics can be calculated as follows:

$$Precision = \frac{TP}{TP + FN} \quad (1)$$

$$Recall = \frac{TP}{TP + FN} \quad (2)$$

$$F1 - score = 2 * \frac{Precision * Recall}{Precision + Recall} \quad (3)$$

The result is between 0 and 1, where 0 indicates the worst possible performance The F1-score ranges from 0 to 1, with 0 indicating poor performance, and 1 denotes perfect precision and recall. An F1-Score closer to 1 suggests that the model's predictions are accurate and reliable, indicating a high degree of agreement between the predicted mask and the ground truth data for built-up and vegetation cover areas.
Employing the F1-Score for comparing the model's predictions against the ground truth is particularly beneficial when there is an imbalance between the presence of built-up areas and vegetation or when the cost of false positives is different from the cost of false negatives. By considering both Precision and Recall, the F1-Score provides a more comprehensive evaluation of the model's performance than using either metric alone, offering insights into the model's overall effectiveness in classifying land cover types accurately.
Once the accuracy of the algorithm's classification using QGIS software is determined by considering Landsat satellite images from 2005, 2015, and 2021, it is possible to assess the changes in built-up and vegetation cover from 2005 to 2021. These changes were evaluated by comparing the areas occupied by built-up and vegetation over time.

3. Results

3.1 Built-up and vegetation cover mapping and classification accuracy estimation

Satellite images from the Landsat dataset for 2005, 2015, and 2021 were acquired using the Google Earth Engine platform. These images were classified using the unsupervised K-means clustering algorithm to identify built-up and vegetation cover areas. As outlined in Section 2, the study area encompasses 15 municipalities, covering a total surface area of approximately 8,685.68 ha, which was classified into built-up and vegetation areas using the K-means algorithm.

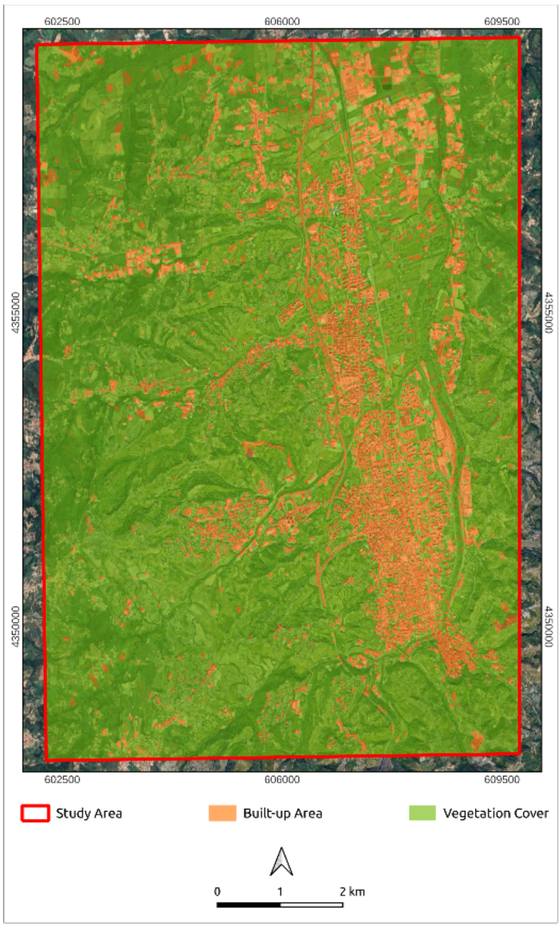

Fig.2 K-means classification algorithm prediction for 2021

To assess the accuracy of the classification, the algorithm's output for the study area in 2021 was compared to the ESA World Cover Map classification, which served as a benchmark. This comparison was performed in the QGIS environment. Fig.2 displays the classified built-up and green areas derived from the K-means clustering algorithm. The classification accuracy was evaluated using Precision, Recall, and F1-Score, with values of 0.63, 0.65, and 0.64 for built-up areas. The F1-Score of 0.64 indicates a moderate level of accuracy, suggesting that the algorithm achieves a reasonable balance between Precision (its ability to correctly identify positive instances) and Recall (its ability to capture all positive instances).

Land Cover Category	Areas [ha]	Changes [ha]	Changes [%]
2005	991.82	-	-
2015	1017.82	26.00	2.62
2021	1158.49	140.67	13.82

Tab.1 Built-Up changes from the k-means algorithm for 2005-2021

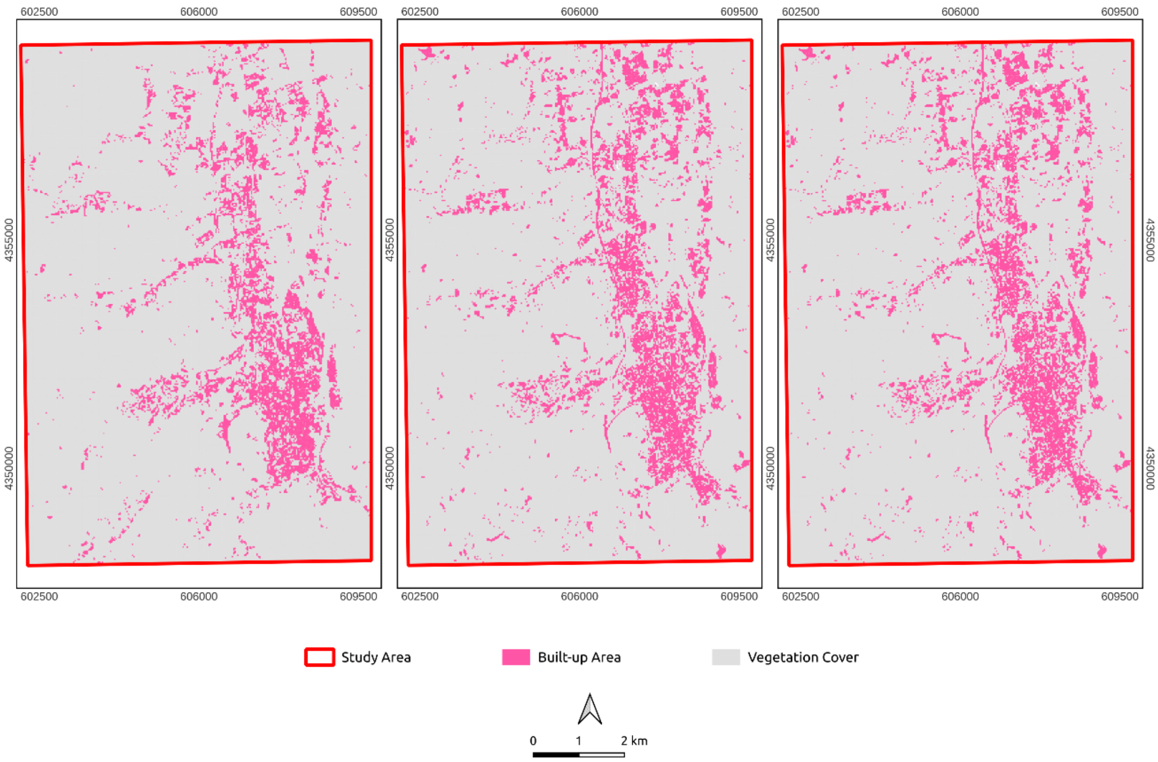

Fig.2 Built-up area evolution for the 2005-2021 period obtained from the K-means classification algorithm

Given that the classification was unsupervised, an F1-score of 0.64 can be considered a favorable result, particularly considering the challenges of accurately classifying the diverse land cover types present in Landsat imagery with a 30-meter resolution.

In contrast, the accuracy for vegetation cover is significantly higher, with Precision, Recall, and F1-Score values of 0.88, 0.95, and 0.92, respectively.

The F1-Score of 0.92 for vegetation cover indicates excellent classification performance. It should be noted that the vegetation cover class used for validation was obtained by merging several categories of the ESA WorldCover v200 dataset (shrubland, grassland, cropland, bare or sparse vegetation, herbaceous wetlands, mangroves, and moss/lichen).

This aggregation ensured consistency with the binary built-up/vegetation classification adopted in this study. Furthermore, vegetation is typically characterized by distinctive spectral properties in satellite images, which the K-means algorithm can readily identify and group into coherent clusters. This suggests that the spectral profiles of vegetation in the study area are well-differentiated from other land cover types, resulting in high Precision and Recall.

3.2 Built-up and vegetation cover classification and change detection

After assessing the accuracy of the K-means algorithm, the built-up and vegetation cover areas for 2005, 2015, and 2021 were determined, and the changes in built-up areas over the sixteen years were calculated (Tab.1 and Fig.3). This analysis was performed using the spatial analysis functions in QGIS software.
As shown in Tab. 1, the built-up areas in the study region experienced accelerated growth from 2005 to 2021. Between 2005 and 2015, the built-up areas across the 15 municipalities increased from 991.82 ha to 1017.82 ha, an increase of 26 ha, or 2.62%. Since the study only considers built-up and vegetation cover as LULC categories, any increase in built-up areas corresponds directly to a decrease in vegetation cover. Therefore, the 26 ha expansion in built-up areas equates to a 26 ha reduction in vegetation cover, assuming the total land area remains constant.
The period from 2015 to 2021 saw a significant acceleration in urban expansion compared to the earlier decade. During these six years, the built-up areas in the study region increased from 1017.82 ha to 1158.49 ha, an increase of approximately 140.67 ha, or 13.82%. This rapid urban growth can be attributed to regional socio-economic factors, notably the expansion of the University of Calabria campus in Rende, which currently serves around 70,000 students. This university has experienced remarkable growth, marking a 23% increase in student enrollment in 2022 compared to pre-pandemic levels. It is one of only three universities in Italy to see consistent increases in new enrollments each year. The expansion of educational infrastructure and related services has been a key driver of urbanization in the area.
In spatial terms, urban growth has been especially concentrated along the eastern and southern edges of the main municipalities, with new development radiating outward from consolidated centers. Expansion has tended to follow the existing transportation network, producing linear patterns of growth along major road corridors, while also including localized infill within already urbanized areas. This morphological mix of sprawl and densification reflects the dual influence of infrastructure accessibility and residential demand generated by the university expansion.
As with the previous decade, the rapid growth of built-up areas from 2015 to 2021 resulted in a corresponding decrease in vegetation cover. Overall, from 2005 to 2021, built-up areas in the study region increased by 166.67 ha, representing a 16.44% rise.

4. Discussion of results

The results presented in the previous section underscore the significance of a methodology that effectively maps and analyzes the relationship between urban growth and environmental changes within a specified study area. This methodology, applied to 15 municipalities in southern Italy, integrates advanced remote sensing techniques, artificial intelligence, and GIS technologies. Using Landsat imagery and an unsupervised K-means clustering algorithm offers a robust framework for quantifying and understanding land-use changes over a sixteen-year period, from 2005 to 2021.
The accuracy of the proposed methodology in classifying built-up and vegetation cover areas was evaluated on two levels. The classification of built-up areas showed a moderate level of accuracy, with an F1-Score of 0.64, revealing some challenges faced by the unsupervised K-means algorithm in differentiating built-up land from vegetation. These challenges may arise from the complexity of built-up areas, such as the diverse construction materials and varying spectral signatures of buildings. Additionally, the intricate nature of urban structures and the mixing of built-up pixels with other land cover types at the 30-meter resolution of Landsat imagery may lead to mixed pixels, further complicating classification. These factors likely contribute to lower Precision and Recall distinguishing built-up areas from other land cover classes.

The comparison of these results with the ESA World Cover map v200, which has a validation accuracy of 76.7%, provides a useful benchmark for evaluating the reliability of the K-means classification in this case study.

In contrast, the high F1-Score of 0.92 for vegetation cover suggests that the unsupervised classification performs well for this land cover type.

The rapid expansion of built-up areas, particularly between 2015 and 2021, is closely linked to broader socio-economic changes in the region. The establishment and growth of the University of Calabria in Rende has significantly contributed to local urbanization, illustrating how educational infrastructure can drive urban development. The university's expansion, which has attracted a large student population, has likely increased demand for housing, services, and amenities, thereby spurring the growth of built-up areas.

Beyond the quantitative increase, the results also reveal clear spatial and morphological patterns of expansion. Growth has predominantly occurred along the eastern and southern edges of urban centers, reflecting a directional tendency shaped by the availability of land and infrastructure connectivity.

Linear development along major road corridors highlights the guiding role of transportation networks, while simultaneous infill processes indicate consolidation within pre-existing built-up areas. Such a combination of sprawl and densification is typical of medium-sized Mediterranean cities, where accessibility and demographic drivers jointly shape urban form. The concurrent reduction in vegetation cover, directly tied to the growth of built-up areas, underscores the environmental consequences of urbanization. This reduction in green spaces affects biodiversity, disrupts ecosystem services, and has broader implications for urban sustainability, such as heightened vulnerability to urban heat islands and reduced recreational spaces for communities.

The high F1-Score for vegetation cover classification reflects the strength of the methodological framework in monitoring these changes, indicating that remote sensing and GIS technologies are effective tools for supporting environmental conservation initiatives.

5. Conclusions

This research highlights the potential of integrating advanced remote sensing, geospatial technologies, and artificial intelligence to monitor and analyze the spatiotemporal dynamics of urban growth and the loss of vegetation cover. Given the continued expansion of urban areas and land consumption in cities worldwide, leveraging these technologies is essential for developing strategies that promote sustainable development while safeguarding critical environmental services. While the study provides valuable insights, several limitations should be addressed. The use of 30-meter resolution Landsat imagery may limit the detection of finer-scale land cover changes. Future research could benefit from incorporating higher-resolution satellite data or combining datasets from multiple sources to capture more detailed spatial dynamics of land use and land cover (LULC) changes. Additionally, exploring supervised learning algorithms, such as Support Vector Machines (SVM), Random Forest (RF), and Convolutional Neural Networks (CNNs), could improve classification accuracy. These supervised algorithms, which rely on labeled training data, may offer more precise classifications of complex urban landscapes and diverse vegetation types. Comparative studies evaluating the performance of these algorithms against unsupervised K-means clustering could provide insights into the most effective methods for classifying specific LULC categories. While the study focuses on built-up areas and vegetation cover, which provides clear insights into urban and environmental changes, it may overlook other important land cover types and their dynamics. Expanding the scope of LULC categories in future research could offer a more comprehensive understanding of land cover transformations. Finally, the socio-economic drivers of urban expansion, exemplified by the growth of the University of Calabria, point to a promising direction for future research into the causal relationships between educational infrastructure, demographic changes, and urban development. Investigating these connections could inform more effective urban planning and policy strategies to balance development with environmental preservation.

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Author's profile

Francesco Lamonaca

M.S. degree in Computer Science Engineering in 2005 and Ph.D. degree in Computer and System Science in 2010 from the University of Calabria, Italy; doctorate equivalences in Science (2010) and Engineering Science (2011) from the Université Libre de Bruxelles, Belgium. He is now associate professor of Electronic Measurements at the University of Calabria. In 2020 he achieved the National Habilitation to Full Professor in Electric and Electronic Measurements. He is member of the National Research Council of Italy, Institute of Nanotechnology and Fellow of the Bruxelles Research Institute for Advanced Studies (BRIAS). He is the Editor in Chief of Acta IMEKO, the diamond open access elecronic Journal of the International Measurement Confederation. He is Senior Member of the Union Radio Scientifique Internationale, Italian Institute of Robotics and Intelligent Machines, IEEE, IEEE IMS, IEEE TC10, TC 25 and TC-37. He has authored and co-authored over 180 papers published in international journals and conference proceedings. He is editor of the standard IEEE: "Standard for Jitter and Phase Noise 2414-2020". He won several national and international competitions as first classified. He was honored with several awards including best paper awards and outstanding reviewers. His current research includes: measurements, signal and image processing and standardization, noninvasive monitoring and testing, IoT and AI based monitoring systems, time synchronization.

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REVIEW NOTES

"Brain gain" in planning academia: learning from Albania's practical approaches

Irina Branko [a], Erida Curraj [b], Dorina Pojani [c]*

[a] Department of Urbanism
Polytechnic University of Tirana, Tirana, Albania
e-mail: irina.branko@fau.edu.al
ORCID: https://orcid.org/0000-0002-5925-107X

[b] Department of Engineering and Architecture
European University of Tirana, Tirana, Albania
e-mail: erida.curraj@uet.edu.al
ORCID: https://orcid.org/0000-0002-5787-3529

[c] School of Architecture, Design and Planning
The University of Queensland, Brisbane, Australia
e-mail: d.pojani@uq.edu.au
ORCID: https://orcid.org/0000-0002-2018-6338
* Corresponding author

Abstract

This Review Note presents two successful "brain gain" initiatives implemented in Albania — READ, a planning research project, and GERMIN, a planning education project. Both programs represent structured efforts to mobilize diaspora expertise in order to strengthen higher education, research, and professional practice, addressing capacity gaps intensified by the prolonged emigration of skilled professionals. In this context, "brain gain" is understood not as permanent return, but as the circulation of talent. These models emphasize knowledge exchange, research partnerships, co-teaching, and global networking, often driven by strong personal and professional ties and implemented at relatively low financial cost. The lessons drawn may provide useful insights for policymakers, educators, and researchers confronting similar issues along the Mediterranean.

Keywords

Brain drain; Brain gain; Planning diaspora

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1. Introduction

The purpose of this Review Note is to present two "brain gain" programs implemented in Albania — READ, a planning research project, and GERMIN, a planning education project — in which the three authors participated. These programs exemplify structured approaches to mobilizing diaspora expertise to strengthen higher education, research, and professional practice in Albania, addressing gaps intensified by the prolonged emigration of skilled professionals. While the focus is on Albania, the experiences documented here have broader relevance in countries across the European Sunbelt — spanning the Iberian, Italian, and Balkan Peninsulas — which face comparable challenges related to brain drain, talent circulation, and the integration of diaspora knowledge (see, for example, GRS, 2024). Accordingly, the lessons drawn from our participation in these programs may provide useful insights for policymakers, educators, and researchers confronting similar issues along the Mediterranean. Below, we provide context on Albanian brain drain challenges before proceeding to a discussion of the READ and GERMIN programs.

2. Albanian emigration trends: the 'brain drain' problem

The dramatic collapse of Albania's communist regime in 1990 catalysed one of the most intense migration episodes in post-World War II Europe. During nearly five decades of strict communist rule, emigration was prohibited and the borders were tightly sealed. With the fall of the regime, all barriers to exiting the country were removed while the economy collapsed (state industries shut down, unemployment soared, and inflation spiked.) Desperate Albanians left the country in large numbers — usually for neighbouring Greece and Italy but also other parts of Europe, North America, and Australia — often in irregular circumstances. Over the three decades following 1990, it is estimated that more than one-third of the Albanian population has left the country — reducing the resident population from around 3.3 million to approximately 2.8 million in 2023 (INSTAT, 2024).

Annual departures have been roughly 42,000 people in recent years. Surveys of potential emigrants indicate that a significant share of young Albanians still contemplate leaving, driven by perceptions of better economic prospects, quality of life and professional opportunities abroad. While emigration continues at high levels, its patterns have evolved. Early migration was heavily motivated by immediate economic survival whereas more recent emigrants seek white-collar work, university studies, and postgraduate qualifications (King & Gëdeshi, 2020).

A core component of Albania's migration dynamics is the so-called "brain drain" — the emigration of highly skilled and well-educated individuals. From the 1990s onward, Albania has lost a substantial portion of its human capital. While the early emigration was heavily motivated by economic survival, also it is estimated that approximately 40% of university professors and research scientists emigrated during the 1990s, significantly weakening the country's academic and scientific capacity (MPI, 2025). Contemporary research on Albanian students abroad shows that large numbers of degree-seeking and highly educated young people do not intend to return (King & Gëdeshi, 2020). The economic implications of this sustained brain drain include not only the loss of national investment in education and training but also reduced innovation capacity and weakened institutional development.

Brain drain also poses a challenge for Albania's governance because it systematically removes the very social groups most critical to democratic consolidation. Skilled professionals such as planners, lawyers, doctors, engineers, and academics are essential for designing, implementing, and evaluating public policy. When these individuals emigrate in large numbers, state institutions become understaffed or reliant on less experienced personnel, reducing administrative effectiveness and policy continuity. In an economically and politically fragile context, this loss of capacity limits the state's ability to deliver services to the citizenry.

Furthermore, brain drain diminishes democratic accountability and civic participation. Educated citizens are disproportionately more likely to vote, engage in civil society, monitor government performance, and demand transparency. Their departure has weakened watchdog functions and reduced pressure on the Albanian political elite to govern responsibly. This has further entrenched clientelism and patronage networks and undermined political pluralism and leadership renewal. With potential reformers gone, the likelihood of domestic institutional reform has been curtailed; the country risks turning into a "kakistocracy."[1]

Finally, brain drain has distorted the state–citizen social contract. Remittances have helped stabilise household incomes and reduce poverty, but they are also substituting for public provision and muting demands for systemic reform. When livelihoods depend more on transnational family networks than on domestic institutions, trust in the state erodes and incentives for political engagement weaken. Practically, brain drain is replacing public participation as the primary response to governance failure. This is a structural challenge — not merely a demographic issue for Albania (see Politico, 2024; Tirana Times, n.d.).

3. A variety of "brain gain" programs

Despite major challenges — including weak governance, democratic deficits, and entrenched corruption — Albania has come to recognise that attracting and retaining skilled professionals is essential for national development. Achieving this requires proactive strategies to mobilise highly qualified members of the Albanian diaspora in the country's economic, academic, and institutional life. The urgency of this effort is heightened by widespread disillusionment with decades of foreign technical assistance, which often failed to produce sustainable outcomes (Pojani & Stead, 2018). External experts frequently lacked a nuanced understanding of the local context and did not speak the language (which is notoriously difficult and unrelated to any other language). In response, Albania has increasingly emphasised diaspora-linked expertise as a mechanism to bridge global knowledge with domestic realities. A number of programs and policy efforts, led by the government, universities, and civil society, have sought to leverage "brain gain" — the return or productive engagement of diaspora talent.

One of the earliest structured efforts was the Brain Gain Programme, initiated in the mid-2000s in coordination with the Government of Albania and international partners such as the United Nations Development Programme (UNDP). The program aimed to create incentives for highly skilled emigrants to return or engage with Albania's institutions by establishing policy frameworks that would welcome and integrate diaspora expertise into academia, public administration, and research sectors. It included an online diaspora database to match expertise with institutional demand and regulatory adjustments to facilitate employment and recognition of foreign qualifications. This approach explicitly targeted academics, researchers, and professionals with overseas experience, envisioning short-term consultancies, joint research projects, and temporary or permanent return placements that could enhance capacities within Albanian universities and public institutions (Zeneli et al., 2013).

More recently, Albania's national policy frameworks — including strategic documents developed under diaspora engagement and economic development umbrellas — have incorporated digital platforms and structured return programs. Notably, the Albrain Platform and the Diaspora Return Program are designed to connect Albanian professionals worldwide with opportunities for short-term projects, consulting, workshops, and innovation collaborations with government, academia, and industry in Albania (GoA, 2025). At the institutional level, some private universities have instituted their own brain gain programs that specifically aim to bring Albanian educators and researchers back into the country's educational landscape. These programs recruit mid-career and senior academics from the diaspora to participate in teaching and research, either through physical presence in Albania or through remote collaboration. The remainder of this Review Note focuses on two programs, READ and GERMIN, in which these authors participated through a planning research project and a planning education project, respectively.

[1] A *kakistocracy* is a system of government in which the least qualified or most unscrupulous people hold power. From Greek: *kakistos* (worst) + *kratos* (rule).

4. In focus: READ and GERMIN

AADF's READ Fellowship. The Albanian-American Development Foundation (AADF) is a non-profit organisation established in 2009 with original support from the U.S. government. Its mission is to advance sustainable development in Albania through strategic investments in education, leadership, entrepreneurship, cultural heritage, and community empowerment. One of AADF's flagship initiatives in the education and research sector is the Research Expertise from the Academic Diaspora (READ) Fellowship Program, launched in 2021 in partnership with the Institute of International Education (IIE). READ is a competitive fellowship designed to connect Albanian universities and other higher education institutions with highly qualified researchers and scholars of Albanian origin based in OECD countries. The program seeks to strengthen Albania's research and teaching capacity by facilitating collaborations such as co-authored research, joint supervision of doctoral candidates, curriculum and course development, and co-teaching activities (AADF, 2025; IIE, 2025).

READ operates on a dual-application model, in which projects are proposed by resident Albanian scholars and subsequently matched with diaspora academics. Fellowships typically support engagement periods of up to one year, either in person or in a hybrid format. The program has already received strong institutional support from Albanian universities, including formal cooperation agreements. A team composed of two of the authors (Erida Curraj as the resident scholar and Dorina Pojani as the diaspora scholar) was awarded a Fellowship for 2023–2024.

The team led a research project designed to provide a more comprehensive understanding of Tirana's gendered mobility and accessibility patterns in post-industrial suburban areas and their connection to urban liveability. Issues of mobility, accessibility, and liveability are, of course, central to *TeMA: Journal of Land Use, Mobility and Environment* and its readership. The Journal was established specifically to connect urban studies with research on mobility in all its aspects, and it seeks to advance novel theoretical and methodological frameworks that move beyond approaches rooted in the scientific culture of the last century. Research on gender issues in the city, as well as within the urban and transport planning professions, is also growing — albeit slowly — within *TeMA*'s volumes (see Stiuso, 2024; Carpentieri et al., 2023; Delatte et al., 2018; Pojani, 2011).

For the READ-supported study, three types of primary data were collected: field observations, quantitative population surveys, and qualitative focus groups. The project involved planning students who assisted with data collection and junior researchers who supported the analysis. Students reported that this experience was particularly valuable for learning how to gather data in a hands-on manner and for gaining exposure to applied research methods. Overall, the project was deemed highly successful, resulting in a conference presentation and an academic research article that is currently under review in a leading planning journal.

<u>EU4Innovation's GERMIN Fellowship</u> - The Global Engagement and Research in Migration Network (GERMIN) is a non-governmental organisation that connects the Albanian and regional diaspora with institutions in their countries of origin (GERMIN, 2025). Its programs are implemented in partnership with the EU4Innovation program, a multi-donor initiative funded by the European Union, the German Federal Ministry for Economic Cooperation and Development (BMZ), and the Swedish International Development Cooperation Agency (SIDA), and delivered locally by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Albania.

Similar to AADF, GERMIN's mission is to facilitate knowledge transfer, professional engagement, and innovation across sectors such as education, entrepreneurship, and research. Its work, however, is more targeted: it leverages diaspora expertise to address gaps between education and labor market needs and thus accelerate Albania's transformation toward a more innovation-driven, knowledge-based economy. As with READ, GERMIN has been well received by Albanian universities (EuroNews Albania, 2025).

Like READ, GERMIN operates on a team-based model. However, in this case, projects are proposed by faculty from the diaspora and implemented in collaboration with resident academics over the course of one year, through a combination of in-person visits and online activities. In 2025–2026, one of the authors (Dorina Pojani, a member of the academic diaspora) was awarded a teaching fellowship, which she carried out in collaboration with Irina Branko (one of the authors, a lecturer in the Department of Urbanism at the Polytechnic University of Tirana).

The fellowship focused on refreshing a landscape planning course led by the resident lecturer. Normally, the course is delivered through a combination of theoretical lectures and studio-based work. Historically, this urbanism program has placed a strong emphasis on design rather than theory or policy. In this case, the key innovation was a series of guest lectures by domestic and international practitioners from the public, private, non-profit, and international assistance sectors. These lectures, complemented by visits to the lecturers' workplaces, introduced students to a range of career opportunities for planning graduates beyond the more typical employment in design studios. Although planning education and careers are not *TeMA*'s specific focus, the Journal is interested in landscape planning, particularly when it relates to environmental sustainability. While case studies from across Europe have appeared in its pages, Italian examples (Leone et al., 2020; Zullo et al., 2015) are especially relevant, as Italy often serves as a reference point for Albania on these matters.

Returning to the GERMIN initiative, student feedback on was very positive. In an anonymous survey completed by more than half of the students (20 out of 37), the course — and particularly the new elements — received an average score of 4.75 out of 5. Beyond the quantitative results, qualitative feedback gathered through a focus group attended by 15 students was especially illuminating. Students clearly expressed a desire for more than technical training. They sought greater exposure to real-world practice, including experiences outside the capital city in coastal and mountainous regions; insight into non-traditional career pathways; and stronger links between urban planning, architecture, and communities. Students highlighted the importance of learning about non-design aspects of professional practice, including coordination with institutions, financial management, budgeting, and project governance — areas they felt were largely absent from their formal training but central to real-world work. They also valued the interdisciplinary nature of several guest organisations. Importantly, students welcomed the territorial breadth of the course, which deepened their understanding of landscape, tourism, and regional challenges, and strengthened their appreciation of planning at multiple scales.

5. Success factors and lessons learned

Here the authors reflect on the factors that, in our experience, contributed to the success of these programs, as well as lessons learned and suggestions for future improvement.

Funding -While both fellowships are competitively awarded, they are low-cost programs. This is a positive feature, as it enables broader participation. The administrative burden is also limited, with short application forms and minimal reporting requirements. This stands in contrast to major EU-funded project applications, which typically have low rates of success but high potential rewards. These projects also involve substantial administrative burdens, often requiring researchers to spend a disproportionate amount of time preparing applications and reporting on the outcome of the project (see Dresler et al., 2022; Kooijman, 2015). In this case, the main cost was the return airfare for the diaspora scholar (who was coming from Australia), along with some project-related expenses and payments for casual research assistants. With planning being a social science discipline, project expenses were relatively low; natural science projects may involve higher costs (such as for labs, materials, and advanced software), and therefore it would be advisable to integrate diaspora scholars into university departments and/or ongoing projects for which the major infrastructure is already in place. READ provided funding for the resident participants, whereas GERMIN did not. Ideally, funding should also be available for domestic researchers and lecturers, as this represents an important incentive for participation — particularly given that academic salaries in Albania are lower than the OECD average.

Presence - While online collaboration is possible, some physical presence is essential for these fellowships to succeed. Research and teaching activities are less effective online than in-person engagement — as was clearly demonstrated during the Covid-19 pandemic. Being present allows the diaspora scholar to guide activities and provide mentorship, in line with Albania's relational culture. During their visit, diaspora scholars often take on additional activities, such as media appearances and workshops, which also help domestic scholars expand their professional networks. This networking support aligns closely with one of the program's key objectives and is highly valued by resident participants. In the case of *planning* academics from the diaspora, their commentary on controversial urban development projects is particularly valued in the media, as they are often freer to critique current practices than local professionals (the latter may face conflicts of interest or feel constrained by political pressures). Engaging senior diaspora academics, who are well respected in both Albania and their country of domicile, further amplifies the program's effectiveness and impact. In Albania's patriarchal culture, junior academics who are without international recognition — while potentially very capable — often struggle to have their voices recognized.

Collaboration - Some grant funding schemes are conservative and prefer teams with an established track record of collaboration. In this case, however, that was not necessary. While team members were acquainted prior to participating in the programs, they had not collaborated professionally before. Yet the programs were successful, driven by a strong motivation to work together. In the teaching fellowship, much of the success can be attributed to the course and resident lecturer being well liked, and to the positive rapport that already existed between students and the lecturer. This created a welcoming environment into which the diaspora academic could be effectively integrated. Both AADP and EU4Innovation have actively supported ongoing connections through formal and informal networking opportunities, including study visits, conferences, workshops, and, in the case of READ, an annual New Year's party for all fellows. While the latter may seem trivial, such events play a meaningful role in sustaining engagement and community.

Support - Government support, even symbolic, is important for the success of these programs. While neither fellowship was directly funded by the Albanian government, the presence of officials at events demonstrates recognition and appreciation, which carries real value. Albania is fortunate to have a diaspora that is emotionally attached to the country — reflected in the old proverb, "Albanian soil is sweeter than honey" — and eager to stay connected and contribute. Many diaspora members who received part of their education in Albania feel a strong desire and/or personal obligation to give back. This represents a special circumstance, whereby diaspora academics are willing to participate for nominal compensation out of allegiance to their country of origin. It is therefore important for the government to acknowledge and value this commitment, rather than only viewing the diaspora as a source of remittances.

6. Conclusion

Some countries, like Italy, take different approaches to brain gain — for example, giving priority in academic jobs to members of the Italian diaspora. However, this type of outcome cannot realistically be expected for Albania until higher education salaries, institutional capacity, and global rankings approach those of OECD countries, where most of the academic diaspora is based. In the Balkans, Serbia is the most committed state in terms of diaspora integration, with formal programs, dedicated budgets, and an established institutional infrastructure (Brojka, 2025).

In Albania's context, "brain gain" is often understood not as permanent repatriation of diaspora scholars and other professionals, but as circulation of talent: diaspora expertise is mobilized through temporary and sometimes virtual collaborations that support domestic development — in planning and other arenas. These models emphasize knowledge exchange, research partnerships, co-teaching, and global networking mainly propelled by human attachment at a very moderate financial cost.

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Authors’ profiles

Irina Branko

She specializes in landscape design. She teaches and conducts research on the ecological and aesthetic dimensions of urban development. Her work highlights the importance of greenery in enhancing urban livability and wellbeing.

Erida Curraj

Her work explores the transformation of design and production practices in post-socialist contexts, with particular attention to the preservation of industrial heritage and cultural landscapes.

Dorina Pojani

Her research focuses on the built environment triad of urban design, transport, and housing in both the Global North and South. She approaches her work from a feminist perspective, considering the role of gender in the city.

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REVIEW NOTES - Regulation and legislation for the energy transition

Digital governance of the energy transition: regulatory frameworks, data infrastructures, and spatial planning

Valerio Martinelli

Department of Civil, Building and Environmental Engineering
University of Naples Federico II, Naples, Italy
e-mail: valerio.martinelli@unina.it
ORCID: https://orcid.org/0009-0007-8703-6573

Abstract

Starting from the relationship between urban planning and mobility management, TeMA has gradually expanded the view of the covered topics, always remaining in the groove of rigorous scientific in-depth analysis. This section of the Journal, Review Notes, is the expression of continuously updating emerging topics concerning relationships between urban planning, mobility and environment, through a collection of short scientific papers written by young researchers. The Review Notes are made of four parts. Each section examines a specific aspect of the broader information storage within the main interests of TeMA Journal. This section, International Regulations and Legislation for the Energy Transition, explores the challenges and opportunities in the urban context to understand the evolving landscape of the global energy transition. The convergence between European energy legislation and data governance is transforming the energy transition into a fundamentally territorial and data-driven process. The contribution analyzes how the EU directives are redefining the operational framework of territorial planning through binding interoperability and digital infrastructure requirements. It concludes with a reflection on the evolutionary role of the urban planner as a mediator between legislation, data ecosystems and territorial transformation.

Keywords

Energy transition; Data governance; Spatial planning; European regulation

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1. Introduction

Contemporary cities face unprecedented energy and climate challenges. Despite occupying less than 3% of the planet's surface, urban agglomerations host most of the world's population and consume over 65% of global energy, producing more than 70% of CO_2 emissions (EEA, 2023). In this context, urban areas can become drivers of the energy transition: thanks to the density of supply and demand, cities offer opportunities for the widespread diffusion of renewable sources, the development of sustainable district heating networks and the promotion of new forms of decentralized energy production (Russo et al., 2025; Stiuso, 2025). Cities and local governments have the potential to play a central role in decarbonisation, integrating energy objectives into urban planning and contributing to national and European climate goals (Ulpiani et al., 2023).
If the technological dimensions of the energy transition have been widely discussed in the literature, an equally transformative, but less explored, dimension concerns the role of data and digital infrastructures as enabling conditions for the effective implementation of energy policies at the territorial scale (Fistola & La Rocca, 2025; Horak et al., 2022). The European Union has responded to this challenge with a dense regulatory architecture that embeds digital requirements directly into the fabric of energy and territorial governance. The Digitalising the energy system - EU Action Plan (COM 2022), the Common European Energy Data Space (CEEDS, 2023), the Data Act (EU, 2023), the Interoperable Europe Act (EU, 2024) and the main energy directives, in particular the Renewable Energy Directive III (EU2023/2413, 2023) and the recast Energy Performance of Buildings Directive (EU 2024/1275, 2024), are progressively building a regulatory landscape in which data interoperability, open access and digital platforms are not simply encouraged, but prescribed (ENTSO-E, 2024).
This contribution focuses on the link between regulatory evolution and progressive digitalisation of territorial governance for energy transition.

2. The European regulatory framework: energy, data and land governance

The convergence between energy regulation and data governance within the European Union has accelerated significantly since 2022, producing an intertwined regulatory architecture that is reshaping the conditions within which spatial planning operates. The Digitalising the energy system - EU Action Plan (COM/2022/552), adopted in October 2022, was the first document to formally link the digitalisation of the energy system to the broader climate objectives of the Fit for 55 package and the REPowerEU plan (EC, 2022). Articulating twenty-four priority actions on six axes: citizen empowerment, energy data exchange, cybersecurity, ICT sustainability, investments in digital infrastructures and a coordinated approach at EU level, the Plan explicitly links digitalisation to the National Energy and Climate Plans (PNIEC) envisaged by the Governance Regulation (EU) 2018/1999 (European Parliament & Council, 2018), thus establishing the institutional channels through which the energy agenda digital enters national planning systems.
At the heart of this framework is the Common European Energy Data Space (CEEDS), an ecosystem for the safe and efficient sharing of energy data between actors, based on common rules and standards. Presented to the European Commission in March 2024 and currently being deployed across six Horizon Europe-funded projects, CEEDS promises to overcome one of the most persistent barriers to integrated energy-territory governance: the fragmentation and inaccessibility of energy data across different institutional levels and sectoral silos (IEA, 2024). The enabling regulatory pillars of CEEDS are the Data Governance Act, the Data Act and the Interoperable Europe Act (International Data Spaces Association, 2025).
The Data Act builds a real regulatory framework for the sharing of data between users, businesses and the public sector, requiring that such exchanges take place under fair, reasonable and non-discriminatory conditions and on transparent contractual bases (European Parliament & Council, 2023a). The Interoperable Europe Act extends these obligations to all public sector entities providing European digital public services and creating a unitary legal basis for the integration of energy data into territorial information infrastructures at all

levels of governance (European Parliament & Council, 2024a). These horizontal data rules are complemented by sectoral planning directives that increasingly incorporate specific digital requirements. RED III (EU) 2023/2413) requires Member States to create a coordinated mapping of the territory for the potential of renewable energy (art. 15b) and the designation of Acceleration Areas for Renewables (art. 15c); the Commission guidelines (SWD/2024/333) explicitly identify GIS technology as a key tool for fulfilling this mapping obligation, a result confirmed by the scientific literature on the integration of multi-criteria analysis and GIS for the spatial planning of renewable energy (EC, 2024; Soares et al., 2025). The EPBD recast (Directive (EU) 2024/1275), introduces digital Building Renovation Passports, digital building logbooks and mandatory updated national energy performance databases (European Parliament & Council, 2024b), creating for the first time a building-scale digital dataset with direct relevance for neighborhood and district energy planning. The overall result is a multilevel regulatory architecture in which energy regulations, data regulations and territorial information systems regulations intertwine with increasing coherence, producing binding effects on the governance systems of municipalities, regions and territorial planning authorities (Martinelli, 2025a; Mazzeo, 2023).

3. Digital platforms and data for territorial energy planning

The convergence between energy regulation and data governance is generating a new generation of spatial information infrastructures: integrated digital ecosystems that combine geospatial data, energy performance data, network data and environmental data within interoperable frameworks (OECD, 2023). The energy transition requires new approaches to urban data management and the use of digital tools for both decision making and operation, as recognized by the Driving Urban Transition Partnership 2024 program (DUT, 2024) in launching the call dedicated to data management and decision support systems as a central challenge for planning Positive Energy Districts (PEDs). This need is confirmed by scientific literature, which has highlighted how energy system models at a national scale still present partial spatial capabilities and how soft linking with explicit spatial models represents the most promising methodological direction to robustly integrate territorial dimensions in energy system modeling (Vrhovac et al., 2025). In this context, interoperability represents the essential enabling condition. The International Data Spaces Association's (IDSA, 2025) updated position paper on the Energy Data Spaces Interoperability Framework outlines strategies to address information barriers, standards diversity, and interoperability issues within the energy sector and across sectors, providing a framework for the governance and policy considerations essential for cross-data-space collaboration.

An emblematic example of this new generation of information infrastructures is the EU Energy Atlas of the Joint Research Center (JRC) of the European Commission (Fig.1), an interactive GIS platform that integrates high-resolution geospatial data on industrial and residential energy consumption, network infrastructures and production sources on a European scale. Cartographic visualization allows you to read the differentiated spatial distribution of the energy intensity of the territory, a fundamental element for any integrated territory-energy planning process and represents an operational prototype of the information infrastructures that European legislation is progressively making mandatory at all levels of governance (European Commission, JRC, 2023).

On a national level, the implementation of European standards is producing concrete digital infrastructures of great relevance for territorial planning. In Italy, the Ministerial Decree of 21 June 2024 regulated the operating rules of the Piattaforma Aree Idonee (PAI), developed by the GSE with the support of the Ministero dell'Ambiente e della Sicurezza Energetica (MASE), designed to provide characterization and quantification of the territory, estimate of the installable potential, exchange and integration of data with other public administrations and full interoperability with the single digital platform for renewable energy plants (GSE, 2024). The PNIEC Monitoring Platform allows progress towards national decarbonisation objectives to be tracked in almost real time, improving the transparency of information for Regions, Autonomous Provinces and private operators (MASE, 2024).

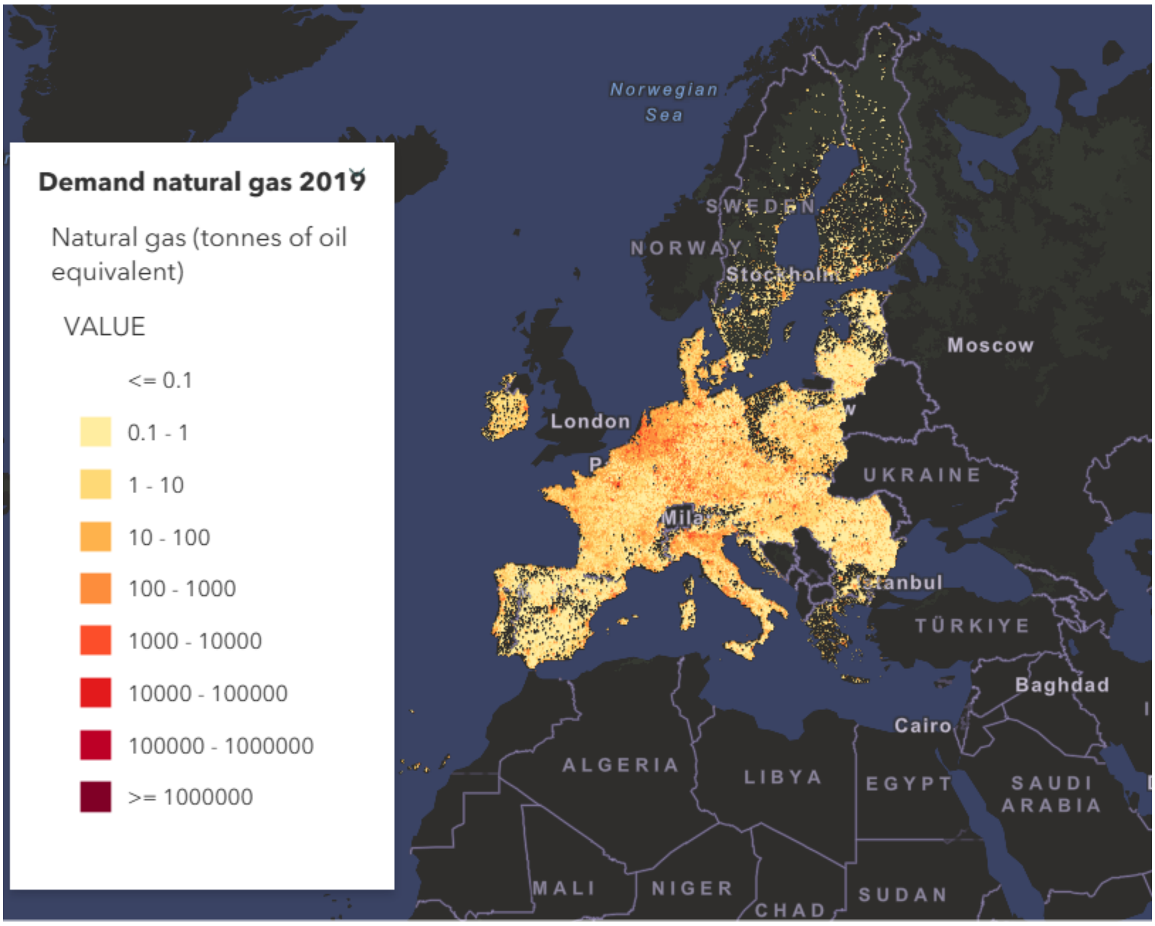

Fig.1 Demand for natural gas in Europe

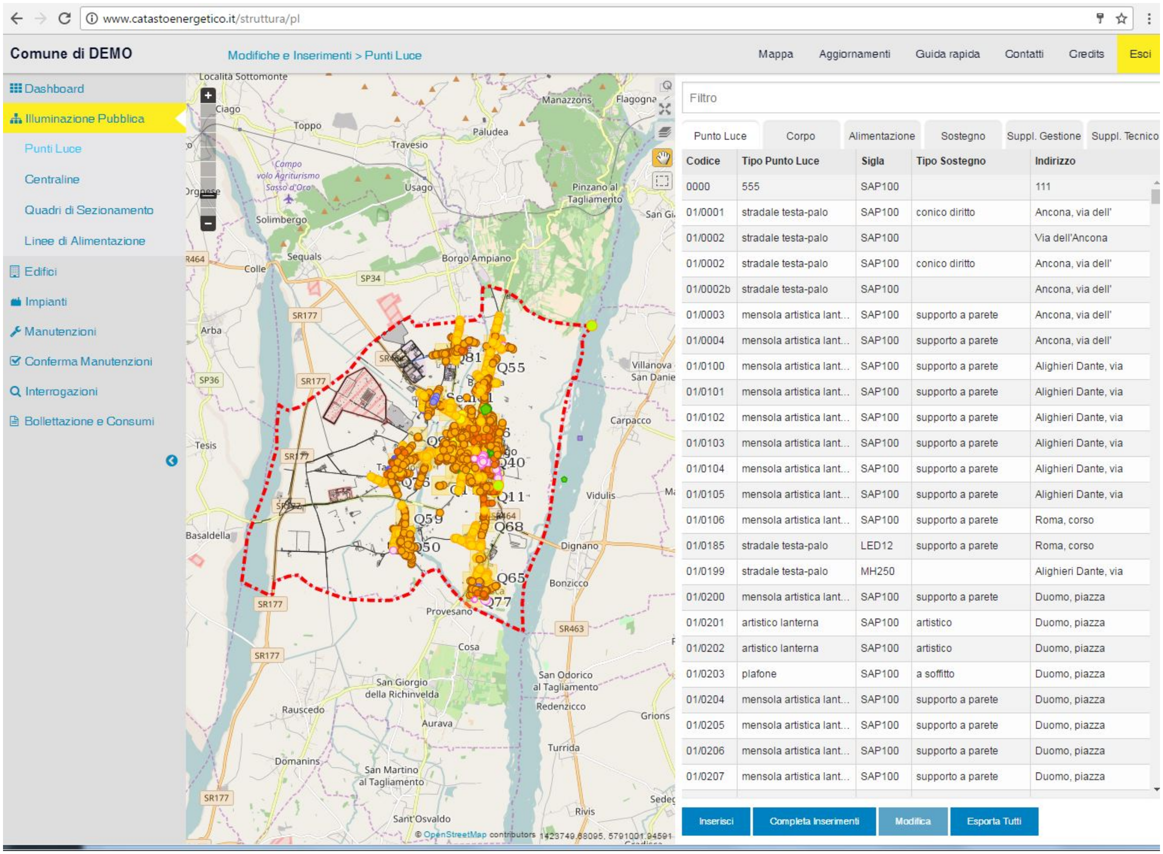

Fig.2 WebGIS of the energy register developed by the Friuli Venezia Giulia Region

Integrated regional energy registers that combine energy performance certificates (APE), inventories of heating systems and municipal consumption data, such as the one developed by APE FVG in Friuli-Venezia Giulia (Fig.2) to support the drafting of SECAPs within the Covenant of Mayors further illustrate how georeferenced energy databases can concretely support local energy governance (APE FVG, 2026).

Finally, the Organization for Economic Cooperation and Development (2023) documented how good data governance can strengthen data quality, expand data collection capacity and define processes and responsibilities in information management to support the monitoring of regulatory compliance in urban development, well-being and environmental sustainability, with the recognition that cities and territories are simultaneously producers, managers and users of their information infrastructure (OECD, 2023).

4. Implications for land governance

The progressive integration between energy regulations and digital infrastructures profoundly reconfigures the conditions in which territorial planning operates in the energy transition, placing urban planning techniques faced with new responsibilities that go well beyond traditional regulatory and design skills. The scientific literature has highlighted with increasing clarity that the delay in the urban energy transition is not primarily of a technological nature, but depends on the persistent separation between energy planning and territorial planning and on the lack of a holistic framework capable of integrating energy supply and demand with the spatial, environmental, social and economic dimensions of the territory (Regen & RTPI, 2025; Stoeglehner, 2020). As argued by Stoeglehner (2020) in developing the theoretical framework of Integrated Spatial and Energy Planning, options for energy strategies are profoundly shaped by local and regional spatial contexts, as both energy efficiency and renewable energy potentials are determined by spatial structures, making spatial planning and energy planning not two separate sides of the same coin but a continuum requiring integrated treatment (Stoeglehner & Abart-Heriszt, 2022). The 2025 report of the International Institute for Sustainable Development Cities in Transition documents how reducing emissions requires not only the diffusion of renewables but an overall redesign of neighborhoods to reduce total energy demand, and how structural barriers in planning such as obsolete governance models, costs of sprawl and lack of integration between energy and urban planning tools are actually preventing cities from building more sustainable communities aligned with climate objectives (IISD, 2025).

The lack of integration between energy planning and spatial planning constitutes a real risk for the energy transition, highlighting significant challenges for local authorities in the integrated implementation of clean energy, renewable heating and urban planning. The International Energy Agency Cities Task 2 (2025-2029), specifically dedicated to "Data for Urban Energy Planning", identified data insufficiency, lack of standardized methodologies and legal barriers as key challenges for cities in transition, underlining that digital solutions are particularly powerful in cities, where the high-density environment creates economies of scale and new opportunities (IEA Cities Task 2, 2024; IEA, 2024). In this framework, the urban planner is called to play a role of critical mediation on a technical-analytical level, he must know how to operate within the digital infrastructures prescribed by law such as GIS platforms, energy data spaces, digital permitting systems, energy cadastres, digital twins, understanding not only the functionalities but also the classificatory assumptions and spatial logics incorporated in the tools, the design and governance of which is itself a planning problem that requires attention to usability, transparency and inclusiveness (Mey et al., 2024). On the political-institutional level, the planner must ultimately operate as a critical interpreter capable of territorializing abstract regulatory requirements, negotiating between competing spatial demands, deployment of renewables, biodiversity protection, agricultural preservation, urban regeneration, and ensuring that the digitalization of energy governance serves, rather than replaces, truly integrated territorial planning (Martinelli, 2025b; Grossi & Welinder, 2024; Caprari et al., 2022).

In this direction, an emerging proposal in the literature suggests the creation of a dedicated professional figure: the Energy Urban Planner (EUP) with the specific task of bridging the gap between the abundance of energy data available, often not integrated with that used in territorial decision-making processes, and the need for a more integrated and intentional planning approach (Boria et al., 2020). For spatial planning, this evolution represents both a mandate and an opportunity.

The mandate consists of the need to integrate an unprecedented volume and diversity of energy data into planning processes, to operate within increasingly digitalised regulatory frameworks and to ensure that the spatial dimension of the energy transition is governed with the rigor and comprehensiveness that the complexity of the challenge requires.

The opportunity lies in the potential to exploit the new data infrastructure for integrated territorial-energy planning capable of accelerating the deployment of renewables and improving the sustainability and equity of territorial transformations (Zhu et al., 2025).

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Fig.1: European Commission, Joint Research Centre (JRC) (2023). EU Energy Atlas - Demand natural gas 2019. https://energy-industry-geolab.jrc.ec.europa.eu/energy-atlas/

Fig.2: Agenzia per l'Energia del Friuli-Venezia Giulia (APE FVG), "Catasto energetico regionale". https://www.ape.fvg.it/catasto-energetico/

Author's profile

Valerio Martinelli

He is an engineer, with a master's degree in Building-Architecture Engineering at the Department of Civil, Architectural and Environmental Engineering of the University of Naples Federico II. He is currently a first year Ph.D. student in Civil Systems Engineering at the same department. His research activity focuses on the study of Renewable Energy Communities.

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REVIEW NOTES - Urban strategies, programmes and tools

Governing the transformations of public space: active travel policies for people's health and well-being

Annunziata D'Amico

Department of Civil, Building and Environmental Engineering
University of Naples Federico II, Naples, Italy
e-mail: annunziata.damico@unina.it
ORCID: https://orcid.org/0009-0005-5481-8064

Abstract

Starting from the relationship between urban planning and mobility management, TeMA has gradually expanded the view of the covered topics, always remaining in the groove of rigorous scientific in-depth analysis. This section of the Journal, Review Notes, is the expression of continuously updating emerging topics concerning relationships between urban planning, mobility and environment, through a collection of short scientific papers written by young researchers. The Review Notes are made of four parts. Each section examines a specific aspect of the broader information storage within the main interests of TeMA Journal. In particular, the Urban strategies, programmers and tools section presents the different strategies and tools that guide the governance of the transformations of public space.

This paper aims to provide an overview of the solutions and policy tools used to transform public space to promote an active lifestyle and collective well-being.

An optimal urban configuration, where public space design is oriented toward movement, encourages active travel and generates public health benefits. This paper illustrates several public space planning and transformation strategies aimed at designing urban environments that encourage daily walking and cycling, combining public health, sustainability, and the quality of the built environment.

Keywords

Policy tools; Urban strategies; Public space; Active mobility; Health; Well-being

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1. Public urban space for an active and healthy life

Public spaces - sidewalks, streets, playgrounds, plazas, public gardens, parks, beaches, libraries, art museums, historical monuments, and more - represent the beating heart of a city's urban fabric, serving as vital infrastructure for socialization, play, and learning, as well as for the circulation and movement of people (Low, 2023).

Every urban context has a specific identity and development potential, so every urban planning intervention must therefore be adapted to the particular characteristics of each city, with the ultimate goal of converting inert and lifeless spaces into dynamic and welcoming public spaces (Yaseen & Bostan, 2024; Chow et al., 2016) where urban design becomes the primary tool for promoting an active society and widespread well-being.

Quality of life, well-being, and public health are now cornerstones of a new vision of public space, where proximity to services and zero-emission travel not only ensure accessibility but also restore public spaces to their fundamental human and social dimension (Carra et al., 2022).

In many urban contexts, public space is still unbalanced in favor of motorized mobility—reaching peaks of 60% in cities like Barcelona—which takes away vital areas for the community and also represents a high cost to health due to smog and noise generated (Nieuwenhuijsen, 2020).

Conversely, an urban environment that fosters active mobility makes the city more attractive and accessible for residents and visitors, triggering a virtuous cycle of economic attractiveness and social excitement, restoring the centrality of public space as a meeting place and a collective identity (D'Amico et al., 2026). Furthermore, the scientific literature widely recognizes active mobility as a powerful catalyst for public health because it can potentially reduce dependence on cars for daily travel and enhance physical activity, reduce air pollution emissions and improve mental health (Kong et al., 2024; D'Amico, 2024b).Protecting public health is an essential prerequisite for building resilient and prosperous communities, representing one of the most significant parameters of sustainable development (UN, 2016). Goal 11 of the Agenda2030 "Make cities inclusive, safe, resilient and sustainable" (Fig.1) encompasses the social, economic and environmental dimensions of sustainable development and focuses specifically on the urban context, identifying Goal 11.7 as an absolute priority, ensuring every citizen's right to safe, accessible and green public spaces (UN, 2015).

Fig.1 Sustainable Development Goals (European Commission, 2019)

The New Urban Agenda of Habitat III promotes "safe, inclusive, accessible, green and quality public spaces" as multifunctional areas designed for social interaction and inclusion, health and human well-being (NUA, 2017). Equally important is the WHO's call to create urban environments conducive to health (WHO, 2022) and the Global Plan (2021), which emphasizes that land-use planning must create infrastructure and services that encourage the choice of alternative, sustainable, healthy, and clean transportation modes, such as walking, cycling, and public transportation.

Public spaces can be considered a powerful tool for urban sustainability, providing environmental, social, economic, and health benefits to cities (Vukmirovic et al., 2019). Far beyond its function as a connection, public space constitutes the infrastructure where public, environmental, socio-cultural and economic needs converge and coexist (Bocca et al., 2024).

A large body of multidisciplinary research, ranging from urban planning to public health, natural sciences and epidemiology, has thoroughly analyzed the correlations between the environment and health or well-being (Krefis et al., 2018; Jabbar et al., 2022; Andalib et al., 2024).

Urban environments and transportation policies influence people's behaviors, for example by promoting cycling and walking as modes of transportation, developing safe infrastructure, and encouraging the creation of accessible green spaces where people can engage in leisure time physical activity. Equally important is to recognize that green areas and open spaces act as crucial infrastructure to combat the climate crisis in urban environments, thanks to their ability to regulate the microclimate and lower urban temperatures, positively influencing the energy efficiency of cities (Stiuso, 2025; Zhang et al., 2014).

In the public health landscape, active mobility is recognized as a fundamental strategy for encouraging physical activity, reducing sedentary lifestyles, and combating chronic diseases (WHO Regional Office for Europe, 2022). This vision is supported by a growing scientific consensus, which sees active movement as an essential driver for people's physical and mental well-being (Groves et al., 2024; Granero-Jiménez et al., 2022).

However, urban policies fail to always meet health standards, fueling settlement patterns that instead encourage car dependence and penalizing pedestrian, bicycle, and community access to essential services and public spaces.

An optimal urban configuration, where public space design is oriented toward movement, encourages active travel and generates public health benefits. The next section illustrates various public space planning and transformation strategies implemented in international contexts, aimed at designing urban environments that encourage walking and cycling every day, combining public health, sustainability, and the quality of the built environment.

2. Integrated urban policies for people's health and well-being

Urban policies influence urban lifestyle, health and sustainability. Truly sustainable urban management requires strategies and policies designed to influence and guide citizen behavior and mobility within urban environments. To achieve future cities that incentivize active travel, cities must focus on long-term planning that invests in active mobility infrastructure, promoting clean, zero-carbon modes of transportation, integrating traditional tools and participatory practices (Papageorgiou et al., 2024; Khavarian-Garmsir et al., 2023).

Promoting active modes requires bold actions and a cross-sectoral vision that connects urban planning and mobility systems through multi-sectoral cooperation.

This contribution aims to provide an overview of the solutions and policy tools used to transform public space to promote an active lifestyle and collective well-being.

Below are some of the international best practices that redefine the concept of public space in favor of active life and sustainable mobility.

Among the most significant European experiences are Barcelona's Superblocks model (D'Amico, 2024b), which reorganizes the street grid to create traffic-free inner oases, and Paris's 15-Minute City with the "Plan Vélo

2021-2026" (D'Amico, 2024a), which emphasizes proximity to services to eliminate car dependence; Berlin's 2018 Mobility Law (Von Schneidemesser et al., 2020) demonstrated the potential to transform mobility policy by integrating citizens into political processes; Utrecht (Netherlands) incentivizes intermodality by promoting the creation of park-and-ride areas on the city's edges, which become intermodal hubs and facilitate resident initiatives to redevelop residential streets, transforming parking spaces into play areas, bicycle parking, and green spaces. It also introduces traffic-free zones where pedestrians and cyclists have priority (Utrecht Mobility Plan 2040, 2021); Vienna experiments with Supergrätzl to combine pedestrianization and climate resilience (Tiran et al., 2025); London's financial district, with its "City Cluster Vision", demonstrates this common trend toward more efficient and effective use of road space and the densification of green spaces and pedestrian and cycle paths (The city cluster vision, 2019).

London (United Kingdom) – *CITY CLUSTER VISION (CITY PLAN 2036)*

The City of London's City Plan 2036 defines urban planning guidelines for the next twenty years, identifying the "City Cluster vision" as one of the key areas for strategic transformation (The city cluster vision, 2019).
At the heart of this vision is the " The Healthy Streets Approach", a framework that prioritizes active mobility—walking, cycling, and public transport—to create a more welcoming and healthy urban environment. This model informs the Transport Strategy, placing citizen well-being and the quality of the street experience at the heart of every decision.
In the City Cluster, this translates into a coordinated approach that integrates the enhancement of public spaces with structural changes to traffic flow. The goal is to rebalance the use of urban space, making walking and staying in the neighborhood safer and more enjoyable (Fig.2). Strategic proposals that directly relate to the feasibility of public space include:

- Increasing pedestrian priority streets and improved pedestrian crossings;
- Providing more public space and delivering world-class public realm;
- Incorporating more greenery into the City's streets and public spaces;
- Reducing rainwater run-off on City street and public realm;
- Ensuring street space is used more efficiently and effectively;
- Using timed and temporary street closures to help make streets safer and more attractive places to walk, cycle and spend time;
- Undertaking traffic management measures through the development of Healthy Streets Plans and targeting Local Zero Emission Zones for City Cluster by 2022.

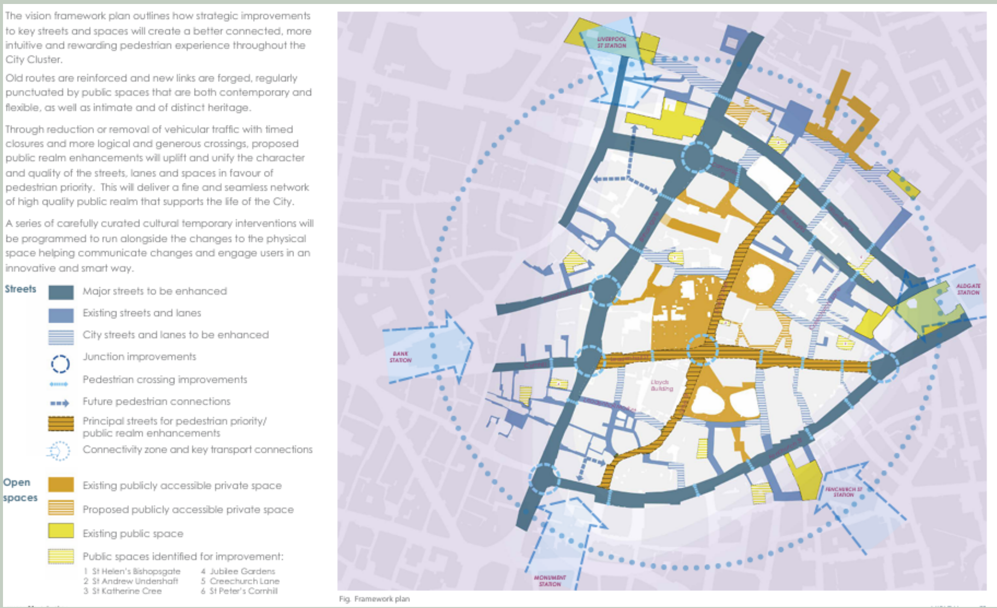

Fig.2 Vision Framework Plan (The city cluster vision, 2019)

In North America, Vancouver's "Transportation 2040" (2012) promote and encourage creative uses of streets and public spaces through pilot projects and competitions. For example, it launched the "parklet program" to promote the conversion of on-street parking into low-cost public spaces (Trasportation 2040, 2012). Sidewalks and streets are not just places of passage, but places to spend time, where transportation needs are met and a vibrant public life that benefits commerce and the community is supported. Walkability and how to transform public spaces for community life should be considered objectives of urban planning (Tan et al., 2024). In New York, the "Open Streets program" transforms streets into public spaces open to all, where the community (associations, schools, businesses, etc.) becomes the steward of their own streets and reinvents them as a valuable local resource. For example, the program allows certain streets to be temporarily closed to vehicular traffic to support schools, particularly those without a gym or dedicated play area: the street in front of the school is used during certain hours of the day to offer safe outdoor spaces as a versatile venue for recess, outdoor learning, lunch, assemblies, graduations, and safe pick-ups and drop-offs.

Vancouver (CANADA) – *TRANSPORTATION 2040 PLAN*

Transportation 2040 (2012) is a long-term strategic plan for the city that will guide transportation and land-use decisions, as well as public investments, for years to come. It defines long-term goals and includes both high-level policies and specific actions to achieve the vision.
Vancouver is a multimodal city as people often use more than one mode of transportation within a single trip, and in recent years its policies have focused on supporting transportation modes that use renewable fuels and transport more people with less pollution, such as electric cars, public transit, and active transportation modes like walking and cycling.
One of the first goals set by the 2040 Plan is that at least 60% of all trips will be made on foot, by bicycle, and by public transport.
The city implements urban design guidelines to promote the safety and attractiveness of the street environment, for example by encouraging building facades with many windows and doors that put "eyes on the street"; to minimize conflicts with cars, driveways are placed in alleys and away from bike paths and pedestrian walkways, wherever possible;
The plan supports programs that encourage creative uses of the street, including temporary and permanent public spaces created by reallocating street space; the city is also evaluating options for making certain streets and plazas pedestrian-priority public space and and for transforming some less frequented streets into low-cost squares, with potential locations identified through community planning processes.Some of the Walking actions to be taken by the city (Fig.3):

- implement an ongoing spot improvement program to address pedestrian safety and accessibility issues;
- provide additional amenities such as benches and enhanced lighting along priority walking streets;
- make the False Creek bridges and other deficient areas safer and more accessible on foot;
- launch a parklet program to foster the conversion of on-street parking spaces into low-cost public spaces;
- implement signal measures to prioritize pedestrian movement at intersections.

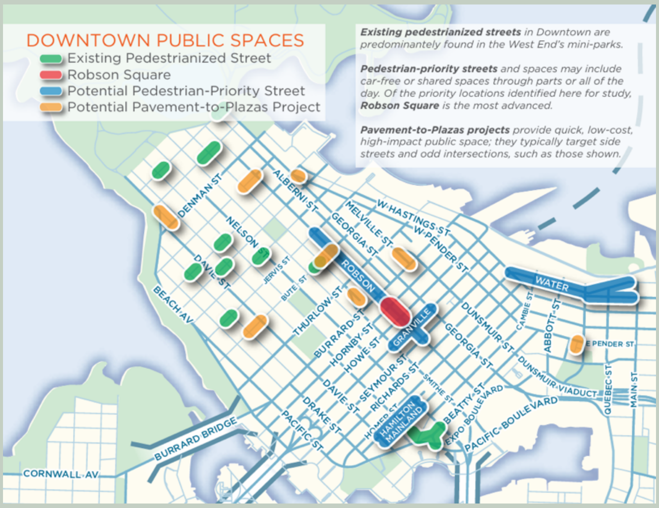

Fig.3 Public space in downtown Vancouver (Transportation 2040, 2012)

Asian metropolises also offer cutting-edge solutions, such as the 2030 "Seoul Plan", which, from a city oriented towards infrastructure development, it is instead revolutionizing its urban policies to restore ecological corridors, or Singapore's system, which integrates active mobility with a vast network of covered sidewalks and interconnected parks (Park Connector Network). The transformation of public spaces to encourage micro-mobility and pedestrianization becomes a driver of economic vitality and social well-being, and also a valuable tool for encouraging the urban resilience needed to meet the challenges of the 21st century. The common trend is the inversion of the mobility pyramid: space is being taken away from asphalt and cars to be given back to people, replacing it with green areas, cycle paths, pedestrian paths and squares. In accordance with these principles, the city of Melbourne, Australia, is implementing a series of strategies to become a "20-minute city", integrating sustainable transport, redeveloped public spaces and accessible car-free services (Plan Melbourne 2017-2050, 2017).

Melbourne (AUSTRALIA) – *PLAN MELBOURNE 2017-2050*

The plan outlines an integrated urban vision focused on proximity and sustainability (Fig.4). Massive investments in infrastructure and public transport will support the transition to a city of "20-minute neighbourhoods", where essential services are accessible without a car. The strategy aims to create safe pedestrian and cycle-friendly neighbourhoods, strengthening local connections and ensuring short, sustainable and accessible journeys for all residents in the vicinity.
Plan Melbourne 2017-2050 (2017) aims to strengthen the city's identity by expanding public spaces, including the selective redevelopment of underutilized areas within existing communities. Melbourne is renowned for its buildings, parks, creative culture, and quality of life. The city aims to further enhance public space by integrating urban planning practices into the management of street space, the boulevard network, and green river corridors for a more livable and sustainable metropolis. Regarding the goal of creating connected communities and an integrated transportation system, the city aims to improve local travel options to support neighborhoods within a 20-minute drive. Actions include pedestrianizing spaces, developing a comprehensive network of bike paths, and optimizing public transportation, locating schools and strategic facilities in accessible and safe hubs to encourage short and sustainable trips.

Fig.4 Plan Melbourne (2017)

3. Conclusion

Contemporary urban planning is changing the way we think about road networks, not just as a "motorized flow channel" but as a public space intended for social life and active mobility.
This transformative vision manifests itself through heterogeneous strategies that, despite originating from distant geographical and cultural contexts, share the goal of restoring public land to pedestrians and cyclists. New strategies and "visions" for the city of the future, such as London's "City Cluster Vision" or "Melbourne's Plan", seek to combine public space planning and transformation strategies with the need to foster environmental sustainability, social interaction, and active mobility.

Although each city adopts different tools, the review of these best practices clearly highlights a common denominator: the desire to transform the city into a place where walking or cycling is not only an ecological choice, but the simplest, safest, and most enjoyable way to experience the urban environment.
This strategy responds to current challenges and ensures the prosperity, sustainability, and livability of our cities.

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Author's profile

Annunziata D'Amico

She is an engineer, Ph.D. student in Civil Systems Engineering at Department of Civil, Architectural and Environmental Engineering of University of Naples Federico II. Currently, her Ph.D. research concerns the topic of MaaS and soft mobility in urban systems for children, to encourage walkability and more sustainable and active mobility.

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REVIEW NOTES - Urban practices

Soft adaptation measures for disaster risk reduction and urban resilience. Early warning systems

Stella Pennino

Department of Civil, Building and Environmental Engineering
University of Naples Federico II, Naples, Italy
e-mail: stella.pennino@unina.it
ORCID: https://orcid.org/0009-0008-4439-0078

Abstract

Starting from the relationship between urban planning and mobility management, TeMA has gradually expanded the view of the covered topics, always remaining in the groove of rigorous scientific in-depth analysis. This section of the Journal, Review Notes, is the expression of continuously updating emerging topics concerning relationships between urban planning, mobility and environment, through a collection of short scientific papers written by young researchers. The Review Notes are made of five parts. Each section examines a specific aspect of the broader information storage within the main interests of TeMA Journal. In particular, the Urban Practices section aims at presenting recent advancements on relevant topics that underline the challenges that the cities have to face.

This note provides an overview of soft adaptation measures and their role in promoting effective disaster risk reduction and urban resilience. It focuses on Early warning systems (EWS), governance and knowledge-based instruments that enhance anticipatory capacity within urban systems by integrating risk knowledge, hazard monitoring and forecasting, communication and dissemination mechanisms, and response capability. Selected international case examples are discussed, illustrating how cities are operationalizing EWS to address extreme weather events. Finally, the contribution outlines policy implications and research directions, emphasizing the importance of integrating EWS deployment into spatial planning and resilience governance frameworks to strengthen city and community adaptive capacity.

Keywords

Climate change; Soft adaptation measures; Disaster risk reduction; Urban resilience; Early warning systems

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1. Introduction: climate change and soft adaptation measures

Global average temperatures continue to rise, with evidence of a growing rate of warming in recent decades (Berkeley Earth, 2026). This accelerating trend is driving an increase in the frequency and severity of extreme weather events and cascading risks (IPCC, 2022). These hazards trigger escalating social, environmental and economic impacts, particularly in urban areas where exposure and vulnerability are concentrated (European Commission, n.d.). This could lead to an increase in both health costs and socio-ecological inequalities that make vulnerable population groups more prone to heat-related impacts (Longato et al., 2025).

In this context of polycrises and deep uncertainty, climate change adaptation and resilience have become strategic priorities to reduce current and future risk and to strengthen institutional, community and infrastructural capacities to cope with disruptive events (UNFCCC, n.d.; UNDRR, 2023). Adaptation options are commonly grouped into broad classes according to the type of intervention they entail (Klein et al., 2014; EEA, 2025). Conventional "grey" measures rely on engineered infrastructure – such as dikes, floodwalls or drainage upgrades – to protect assets from hazards. However, they are capital-intensive, have long lifetimes, and can quickly become inadequate under higher levels of warming or changing risk patterns (Klein et al., 2014; IPCC, 2022). Recognizing the limits of stand-alone grey solutions, "green" measures – such as nature-based solutions, urban forestry and green infrastructure – have emerged as important complementary options that enhance ecosystem services while contributing to risk reduction (EEA, 2025; Anderson et al., 2022). Yet these measures also face constraints, including land availability, context-dependent performance, and the need for continuous maintenance and monitoring to remain effective over time (Anderson et al., 2022; IPCC, 2022).

Building on socio-technical and socio-ecological systems perspectives, recent literature underscores the central role of communities, institutions and practices in shaping risk, while co-producing and operating both grey and green measures (Chappin & Van der Lei, 2014; Hossain et al., 2024). This perspective is particularly relevant for cities, which are increasingly recognized as key arenas of socio-technical change (Pennino, 2025). This has brought renewed attention to so-called "soft" adaptation measures – non-structural or behavioral strategies that manage risk through governance, policy, planning and capacity-building rather than through large-scale physical works (GWP, 2017; Kehler & Birchall, 2023). Many of these measures directly overlay with disaster risk reduction and disaster risk management, for example land-use regulation, early-warning systems, preparedness planning and public awareness initiatives (UNDRR, 2019; 2023).

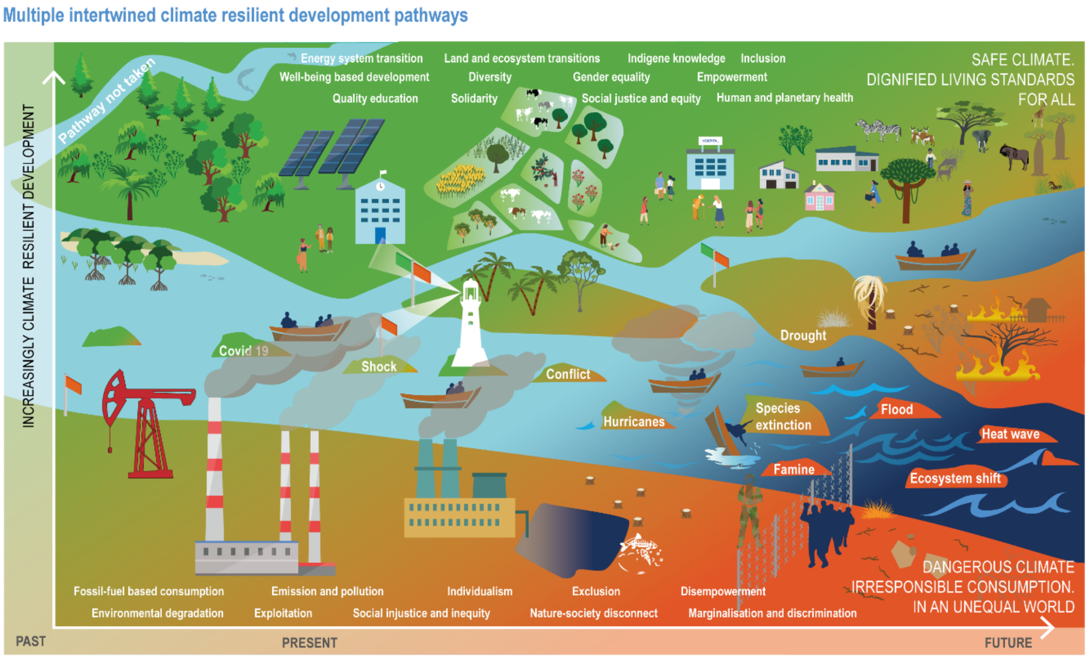

Fig.1 Climate-resilient development pathways

The active interplay between human systems, technology and the environment links climate adaptation to broader sustainable development agendas. Framing adaptation not as an optional add-on but as an integral component of development pathways resonates with the IPCC concept of climate resilient development, which emphasizes the joint pursuit of adaptation, mitigation and sustainable development to reduce climate risk for all (Schipper et al., 2022). This Review Note examines the role of soft adaptation measures for disaster risk reduction and urban resilience, with a specific focus on multi-hazard early warning systems. It also discusses how urban planning can enable or constrain the integrated development of socio-ecological and socio-technical systems that can advance sustainable development while confronting climate change and moving towards more climate-resilient urban futures.

2. Urban resilience and urban planning

Urban planning directly shapes urban resilience by influencing how cities grow, function and are governed. General urban plans and building codes determine the form and performance of the built environment, steering land-development patterns towards more – or less – climate-resilient configurations and mediating the deployment of grey and green adaptation measures (Keith et al., 2023a). They guide land-use allocation, urban design and the integration of greenery, while disaster risk reduction and management plans, hazard mitigation plans and climate action plans articulate policies, governance arrangements and management actions for reliable energy access, public health interventions, emergency management and exposure reduction (Keith et al., 2023b; UNDRR, 2019).

The inherently multidisciplinary nature of urban planning positions it as a key convenor in urban governance and disaster risk management. Strategic and action plans can provide platforms for bringing together the multiple actors involved in disaster risk reduction and management, and for coordinating urban resilience strategies across sectors and scales (UNDRR, 2019; IPCC, 2022). However, fragmented mandates, siloed knowledge and sectoral planning often limit their effectiveness, prompting calls for more integrated approaches that engage stakeholders horizontally – across urban management sectors – and vertically – across local, regional and national levels (Keith et al., 2023a; Oneto & Canepa, 2023). Planners might also lack training in urban climatology or have limited access to usable risk information and tools to translate it into spatially targeted strategies. These challenges underscore the need for closer collaboration with universities, research institutions and other knowledge brokers to embed climate and risk science in planning practice (Keith et al., 2019; IPCC, 2022).

For urban heat, Keith et al. show that resilience requires integrated planning that prioritizes mitigation and management actions for the most vulnerable communities, yet this coordination is often missing in practice (Keith et al., 2023a). Their analysis highlights a lack of clear leadership and coordination in urban heat governance, and identifies a significant opportunity for urban planners to assume a leading role by integrating heat mitigation and management into comprehensive plans, besides hazard mitigation plans and heat action plans (Keith et al., 2023a; 2023b). Concerning urban flooding, the relative ease of spatially visualizing pluvial and fluvial hazards has fostered the development of planning-support tools that operationalize climate risk assessment and monitoring. Truu et al. propose the Extreme Weather Layer (EWL) method, which dynamically links land-development scenarios to the performance of urban drainage systems and other determinants of flood risk, supporting planners in identifying flood-prone areas and testing alternative spatial configurations (Truu et al., 2022). In a complementary review, Oneto and Canepa emphasize the active role of urban planners in flood risk management for climate adaptation, highlighting how their position at the interface between spatial analysis and policy design is crucial for integrating flood resilience into urban development pathways (Oneto & Canepa, 2023). Overall, the role of urban planning in promoting urban resilience is emerging as critical, yet remains only partially realized. Planning can intervene along the full disaster risk management cycle, from risk analysis and assessment to the design of spatial policies, governance arrangements and community engagement processes (UNDRR, 2019; IPCC, 2022). Embedding these functions within integrated and adaptive resilience planning processes can enhance the coherence and effectiveness of both short-term and long-term actions. Within this context, instruments such as climate action plans and heat action plans offer important opportunities to coordinate and mainstream urban resilience strategies across sectors and scales (Keith et al., 2023a, UNDRR, 2019).

3. Early warning systems

With the rapid evolution of information and communication technologies (ICTs), disaster risk reduction (DRR) and disaster risk management (DRM) literature has highlighted a range of innovative strategies to support adaptive urban resilience (UNDRR, 2019; IPCC, 2022). Among these, early warning systems (EWS) stand out as a key soft adaptation measure, leveraging advances in weather and climate observation, forecasting and communication technologies, to protect lives and health in the face of extreme events (UNDRR & CIMA Research Foundation, 2024; UNDRR & WMO, 2025).

EWS can be understood as integrated arrangements of processes, activities and actors that generate and disseminate early warnings – timely and targeted information on imminent or emerging hazards – to enable early action – anticipatory measures by authorities and communities to reduce impacts on people, infrastructure and other assets (UNDRR & CIMA Research Foundation, 2024). Recognizing their central role in DRR, international organizations have strongly promoted their expansion, most notably through the Early Warnings for All (EW4All) initiative. It is organized around four independent pillars: (i) disaster risk knowledge and management; (ii) hazard detection, observation, monitoring, analysis and forecasting; (iii) warning dissemination and communication; and (iv) preparedness and response capabilities (WMO, 2022; UNDRR & CIMA Research Foundation, 2024). EWS can be designed and operated at multiple governance levels – from national meteorological and hydrological services to regional platforms and local, city-scale systems – and differ in how comprehensively they implement and integrate these four pillars (UNDRR & WMO, 2025; UNDRR & CIMA Research Foundation, 2024).

Fig.2 The four pillars of Early Warnings for All

Given the specific exposure and vulnerability of cities to climate-related extreme weather events, Sheehan et al. conducted a global assessment of urban extreme-weather early warning systems in large cities reporting to the CDP Carbon Disclosure Project Cities Adaptation Actions database (Sheehan et al., 2025). They classified city-reported systems against the EW4All pillars and identified substantial gaps in pillars' coverage, geographic uptake, cross-sectoral coordination and public health engagement, particularly in low- and lower-middle-income contexts. While many cities reported health and spatial justice as an objective of their EWS, fewer explicitly assigned roles to health agencies, and few appeared to target the most vulnerable communities, underscoring the need for more comprehensive, multi-sectoral and equity-oriented urban EWS (Sheehan et al., 2025). Their findings provide several critical entry points for DRR and urban resilience from an urban planning perspective.

The first key aspect is the multi-hazard perspective. When viewed spatially, the same urban elements can simultaneously contribute to, and help reduce, different types of risk (IPCC, 2022; WMO, 2025). For example, green spaces can mitigate both heath and pluvial flooding, while dense urban fabrics may provide shading that lowers cooling demand yet also intensify the urban heat island effect and concentrate exposure (Klein et al., 2014; Anderson et al., 2022). Developing multi-hazard EWS therefore demands systemic thinking and planning, encouraging stakeholder engagement and multilevel governance so that trade-offs and co-benefits are understood and managed across hazards and sectors (UNDRR, 2019; UNDRR & WMO, 2025).

Effective EWS also depend on robust spatial risk knowledge, including detailed information on local hazard patterns, exposure and vulnerability (UNDRR & CIMA Research Foundation, 2024). Identifying populations and places at risk, including particularly vulnerable groups, can reveal spatial patterns of inequality and climate injustice that are often embedded in urban development trajectories (Sheehan et al., 2025; IPCC, 2022). This evidence can inform both long-term urban policies – such as zoning, infrastructure investment and housing strategies – and short-term actions, including the targeting of warning messages, the design of communication channels, and the prioritization of field operations by civil protection and emergency services during extreme weather events (UNDRR, 2019; UNDRR & CIMA Research Foundation, 2024).

Finally, the design and operation of EWS require coordinated governance, cross-sectoral cooperation and meaningful community engagement (UNDRR, 2019; WMO, 2022). Establishing networks of relevant city agencies (e.g. planning, health, emergency management, utilities) and co-developing protocols and response plans with local communities are essential conditions for effective local DRR, and at the same time foundational for long-term urban resilience where risk knowledge, preparedness and adaptive learning are embedded in everyday governance (UNDRR, 2019; UNDRR & CIMA Foundation, 2024). To provide empirical insight into how EWS deployment can be integrated within urban planning processes, the following sections present three case studies of urban practices.

Fig.3 Early Warnings for All initiative's logo

1.1 Taipei, Taiwan

Fig.4 Taiwan Weather App

Taipei, Taiwan stands out as one of the most comprehensively documented examples of a fully integrated, multi-hazard urban EWS. The city's system addresses a broad spectrum of hazards – including typhoon-induced flooding, dam failures, windstorms, fires, earthquakes, volcanic activity, explosions and chemical poisoning – reflecting the compounded and cascading risk profile of a dense metropolitan area located in one of the world's most exposed disaster hotspots. Institutionally, the EWS is coordinated across public health, networked infrastructure, social services and city administration, exemplifying the kind of cross-sectoral governance that the EW4All framework identifies as foundational to pillar integration (Sheehan et al., 2025; UNDRR & WMO, 2025). On the technical side, flood control infrastructure leverages an IoT network integrating rainfall and stormwater monitoring with automated pump station operations, and recent advances have incorporated hybrid deep learning models – combining convolutional and back-propagation neural networks – into the real-time urban drainage early warning system, achieving high predictive accuracy for sewer and river water levels at short forecast intervals (Chang et al., 2025). Despite these advances, flood management remains challenging under typhoon-induced extremes, and decades of rapid urbanization in the Tamsui River floodplain have entrenched structural vulnerabilities that no warning system alone can resolve (Su, 2016). Taipei's experience thus underscores a central argument: technically sophisticated EWS, however effective in reducing mortality in the short term, must be coupled with land-use governance and long-term spatial planning reform to address the root drivers of urban exposure.

1.2 Rio de Janeiro, Brazil

Fig.5 Alarm sirens in a favela in Rio de Janeiro

Rio de Janeiro, Brazil offers a paradigmatic case of a city-level EWS that evolved iteratively in response to repeated disasters, gradually expanding from single-hazard monitoring to a horizontally integrated, multi-agency arrangement. The primary hazards addressed are rainfall-induced landslides and flash floods – hazards disproportionately affecting favela communities on steep hillsides and low-lying floodplains, where informal settlement, deforestation and inadequate infrastructure converge to produce high and unequally distributed vulnerability. The system's technical architecture combines a rain gauge network and Doppler radar managed by GeoRio, the municipal geotechnical office, with the community-based alert and alarm system (A2C2), which operates through a two-tier protocol: Civil Defense agents transmit SMS alerts to trained community leaders at the first level, while imminent threats trigger sirens and mandatory evacuation at the second (Ortigao, 2013). Institutionally, the Center of Operations Rio (COR), established in 2010, centralizes data from over thirty agencies and serves as the coordinating body for all warning and response actions (Sandholz et al., 2018). Sheehan et al. (2025) explicitly recognize Rio de Janeiro among cities demonstrating horizontally integrated multi-hazard EWS capacity, noting that its warnings are explicitly targeted to vulnerable groups – a feature consistent with the spatial justice dimension highlighted in this note. The demonstrable life-saving effectiveness of the system – zero fatalities recorded during a severe rainfall event in March 2013 – stands as evidence of what coordinated governance across pillars can achieve. Nevertheless, persistent inequities in coverage, chronic under-investment in favela communities, and the growing intensity of extreme rainfall events driven by climate change continue to expose the limits of warning systems operating within an urban fabric shaped by decades of unplanned growth (Bartaburu, 2025). Rio's case reinforces the imperative of coupling EWS deployment with long-term urban planning instruments capable of reducing exposure at source.

1.3 Rosario, Argentina

Fig.6 Rosario's 2030 Local Climate Action Plan

Rosario, Argentina provides a compelling illustration of how risk knowledge generated through EWS processes can be progressively mainstreamed into urban planning frameworks, making it particularly relevant to the planning-centered argument of this review. The city faces compound climate hazards, most critically river flooding from the Paraná – classified as high risk by international hazard assessments – alongside extreme rainfall events, heatwaves and urban drainage failures. The EWS operates across multiple governance scales: nationally, the Servicio Meteorológico Nacional (SMN) issues colour-coded storm alerts; at the provincial level, the Autoridad Hídrica Provincial manages a telemetric hydrological network linked to a distributed mathematical model for river level forecasting; and at the municipal level, the Department of Water Management, in collaboration with the University of Rosario, has developed risk thresholds based on precipitation records to redefine flood zones and restrict construction in high-exposure areas (Hardoy & Ruete, 2013). Crucially, Sheehan et al. (2025) document Rosario's public health agency as an active contributor to EWS across multiple pillars: under Pillar 1, it maps extreme heat and zoonotic disease risk and makes climate-health epidemiological data publicly available to foster community participation in risk tracking; under Pillar 2, it monitors weather conditions in coordination with health authorities to anticipate vector-borne disease outbreaks. The municipality further published comprehensive climate risk maps in 2024, estimating that approximately 35% of the population is exposed to high risk from flooding and torrential precipitation (Municipality of Rosario, 2024). These data-driven outputs have been progressively embedded in spatial governance, informing density redistribution policies, construction restrictions along stream corridors, and nature-based solutions such as the Green Belt Project – a land-use ordinance permanently reserving peri-urban land for agroecological use that simultaneously delivers flood attenuation and urban heat island mitigation. Rosario's trajectory thus offers one of the more instructive examples available of risk intelligence – generated through EWS monitoring, community mapping and public health surveillance – feeding directly and iteratively into urban planning decisions.

4. Considerations from case studies

The urban practices presented offer multiple insights that can contribute to strengthening and furthering the development of EWS, while also surfacing limitations that warrant attention. Collectively, they provide evidence of the critical relevance of urban planning for the effectiveness of both short-term and long-term resilience and adaptation measures.

Taipei's EWS stands out for its multi-hazard integration within a single smartphone app, a design choice that reflects the inherent interconnectedness of hazards in complex metropolitan environments, where floods, windstorms, fires and infrastructure failures can cascade rapidly across an exposed urban system. Beyond its technological sophistication, the system is notable for the effective coordination of a wide range of institutional stakeholders and for its near-real-time monitoring infrastructure, which leverages IoT networks and advanced machine learning models to generate actionable forecasts at short temporal intervals. Rio de Janeiro's EWS presents two distinctive features of relevance to equity-oriented DRR. The first is a deliberately differentiated warning communication strategy: the involvement of trained community leaders as intermediaries, alongside the activation of sirens for the most imminent threats, reflects a bottom-up approach that tailors the alert system to the social fabric and spatial characteristics of the communities at risk, rather than imposing a one-size-fits-all broadcast model. The second is the explicit focus of the coupled landslide–heavy rainfall warning system on favela communities, a targeting strategy that directly addresses the most structurally vulnerable groups through site-specific, proximity-based action. Rosario's case demonstrates the most advanced integration across all four EW4All pillars and, critically, the most developed articulation between EWS operations and urban planning and development. It features cross-sectoral and cross-level cooperation spanning municipal, provincial and national institutions; the active involvement of the University of Rosario as a strategic knowledge partner; and a central role of the public health agency, which enables the system to bridge hydrometeorological hazards – flooding and extreme heat – with disease outbreak risk, extending the EWS's anticipatory scope beyond conventional disaster management. The entire process is designed to be transparent and participatory, engaging the community both for awareness-raising purposes and as contributors to citizens science monitoring initiatives.

Turning to the implications for urban planning, the three cases together illuminate both the current state and the potential evolution of the relationship between EWS and urban resilience governance.

Taipei's technically advanced monitoring infrastructure, deeply rooted in the spatial analysis of the urban environment, demonstrates the transformative potential of integrating real-time data systems into city operations. Yet its predominantly short-term, event-response orientation also reveals a structural limitation: EWS reach their ceiling of effectiveness when the four pillars are not scaled up and embedded in long-term climate action plans, hazard mitigation plans or climate-proof urban development and redevelopment strategies (Sheehan et al., 2025; UNDRR, 2019). Warning systems can save lives in the immediate term, but they cannot reduce the exposure that makes warnings necessary in the first place – a function that belongs, ultimately, to spatial planning.

Rio de Janeiro's case makes this tension even more explicit. Despite a well-tailored and demonstrably effective EWS, the system operates within an urban fabric fundamentally shaped by informal, unplanned development on hazard-prone slopes and floodplains. This structural condition imposes a ceiling on what any warning system can achieve and highlights the urgent need to adaptively transform those urban contexts that are recursively exposed to intensifying hazards – through managed relocation, incremental upgrading, and the integration of DRR objectives into housing and infrastructure policy (IPCC, 2022).

The Rosario case, however, offers a more generative perspective on this relationship. Its sustained and recursive cycle of risk mapping, hydrological monitoring, public health surveillance and community engagement has demonstrated that iteratively produced, multi-sectoral risk knowledge can trace persistent spatial risk patterns with sufficient resolution and credibility to directly inform planning decisions. In Rosario, this has translated into modified zoning regulations along stream corridors, construction restrictions in flood-prone areas, and the institutionalisation of nature-based solutions through binding land-use instruments such as the Green Belt Project. This trajectory suggests that when EWS are designed not merely as emergency response tools but as ongoing knowledge infrastructures embedded in urban governance, they can actively guide future development – limiting urban expansion into risk-prone areas, constraining hazard-generating land-use change, and orienting redevelopment towards more climate-resilient configurations.

Taken together, the three cases point towards a progressive understanding of EWS as a connective tissue between disaster risk management and urban planning: most effective not when they operate in isolation, but when they are institutionally anchored, spatially informed, equity-oriented and iteratively integrated into the adaptive governance processes through which cities confront – and over time reshape – their relationship with climate risk.

We can then reaffirm the importance of collection, management and representation of knowledge as operational instruments of action and decision that are as effective as possible in preventing what can be foreseen as likely (Stufano Melone & Camarda, 2025), therefore moving from analysis to planning and implementation. Moreover, the importance of land use for disaster risk reduction and climate change underlines the necessity of integrated and adaptive land use policies, that address climate-induced challenges and promote sustainable development (Okafor et al., 2025).

5. Conclusions

In this note we reviewed climate adaptation categories and dived more deeply into soft adaptation measures and their role for disaster risk reduction and urban resilience. The close, causal, relationship between urban planning practice and urban resilience was analyzed, highlighting the crucial role of urban planners in integrating adaptation across sectors and governance levels, taking up a leading role in guiding both short-term disaster risk reduction and long-term climate adaptation. We then focused on early warning systems, an effective disaster risk management measure that contributes to creating governance practices aimed at reducing impacts from extreme weather events, while contributing to strengthening long-term resilience, and institutional and community response. We proposed three exemplary cases of multi-hazard EWS in different contexts: Taipei in Taiwan, Rio de Janeiro in Brazil and Rosario in Argentina. The case studies proved the relevance of EWS in supporting urban planning practices in several ways. First, they encourage constant and updated risk assessment and monitoring, which can inform risk-informed urban policies and plans in the long-term. Second, they enable the creation of a strategic network of stakeholders relevant both for short term DRR & DRM, and for long-term climate change adaptation, including universities, civil protection, and public health authorities. Third, they support the spatial analysis of specific contexts, identifying vulnerable communities to tailor communication and emergency procedures. Finally, they stress how cross-sectoral and cross-level cooperation are crucial, posing an incentive to integrated planning and the proactive role that urban planners assume in developing urban policies towards resilient urban futures. Further research is needed to tackle the bridge between EWS and DRM measures, including the identification and operationalization of climate shelters, and the development of emergency management plans.

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Author's profile

Stella Pennino

She is an engineer and Ph.D. candidate in Civil Systems Engineering at the Department of Civil, Building and Environmental Engineering of the University of Naples Federico II. Her research focuses on adaptation to climate change in urban systems, with particular attention to risk assessment, urban resilience, and local climate governance processes. She investigates how planning tools, policy frameworks, and innovative approaches can enhance the capacity of public administrations to address climate-related risks and support sustainable urban transitions. Her work aims to contribute to the integration of climate adaptation and sustainability principles into urban planning and decision-making processes.

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REVIEW NOTES - Urban planning literature review

Modelling microclimatic characteristics for climate change adaptation solutions: the ENVI-met simulation tool

Tonia Stiuso

Department of Civil, Building and Environmental Engineering
University of Naples Federico II, Naples, Italy
e-mail: tonia.stiuso@unina.it
ORCID: https://orcid.org/0009-0006-2474-8138

Abstract

Starting from the relationship between urban planning and mobility management, TeMA has gradually expanded the view of the covered topics, always remaining in the groove of rigorous scientific in-depth analysis. This section of the Journal, Review Notes, is the expression of continuously updating emerging topics concerning relationships between urban planning, mobility, and environment, through a collection of short scientific papers written by young researchers. The Review Notes are made of five parts. Each section examines a specific aspect of the broader information storage within the main interests of TeMA Journal. In particular, the Urban planning literature review section presents recent books and journals on selected topics and issues within the global scientific panorama.

For the first issue of TeMA Journal, volume no. 19, this section provides a comprehensive overview of the ENVI-met simulation tool, focusing on its methodological framework and operational potential in the field of climate change adaptation. Using a variety of scientific sources and practical resources, this contribution examines ENVI-met's core functionalities, highlighting its capacity to simulate the complex interactions among physical, functional, socio-economic, geomorphological and microclimatic characteristics, examining the solutions proposed in the scientific literature, specifically in books, journals, and reports.

Keywords

ENVI-met; Microclimate simulation; Literature review; Climate change adaptation; UHI

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1. Introduction

Contemporary cities face increasingly complex challenges stemming from climate change, such as the intensification of urban heat islands (UHI), rising energy consumption for building cooling, and the need to ensure outdoor thermal comfort for citizens, who are particularly vulnerable during heat waves (Carpentieri et al., 2024). These issues, exacerbated by urban population growth and rising energy demand, require the adoption of innovative methodologies that integrate microclimate simulation tools into decision-making processes for land-use planning and governance. In this context, microclimatic modeling not only enables the prediction of future climate impacts but also supports the design of adaptation strategies, while contributing to emissions reduction and energy savings (Gargiulo & Zucaro, 2023). The integration of these tools into the management of urban transformations allows for the alignment of land-use planning tools, such as adaptation plans, with the resilience objectives set forth by the 2030 Agenda, promoting shared energy management practices such as energy communities (Martinelli, 2025), or initiatives such as startups and local organizations (Pennino, 2025). Over the past two decades, ENVI-met has become one of the leading microclimate simulation tools for studying the effects of climate adaptation solutions in urban settings, particularly regarding the urban heat island effect and outdoor comfort. The model, developed starting in the 1990s by M. Bruse, is now used in thousands of studies to evaluate scenarios involving urban greenery, cool surfaces, sustainable building design, and adaptation solutions at the block or neighborhood scale. The growing availability of high-resolution climate data and the need to support planning decisions have driven the widespread adoption of ENVI-met for urban microclimate modeling, with applications ranging from quantifying the cooling potential of vegetation to estimating energy savings for buildings and entire neighborhoods. In the context of climate change adaptation, ENVI-met enables the analysis of interactions between urban geometry, land use, vegetation, and the atmosphere, simulating variables such as air temperature, surface temperature, wind speed, relative humidity, and radiative temperatures (ENVI-met, 2017). This makes it particularly well-suited for evaluating the effectiveness of urban cooling strategies, from afforestation to reflective surfaces, in scenarios of increasingly frequent heat waves, providing outputs that can be integrated into GIS workflows for the spatial assessment of energy and comfort indicators (Longato et al., 2025).

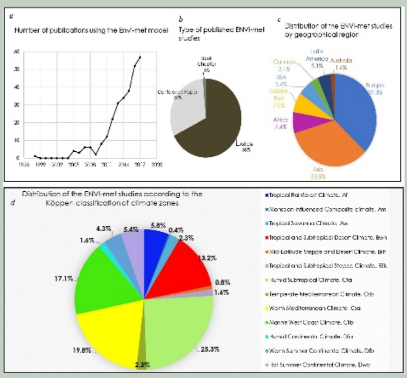
2. Advantages, disadvantages, and performance limitations

ENVI-met is a three-dimensional microscale model based on the solution of the Navier-Stokes equations for incompressible air flows and on specific modules for heat and mass exchange between surfaces, vegetation, and the atmosphere (ENVI-met, 2017). The computational domain is discretized into a regular 3D grid, with a spatial resolution of approximately 0.5–10 m and a time step of 1–2 s, allowing for detailed simulation of the evolution of temperature, wind, and humidity fields in complex urban environments (Alsaad et al., 2022). The model includes explicit representations of buildings, trees, soils, and water bodies, as well as a k–ε closure turbulence model of order 1.5 and schemes for short-wave and long-wave radiation (Chatzinikolaou et al., 2018). The main inputs include: boundary meteorological conditions (time series of temperature, humidity, wind, global radiation, or components), a three-dimensional digital model of the study area, material parameters (albedo, emissivity, heat capacity), and vegetation profiles (height, LAI, leaf density, physiological parameters). The outputs, typically extracted at 10-60-minute intervals, include 3D fields of air temperature, surface temperature, wind speed and direction, relative humidity, radiative fluxes, and comfort indices such as PET or UTCI, derived via add-on modules (Tsoka et al., 2018). Version 4.x also introduces features for simulating green facades and roofs, as well as tools for post-processing and exporting to GIS (UK Green Building Council, 2024). One of the main advantages of ENVI-met is its ability to consistently represent the interaction between complex urban geometry, three-dimensional vegetation, and atmospheric conditions, providing a detailed description of the microclimate at the pedestrian scale (Gargiulo et al., 2025). The literature shows that the model accurately reproduces the diurnal variation of air temperature, surface temperature, and radiative temperatures, with medians of MAE and RMSE for T_air of 1.34 °C and 1.51 °C, respectively, in a meta-analysis of 52 studies. The availability of modules dedicated to nature-based solutions, such as trees, permeable soils, and green roofs, makes it a versatile tool for comparing alternative design scenarios, quantifying cooling potential and energy savings (Schöneberger et al., 2025; Stiuso, 2025). On the other hand, ENVI-met has significant performance limitations. The high spatial and temporal resolution results in long computation times: 24-hour simulations over domains of a few hundred meters often require many hours of CPU time, making the analysis of multiple scenarios or very large domains computationally intensive (Yang et al., 2021). Furthermore, several studies report a tendency to overestimate or underestimate air temperature under specific conditions, such as within densely vegetated green spaces, due to simplifications in the representation of turbulent exchange and vegetation physiological processes. The quality of the results depends heavily on the calibration of material and plant parameters, which are not always comprehensively documented in practical applications. Finally, the maximum manageable domain with acceptable performance (a few hundred meters) limits the model's use to the neighborhood scale, requiring nested approaches or couplings with mesoscale models for urban-scale analysis.

3. Conclusion

Overall, the literature indicates that ENVI-met is a powerful tool for supporting the design of climate adaptation strategies, particularly for evaluating combinations of urban greenery, permeable surfaces, reflective materials, and landform modifications (Schöneberger et al., 2025). The ability to simulate comparable scenarios under heatwave conditions allows for a comparative quantification of the benefits of different interventions, providing actionable insights to decision-makers and planners. However, limitations in terms of computation time, scale of application, and sensitivity to parameters suggest that ENVI-met should be used in conjunction with other tools, such as mesoscale models or statistical analyses of observational data, to obtain a more robust picture. For Mediterranean contexts, characterized by hot, dry summers and often dense urban fabrics, ENVI-met has proven particularly useful in assessing the potential of urban afforestation, shaded courtyards, and green-gray solutions (Mora-Esteban et al., 2025). The growing availability of updated versions and detailed manuals, along with active user communities, represents a further positive development, but the need to standardize calibration and validation protocols remains a priority for improving the reliability of results, especially when used to support public policies.

Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–A review



Authors/Editors: S. Tsoka, A. Tsikaloudaki, T. Theodosiou

Affiliation:
Laboratory of Building Construction and Building Physics, Faculty of Civil Engineering, Aristotle University of Thessaloniki, Greece
Publication year: 2018

A meta-analysis was conducted of 52 studies that had evaluated the performance of ENVI-met by comparing simulations with in situ measurements in various urban settings. The study shows that the model is capable of representing diurnal variations in temperature and humidity with good reliability, while its performance is more variable for wind speed and radiation, which are often influenced by input errors or parameterization choices. The authors highlight that ENVI-met is used primarily for scenario studies rather than for exact reconstructions of existing microclimatic conditions. The meta-analysis concludes that the model is suitable as a design support tool, provided that uncertainties are managed appropriately and specific local validations are performed.

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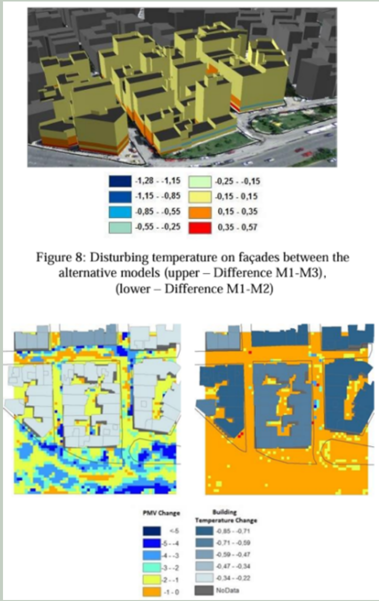
Urban microclimate improvement using envi-met climate model



Authors/Editors: E. Chatzinikolaou, C. Chalkias, E. Dimopoulou

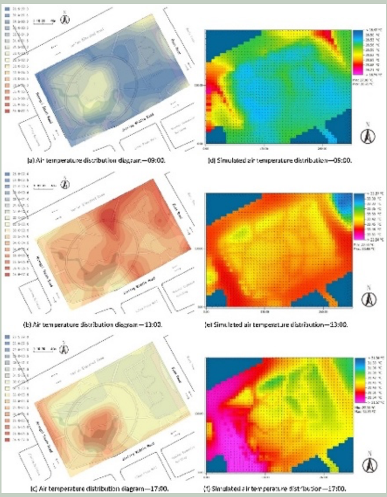
Affiliation:
School of Rural and Surveying Engineering, National Technical University of Athens, Greece;
Iroon Polytechneiou str 9, Zografou 15780 - e.chatz175@gmail.com, efi@survey.ntua.gr;
Department of Geography, Harokopio University, El. Venizelou 70, Athens 17671, Greece - xalkias@hua.gr.

Publication year: 2018

In a study of a residential area in Athens, a methodology based on ENVI-met 4 was applied to evaluate different climate scenarios aimed at reducing the summer heat island effect. The simulation domain included a high-density residential block, where interventions such as the introduction of street trees, the replacement of asphalt pavement with highly reflective materials, and the installation of green roofs were tested. The results showed average air temperature reductions of up to 1–1.5 °C during the hottest hours and much greater decreases in average radiant temperature, with significant improvements in comfort indices for pedestrians. However, the study also highlights limitations in the representation of certain light wind conditions and in the estimation of temperature within denser vegetation.

Retrieved from: https://isprs-archives.copernicus.org/articles/XLII-4/69/2018/isprs-archives-XLII-4-69-2018.pdf

Verifying an ENVI-met simulation of the thermal environment of Yanzhong Square Park in Shanghai



Authors/Editors: Junyan Yang, Xinyu Hu, Haiyi Feng, Simon Marvin

Affiliation:
School of Architecture, Southeast University, Nanjing 210096, China;
College of Landscape Architecture, Nanjing Forestry University, Nanjing 210037, China;
Urban Institute, Sheffield University, ICOSS, 219 Portobello, Sheffield S1 4DP, UK.

Publication year: 2021

A study conducted in Shanghai evaluated the performance of ENVI-met in simulating thermal conditions at Yanzhong Square Park, a green space surrounded by high-density buildings. The authors compared air temperature measurements and other microclimatic parameters with the model results, highlighting that, although ENVI-met correctly reproduces diurnal trends, it is less accurate in representing temperatures within the park, with underestimates of up to 2–3 °C. The research suggests that standard vegetation parameterization may not be adequate for complex green spaces in dense settings, underscoring the importance of specific calibrations and greater attention to the representation of turbulent flows within the canopy. This case clearly highlights how the model's performance is strongly dependent on the quality of the input data and the chosen configuration.

Retrieved from: https://www.sciencedirect.com/science/article/pii/S1618866721004118

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Author's profile

Tonia Stiuso

She is an engineer and research fellow at the Department of Civil, Architectural and Environmental Engineering at the University of Naples Federico II. Her research currently focuses on the theme of urban sustainability, in particular the study of gender inequalities and adaptation to climate change.

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REVIEW NOTES - Reports and documents

Adaptation insight: the state of climate knowledge

Laura Ascione

Department of Civil, Building and Environmental Engineering
University of Naples Federico II, Naples, Italy
e-mail: laura.ascione2@unina.it
ORCID: https://orcid.org/0009-0000-4366-4665

Abstract

Starting from the relationship between urban planning and mobility management, TeMA has gradually expanded the view of the covered topics, always remaining in the groove of rigorous scientific in-depth analysis. This section of the Journal, Review Notes, is the expression of continuously updating emerging topics concerning relationships between urban planning, mobility, and environment, through a collection of short scientific papers written by young researchers. The Review Notes are made of five parts. Each section examines a specific aspect of the broader information storage within the main interests of TeMA Journal. In particular, the Urban planning literature review section presents recent books and journals on selected topics and issues within the global scientific panorama.

For the first issue of volume 19 of TeMA Journal, this section offers a critical and comparative reading of recent reports and documents related to climate adaptation in urban areas. These reviews line up to explore both the similarities and differences between the approaches, priorities, and strategies of the reports analysed, with the purpose of strengthening the dialogue between science, policy, and climate planning practices. This first contribution is dedicated to a review of reports on the state of knowledge on climate change in terms of emerging risks, observed impacts, and the conditions of vulnerability that amplify its effects in different territorial and social contexts.

Keywords

Climate change; Adaptation; Global reports

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1. Introduction

In recent decades, the increasing frequency and intensity of extreme weather events have made climate risk one of the key drivers of the global economy (Pennino, 2025). According to the World Economic Forum's (WEF) Global Risk Report, the failure of climate policies, extreme weather events and the loss of biodiversity are among the three main systemic risks that humanity will face in the coming decade (World Economic Forum, 2022). At the urban level, the most recent estimates indicate that around 44% of the GDP generated in global cities, corresponding to over 31 trillion dollars, is currently exposed to the risk of destruction resulting from the loss of natural ecosystems and the climate crisis (World Economic Forum & AlphaBeta, 2022). These figures point to a transformation in the relationship between urban systems and the climate system, which calls for a fundamental rethinking of the strategies through which institutions and governments prepare to address future risks (Ascione et al., 2025). In this context, climate adaptation has gradually taken on a central role in international political agendas (Longato et al., 2025). Although mitigation initially dominated the global climate debate, the realisation that some of the climate change currently underway is now impossible to avoid has shifted the focus towards the need to adapt territorial and social systems to different climatic conditions (Bichueti et al., 2025; Alexandrov, 2023). This changing perspective was formally recognised at an institutional level by the Paris Agreement (UNFCCC, 2015), which for the first time accorded adaptation the same political importance as mitigation, and was further reinforced by the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015), which explicitly integrated climate risks into the global framework for disaster risk reduction. In this context, the main international reports on climate change and climate risk serve a function that goes far beyond summarising the available scientific knowledge (Sharek & Shah, 2021). These documents do not merely record the state of the art in research but actively contribute to defining how climate risks are conceptualised, which dimensions of the problem are made visible, and which solutions are identified as priorities for public policy. In this sense, these reports constitute genuine instruments for shaping the global climate agenda (Jasanoff, 2010).

This paper proposes a critical and diachronic analysis of several international reports on climate adaptation to trace how understanding of adaptation has evolved over the last decade. The analysis does not merely compare different reports. Still, it traces the evolution of specific reports published by UNEP and UNDRR, to highlight how the dominant conceptual frameworks, priorities and language used to describe risks, and possible responses have changed over the years. The underlying assumption is that this evolution reflects not only advances in scientific knowledge, but is also the result of institutional pressures, extreme events and political negotiations that have redefined what matters. The paper is structured as follows. Section two discusses the role of global reports as tools for building institutional climate knowledge, and section three analyses the evolution of the Adaptation Gap Reports and the Global Assessment Report, respectively. Section four discusses emerging cross-cutting trends and unresolved gaps. Section five concludes with implications for research.

2. Summary of the evolving landscape of climate adaptation

Adaptation Gap Report (UNEP)

Fig. 1 Collection of covers of the Adapation Gap Reports analysed

The series of Adaptation Gap Reports published by UNEP was launched in 2014 in response to the need to address the lack of a systematic tool for monitoring global adaptation. There was a lack of shared metrics to assess progress in this area after the UNFCCC had established the political importance of adaptation. The first editions (2014), published in the year of COP20 in Lima, together with the 2015 and 2016 editions focuses almost exclusively on the adaptation finance gap: the gap between the funding needed to address expected climate impacts and the funding actually mobilised. The framework is largely quantitative and reflects the logic of international negotiations at that time, which were based primarily on financial resources, to understand how much might be needed or where it is being allocated (UNEP, 2014). The 2017 and 2018 editions mark the first change of direction. The adoption of the Paris Agreement in 2015 established a Global Goal on Adaptation, which called for new tools to assess progress that could not be reduced to financial considerations alone.
The 2017 AGR, focuses on the methodological challenges of measuring adaptation on a global scale, explicitly acknowledging that progress in adaptation is inherently difficult to quantify. Unlike greenhouse gas emissions, adaptation does not have a universal unit of measurement (UNEP, 2017). The 2018 AGR expands on this by introducing the distinction between planning gaps and implementation gaps: it is not enough to adopt national adaptation plans; these must be translated into concrete actions on the ground. This shift is conceptually significant because it shifts responsibility from the realm of resources to that of institutional capacity. It implicitly acknowledges that the problem of adaptation is not merely financial, but political and organisational (UNEP, 2018).
The 2020–2022 editions represent a phase of consolidation and radicalisation. The reports from these years gradually incorporate the evidence that progress on adaptation is consistently insufficient compared to the speed at which climate risks are intensifying (UNEP, 2022). The 2022 GAP, explicitly titled 'Too Little, Too Slow', marks a turning point. The language of the reports becomes more urgent, estimates of the gap between needs and actions more worrying, and, for the first time, the issue of maladaptation emerges strongly. Maladaptation is defined as the risk that poorly designed adaptation measures may reduce vulnerability in the short term, whilst increasing it in the long term (UNEP, 2022). The report also introduces a more systematic focus on regional disparities. For examples, the reports talk about the low-income countries and small island states that show the greatest adaptation deficits precisely where climate risks are most acute. This dimension revealing a structural injustice that previous editions had treated more marginally.
The most recent editions, AGR 2023 and AGR 2024, continue in the vein of previous reports, introducing two significant new conceptual elements. The first is the issue of loss and damage, that is, the explicit recognition that there are climate impacts that can no longer be prevented or adapted to, requiring compensation mechanisms distinct from adaptation policies. This marks a break from the framework of previous editions, according to which every climate risk is, in principle, manageable with sufficient resources (UNEP, 2023; UNEP, 2024). The second element is the recognition of the limits of adaptation. Acknowledging that there are thresholds beyond which adaptation is no longer possible, or no longer desirable, implies a profound revision of the optimistic framework that had characterised the first editions of the series. The AGR 2025, recently published under the title 'Running on Empty', also reinforces this direction by highlighting how the funding gap for adaptation in developing countries is putting lives, livelihoods and entire economies at risk (UNEP, 2025).

Global Assessment Report (UNDRR)

Fig. 2 Collection of covers of the Global Assesment Reports analysed

The Global Assessment Reports (GARs) have a slightly different, albeit related, focus compared to the AGRs: disaster risk reduction. The reports are published every two years by UNDRR and primarily refer to the Sendai Framework for Disaster Risk Reduction 2015–2030, which sets targets for reducing disaster losses in terms of fatalities, people affected, and economic and infrastructure damage (UNDRR, 2015). The gradual integration of climate change into the GARs framework reflects the growing difficulty in distinguishing extreme weather events (natural hazards) from current climate trends that are increasing the frequency and intensity of such events.

The 2022 edition, entitled 'Our Shared Responsibility', introduces the concept of systemic risk as a central framework (UNDRR, 2022). The underlying argument is that disaster risks can no longer be understood by isolating one system at a time. The impacts of an extreme event propagate through interconnected economic, social and infrastructural systems, generating cascading risks that amplify losses beyond the geographical and sectoral scope of the original event (Thompson et al., 2024). This perspective has direct implications for urban and climate governance, as traditional disaster management structures, organised by sector and across separate territorial scales, are now inadequate for addressing risks (UNDRR 2022). The GAR 2022 therefore proposes an agenda for reforming risk governance, focused on cross-sectoral approaches and multi-level coordination.

The GAR 2025, entitled 'Resilience Pays: Financing and Investing for our Future', represents the most recent development (UNDRR, 2025). Its main contribution is not only analytical but also policy oriented. The report systematically argues that investing in risk reduction is not only necessary but also economically viable, and that a failure to invest leads to spiralling debt, a loss of insurability and structural humanitarian need (UNDRR 2025). The figures presented in the report are striking whilst the direct costs of disasters averaged $70–80 billion annually between 1970 and 2000, they rose to $180–200 billion between 2001 and 2020; and when indirect impacts and ecosystem costs are included, the total estimated annual cost of disasters exceeds $2.3 trillion (UNDRR, 2025). This figure, almost ten times higher than the direct losses reported in official statistics, constitutes one of the strongest arguments in favour of a paradigm shift in public and private investment policies. The alignment with the climate adaptation agenda is more explicit in this edition; indeed, the GAR 2025 openly acknowledges that systemic disaster risk and long-term climate risk are two sides of the same structural problem, and that addressing them separately, as has been done for decades, is one of the main causes of the inadequacy of current responses (UNDRR, 2025).

3. Discussions and critical overview

An analysis of AGRs and GARs shows that, although they began as reports with distinct objectives, over the last decade, they have converged in a single direction. The AGR has shifted from an almost entirely financial framework to one focusing on institutional and political dimensions and vulnerability. Meanwhile, despite continuing along its trajectory of disaster risk reduction, the GAR has arrived at the conclusion regarding cascading risks and the need to implement multi-sectoral actions. The consequence of this alignment is that both reports ultimately point to the inadequacy of traditional sector-specific tools given the interconnected nature of risks. However, one question that remains unanswered is how to translate the reports' recommendations into operational governance tools that are genuinely different from existing ones. Among the most significant data from the GAR is the estimate that the total annual cost of disasters exceeds 2.3 trillion dollars. The difference compared with the losses recorded over the previous two decades is staggering and makes it clear that climate risk has been underestimated. This data takes on further significance when read alongside the latest UNEP reports, which document the inadequacy of responses to the actions required. There is not only a lack of political commitment to implement effective measures, but also a failure to allocate sufficient investment to prevention and adaptation. Taken together, the two reports thus describe the two sides of the same problem: on the one hand, the growing gap between needs and resources for adaptation; on the other, the economic underestimation of the costs of inaction. The conceptual convergence between the two approaches does not remove differences that remain significant. GAR retains an event-oriented approach; indeed, its primary unit of analysis is the disaster as a measurable event. AGR, on the other hand, consists of reports that track long-term trends and processes. This difference in temporal focus leads to practical recommendations that are not always consistent with one another

4. Conclusions

This paper aims to reconstruct, through a critical and diachronic analysis, a series of reports on the state of knowledge regarding climate adaptation and how this has evolved over recent decades. The intention was to highlight how priorities have shifted over time. In terms of research, the most significant gaps identified by this review concern three dimensions. The first is the marginalisation of local scales and the cultural dimensions of adaptation. To produce a global report, local contexts must also be generalised, rendering invisible the contextual specificities that determine whether and how policies work in practice (Stufano Melone & Camarda 2025). The second is the difficulty of measuring adaptation quantitatively, in order to understand whether the measures implemented actually reduce vulnerability or risk of maladaptation. The third concerns the power dynamics in knowledge production. In this case, the convergence between AGR and GAR also reflects a convergence between institutional communities with very different resources and visibility, and it would be important to analyse whether and how the voices of the most vulnerable contexts manage to influence the dominant frames, or whether they remain structurally excluded. At a more practical level, the most pressing message that emerges is the need to bridge the gap between climate adaptation and disaster risk reduction and to consider them in parallel. However, moving from the theory set out in these documents to practice by translating this knowledge into operational tools remains a challenge to this day. This review represents the first such general overview. The two subsequent reviews will examine, respectively, the mechanisms through which the knowledge produced by these reports is, or is not, translated into national and local policies, and the metrics used to monitor progress in adaptation at global and local scales. Together, these three contributions aim to offer a critical and systematic analysis of institutional climate knowledge, at a time when the pressure of events makes it increasingly urgent to translate this knowledge into action.

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Image Sources

Fig.1: https://unepccc.org/adaptation-gap-reports/

Fig.2: https://www.undrr.org/gar

Author's profile

Laura Ascione

She is an engineer and a Ph.D. student in Civil Systems Engineering at the Department of Civil, Building, and Environmental Engineering of the University of Naples Federico II. Her research focuses on the relationship between urban characteristics and adaptation measures in urban planning to address climate change.