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Multilevel scientific approach to impacts of global warming on urban areas, energy transition, optimisation of land use and emergency scenario

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TeMA Journal was established with the primary objective of fostering and strengthening the integration between urban transformation studies and those focused on mobility governance in all their aspects, with a view to environmental sustainability. In other words, the mission of this initiative is to contribute to developing a novel theoretical and methodological framework that transcends the boundaries separating these research domains and develops innovative solutions for issues currently being addressed with methods and techniques rooted in the scientific culture of the last century.

The three issues of the 2025 volume of TeMA Journal propose articles that deal with the effects of Global warming, reduction of energy consumption, immigration flows, optimization of land use, analysis and evaluation of civil protection plans in areas especially vulnerable to natural disasters and multilevel governance approach to adaptation.

In this issue, the section "Focus" contains three researches.

The first paper, titled "Aging population and the accessibility of public transportation services: policy perspective for Turkey" by Süleyman Nurullah Adahi Şahin, Abdulkadir Ozden, Ardeshir Faghr, Michael L. Vaughan (Sakarya University of Applied Sciences in Turkey and University of Delaware in USA), offers a comprehensive evaluation of Turkey's national public transportation accessibility policies and explores their potential relevance for other countries. The findings underscore the need for standardized design, stronger policy enforcement, and more inclusive digital and physical mobility solutions to ensure active aging and social participation.

The second contribution is "The role of renewable energies in landscape transformation. Methodological proposal and application to the Valdagno case study", by Elena Mazzola (University of Padua in Italy) examines the significance of harmonising energy requirements with landscape conservation, emphasising the imperative for strategic and methodological approaches to integrating renewable energies into landscape and social contexts. The objective is to propose an analytical methodology that ensures a balance between energy efficiency and landscape conservation, thereby fostering careful design and conscious integration in order to minimise visual and environmental impacts while contributing to energy sustainability. The methodology is then applied to the case study of the Municipality of Valdagno in Italy.

The last contribution of the section is "Land transformation and new road infrastructures. An analysis on direct and inducted impacts due to the Brebemi highway" by Rossella Moscarelli, Marialaura Giuliani (Politecnico di Milano in Italy). The paper investigates the impacts on land transformations and on the increase of soil sealing derived from the construction of a new road infrastructure, such as highways. The analysis focuses on land transformations producing soil consumption, namely on the transformation of natural soil (rural or wooded) into urbanized and sealed areas.

The section “LUME” includes three papers. The first contribution of section is "Mobility changes occasioned by COVID-19 lockdown measures: evidence from an emerging economy" by Ernest Agyemang, Samuel Agyei-Mensah, Aruna Sivakumar, Ricky Nathavni and Majid Ezzati (University of Ghana and Imperial College London in UK). This reaserch aims to fill that gap by examining the effects of government-imposed travel restrictions on people's attitudes and mobility behavior in urban Ghana. Using a combination of data sources, including surveys and photographic evidence, it analyzes the spatial variations in mobility patterns during the COVED-19 lockdown.

The second contribution is "An evaluation on the change of natural areas: the case of Eastern Black Sea settlements" by Doruk Görkem Özkan, Sinem Dedeoğlu Özkan, Seda Özlü (Karadeniz Technical University in Turkey), analyzes land use/land cover changes depending on natural environmental elements in the settlements of the Eastern Black Sea Region for a period of approximately 20 years. The data set of the study was provided by CORINE and TUIK and Two-Step Clustering Analysis was used as the method. As a result of the study, the changes over time of the districts in similar and different clusters according to their natural environment components were evaluated by comparative discussion.

The third article, "Mode choice patterns and socio-spatial equity in contrasting transitional urban mobility systems" by Muhammad Mashhood Arif, Ahmad Adeel, Nida Batool Sheikh (Katholieke Universiteit Leuven and Ghent University in Belgium and German University of Technology in Oman), explores a comparative analysis of mode choice behavior in Bundang and Ilsan, two distinct new towns in the Seoul Metropolitan Area, using Nested Logit Model (NL) to unravel how socio-demographic, trip-specific, and land-use variables interact with urban morphology to shape mobility preferences.

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

The Urban planning practice section of Review Notes, "Positive Energy Districts for urban energy transition: regulatory challenges and implementation strategies", by Valerio Martinelli, analyzes the role of Positive Energy Districts (PEDs) in the urban energy transition, highlighting key regulatory barriers and the potential of Renewable Energy Communities (RECs) as an enabling tool. Through an examination of the European legislative framework, the text emphasizes the importance of integrated urban planning and proposes policy recommendations to facilitate the widespread implementation of PEDs in European cities.

The second section, "Digitalization in urban planning: new digital technologies for sustainable cities", by Annunziata D'Amico, explores how digitalization is transforming cities, which are becoming increasingly human-scale, relying on the development of so-called "smart cities" and "resilient cities" to address current pressing challenges, such as climate change and resource management, and to influence urban governance toward sustainability principles.

The third contribution, "Competitive climate adaptation. European startups driving climate change adaptation in cities", by Stella Pennino, explores the contribution of innovative climate-oriented startups to urban climate adaptation and competitiveness. Within the broader debate on the relationship between urban planning, environmental challenges, and territorial transformation, the note highlights the strategic role these entities can play in supporting resilient urban transitions in Europe. Three exemplary cases are described, offering insight into the relevance of these initiatives in shaping adaptive and competitive urban futures.

The fourth section, "Exploring open and green space characteristics for climate change adaptation: a focus on flooding phoenomenon", by Tonia Stiuso, provides an in-depth analysis of emerging issues in urban planning, mobility and the environment. The aim is to shed light on effective approaches and innovative strategies to deal with flooding events and how different characteristics of urban open and green spaces contribute to climate adaptation.

The last section, "Global warming reports: a critical analysis of NGOs publications", by Laura Ascione, aims to provide a comprehensive understanding of Non-Governmental Organizations (NGOs) perspectives on climate change, examining their role as intermediaries between scientific research and public awareness, while critically assessing both the strengths and potential limitations of their reporting approaches.

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Aging population and the accessibility of public transportation services: policy perspective for Turkey

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Abstract
Projections indicate that elderly individuals will constitute approximately 25% of the total population within the next 30 years. As aging and mobility-challenged populations require targeted planning, policies and physical infrastructure related to public transportation must be reassessed with greater precision and inclusivity. This study offers a comprehensive evaluation of Turkey's national public transportation accessibility policies and explores their potential relevance for other countries. Additionally, interviews with four leading NGOs in Turkey were conducted to identify practical challenges faced by the elderly in urban transport systems. Thematic analysis of the feedback revealed critical deficiencies in vehicle design, fare policy, pedestrian infrastructure, traveler information systems, and driver behavior. Based on this multi-source analysis, the study proposes actionable policy recommendations to improve the accessibility, safety, and usability of public transportation services for elderly populations. The findings underscore the need for standardized design, stronger policy enforcement, and more inclusive digital and physical mobility solutions to ensure active aging and social participation.

Keywords
Accessibility; Urban mobility; Elderly people; Public transportation accessibility; Societal aging

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1. Introduction

In the past century, significant improvements in human longevity have led to noticeable changes in societal aging trends. According to the Organization for Economic Co-operation and Development (OECD), the proportion of the population aged 60 and over increased from 7.7% in 1950 to 17.8% in 2010, and is projected to reach 25.1% by 2050 (OECD, 2015). Fig.1 highlights the proportion of the elderly population in global averages between 1960 and 2023.

These aging trends have prompted research into the social and economic consequences of an aging population. The World Health Organization (WHO) identifies eight strategic domains essential to promoting age-friendly cities: "housing, outdoor spaces and buildings, transportation, social participation, respect and social inclusion, civic participation and employment, communication and information, and community support and health services" (WHO, 2011). As the global population becomes increasingly urbanized, the demand for accessible and inclusive transportation systems is expected to rise accordingly.

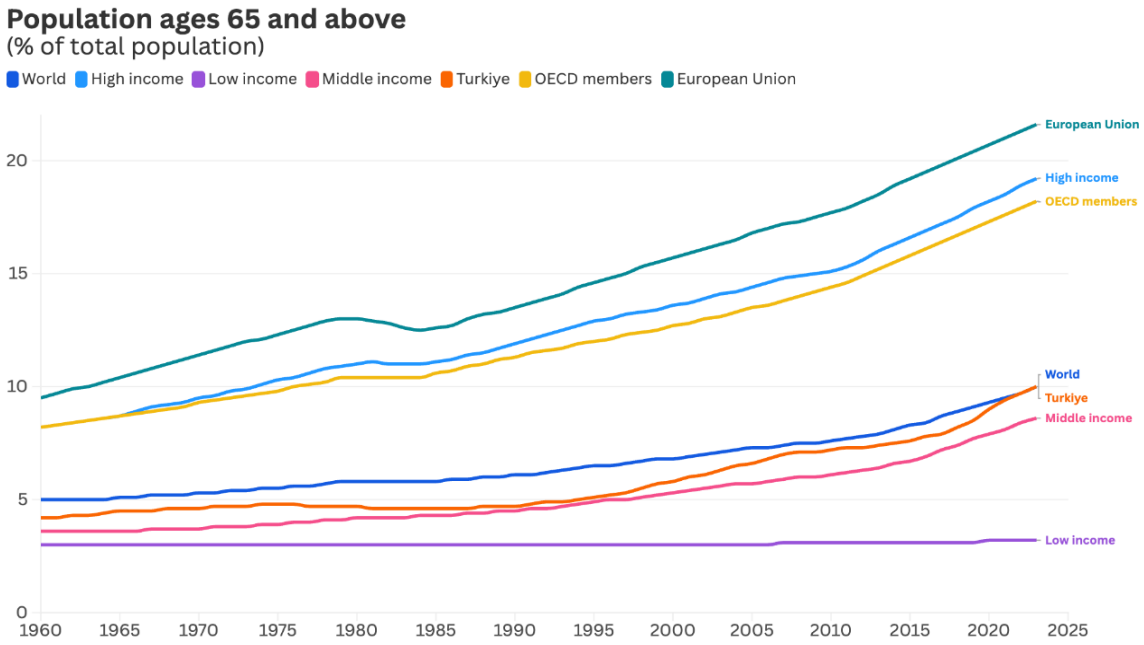


Fig.1 Trends in the proportion of the population aged 65 and above between 1960 and 2023, comparing Turkey with global averages, income-level groups, OECD members, and the European Union

Public transportation services, beyond forming the backbone of urban mobility, play a vital role in enabling daily activities. An efficient and inclusive public transport system can enhance urban mobility, reduce environmental impacts, contribute to public health, and support economic growth. Moreover, when "accessibility" is treated as a central parameter in the planning, design, and operation of transport systems, these services can more effectively meet the needs of mobility-challenged individuals, particularly the elderly. The steady growth of the elderly population underscores the urgent need to develop transportation approaches that enhance both accessibility and mobility. Urban strategies should be adapted to accommodate the needs of this demographic, making cities more accessible, safer, and inclusive through well-organized public spaces and mobility networks (Gargiulo et al., 2018).

1.1 Definition of accessibility and mobility

Mobility and accessibility are two foundational concepts in contemporary sustainable urban planning. Both contribute to the movement of people and goods in environmentally friendly ways that support our increasingly diverse, dense, and fast-paced lifestyles. Specifically, mobility and accessibility can pose significant barriers

for individuals with physical challenges, including the elderly. These factors are becoming increasingly important given the rising percentage of older adults in the global population.

Accessibility is a broad concept with multiple definitions and perspectives in the literature. Among the various definitions, those related to cities, buildings, and transportation predominantly refer to individuals with reduced mobility. According to Vuchic (2017), accessibility can be broadly defined as the ability to travel between different activities. It is often associated with the ability to access goods, services, destinations, or the ease of doing so (Sinha & Labi, 2011). This aligns with Engwicht's (1993) interpretation of accessibility as "the ease with which exchange opportunities can be accessed." Lynch (1984) similarly emphasized the element of ease through the notion of proximity, defining accessibility as "the general proximity in terms of time of all points … to a given kind of activity or facility." He further identified three sub-attributes of accessibility: diversity, equity, and control. For Grava (2003), accessibility also serves as a measure of a community's operational effectiveness and quality. Recognizing that transit must serve everyone leads to the principle of fully accessible transit (Vuchic, 2017), and is supported by Corazza et al. (2017), who emphasize that "a public transportation system needs to be accessible to people who can use it." Similarly, Banister (2005) states that the primary aim of transportation is "to maintain a high level of accessibility with trip lengths being as short as possible." In this study, accessibility refers to both the ability to use transportation services and the ease of using transit systems.

Beyond definitions, accessible transportation applies to public transport services, terminals and facilities, personal vehicles, and road infrastructures—especially pedestrian networks (Somenahalli et al., 2016). After age 55, private car usage declines steadily, while walking increases, and public transport becomes a preferred option, especially for those aged 75 and above (Hounsell et al., 2016). Transforming a city center into a pedestrian-friendly zone affects both accessibility and modal choices while also increasing the attractiveness of the area for new residents, workplaces, and retail businesses—thus increasing transport demand (Wang et al., 2015). The Bocca (2024) provides a strong conceptual framework for understanding how urban design principles, such as the "15-minute city" and the strategic use of public spaces, directly contribute to the accessibility and livability of urban environments. Transportation is no longer used solely for commuting between home and work; people now rely on it for social interaction and other daily activities. Therefore, accessible transport systems should be recognized not only as a key means of social connection for individuals with limited mobility but also as universal systems from which all users can benefit (Zając, 2016).

Mobility is another essential concept in the context of societal aging, especially regarding daily life and transportation. From Schwanen's perspective, mobility and independence are key components of well-being: mobility allows older individuals to engage in meaningful activities outside the home, while independent living grants control over when and where those activities occur (Schwanen & Ziegler, 2011; Banister & Bowling, 2004; Schwanen et al., 2012). Mobility involves how an individual moves, the physical and infrastructural conditions encountered, the quality of transport services, and the ease of movement. In contrast, accessibility concerns the purpose of movement and reflects the time, distance, and available travel options between a given origin and destination (Levin, 2019). The difference lies in that mobility refers to the quantity of trips made, while accessibility indicates how easily those trips can be accomplished (Fatima & Moridpour, 2019). As urbanization and the pace of modern life accelerate, "we live in a 'hypermobile' society that requires a high degree of mobility to participate in family and social activities, services, and economic life" (Cohen & Gössling, 2015).

1.2 Societal aging and mobility

The main focus has been placed on this issue within urban policy frameworks (OECD, 2015), which should support the development of urban models aimed at reducing the social exclusion of elderly individuals (Gargiulo et al., 2018). For senior citizens who are no longer part of the workforce, transportation plays a critical role in maintaining social interaction (Aguiar & Macário, 2017) and community engagement (Davey, 2007). To ensure

that elderly individuals remain actively involved in daily life, it is essential that public transportation systems offer adequate levels of mobility that meet their specific needs (Browning & Thomas, 2013; Dickerson et al., 2007; Ranković Plazinić & Jović, 2018).

Moreover, older adults wish to remain active participants in society and avoid being marginalized due to their age (Metz, 2017). In fact, their travel needs may even exceed those of younger individuals, as they often require more time for non-home-based activities and make more frequent trips for health care and social services (Kara & Bilgiç, 2021; Kara et al., 2025; Kim & Ulfarsson, 2004). A lack of mobility and accessibility can discourage elderly individuals from participating in community life, potentially leading to depression and loneliness (Atkins, 2001). The rising proportion of elderly people underscores the need for transportation systems to be accessible—this should be a top priority for transportation policymakers (Wong et al., 2018). In many cases, developing countries, also known as the Global South, fail to adequately prioritize mobility and accessibility in the planning and decision-making processes related to transit operations, which calls for further evaluation (Aguiar & Macário, 2017; Saif et al., 2019).

The primary aim of this study is to evaluate current policies on the accessibility of public transportation systems and to offer policy recommendations by integrating findings from the literature, current practices, and feedback from contacted NGOs. This research is organized into three stages:

- A comprehensive assessment of accessibility-related policies and practices in Turkey and internationally;
- Engagement with selected NGOs to evaluate, explain, and conceptualize key accessibility challenges in Turkey, and to identify shortcomings in current practices;
- Development of policy suggestions for decision-makers to improve the accessibility of transportation systems and enhance the mobility of elderly populations.

The scope of this study and the discussions with NGOs primarily focus on transportation services and the accessibility of related infrastructure. Key themes include transit vehicles, bus stops, transfer points, sidewalks, fare policy, and driver behavior. In addition, the study evaluates mobility options and levels of accessibility. Other infrastructural elements — such as the accessibility of public buildings or the availability of services for elderly individuals with special needs — were not considered within the scope of this research.

This study aims to identify and document shortcomings and gaps in current transportation policies and practices concerning accessibility for elderly individuals. It is also anticipated that these findings will align with the feedback received from NGOs that represent and support those most affected by these issues. Accordingly, this evaluation and its recommendations are intended to support relevant institutions and policymakers in addressing accessibility challenges in public transportation by strengthening policies and improving implementation.

2. Methodology

Proper characterization of an existing problem is essential to solving it. This study begins by examining research from Europe, Asia, and Oceania focused on transportation accessibility and mobility for elderly populations. The evaluation adopts a public transportation perspective, specifically analyzing vehicle design, infrastructure (e.g., sidewalks, walking paths, bus stops), fare policy, and driver behavior. This approach enables a deeper understanding of the issues involved and allows for the consideration of policies and practices implemented in other regions. Furthermore, current national policies in Turkey are evaluated and compared with those of other countries. As a second step, interviews were conducted in November 2020 with four major NGOs in Turkey that advocate for the rights of elderly individuals across various platforms. These organizations, primarily based in Ankara and Istanbul but active nationwide, were selected based on their expertise in elderly issues. The interviews employed an unstructured, face-to-face format with NGO leaders who possess deep knowledge of the subject. This method allowed for flexible, open-ended discussions centered on the study's core themes. As noted by Sönmez and Alacapınar (2013), unstructured interviews are

particularly effective when working with experienced participants, allowing the researcher to explore emerging ideas in depth. Due to the second wave of the COVID-19 pandemic in late 2020, the interview process was adapted to a hybrid format. Initial contact was made by phone to explain the study's purpose, scope, and interview themes. The final interviews included 10 questions addressing challenges faced by elderly populations in daily life—particularly regarding transportation and mobility—as well as their views on existing national policies and alignment with literature-based recommendations.

The NGOs involved in this process were:

- Plus Breath (Artı Nefes)[1];
- Elderly People's Rights Association (Yaşlı Hakları Derneği)[2];
- International Federation of Respect for the elderly people (UYSAK-Uluslararası Yaşlılara Saygı Federasyonu)[3];
- Seniors Council Association (TURYAK – Yaşlılık Konseyi Derneği)[4].

The qualitative data obtained from these interviews were analyzed using thematic analysis, following the approach proposed by Braun and Clarke (2006). This method was selected due to the relatively small number of interviews and the need for in-depth interpretation of open-ended stakeholder input. Thematic analysis enabled the identification of recurring themes while preserving the richness of participants' perspectives, making it particularly suitable for policy-focused qualitative research. Although alternative methods such as Framework Analysis might be appropriate for policy-oriented studies, the unstructured nature of the interviews limited its applicability here. Likewise, Content Analysis, which typically involves frequency-based coding and is more suited to larger data sets, would not have captured the depth of insight required in this context. Given that the study sits at the intersection of social policy and urban accessibility, and seeks to derive actionable recommendations through stakeholder engagement, thematic analysis proved to be the most appropriate. As Braun and Clarke (2006) emphasize, this method is widely used not only in psychology but also in social policy, education, urban planning, public service design, and participatory research. Feedback from interviewees — covering suggestions, critiques, and identified deficiencies — was compared against current Turkish national policies and large-scale practices. This comparison, along with international examples, helped assess key similarities and differences. By integrating expert NGO perspectives with relevant literature, the study proposes new policy recommendations aimed at improving national strategies for accessible transportation. These recommendations focus on promoting social inclusion, enhancing mobility and access, and supporting the physical and psychological well-being of elderly populations through improved service capacity.

3. Worldwide elderly people accessibility and mobility

Many policy, regulatory, and infrastructural decisions around the world aim to enhance the lives of individuals with reduced mobility. The European Commission's first formal identification of such individuals was presented in the Technical Specifications for Interoperability (Council of the European Union, 2008), offering a notably comprehensive definition. "Persons with Reduced Mobility" (PRM) refers to all individuals who experience difficulty when using transportation systems. These groups are summarized in Table 1.

A more recent version of the regulation (European Parliament & Council of the European Union, 2014) provides a broader and less disaggregated definition:

"Person with disabilities and person with reduced mobility means any person who has a permanent or temporary physical, mental, intellectual or sensory impairment which, in interaction with various barriers, may

[1] https://artinefes.org.tr
[2] https://yaslihaklaridernegi.org
[3] http://www.uysaf.org.tr
[4] http://www.uysaf.org.tr

hinder their full and effective use of transport on an equal basis with other passengers or whose mobility when using transport is reduced due to age."

TSI PRM
Wheelchair users
People with ambulant difficulties
People with children
People with heavy or bulky luggage
Elderly people
Blind people
Deaf people
Communication impaired
People of small stature (including children)

Tab.1 Categories of Persons with Reduced Mobility as defined by the European Commission, 2008

While it is clear that not all elderly individuals face the same mobility limitations, this study focuses on older adults who are capable of participating in daily travel. Under existing regulations, elderly individuals are generally included among persons with reduced mobility. Although maintaining mobility is a key goal, expanding accessibility opportunities is ultimately the most effective way to overcome mobility constraints. Elderly individuals primarily face three types of barriers to accessibility: facility and vehicle design, system operation, and cost (Ashford & Bell, 1979). Additionally, transportation and environmental planning efforts have historically tended to overlook the needs of older adults (Rosenbloom & Morris, 1998). As Wong et al. (2018) note, the growing impact of aging populations on transportation systems remains largely underrecognized by policymakers, despite evidence that many existing systems fall short of meeting the evolving needs of elderly users.

3.1 Seat and vehicle availability

Vehicle accessibility is among the most critical components of accessible transportation. One of the key difficulties faced by elderly individuals is the lack of available seating. Priority seats, often occupied by other passengers, are not always accessible or respected, compromising safety and comfort for elderly users (Wong et al., 2017). Ensuring seat availability is a top priority for improving accessibility for a large portion of this demographic. The culture of offering seats to those in need—including elderly individuals, persons with disabilities, and pregnant women—is generally promoted through education, in-vehicle signage, and public awareness campaigns encouraging respectful behavior (Wong et al., 2018). In addition, vehicle interior designs should prioritize safety and ease of movement, such as wider aisles, low-floor entries, and accessible seating arrangements across all public transport modes.

3.2 Fare policy

Accessibility and mobility in public transportation can be significantly improved for people with reduced mobility when cost-related barriers are eliminated. This can be achieved through fare policies that reflect the specific needs of elderly passengers (Zając, 2016). Providing transportation services through public subsidies or regulated fare discounts ensures affordability and encourages usage among elderly individuals (Metz, 2017). Wong et al. (2017) recommend expanding fare concession programs to include individuals aged 60–64 and offering full fare coverage for those over 80 to promote social engagement. In England, the concessionary

fare scheme—commonly known as the "free bus pass"—allows individuals over the retirement age for women to travel free of charge throughout the UK, with minor restrictions such as morning peak-hour exclusions (Shrestha et al., 2017).

3.3 Bus stop design

Walking distance and wait times are critical factors that influence public transport accessibility for elderly users. Excessive waiting times, compounded by weather exposure or inadequate seating, can discourage use. Therefore, it is essential that bus stops are designed to shield users from adverse conditions such as wind and rain and that they include seating areas (Shrestha et al., 2017; Wong et al., 2017). Visibility of incoming buses is also a significant design consideration. In Rome, a methodology was developed to assess the accessibility of bus stops, emphasizing the importance of weather protection, user-friendly information systems, and adequate infrastructure that corresponds to passenger demand (Corazza et al., 2017).

3.4 Traveler information system

Due to age-related limitations, many elderly individuals eventually cease driving, becoming increasingly reliant on public transportation (Whelan et al., 2006). As Goodwin and Lyons (2010) point out, elderly users rely on public transit more heavily than younger generations due to reduced driving and walking abilities. In this context, a reliable and accessible information system becomes essential. Information covering various operational aspects—such as schedules, routes, accessibility features, and fare structures—is crucial in empowering elderly users to navigate the system. Lack of access to such information remains one of the primary barriers for older adults (Hounsell et al., 2016). The rise of digital platforms poses further challenges, as many elderly individuals experience difficulties adapting to digital tools. In Beijing, Shi et al. (2020) analyzed smart card data to study travel patterns among the elderly, leading to policy suggestions that underscore the importance of information systems in understanding travel distance, duration, and frequency.

3.5 Accessibility to public transport facility

Various urban features—such as street lighting and traffic awareness—significantly influence elderly individuals' sense of safety and their ability to participate in social life (Gargiulo et al., 2018). Walking, a fundamental element of mobility, contributes to health and quality of life for many and is often the preferred mode of transport among elderly people. Enhancing walking paths is thus vital for promoting their greater integration into society. Alongside traditional methods for gathering, analyzing, and assessing data on walking behavior, new technologies such as GPS, GIS, and video-based techniques offer researchers more comprehensive data collection and analysis opportunities (Türken & Conticelli, 2024). Safety remains a serious concern, as elderly pedestrians are more susceptible to severe injuries, require longer recovery times, and may experience deeper psychological impacts than younger individuals in similar accidents (Shrestha et al., 2017). In Japan, new legal standards have reduced the slope of sidewalk ramps from 8% to 5%, and the curb height from 150 mm to 50 mm to improve pedestrian accessibility (Somenahalli et al., 2016). According to Mackett (2015), features such as more benches, public toilets, and improved street lighting can make walking more comfortable and appealing for elderly individuals.

3.6 Drivers' behavior

Many elderly passengers have reported that drivers often appear to be in a rush and fail to pay adequate attention to their specific needs. Some noted that vehicles frequently began moving before they were seated, while others mentioned that doors were closed too quickly, limiting safe boarding time. Therefore, road-based public transport operators must provide comprehensive training and guidance to drivers to raise awareness

about elderly passengers and to ensure safe, respectful driving behavior (Wong et al., 2017). In a study conducted in the United States, a joint training program involving interactive online modules—such as videos, presentations, quizzes, applications, and games—was developed as part of an EU Erasmus+ project and was identified by both trainers and drivers as a key tool for improving driver performance and motivation (Catenazzi et al., 2018). In addition, public transportation drivers should receive proper training in first aid and emergency response, which can be critical when transporting elderly passengers.

4. Turkey and NGOs' transportation policy perspective

In the population survey conducted by TURKSTAT, the population aged 65 and over—considered the elderly population—increased by 21.9% over the previous five years, reaching more than 7.5 million people in 2019. The proportion of elderly individuals in the total population rose from 8.0% in 2014 to 9.1% in 2019. The growth trends are illustrated in Fig.2, presenting projected elderly population through 2080.

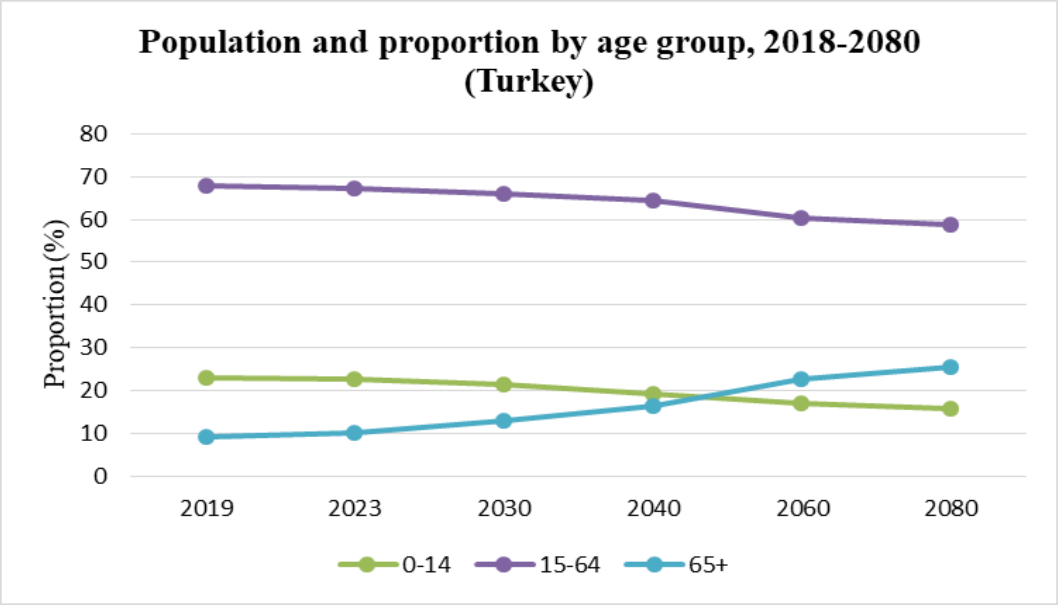


Fig.2 Population and proportion by age group, 2018-2080, Turkey

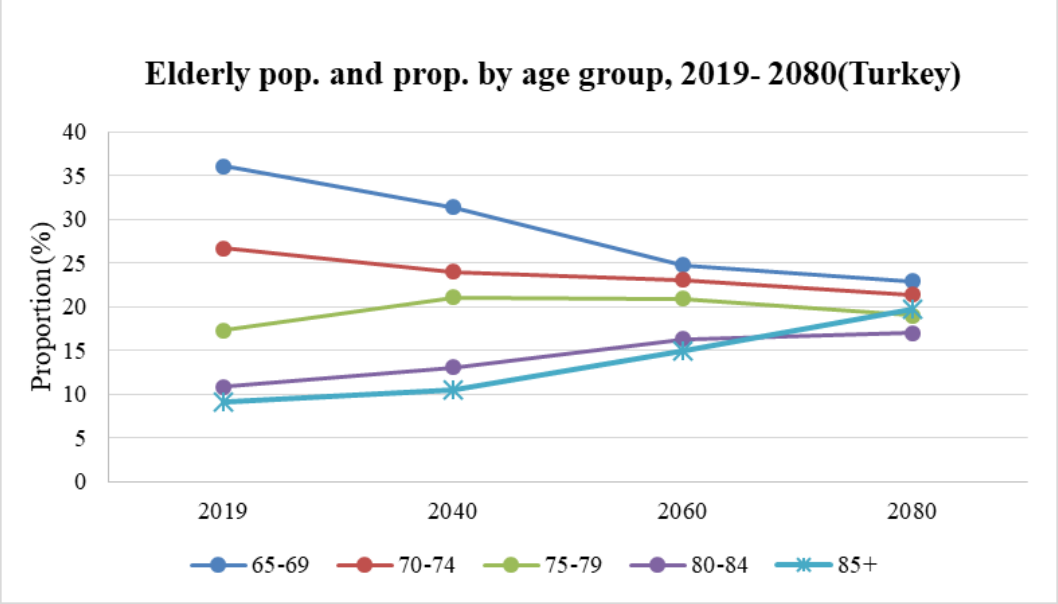


Fig.3 Elderly population and proportion by age group, 2019-2080, Turkey

In 2019, 62.8% were in the 65-74 age group, 28.2% were in the 75-84 age group, and 9.1% were in the age group of 85 and above. The population projections for elderly individuals and their age group proportions are shown in Fig.3.

4.1 Current national policies in Turkey

Considering the steady increase in the elderly population, policy recommendations and strategic planning for accessibility and mobility within national transportation systems have become increasingly critical. The travel behavior of elderly individuals largely depends on their residential environment, the geographical characteristics of the area, access to public transportation, cost of trips, and trip purposes (Goodwin & Lyons, 2010). Understanding the available public transport services, especially in terms of accessibility, is essential for elderly passengers (Hounsell et al., 2016). With regard to affordability, elderly individuals expect concessions such as discounted fares, simple and user-friendly ticketing systems, and transferable fare cards. Fare subsidies are widely used policy instruments to encourage public transportation usage among elderly populations. Such fare reductions are implemented at both national and local levels by governments and operators (Wong et al., 2017).

Vehicle accessibility

Low-floor public transport vehicles are used in many metropolitan municipalities — particularly in Istanbul — but this practice has not yet been adopted as a nationwide policy (Public Buses Operation Instructions, 2009). According to Articles 3 and 7 of Law No. 5379 on Persons with Disabilities (Official Gazette, 2014), all public and private transportation providers offering shuttle services are obligated to provide accessible transport services to persons with reduced mobility or students upon request, by the deadline of July 7, 2018. However, there is insufficient evidence confirming the full implementation of this regulation since 2012. Although priority seating for the elderly, individuals with disabilities, and pregnant women is a common practice nationwide, compliance is often weak, and such seats are frequently occupied by other passengers.

Fare policy

According to the "Free or Discounted Travel Cards Regulation," published in the Official Gazette on March 4, 2014 (No. 28931), Article 5 includes eligibility for elderly individuals, disabled persons and their companions, veterans, relatives of martyrs, and certain other groups. The Ministry of Transportation and Infrastructure (MTI) and the Ministry of Family and Social Policies (MFSP) are the two main authorities responsible for developing fare policies for elderly individuals and those with reduced mobility. Under the current policy framework, state-operated urban public transportation systems are free of charge for individuals aged 65 and over, while those aged 60–64 benefit from reduced fares. Additionally, these age groups are eligible for substantial discounts (often up to 50%) on rail, maritime, and intercity transportation services operated or supported by state institutions according to Free or Discounted Travel Cards Regulation (Official Gazette, 2014).

Bus stop design

According to the national guideline titled (Turkish Standards Institution, 2003) the design of bus stops plays a vital role in enabling safe and comfortable boarding and alighting for elderly and mobility-challenged individuals. Elevation differences between bus stops and sidewalks must be minimized to improve accessibility. Additionally, seating benches and grab bars must be placed appropriately, with consideration for wheelchair areas and protection from environmental factors. National design standards, such as TS 12576, provide guidance for minimizing barriers for persons with reduced mobility. However, these standards are

inconsistently applied due to infrastructure limitations such as narrow sidewalks, unauthorized curbside parking, and other physical barriers that hinder proper access to bus stops.

Traveler information system

Traveler information systems are currently implemented by local transport authorities and municipalities at varying levels of completeness. These systems include in-vehicle travel announcements, smart boards at stations and stops, as well as transportation information on websites and mobile applications (Turkish Standards Institution, 2003). However, challenges related to financial investment, technological capacity, and municipal size prevent standardization across the country. The Ministry of Transportation and Infrastructure (MTI) addressed this issue through the *National ITS Strategy Document and 2020–2023 Action Plan*, which aims to promote technology adoption and standardize traveler information systems by outlining the responsibilities of relevant stakeholders (Ministry of Transport and Infrastructure, 2020).

Accessibility to public transport facility

Sidewalks must be kept clear of physical obstacles to allow free movement for individuals with reduced mobility. Steep, narrow, angular, or uneven roads and pavements limit mobility and pose serious safety concerns. Pedestrian infrastructure must be designed with consistent elevation, smooth surfaces, and minimal gradient. Dangerous irregularities — such as drainage grids, extended parking chains, uneven paving, potholes, and sudden level differences — should be eliminated (Turkish Standards Institution, 2003). Despite the existence of national and local standards, many individuals with reduced mobility still face access challenges across Turkey. To ensure safe and unobstructed movement, sidewalks must offer adequate width, non-slippery surfaces, tactile routing, visual or audible warning elements, and clear headroom (Turkish Standards Institution, 2003).

Driver behavior

The *Urban Public Transport Bus Driver Level 3* national standard, published by the Turkish Confederation of Tradesmen and Craftsmen and announced in the Official Gazette on December 26, 2013 (No. 28863), outlines technical, behavioral, and attitudinal expectations for public transport drivers (National Occupational Standard, 2013). However, despite its comprehensive scope, implementation has been inconsistent, and the standard does not offer sufficient guidance regarding accessibility and mobility for elderly individuals. This lack of effective application is an important concern that policymakers must address in future policy revisions. In this regard, the establishment of the Accessibility Unit within the Ministry of Transportation and Infrastructure represents a promising step. The work and authority of this unit are crucial for enhancing transportation access and services for all individuals with reduced mobility, including elderly populations.

4.2 NGOs' perspective

Four prominent NGOs were contacted to gather insights on the state of public transportation with respect to elderly individuals. The interview questions were structured around the categories listed in Tab.2 and included open-ended questions to collect detailed views and suggestions from the participants.

Interview Categories
Increasing mobility as a result of the elderly people traveling less than other individuals
Deficiencies in public transportation due to the low frequency of using
Difficulties encountered on walking and pedestrian paths and infrastructural deficiencies

Deficiencies in public transportation in terms of social and psychological recovery
Transportation safety for elderly people
Driver behavior and training
Accessibility of bus stop
Five important policy suggestions for more accessible and mobile transportation
Current price policy consideration

Tab.2 Interview Categories Used in NGO Consultations on Elderly Accessibility and Mobility in Public Transportation

Vehicle accessibility

As the population ages, the need for accessible public transportation increases. However, NGOs emphasized several barriers that limit its usability for elderly individuals. The most common concerns included the insufficient use of low-floor vehicles and the frequent occupation of priority seating by other passengers. Additionally, NGOs pointed out the mismatch between sidewalk curb heights and the entrance steps of vehicles, making boarding difficult for elderly passengers.

Fare policy

NGOs expressed support for the current national fare policy, noting that free or reduced fares significantly enhance the daily mobility of elderly individuals. Increased mobility was credited with improving the physical and mental health of the elderly—particularly retirees who would otherwise remain at home. NGOs further suggested expanding these benefits to include intercity buses and air transport to better support the travel needs of elderly populations.

Bus stop design

It was reported that the integration between transport modes remains insufficient, particularly for elderly passengers. Long distances between transfer points were cited as a major issue. Additional concerns included inadequate infrastructure at stops — such as limited protection from weather conditions and insufficient seating capacity. NGOs recommended dedicated seating areas at bus stops for individuals with reduced mobility, similar to those found inside public transport vehicles.

Traveler information system

NGOs stressed the need to improve real-time information systems, ensure service continuity and frequency, and support trip planning from door to door. TURYAK, in particular, noted that current information—such as departure times and vehicle numbers—is often inadequate. NGOs emphasized the importance of installing electronic boards at bus stops that are both visible and easily readable for elderly passengers. They also underlined the need for mobile applications to be fully accessible. In large cities like Istanbul, providing large digital displays at modal transfer points—similar to those used in air travel—was recommended as a way to increase usability and confidence among elderly passengers.

Accessibility to public transport facility

While younger individuals may be able to navigate infrastructural deficiencies more easily, many elderly individuals experience significant difficulty and a sense of insecurity. NGOs considered this issue highly important. Specific concerns included excessive stair use and step heights exceeding 15 cm, lack of rest areas along walking routes, poor-quality sidewalk materials that cause tripping hazards, and slippery surfaces in wet

conditions. Proposed solutions included using non-slip materials, installing more urban furniture, and improving overall pavement design.

Driver Behavior

The effect of driver behaviors on elderly people, which in many ways can constitute a security problem, should be considered. Driving formats and vehicle placement techniques that cause drivers to pick up passengers without fully approaching the stations, opening and closing the doors quickly during boarding and alighting, and driving techniques that cause sudden acceleration and deceleration are among the main problems mentioned by NGOs. This situation considerably reduces the sense of trust experienced by elderly users within the transportation system. Transportation systems that are more accessible and mobile for elderly populations, encourages increased participation and integration into society. Encouragement of active aging, connection of other individuals, and dynamic and contemporary understanding of society are among the factors that will come as benefits of increased transportation accessibility and mobility.

5. Discussion and policy suggestions

Expectations of elderly populations for better and more accessible transportation were identified through a review of the literature and consultations with NGOs. These findings are presented under five main categories: vehicle design, fare policy, facility and sidewalk infrastructure, driver behavior and operations, and traveler information systems. Based on these evaluations, policy recommendations are provided for decision-makers to address the deficiencies identified in both the literature and stakeholder feedback.

5.1 In-vehicle accessibility

Vehicle accessibility is a common challenge for elderly individuals, both in terms of in-vehicle design features and ease of boarding and alighting. Although modern buses increasingly include features such as slip-resistant and low-glare flooring, low-floor (kneeling) platforms, and wheelchair ramps, these enhancements should be standardized across all public transport vehicles through comprehensive regulations and, where necessary, incentivized implementation.

In Turkey, vehicle accessibility is regulated by Law No. 5378, Article 50/Temporary Article 3, enacted in 2005, which states:

"Municipalities and metropolitan municipalities shall take the necessary measures to ensure that public transportation services offered or controlled by them are accessible to persons with disabilities. All public and private vehicles in operation must be made accessible within eight years from the effective date of this law." (Official Gazette, 2005).

Despite this legal framework, the definition and enforcement of "accessibility" remain ambiguous, particularly in vehicles not operated by municipalities—an issue most evident in small and mid-sized cities. NGO feedback highlighted the urgent need for low-floor and kneeling buses, especially in minibus services, which are often privately operated. Given that more than half of Turkey's public transportation fleet is managed by the private sector (including buses, minibuses, and paratransit vehicles), mid - and long-term policies — supported by enforcement mechanisms — are essential to ensure consistency and improve accessibility standards nationwide.

Another key concern raised by NGOs and supported in the literature (Wong et al., 2018) is the lack of enforcement regarding priority seating for elderly passengers. Public awareness campaigns should be launched to promote respectful seat use, and related educational materials should be disseminated through schools and public institutions. Additionally, in-vehicle visual aids — such as color-coded seats and stickers — should be

implemented not only on municipal buses but also across all modes of public transport, including privately operated services.

Interior design also plays a critical role in passenger safety. To reduce the risk of injury during sudden stops or turns, vehicles should be designed to minimize the severity of falls. This includes the careful placement and shaping of interior elements such as handrails, poles, and partitions, as illustrated in Fig.4.

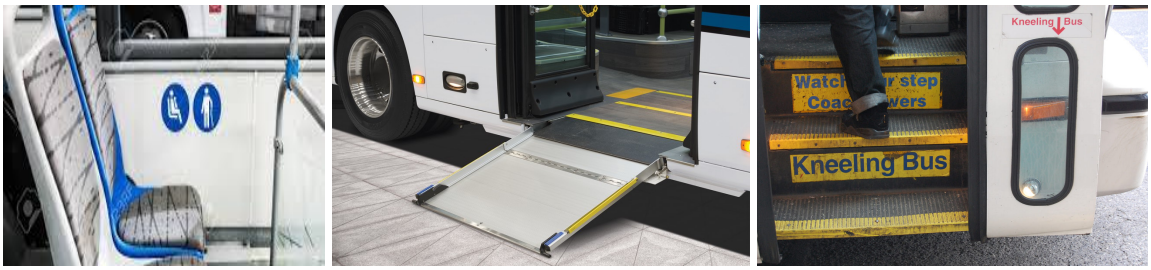


Fig.4 In-vehicle design and signage for elderly accessibility and fall prevention

5.2 Fare policy

Fare policies differ across countries, however, many provide free or discounted public transportation access for individuals over a certain age—commonly 65 and above, and in some cases, specifically for elderly women (Shrestha et al., 2017). Turkey's national policy is comparatively generous, offering free transportation for individuals aged 65+ and discounted fares for those aged 60–64 (Public Buses Operation Instructions, 2009). This policy was highly appreciated by the NGOs consulted in this study. However, NGOs also advocated for the expansion of fare concessions to include intercity bus services and domestic flights.

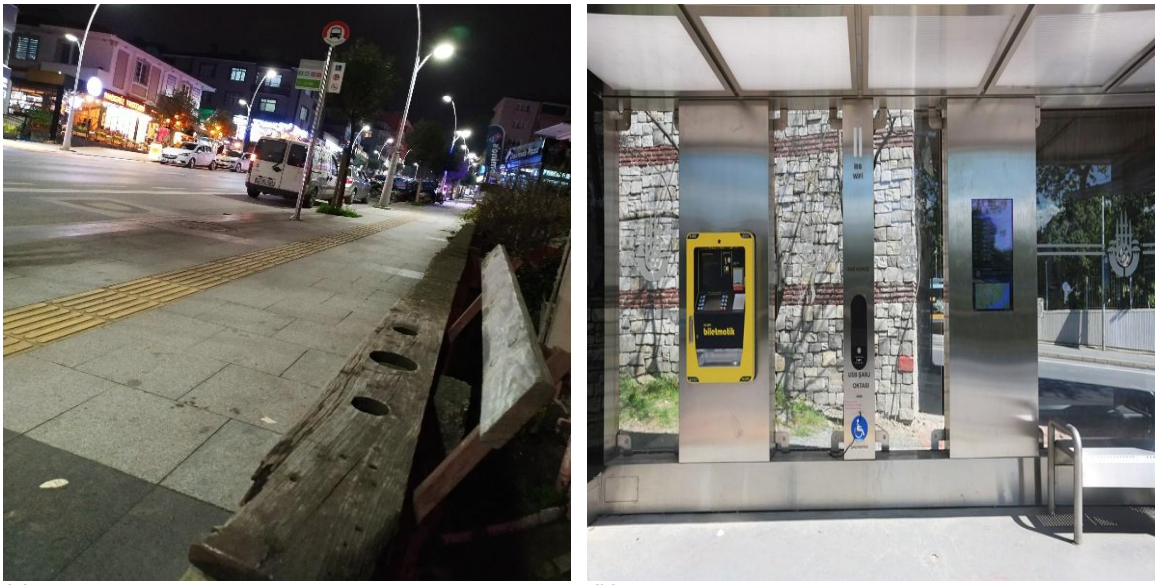
Higher usage rates of the public transportation by the elderly population raises the question of fare policy, specifically for the peak hours. The incentives provided to the elderly population should be managed in a way that does not constrain the use of public transportation by others. The most prominent solution was cited as limiting the free or discounted use during rush hours; however, it should also be noted that some of this 65+ age group may still be a part of the workforce and need to travel in these specific hours with commuters. Therefore, it is important that these individuals continue to receive this benefit.

5.3 Facility and sidewalks design policy

One of the most critical issues in public transportation infrastructure is the inadequate design of vehicle stops. Specifically, the lack of weather protection and insufficient seating at bus stops significantly contribute to elderly individuals' hesitation in using public transport (Wong et al., 2017). Pedestrian perception studies from developing countries also highlight how poor infrastructure and lack of pedestrian-friendly design exacerbate walkability barriers, especially for vulnerable groups such as the elderly (Ahsan et al., 2023). On the other hand, well-designed pedestrian infrastructure encourages active mobility and contribute to social sustainability (Rainieri et al., 2024). While not all stops are in poor condition (Fig.5), there is clear room for improvement. In contrast, urban rail stations, subways, and major transit hubs are generally satisfactory in terms of design, though issues related to crowding and limited seating can still make them less user-friendly for elderly passengers attempting to follow schedules or wait comfortably.

Improvement strategies can be grouped into two categories. First, physical upgrades to bus stops should include shelter from adverse weather, adequate and clearly designated seating for elderly users, improved visibility of approaching vehicles, and the use of clear markings and signage for seating priority and real-time or printed timetables. Second, enhancements to pedestrian access routes leading to vehicle stops should focus on uninterrupted, level sidewalks; standardized curb heights; and the use of non-slip, durable paving materials. Specific curb designs, such as Kassel-type curbs, can further facilitate safer and easier boarding and alighting for elderly passengers.

In suburban and peripheral areas—where public transport is less frequent and stop infrastructure is often neglected—traveler information becomes even more essential. While printed timetables and real-time digital boards are effective, reliance on mobile applications may not adequately serve elderly populations due to lower digital literacy rates. Therefore, information must also be presented clearly and accessibly at the stop itself.
NGOs also emphasized that service reliability plays a vital role in building trust among elderly users. Furthermore, during transfers between modes, the distance between connection points and the coordination of schedules are key factors influencing user decisions and perceived service quality.



(a) (b)

Fig.5 Bus stop example in Turkey: (a) poor condition (b) good condition

Public transportation accessibility for elderly individuals must consider the full journey chain, including walking to and from vehicle stops. Literature highlights the importance of pedestrian infrastructure, including adequate lighting (Gargiulo et al., 2018), consistent and low curb heights (Wong et al., 2017), and urban furniture such as benches and public toilets (Shrestha et al., 2017).
NGO feedback also raised concerns about inconsistent curb standards, even within the same neighborhood, which creates physical barriers for elderly users. Standardizing curb heights and ramp slopes—along with implementing traffic-calming measures at pedestrian crossings—would enable safer mobility for all, as illustrated in Fig.6.

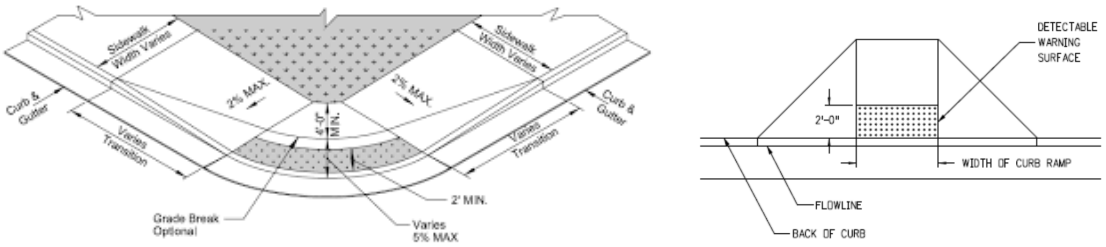


Fig.6 Examples of proper curb design

Additional concerns include sidewalk paving materials becoming slippery in poor weather, broken or uneven surfaces, and various physical obstacles. The design of sidewalks, walkways, and curbs has long been debated among urban design authorities in Turkey.
NGOs and civil society organizations should advocate for stricter implementation of national standards and push local governments to improve pedestrian infrastructure, especially during winter and rainy seasons.

Particular attention should be paid to ensuring that intermodal transfer surfaces are slip-resistant and elderly-friendly.

5.4 Driver behavior policy

Driver behavior is one of the most frequently cited concerns in both the literature and NGO feedback regarding elderly users' public transportation experiences (Mackett, 2015). Elderly passengers are particularly vulnerable to unsafe driving practices such as sudden acceleration and deceleration, which may result in falls or injuries. Failure to properly position the vehicle close to the stop, premature door opening or closing, and a general lack of attentiveness during boarding and alighting further complicate travel for elderly individuals. In many instances, drivers often fail to wait for all passengers to be safely seated before moving the vehicle, significantly increasing the risk of accidents. These issues are often attributed to the pressure placed on drivers to adhere strictly to time schedules, leading them to rush through passenger boarding and overlook critical safety considerations (Svärd, 2017).

To address these challenges, driver behavior should be continuously monitored, and regular theoretical and practical training programs should be implemented. Such training may include driving technique refinement, effective communication strategies, and psychotechnical assessments. In addition, transportation operations should be reviewed to reduce schedule pressure, thereby allowing drivers sufficient time to support safe boarding and alighting for all passengers—particularly elderly individuals. Lastly, roadway design and curb access must be improved to enable vehicles to stop safely and closely to boarding areas. Proper parking regulations and stop geometry should be enforced to support consistent and secure boarding conditions for elderly users, contributing to safer and more inclusive public transportation systems.

5.5 Traveler information system

Providing accessible and reliable travel information is essential for enabling elderly individuals to confidently use public transportation systems. As aging populations often experience challenges with rapidly changing technologies and digital tools, well-designed traveler information systems can help bridge the gap between service availability and actual usability (Hounsell et al., 2016). Real-time travel information — such as arrival times, route changes, and service disruptions — should be made available through multiple channels, including mobile applications, audible announcements, and digital displays at stations and stops. In international contexts, countries like the UK and Japan have implemented inclusive information systems that incorporate large-font digital displays, tactile interfaces, and multilingual options to accommodate elderly users (Wong et al., 2017; Lin & Cui, 2021). In contrast, Turkey's deployment of such systems remains uneven and limited to larger metropolitan areas. In many mid-sized cities and rural regions, the absence of real-time information at bus stops or the lack of user-friendly mobile platforms significantly impairs the travel experience of elderly passengers (Bozdağ et al., 2017). To enhance accessibility, Turkey can adopt policies that mandate standardized digital signage at transport hubs, simplify mobile application interfaces, and offer digital literacy support programs tailored for older adults. Additionally, audible announcements on vehicle arrival times and route changes can further improve confidence and independence among elderly travelers. The integration of traveler information systems must be accompanied by user-oriented design principles and inclusive technological infrastructure to ensure that elderly populations can plan their journeys effectively and safely.

5.6 Comparison of national policies with international practices

While the international literature offers a wide spectrum of best practices on accessibility for the elderly, Turkey's policy landscape shows only partial alignment with these models. For instance, Japan and the UK have implemented cohesive frameworks that integrate infrastructure, service design, and passenger support with the specific needs of elderly populations in mind (Wong et al., 2017; Lin & Cui, 2021). In contrast, Turkey's

approach has been more fragmented, with limited enforcement and regionally inconsistent applications, as observed in fare concessions and vehicle accessibility (Bozdağ et al., 2017). This gap between global benchmarks and national implementation suggests a need for more robust and centralized policy enforcement in Turkey. Moreover, while both Japan and the UK have institutionalized inclusive design principles—ranging from tactile guidance and step-free access to driver behavior training—Turkey's regulatory framework tends to focus more on compliance rather than proactive inclusivity (Bozdağ et al., 2017; Szeto et al., 2017). For example, despite the presence of relevant regulations such as Law No. 5378 in Turkey, practical adoption remains limited, particularly among privately operated vehicles. In contrast, the UK's Equality Act has not only shaped vehicle and infrastructure design but also mandated continuous monitoring and staff education, ensuring sustained attention to elderly users' needs (Wong et al., 2018). These contrasts highlight the opportunity for Turkey to translate its formal policy intentions into concrete and enforceable practices aligned with proven international models.

6. Conclusion

Transportation in Turkey plays a crucial role in reducing physical, psychological, and social disadvantages; and has become an essential component of daily life for elderly individuals. It supports their societal participation, fulfills their mobility needs, and facilitates access to vital services. However, in light of the growing elderly population, increasing urban density, and evolving lifestyle demands, current public transportation systems remain inadequately designed to meet the needs of individuals with physical and mobility-related challenges, including older adults. Despite certain improvements, significant progress is still required to enhance the accessibility of public transportation systems and infrastructure for disadvantaged populations.

This study provided a comprehensive evaluation of national and international policies and practices concerning public transportation accessibility for elderly populations. In addition to literature-based insights, interviews conducted with leaders of four major NGOs helped identify key challenges faced by elderly individuals in Turkey. The findings revealed that bus stop conditions, infrastructural deficiencies, and driver behavior are among the most pressing issues. Simple yet effective solutions—such as improved shelter design and seating at stops—were identified as practical and cost-efficient interventions. Furthermore, it is recommended that transportation authorities and municipalities establish regular in-service training programs for drivers and staff, in collaboration with relevant institutions. These programs should focus on communication skills, vehicle positioning, passenger safety, first aid, and emergency response.Although accessibility features such as low-floor platforms and user-friendly vehicle interiors have become more common in municipality-owned buses, these improvements are not consistently adopted by privately operated vehicles, including minibuses and paratransit services. Enforcement of existing accessibility regulations, along with gradual retrofitting of older vehicles, should be prioritized through coordinated efforts involving relevant stakeholders.

The introduction of free fare policies for individuals aged 65 and over, and discounted fares for those aged 60–64, has been well received by elderly passengers. However, there is a growing need to extend these policies to intercity transportation services, including rail and air travel. Another major concern is the accessibility of traveler information. Many elderly individuals face difficulties due to digital illiteracy, making the availability of printed or real-time information at transit stops particularly important for ensuring independent travel.

Finally, improvements to the physical infrastructure—such as standardized curb heights, the repair of broken sidewalks, installation of adequate lighting, and use of non-slip materials—are essential for increasing the walkability and overall accessibility of public transportation in both urban districts and residential neighborhoods. These enhancements would significantly support the mobility, independence, and well-being of elderly populations.

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Fig.4: Elaboration by authors;

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The role of renewable energies in landscape transformation. Methodological proposal and application to the Valdagno case study

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Abstract
Energy has consistently exerted a profound impact on the landscape and human settlements, and it continues to serve as a pivotal force in the formation of our environment. The current era is characterised by an energy transition, driven by an increasing necessity to transition from fossil fuels to renewable energy sources. In evaluating the adoption of these new energy sources in a specific area, it is essential to consider not only the technical aspects but also the landscape and social factors. This paper examines the significance of harmonising energy requirements with landscape conservation, emphasising the imperative for strategic and methodological approaches to integrating renewable energies into landscape and social contexts. The main renewable energy sources are reviewed, their impacts analyzed, and recommendations for better integration into the context are identified. The objective is to propose an analytical methodology that ensures a balance between energy efficiency and landscape conservation, thereby fostering careful design and conscious integration in order to minimise visual and environmental impacts while contributing to energy sustainability. The methodology is then applied to the case study of the Municipality of Valdagno in Italy.

Keywords
Renewable sources; Landscape; Valdagno

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1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) and the subsequent Kyoto Protocol, adopted in 1997, marked the beginning of a shift in global awareness towards the urgent need to address climate change. This has led to the development of national and supranational energy policies, which have become a central aspect of strategies to tackle this global challenge. These policies are officially guided by a number of objectives, including security of energy supply, environmental concerns, the development of export technologies, and rural development. This has resulted in a significant increase in the use of renewable energy, with state support in most developed and many developing countries (Nadai & van der Horst, 2010). This new policy responds to our continuous dependence on electricity and its continuous increase in demand, which has led to a deterioration in the environment, increasing global warming, the production of radioactive waste, deforestation, and so on. The initial focus was on the development of more efficient technologies that could be used in conjunction with fossil fuels, rather than on a complete transition to renewable energies (Pasqualetti, 2011).

In his book (Brown, 2015), Lester Brown advocates for the "solar revolution" through the use of photovoltaics and solar thermal energy, presents the "wind age" with wind power, and discusses the potential for harnessing the Earth's heat with geothermal energy. These arguments highlight the growing recognition of the necessity for renewable energy sources (Schiermeier et al., 2008; Balletto et al., 2023). On a global scale, the proportion of electricity generated from renewable sources reached and exceeded 30% this year, largely due to an increase in solar and wind power (Wiatros-Motyka et al., 2024). At the European level, the figure is in excess of 40%, with prospects for continued improvement as electricity production becomes increasingly environmentally friendly on an annual basis. The objective is to achieve climate neutrality by 2050 (Consiglio dell'Unione europea, 2024).

The potential benefits of utilising renewable energy sources in lieu of fossil fuels include a reduction in external energy dependency, local availability, sustainability with low or no emissions, and a diminished environmental impact for electricity production and processing. Additionally, renewable energy sources do not require cooling water, which is a significant advantage over nuclear power. Furthermore, the deployment of renewable energy sources can stimulate local or regional manufacturing industries, promote regional engineering and consulting services specialising in the use of renewables, and boost research and development. This can, in turn, lead to an increase in the level of services available to rural populations, the creation of jobs, and other economic benefits (Miguez et al., 2006; Hepbasli, 2008).

Conversely, the advent of these novel sources can give rise to a number of challenges, such as:

- Technical, pertaining to temporal and spatial variability, which, in contrast to fossil sources, introduce complexity into the energy system and raise questions about the stability of an energy network. The presence or absence of sunny days, constant wind or water, for example, complicates the need for continuous energy production. Evidence of this can be observed in the production graphs of renewable energy plants, which demonstrate significant variations even within the same day. This necessitates the implementation of effective balancing mechanisms and meticulous planning strategies that take into account the spatial and temporal dynamics of each energy carrier, specifically the alignment between the sources' production capabilities and the prevailing demand. A preliminary, albeit restricted, practical response to this issue is underway, manifesting in the implementation of novel demand-response mechanisms. These mechanisms adapt energy consumption patterns in accordance with the fluctuations in supply, with the objective of optimising energy utilisation and mitigating peak loads (Guida, 2023). A notable illustration of this approach is evidenced in the utilisation of such systems within renewable energy communities (RECs), which are founded on the principle of maximising the utilisation and sharing of energy produced within the community itself. A similar approach is employed by Positive Energy

Districts (PEDs), wherein the primary objective is to achieve a net energy surplus within the district beyond the level of internal consumption (Gaglione, 2023; Volpatti et al., 2024);

- Territorial, with a low density due to both geographic variations and energy supply and demand (Blaschke et al., 2013); additionally, they typically have a considerably lower production capacity per unit area than fossil fuel plants, necessitating significantly larger spaces (Magoni, 2013);
- Landscape, with the increasing debate over the placement of renewable energy facilities in visually sensitive landscapes. Such areas may be of significant national importance due to their qualities, as exemplified by national parks. Alternatively, they may be of local importance, generating resistance to significant changes to their character, such as rural or historical environments in close proximity to human settlements. Furthermore, the accelerated pace of energy development presents an unprecedented potential for environmental change (Apostol et al., 2017).

The latter issue is linked to the concept of landscape, which does not simply refer to the contest, but to the world as perceived by people. This perception creates connections between people, between people and places, and between society and its environment (Forman, 1995; Naveh, 2000). The importance of local identity, collective perception and historical memory in relation to the landscape underscores the fact that it is also a reflection of everyday practices and the emotional bond that people form with their territory. The concept of landscape is not static; rather, it is a dynamic and evolving phenomenon that is shaped by a multitude of factors, including technological, economic, cultural, and social developments (Romani, 1994).

At the European and Italian levels, the concept of landscape is defined in the Treaty of the European Landscape Convention, held in Florence in 2000, and adopted as law in Italy in 2006. In this document, landscape is defined as a certain part of the territory, as perceived by populations, whose character derives from the action of natural and human factors and their interrelationships (Council of Europe Landscape Convention, 2000). Landscape is a powerful, diverse and dynamic cultural heritage, a resource for humanity. It is an integral part of our culture, comparable to other forms of cultural expression such as literature, art and language. If the environment is the inevitable physical aspect of our existence, then the landscape, whether urban or rural, provides the concept of 'place' that is linked to community. Furthermore, it has the capacity to transform perceptions of the world through psychological boundaries, lifestyles and identities (Blaschke et al., 2013).

Energy has the potential to influence the landscape in a number of ways. Firstly, it can be observed directly through the presence of artefacts, installations and related activities. Secondly, it can be perceived indirectly through the characteristics of human settlements, which in cold climates are characterised by compact and enclosed buildings, while in warmer territories they are more open to the elements. Thirdly, energy can be considered as an inherent component of the landscape, whether embedded in the construction of artefacts or in the natural environment itself (Magoni, 2013).

The preservation of landscape resources with respect to new renewables may present a number of challenges, including:

- The potential impact of large-scale energy production systems (e.g. wind or concentrated solar power systems) on the landscape;
- The risk of damaging the visual quality of the seascape near the coast, where the lack of topography, vegetation or other mitigating visual factors could result in significant negative effects on the landscape;
- The dynamic visual qualities of renewable energy. The rotation of the blades, the switching on and off of lights, the movement of wave buoys, and the changing intensity and direction of solar glare as the sun crosses the sky all present challenges to the conventional approaches to visualising and measuring impacts, including technology simulation;
- The lack of meaningful mitigation measures, which are sometimes very complex or expensive to implement;

- The difficulty of finding relevant energy's landscape perception studies, such as visual preference assessment surveys and the extent to which people judge renewable energy through, instead, their energy policy biases (clean = good, global warming = hoax);
- The absence of an integrated policy framework;
- The visual impact of the night sky, such as that caused by wind turbines and solar towers, must be considered. These structures are often lit day and night to assist pilots in avoiding potential collisions. The prevalence of dark, starry skies in remote locations, including deserts and previously undeveloped grasslands, is at risk of being compromised by the proliferation of thousands of flashing lights that can be seen from afar. This represents a novel challenge in the field of scenic resource management, with the assessment of impacts on night skies representing a particularly difficult task (Apostol et al., 2017).

In addition, the issue of landscape is, above all, a social issue. Indeed, the utilisation of renewable energy sources serves to illustrate that our energy is derived from a specific source, thereby raising awareness of the impacts and consequences of our energy demand. This, in turn, gives rise to a recomposition of the socio-technical links between landscape and energy. However, it also gives rise to various protests against their application, as people expect 'permanence' in their landscapes. This belief has developed in conjunction with an understanding of the slow workings of nature since the time of the first humans. As a consequence of the increasing distance between humans and the environment, the advent of technology and the development of urban living, there has been a growing insulation from the direct environmental costs of energy. This has led to a corresponding reduction in awareness and tolerance of the encroachment of energy development on personal space. Indeed, on a perceptual level, the less overt the technological landscape, the more likely it is to be appreciated by the general public (Thayer, 1993). It would appear that the general public is in favour of not being aware of the sources of the energy they use, thereby avoiding any sense of responsibility for the source of their energy. This perception is abruptly challenged when there is a sudden and fundamental change in the landscape (Pasqualetti, 2011).

In light of the energy challenges that we are currently facing and will continue to face in the future, it is imperative that we reassess the concept of the energy landscape. This is also necessary because the landscape cannot be preserved in its current state, regardless of whether or not it is transformed by renewables. Indeed, if the demand for electricity is not curtailed, and if climate change is not adequately addressed, even remote wilderness areas will be transformed into unrecognisable environments. Many forests will be stressed due to plant diseases that will spread, and fires will increase in size and intensity. Additionally, glaciers will continue to shrink, and rivers may dry up. Indeed, failure to pursue this energy revolution could result in one or more of the following scenarios: a greater reliance on nuclear energy, increased use of "clean coal," a more rapid growth in greenhouse gas emissions, greater dependence on imported energy, greater pressure for mandatory restrictions on consumption, and/or a more significant shift towards environmentally burdensome resources such as oil shale and tar sands (Pasqualetti & Schwartz, 2011).

In order to surmount the technical, territorial and landscape difficulties associated with the introduction of renewable energy sources, which have just been outlined and are usually assessed individually in the literature, it is therefore necessary to prepare an interdisciplinary model of integrated analysis to be made available to the decision-maker or planner. This model will allow the advantages and disadvantages of the technology to be correlated and assessed. To this end, this contribution examines the intimate connection between landscape and energy, tracing its evolution and examining the various renewable energy sources currently in use. Subsequently, the points that require attention for more effective integration of these new sources within each landscape context are identified, and a territorial analysis methodology is proposed for assessing both the technical issues and the landscape, spatial, social, geographical and historical aspects of energy. The objective of this analysis is to propose a methodology that could be adopted by public administrations or technicians when dealing with the installation of large-scale renewable energy sources. This methodology would guarantee

a balance between the energy transition that is now necessary and the preservation of the landscape, favouring an integrated design. In conclusion, the case study of the Municipality of Valdagno is presented, together with an evaluation of the strengths and potential improvements to its urban and energy plans, in accordance with the methodology previously outlined.

1.2 The interconnection between the landscape and energy

Energy has consistently influenced the configuration of our landscape. The historical trajectory of human settlement appears to be shaped by the dynamic interplay between energy demand and the fluctuating availability of energy sources. In the early stages of European history, wood was the primary fuel source, resulting in immediate and localised environmental consequences. Pollution from the burning of wood enveloped cities, and the forests that once defined landscapes were cut down at a faster rate than they could be replenished, leading to the replacement of forests with grasslands. As ever more extensive areas of forest were felled, the urgency of identifying alternative fuels intensified.

This resulted in a shift towards coal, which gave rise to significant alterations in the spatial configuration of energy impacts. There was a transition from a relatively uniform and dispersed utilisation of wood to a concentrated and intensified use of coal, which was employed in a limited number of locations.

This constituted a shift from a centuries-old pattern, resulting from the transition from low-value and widely available resources such as wood to a more spatially concentrated resource like coal. A further shift occurred with the advent of oil in the early decades of the 20th century, which was more readily and economically transported over longer distances. In the final third of the 20th century, uranium became a significant source of electricity generation. However, declining reserves and the emergence of hitherto unidentified and insidious risks prompted a decline in interest in this form of energy production. In the present era, with population growth and the transition to renewable energy sources, the discrepancies between supply and demand are once again diminishing. Additionally, a novel phenomenon is emerging: while the consequences of coal, such as air pollution and mercury deposition, are often imperceptible and confined to specific regions, those of renewable energy are conspicuous and localised, reminiscent of the impacts of wood utilisation in the past. From a spatial perspective, we are witnessing a clear return to historical practices.

In general, energy is not a directly visible element. However, it is capable of generating visible structures in the territory due to the ways in which it is produced (Pasqualetti, 2011) The various energy infrastructures are material and visible elements within the space. However, since the landscape is the set of technical, cultural, economic, social and political elements that have given rise to a given morphology of the territory, they also generate immaterial and not directly observable elements. This is in addition to the numerous 'physical' factors that contribute to the determination of the landscape's energy needs and consumption, including the shape and size, the density and dispersion of residents, climatic conditions, the type of building, and the way these factors are managed. Indeed, it has been demonstrated that urban density, building orientation, and the finishing materials of facades and ground surfaces can enhance solar energy production (Lobaccaro et al., 2017).

It can thus be proposed that if each morphological element is in fact associated with a set of invisible, relational elements, which are expressed by the term 'territoriality', then the energy landscape can also be defined as a set of visible morphological elements and invisible relations. These relations are intangible and not directly perceivable, yet they produce the landscape.

A detailed examination of the development of renewable energy sources from a landscape perspective reveals the following impacts:

- Geothermal energy: this source has a significant landscape impact, as it must be developed close to the resource, regardless of topography or land use. Every stage of the process, from exploration to the drilling of wells (which can lead to the emission of unpleasant odours), from construction to the operation

of the power plant and the re-injection of fluids, takes place at the site where the resource is available. At each stage, the activity must adapt to the existing landscape, whether flat or mountainous. Furthermore, geothermal resources have a lower energy density than other fuels, which means that larger areas must be disturbed to produce equivalent amounts of electricity. Taken together, these characteristics result in a relatively large, unavoidable and permanent landscape footprint;

- Wind turbines: the visual impact of turbines is evident due to their physical presence, warning lights and the movement of the blades (Fistola et al., 2023). Such structures have the potential to generate noise and pose a threat to avifauna. However, from an environmental standpoint, they require no cooling water, produce no emissions, are easily assembled and disassembled, and can be rapidly installed in a multitude of locations. Despite the numerous advantages and growing popularity of wind energy, it continues to encounter social difficulties. These difficulties can be divided into two main categories: general barriers, such as the obvious and unavoidable presence of turbines in the landscape, and site-specific barriers. The latter vary according to local natural and cultural sensitivities, but the greatest concern remains the visual disruption that turbines create in the landscape (Pasqualetti et al., 2002);
- Solar: the installation of these plants can alter both the natural and man-made environment. In the former case, the utilisation of extensive land for energy production represents a significant concern, with the potential for adverse impacts on local fauna and flora. Nevertheless, this technology is lauded for its capacity to furnish clean and limitless energy, with no greenhouse gas emissions or long-term waste production, no necessity for cooling water and no noise;
- Hydroelectricity: this is one of the oldest and most widespread renewable sources globally, although production has declined in recent years due to major droughts (International Energy Agency - IEA, 2023). This source has a minimal environmental impact and high efficiency and can also be employed as a storage system for photovoltaic energy production through pumped storage plants. From a landscape perspective, the incorporation of hydropower infrastructure can both alter and intensify existing landscape features, thereby revealing their original character (Selvafolta, 1998). This process can also create new scenarios. However, the process of landscape and hydroelectric infrastructure heritability, to which new cultural values are attributed, should also be considered, as evidenced by the increasing tourist flow (Fontana, 1998);
- Biomass: this source requires a considerable amount of space for energy production. However, it is capable of functioning in environments where other renewable sources are less effective due to its resilience to the topography of the land (the presence or absence of shade or low solar factors) and weather conditions (the presence of wind or sun). However, in contrast to other renewable energy sources, the combustion of biomass releases gases and dust into the atmosphere, contributing to the pollution of the environment.

A synopsis of the aforementioned information can be found in Tab.1, which permits a comparison of the assorted renewable energy sources in relation to the disparate issues discussed. The diagram enables a comparison of the specific advantages, disadvantages and impacts of each energy source.

Preserving the landscape does not imply opposing renewable energy or hindering its development by exaggerating its visual impact. Conversely, it is foundamental:

- Optimise technologies to enhance their efficiency, potency, aerodynamics, minimalism, security and dependability;
- Evaluate energy integration in landscapes in order to gain insight into the interrelationship between energy and its sources with the territory. This can be achieved by conducting research on existing themes that link energy and landscape, as well as through an analysis of the symbolic perception of installed technologies;

- Identify and protect the most significant landscapes, taking into account not only their boundaries but also the areas of visibility or visual influence. In essence, it is of paramount importance to determine suitable and unsuitable locations for renewable energy development, promoting construction only in suitable areas and utilising design and mitigation measures to reduce visual impacts wherever facilities are located;
- Reduce visual impact by designing them in a way that better integrates them with their surroundings. This can be achieved by limiting the number of installations in a given area or by adapting aesthetic expectations to accommodate renewable energy as a new cultural feature (Selman, 2010; Sheppard, 2012);
- Integrate systems into individual landscapes with due consideration of the relevant factors, including scale, design symmetry, road construction, site preparation and equipment maintenance (Nielsen, 1996);
- Raise awareness of the impact of modern conveniences and lifestyles, making them aware of the associated costs, which should not be hidden or ignored. Social barriers, which are often underestimated, can impede or even obstruct the implementation of projects (Pasqualetti, 2011);
- Develop non-standardised plans, adapted to the local specificities of the energy transition, and that the needs and social conflicts encountered be taken into account (Koelman et al., 2018).

Source	Efficiency	Continuity	Clean Energy	Landscape	Other elements
Geothermal	10-20%			need for large areas	need proximity between producer and consumer
Wind	35%	depends on the winds		evident landscape change	noise and danger to birds
Solar	15-30%	depends on the sun		especially for possible developments on land	
Hydroelectric	70-90%	depends on the flow and availability of water		creation of new landscapes	usable as a photovoltaic battery
Biomass	20-35%		gas and dust emissions	need for large areas	

Tab.1 schematisation of technical and landscape information related to renewable energy sources. The efficiency was derived from the literature (Blaschke et al., 2013)

2. Methodological proposal

In order to address the spatial, social, geographical and historical aspects of energy in a balanced and integrated manner, it is necessary to identify a tool that can assess these elements jointly (Castiglioni et al., 2015). The objective of this tool is to explore the spatial dimension of energy, thereby making it visible and aware of its fundamental role for the city and the territory. Furthermore, in light of the multitude of conflicts that define the contemporary energy transition, it is imperative that spatial and landscape awareness be promoted in energy policies, thereby rendering them more effective and inclusive, and compelling them to consider spatial, temporal, and social aspects that are frequently overlooked (Nadai & van der Horst, 2010).
In order to achieve this objective, Nadai and van der Horst (Nadai & van der Horst, 2010) put forth two parallel lines of research: a reading of energy through the landscape, with the aim of making energy projects more sensitive to the needs of the landscape itself; and a reading of the landscape through energy, with the goal of understanding the relationship between energy and the landscape. This approach enables the landscape to "speak", elucidating how interactions with energy have influenced its evolution over time. It also emphasises the ways in which the relationship between society and energy has manifested itself even in apparently unrelated elements, such as the shape of settlements, agricultural structures, agronomic dynamics, road or tourist infrastructures and vegetative dynamics. From a social perspective, this novel approach to planning

can facilitate discourse on the future of the territory and act as a conduit between society and the energy transition, addressing the intricate challenges it presents. In this context, the term 'landscape' should be understood not merely as a means of simplifying technical knowledge, but rather as a key element in the reinvention of the territory. This transformation should be such that the landscape is no longer perceived as a mere obstacle to the energy transition, but rather as a tool to facilitate the democratic territorialisation of the territory in question (Castiglioni et al., 2015). It is therefore imperative to consider both the technical aspects and the perception of risk, interference with established lifestyles, altered landscapes and the potential violation of new projects on the local sense of fairness and injustice. In this context, it is necessary to re-evaluate project evaluation processes, with a particular focus on social considerations and the integration of social factors. Early and thorough engagement in understanding the human landscape and the people involved is essential for them to perceive and receive significant benefits from proposed projects for the landscapes they value (Pasqualetti, 2011)

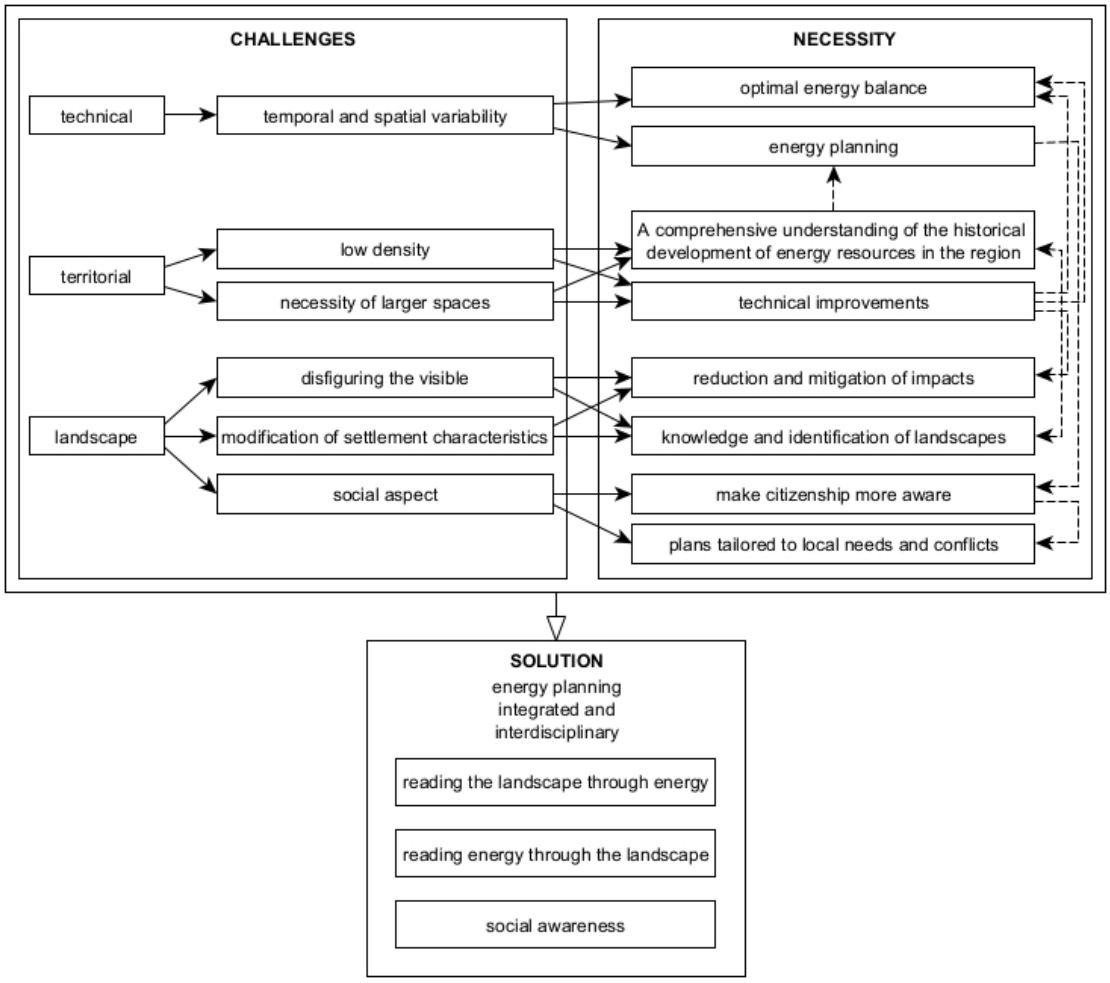

Fig.1 The proposed methodology, divided into potential disadvantages, identifying necessary requirements and suggesting solutions to address. The continuous arrows indicate direct relationships between the three themes, whereas the dashed arrows represent indirect and internal relationships between the needs alone

In terms of scale, the energy transition should be preceded by strategic spatial planning. While landscape transformations are primarily perceived at the local level, they reflect socio-spatial evolutions involving significantly larger spatial dimensions. This is exemplified by the typical relations between mountains and plains in the context of hydropower. Such transformations can thus also be analysed at a higher scale (Castiglioni et al., 2015).

In conclusion, a methodology is proposed (Fig.1) that aims to resolve, at least in part, the issue of the link between landscape and energy. This is to be achieved through the systematic integration of the aforementioned elements. Commencing with the enumeration of the various disadvantages associated with the utilisation of renewable energy sources, as outlined in the introduction, the technological, territorial and landscape requirements, as articulated in the preceding paragraph and derived from extant literature, are catalogued and correlated. These requirements can be addressed through integrated and interdisciplinary energy planning, which is not distinct from other plans, but becomes an integral and indispensable component of them. The proposed planning will be carried out through the following readings of landscape through energy, energy through landscape and social awareness, which have just been defined.

The limitations of this methodology are contingent upon the availability and quality of the documentation pertaining to the territorial analysis, both in terms of landscape and energy. In particular, the lack or incompleteness of tools such as Land Use Plans or updated Intervention Plans, which identify areas of special interest, can constitute a significant obstacle. Furthermore, the absence of a comprehensive energy balance or delineated actions within the Sustainable Energy (and Climate) Action Plan may impede the capacity to conduct a comprehensive and precise analysis.

Once the proposed method has been applied, it will be possible to obtain comprehensive energy and territorial considerations capable of assessing, for each specific territory, the relative merits and shortcomings associated with new installations of renewable sources. This approach will facilitate the integration of the gathered information with the technical, territorial and landscape issues encountered. In order to achieve this, the diagram in Fig.2 is proposed, which relates the technical information presented in the previous paragraph with the main drawbacks usually associated with each renewable source.

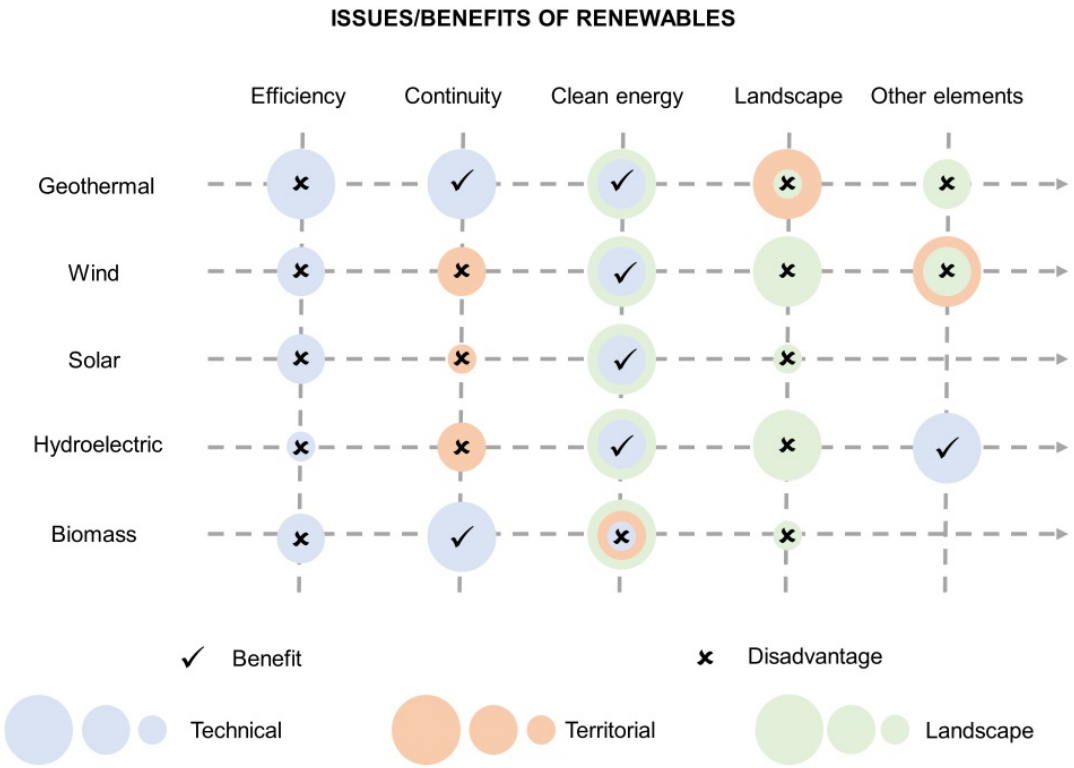

Fig.2 The system of technical and landscape information on renewable energy sources in Tab.1 in relation to the benefits (✓) or disadvantages (✕) identified in the introduction. The technical aspects are indicated by blue circles, the territorial aspects by orange circles, and the landscape aspects by green circles. The dimensions of the coloured circles indicate the degree of significance of the disadvantage or benefit in question

The proposed methodology is employed for the analysis of the current situation in the Municipality of Valdagno, which serves as a case study in this paper. In this manner, it will be feasible to observe how the application

of the method will result in the alteration of the relative merits and demerits of individual source technologies within a specified geographical area, thereby furnishing the decision-maker with a more comprehensive perspective on the potential transition scenarios. Indeed, this approach allows for a comprehensive examination of the municipality's particular energy and territorial characteristics, evaluating the impact of renewable energy installations and identifying potential solutions to reconcile energy needs with the preservation of the landscape and local social dynamics.

3. The Valdagno case study

The municipality of Valdagno, situated within the province of Vicenza, encompasses an area of approximately 50 km², exhibiting a considerable altimetrical variability. The altitude of the municipality ranges from 214 to 1,340 metres above sea level. The territory is encircled by a distinctive natural amphitheatre, delineated by the Lessini Mountains on one side and the Little Dolomites on the other. The principal settlement is situated in the valley, while the surrounding slopes and hillsides are home to a number of rural agglomerations with a predominantly agricultural character. The naturalistic context of Valdagno is characterised by a rich and diverse array of habitats, with woodlands occupying the pre-alpine belt and alternating with cultivable land and pastures in the hilly areas. The valley bottom is where human activity is most evident, due to the abundance of water resources in this area.

Valdagno represents a significant case study in urban planning, exemplifying the concept of a 'social city' in Italy, which was developed between the 19th and 20th centuries. The driving force behind this development was the Manifattura Lane Gaetano Marzotto & Figli, Italy's largest wool company, which had already become a leader in the sector by the 1930s. This was achieved through the exploitation of hydraulic power for textile production. The company was established in 1836 and rapidly established itself on the international market, distinguishing itself in the production of combed yarns and fabrics for men (Roverato, 1983). The area was selected for its proximity to waterways, which were crucial for both transport and production; the availability of local raw materials; and the presence of established manufacturing activities and expertise. The planner in charge was able to exert control over the urban scale, from the quality of public spaces to places for collective entertainment and recreation, to the updating of housing solutions in accordance with the hygienic and sanitary standards of the time (Del Monaco, 2016).

The current urban planning of the Municipality is comprised of three key elements: a Municipal Regulatory Plan (P.R.C.), articulated in an Inter-municipal Territorial Layout Plan (P.A.T.I.) developed in collaboration with the Municipality of Schio, and a Plan of Interventions (P.I.). Furthermore, in 2016, the municipality joined the Covenant of Mayors in collaboration with the municipalities of Brogliano, Castelgomberto, Cornedo Vicentino, Recoaro Terme and Trissino. This resulted in the formulation of a Sustainable Energy and Climate Action Plan (SECAP) at the valley level.

The data obtained from the diverse urban planning and energy tools can be subjected to analysis using the aforementioned methodology.

Indeed, as illustrated in Fig.1, the solution section provides a framework for subdividing the information on the use of renewable energy sources in the territory according to the three main themes of the reading of the landscape through the lens of energy, the reading of energy through the lens of the landscape, and social awareness.

In particular, Tab.2 illustrates the data of interest, organised according to the plan to which they refer, thus allowing for an integrated comparison between the landscape, energy and social aspects that characterise the municipal territory. This scheme enables the identification of areas of conflict or synergy, thereby facilitating more informed and conscious planning.

Reading the landscape through the lens of energy

The presence of landscape constraints, areas with VINCA applications, and other zones with potential exemption possibilities may restrict the installation of renewable energy sources.
The settlement structure is markedly shaped by the topography of the region, with a discernible delineation between the urban structure and the hamlets. The construction of the civil buildings was undertaken during the entrepreneurial period of the Marzotto family, with the design of the buildings (including their shape, layout and sun exposure) taking place in the 1930s. This included the school complex, the hospital (which has since been renovated), the music school, the recreational clubs and the theatre. In the period following the Second World War, further extensions of the city were undertaken, always in accordance with urban planning projects, with the objective of ensuring compactness and the containment of land use.
The area exhibits a pervasive influence of industrial culture, evident in the presence of early industrial sites, architectural heritage, and industrial archaeology. It thus becomes evident that a conjunction between policies aimed at the industrial sector and those related to education, research, urban quality and landscape is required, with the aim of achieving greater sustainability value.
The invariants of a landscape nature, with the identification of elements with specific and identifying characteristics that distinguish a place and that must be safeguarded. The areas of high value identified are the slope with Castelvecchio meadows and the riverine countryside of Maglio/Menovre.
The invariants of an environmental nature, with the identification of areas of particular ecosystem and biodiversity value to be protected and safeguarded. In particular, the Castiglieri high wooded slope and the Monte Scandolara high wooded slope are reported.
The invariants of a historical-monumental nature.
On a landscape level, the advancing woodland area with brambles, locust trees and hazels is presented as problematic. Historically, the forest was managed for timber and foliage, which were used as animal bedding. In contrast, the forest now exists as scrubland with tangled undergrowth.
POSSIBLE FUTURE DEVELOPMENTS
In regard to quarries, the objective of environmental protection is not the establishment of new sites, but rather the rehabilitation of existing ones. This approach extends beyond the conventional concept of restoration, encompassing the redevelopment and intensification of supervisory activities.
Gradual rehabilitation and valorisation of existing plants producing energy from renewable sources.
One potential avenue for further development is the unification of the territory with other municipalities to achieve economies of scale in the provision of utilities. Additionally, there is scope for experimentation with renewable energy sources, such as the RECs.
The promotion of projects with the objective of utilising renewable energy and energy efficiency.

Reading energy through the lens of landscape

There is considerable potential for the utilisation of both fermentable biomass, derived from livestock manure and FORSU, and ligno-cellulosic biomass, derived from agricultural waste and forest wood.
The municipality exhibits a relatively low level of producibility in comparison to its windiness.
A total of six hydroelectric power stations are present, with a collective nominal power of 6.8 MW. In addition to their function as energy production facilities, these are regarded as landmarks for tourist itineraries.
The production of photovoltaics in this region is below the provincial and regional average. Specifically, it is 0.114 kWp/inhabitant, compared to 0.275 in the Province of Vicenza and 0.330 in the Veneto Region.
POSSIBLE FUTURE DEVELOPMENTS
Provide for the regeneration of the historical heritage through reuse and redevelopment, with a view to enhancing energy and climate performance.
Blighted areas have been identified, with the objective of improving their energy performance and saving energy resources, among other things.
Installation of new photovoltaic systems on public buildings and promote this also in the private residential and tertiary sector (expected percentage change of 31% between the years 2013 and 2030).

Social awareness

The establishment of the 'Punto Risparmio Energetico' (Energy Saving Point) desk at Confartigianato Vicenza as a forum for discussion and consultation on energy-saving interventions and incentives with professionals.
POSSIBLE FUTURE DEVELOPMENTS
Encourage quality building through courses and the dissemination of meaningful project experiences.

Promoting the restoration and use of hydroelectric power stations.
Drawing up a "Valley" energy balance oriented towards a carbon-free policy.
Promoting an Energy City project for the improvement of energy efficiency and the coordination of different individual interventions.
Provide information and awareness campaigns for the installation of photovoltaic systems.

Tab.2 Information gathered from the various urban and energy plans prepared and published by the Municipality of Valdagno. In particular, the data available in the P.A.T.I. (Comune di Valdagno, 2016) are indicated in light blue, those in the P.I. (Comune di Valdagno, 2019) in pink and those in the P.A.E.S.C. (AzzeroCO2 S.r.l. et al., 2016) in green

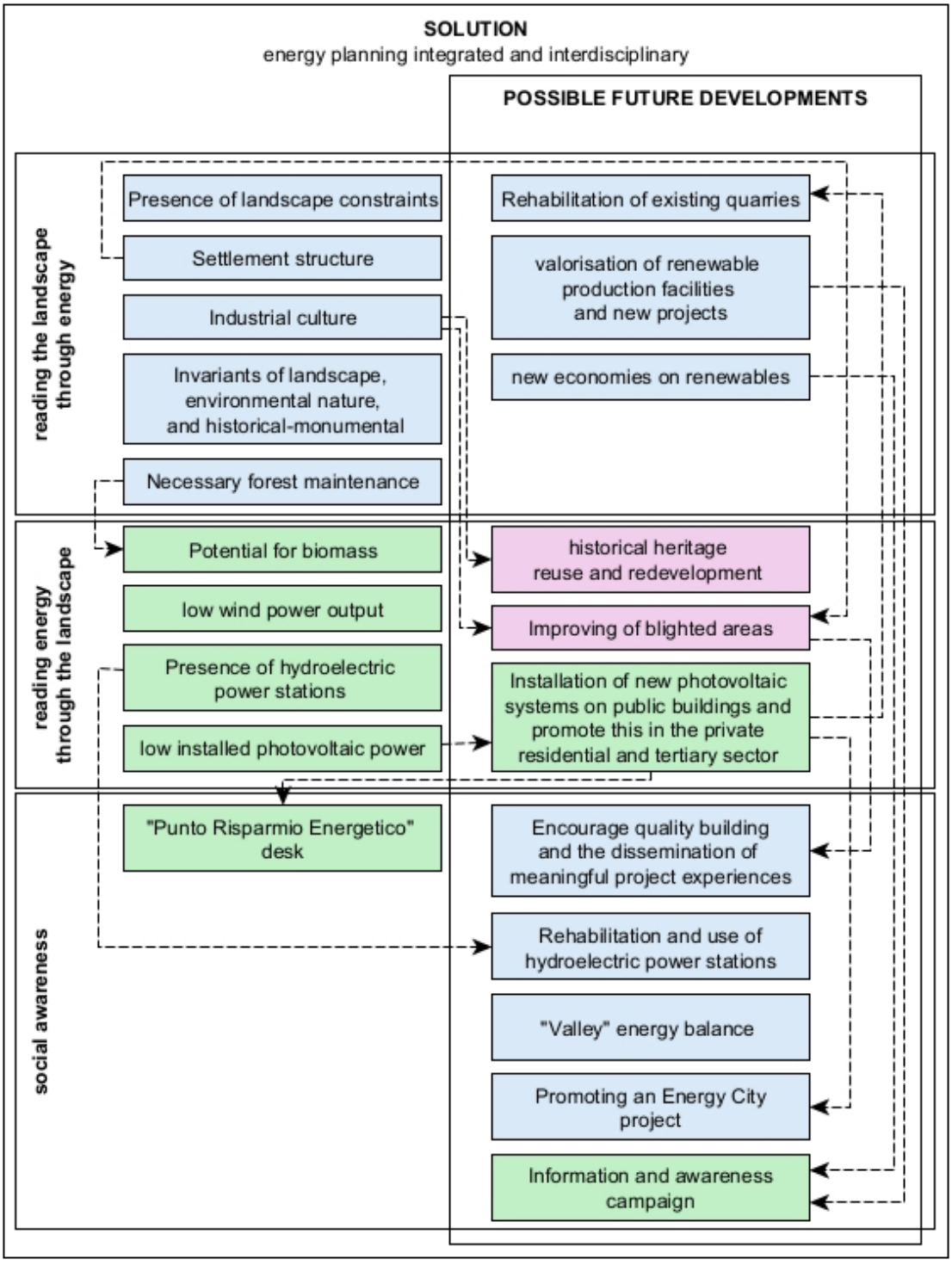

Fig.3 Diagram of the methodology proposed above applied to the case study of the Municipality of Valdagno. The information available in the P.A.T.I. (in light blue), in the P.I. (in pink) and in the P.A.E.S.C. (in green) is shown in the same colours as in the previous tables. The use of dotted arrows indicates the presence of identified relationships

In particular, a number of significant observations emerge with regard to the municipality of Valdagno. Biomass, for instance, represents not only a useful renewable source, but also has the potential to actively contribute to the maintenance of the local landscape. In contrast, hydropower has a longstanding presence in the region, constituting a pivotal element of its energy identity. Furthermore, areas that have undergone degradation have been identified as requiring redevelopment, including in terms of energy. Awareness and information initiatives targeting the community on these issues have already been planned.

In consideration of the methodology previously outlined, it is observed that the urban planning instruments adopted by the municipality are significantly interrelated, despite often being presented and evaluated in isolation. This reinforces the notion that energy is inextricably linked to the built environment and the local landscape heritage. The aforementioned synergies are illustrated in Fig.3, in which the last point of the methodology concerning the 'solution' to the energy and landscape problem, dropped on the case study, is presented again.

The information gathered allows for the reformulation of the system proposed in Fig.2, with the aim of adapting it specifically to the Valdagno case study. As illustrated in Fig.4, the benefits and disadvantages associated with different renewable sources are contingent upon the local context. For example, hydropower, which is already integrated into the territory, will result in minimal landscape disadvantages. Similarly, the use of biomass may be perceived less as a social or territorial problem, offering the advantage of contributing to the maintenance of forests, a distinctive element of Valdagno's landscape.

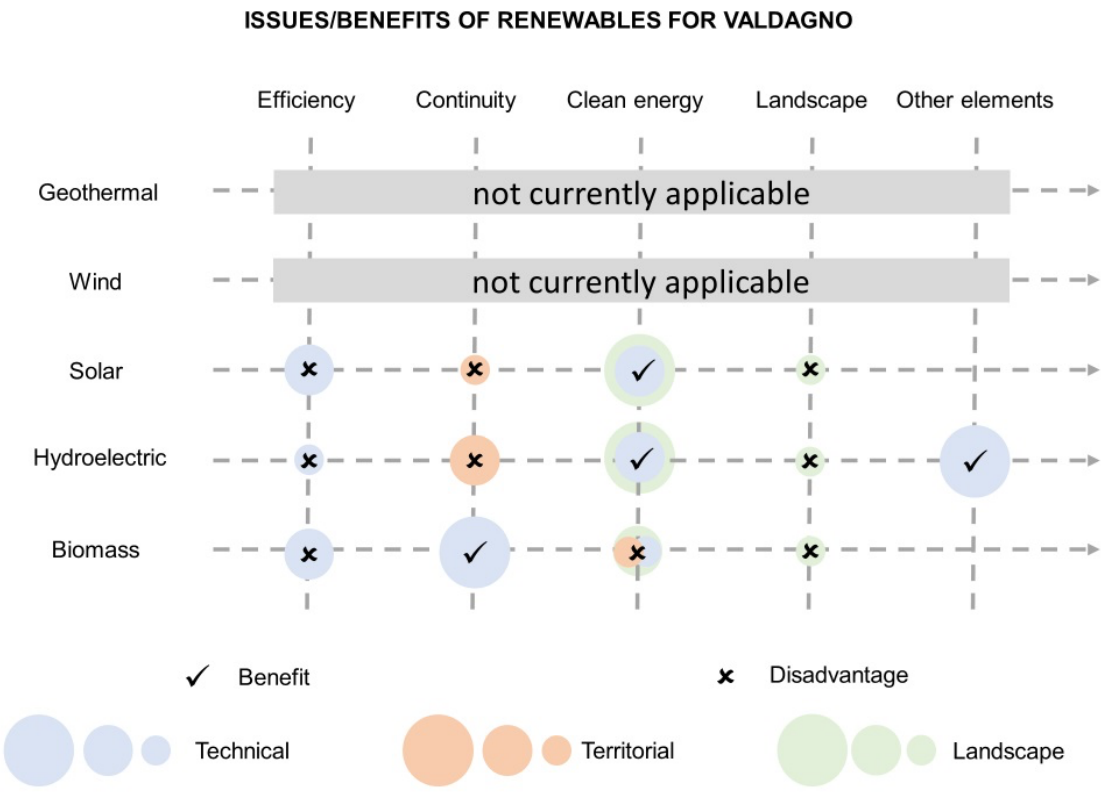

Fig.4 The system of technical and landscape information on renewable energy sources in relation to the benefits (✓) or disadvantages (✕) identified for the case study of Valdagno. The technical aspects are indicated by blue circles, the territorial aspects by orange circles, and the landscape aspects by green circles. The dimensions of the coloured circles indicate the degree of significance of the disadvantage or benefit in question

4. Conclusion

If future energy systems are to be characterised by three fundamental qualities - low energy consumption, achieved through the adoption of highly efficient technologies, low carbon emissions, made possible by the

phasing out of fossil fuels in favour of renewable energies, and short transport distances, through localised energy production (Schleicher, 2010) - it becomes essential to assess how these transformations will affect the landscape during the current energy transition. This paper examines the historical evolution of the landscape in relation to changes in energy sources and analyses the specific challenges related to the integration of renewable energy sources. In conclusion, a methodology for analysis is proposed that is not limited to technical aspects, such as the assessment of the producibility of specific technologies in a given area or their impact on urban energy budgets, nor to isolated landscape or social considerations. Instead, an integrated approach is proposed that considers both aspects simultaneously, thus enabling the development of balanced and viable solutions. The rationale behind this methodology is that it is not possible to establish a priori which renewable energy source is the most suitable, but rather an interdisciplinary assessment in the context of the situation is necessary. Indeed, all the technologies presented, which are useful for the energy transition, denote problems and advantages that should always be evaluated. Consequently, it becomes evident that established considerations, which are commonly regarded as valid for any given situation and illustrated in Fig.2, may undergo variation when the method is employed in a particular context. For the Municipality of Valdagno, the case study of this contribution, hydroelectric and biomass energy are particularly salient due to their alignment with the local territorial, technical and landscape characteristics. While these results are qualitative in nature, they are derived from a meticulous social and territorial analysis of contemporary urban plans. It is hoped that such analyses will be addressed and materialised through projects and plans in future.

Potential future developments of the research could include:

- The application of the proposed methodology in other municipalities to facilitate a comparison of the quantity and quality of data reported in the different plans, or on a larger territorial scale, such as the Agno Valley, including the entire P.A.E.S.C. This would enable an assessment of the methodology's applicability in different contexts;
- The utilisation of GIS tools for the mapping of information collated from the various plans will facilitate the identification of novel areas conducive to the construction of renewable energy facilities. Furthermore, this approach will enhance the efficacy of information and awareness campaigns.

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Image Sources

Figg.1 - 4: Authors' elaboration

Author's profile

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Land transformation and new road infrastructures. An analysis on direct and inducted impacts due to the Brebemi highway

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Abstract
The paper reflects on the relation between land transformations and the construction of new road infrastructure, by focusing on the quantification of soil consumption related to highways. Such infrastructures are relevant cases since they can impact both directly and indirectly on the land cover: directly if we consider the soil sealing produced by the infrastructure itself (the natural soil urbanized to realizing the highway); indirectly if we consider the inducted transformations enhanced by the realization of the highway (e.g. other new infrastructures connected to the highway or productive and logistic areas close to it).
The paper focuses on the Italian case study of the Brebemi highway, recently realized in the Lombardy Region (Italy). It represents one of the first scientific quantification of direct and inducted land transformations related to this new mobility infrastructure. The results demonstrate the heavy direct impact on soil consumption (278.3 ha), but also an alarming inducted soil consumption due to the secondary infrastructures realized in connection to the new highway (116.8 ha) and to the urbanization increase in a buffer zone of 1km (650 ha).

Keywords
Soil&land consumption; Soil sealing; Infrastructure; Highway; Brebemi

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1. Road infrastructures and environmental impacts: the case of the highways

The paper investigates the impacts on land transformations and on the increase of soil sealing derived from the construction of a new road infrastructure, such as highways. The analysis focuses on land transformations producing soil consumption, namely on the transformation of natural soil (rural or wooded) into urbanized and sealed areas. In this sense, soil consumption can be regarded as land take (Nuissl et al., 2009), i.e. as previously undeveloped soil taken into the built housing, utilities, transport, industry, commercial and recreation activities (Huber et al., 2008).

Many researches were carried out to analyze and quantify the recent urban transformations in the Italian context, by focusing on their effects on the soil sealing and land-use changes (Munafò, 2024; Ronchi et al., 2023; Zullo et al., 2015; Mazzeo & Russo, 2016; Boschetto & Bove, 2012). The study discussed in the paper contributes to enriching such debate by considering the specific case of land transformations due to a new highway (Iacono et al., 2015). Thus, it can be regarded as part of a broader reflection on the environmental impacts of road infrastructures, generated both in the phases of realization and operation.

For what concerns the realization phase, the most relevant environmental impacts are those on land transformations (Barberis, 2005; Castiglioni et al., 2015), ecosystems fragmentation and modification (Fabietti et al., 2011; González-Gallina et al., 2013; Koemle et al., 2018; Madadi et al., 2017), alteration of the hydrological network (Fabietti et al., 2011) and of animals' habitats and behaviors (Benítez-López et al., 2010; Halfwerk et al., 2011; Long et al., 2017; Paemelaere et al., 2023; Summers et al., 2011).

Moreover, the operation of the infrastructure, with its relevant vehicular traffic, causes other environmental negative impacts: pollution on air and water, included groundwater through runoff and percolation (Kibblewhite, 2018; Nikolaeva et al., 2017; Uliasz-Misiak et al., 2022; Werkenthin et al., 2014); impacts on vegetation due to the deposition of road dust and nitrogenous compounds (Feng et al., 2021; Gadson et al., 2009; Rahul et al., 2014); detrimental consequences on local fauna, together with its direct mortality (Fabietti et al., 2011; Orlowski, 2008; Qin et al., 2023; Van Der Ree et al., 2015); negative effects on human beings, due to the traffic noise, to the direct inhalation of contaminants and to the assumption of contaminated food produced in the rural areas closed to the highway (Gargiulo & Romano, 2011; Kibblewhite, 2018; Kole et al., 2017; Turer et al., 2003).

Many of these impacts can affect not only the territory directly involved in the realization of the road, but also a broader buffer zone. The most intuitive case is probably the air pollution caused by exhaust and non-exhaust emissions, whose contaminants can reach, with adverse meteorological conditions, a distance of many kilometers from the roadside. Richard Forman, initiator of the road ecology, was one of the first who theorized the so-called *road-effect zone* (i.e. the buffer area in which it is possible to detect environmental impacts caused by the infrastructure) and who tried to quantify it by studying the case of some American highways (Forman, 2000). In his research, he analyzed a highway of four lanes close to the city of Boston by considering its impacts on different ecological aspects (local fauna and flora and hydrological system). The result was the definition of a road-effect zone of 600 meters from both sides of the highway. More recently, other studies have identified other dimensions for the road-effect zone: 400 meters (Wu et al., 2014), 250 –1,000 meters (Eigenbrod et al., 2009) and 1,000-1,300 meters (Theobald et al., 2011). All these studies agree on the huge environmental impact of a large infrastructure (Coffin, 2007), even if it emerges a high variability depending on the typology of the road, on the impacts investigated and on the specific landscape crossed (Feng et al., 2021). It is still little investigated how quantifying the road-effect zone in the case of the impacts on land transformations and soil consumption, object of the analysis. Nevertheless, the influence of the infrastructure in the increase of urban sprawl is well known (Pileri, 2024; Castiglioni et al., 2015; Romano et al., 2017; Squires, 2002). As a matter of fact, many scholars have described how a highway can be regarded as a lever of the land transformations in the surrounding territory (Vendemmia, 2011), by enhancing the construction of new connecting roads and urbanized areas, both productive and residential (Assennato et al., 2019; Munafò,

2022; Pileri, 2022); still, attempts and procedures to quantify this effect are lacking. In order to expressly measure this influence, the study conducted and here reported on the Italian highway Brebemi (Brescia-Bergamo-Milan) investigates the impact on soil consumption caused not only by the infrastructure itself (hereby defined as direct soil consumption, Dsc), but also caused by the new infrastructures connected to the highway (linear inducted soil consumption, linear Isc) and by new urbanized areas located in a buffer zone of 500m from each side of the highway (areal inducted soil consumption, areal Isc).

In the following, the case study is introduced, its relevance and the reasons for which the Brebemi highway was selected as a valid sample. Then, the methodology of the quantification of the direct and inducted soil consumption is described, together with the dataset used to calculate the land cover transformations. After that, the results of the analysis are discussed, for both the direct and inducted soil consumption cases. Such results are then discussed by considering their weight on the general variation of urbanized areas and soil consumption in the municipalities crossed by the highway. This analysis allows to better understand how much these two aspects have changed in the pre-Brebemi period, e.g. before the realization of the highway, and post-Brebemi period, e.g. after its construction. In the conclusions, the limits of the analysis and the hypotheses of future development of the research are commented.

2. The case study: the Brebemi highway in Lombardy Region

The Brebemi highway is located in the Lombardy Region, in the north of Italy, and it connects the cities of Brescia and Milan by a track of 62 kilometers (Fig.1). It crosses 27 municipalities, in four different provinces (Brescia, Bergamo, Lodi and the Metropolitan area of Milan).

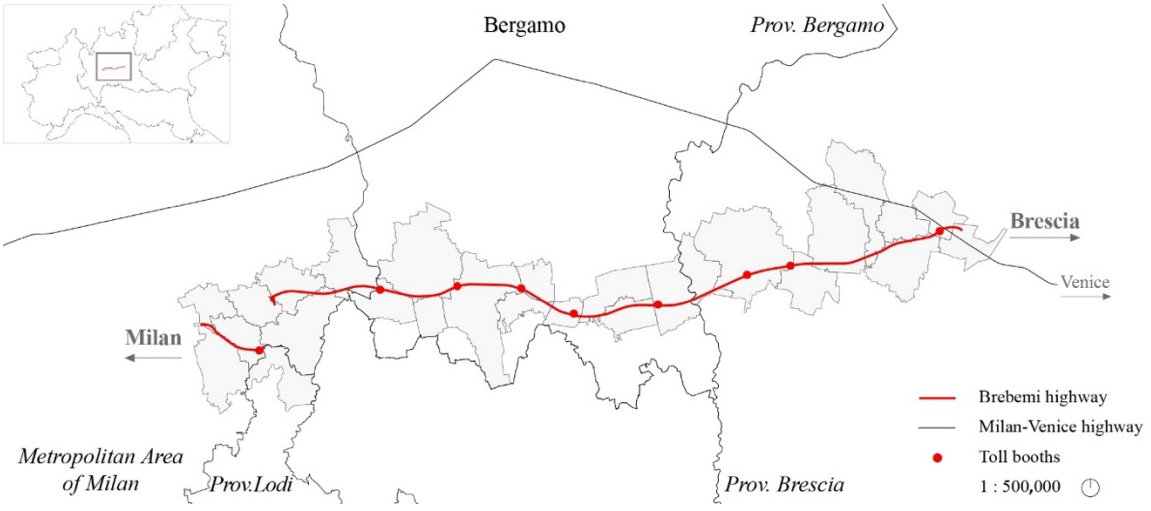

Fig.1 The Brebemi highway.

The Brebemi highway was selected as case study for the following reasons:

- its realization is recent (the construction started in 2009 and ended in 2014, while the project had begun to be discussed before the 2000s) and, therefore, it is possible to deeply study the land transformations derived from it. As a matter of fact, the best dataset on land cover in the Lombardy Region (the DUSAF[1]) provides data for the years 1999, 2007, 2012, 2015 and 2018[2]. The availability of such data allows us to define two periods of analysis, one to study the situation pre-Brebemi (by taking the period 1999-2007) and the other to study the situation post-Brebemi (by taking the period 2007-2018);

[1] DUSAF is a land use analysis and monitoring tool of the Lombardy Region. It is a vector resource capable of classifying the territory on the basis of land use into five levels and five related sub-levels, with a spatial resolution of 1:10000.
[2] Actually, a latest version of the DUSAF was recently released (DUSAF 7, referred to 2021), which however was not considered in this analysis because it was subsequent to the collection of the results.

- its importance in the public debate (local, regional and national). The highway was originally proposed with the stated purpose of relieving traffic congestion in the area of Brescia but, in the past such as at the present, it has been strongly criticized since there was already a highway connecting Brescia and Milan (the Milan-Venice highway) that it is still the most used due to the less expensive toll (Cuda et al., 2015; Giuliani, 2023). Despite such interest in public debate, the case was still poorly studied by scholars and there is not any precise quantification of soil consumption due to the highway[3]. There is just a preliminary evaluation done before the conclusion of the work (Di Simine & Salata, 2014), to which the results of the present analysis will be compared in the following sections;
- its location in a plain and rural context with a high natural value. The Brebemi crosses four regional parks related to the rivers Oglio, Serio and Adda and the regional Milan Southern Agricultural Park in last section of the track from Liscate to Milan. In addition, a huge portion of the territory crossed by the Brebemi highway is classified by the Lombardy Region as *Priority areas for the biodiversity*[4] (Fig.2);

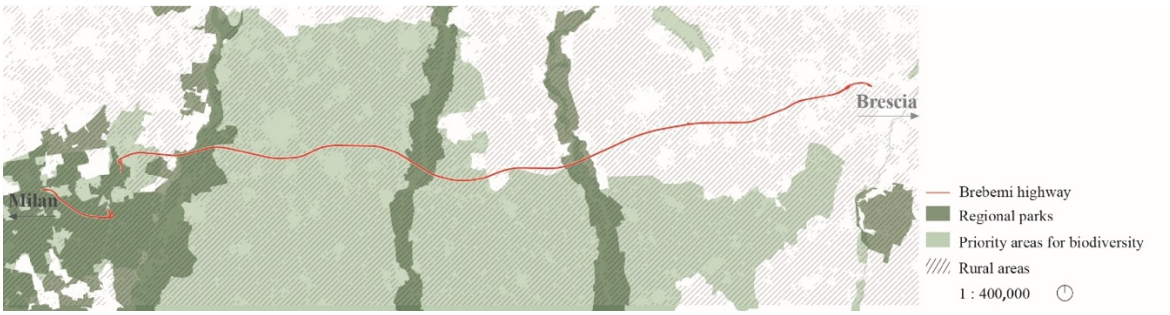

Fig.2 The Brebemi highway and the natural and rural environment.

- its relevance in the field of the soil consumption studies: on the one hand, because in the Italian context the road infrastructures represent the 30-40% of the national soil consumption (Assennato et al., 2019); on the other, because the Lombardy is one of the first Italian region for soil consumption and soil sealed (Munafò, 2024). In this sense, the case of the Brebemi is emblematic since the highway is located in a dense urbanized area where many land transformations have occurred in the last years.

3. Methodological issues to quantify direct and inducted soil consumption

All the calculations on land cover and its transformation due to the Brebemi highway were carried out with Gis analysis (in particular, using the ArcGIS software) and thanks to the regional database DUSAF. Such database is organized with the same legend and classification of the European Corinne Land Cover: class 1 refers to artificial surfaces, class 2 to agricultural areas and class 3 to forest and seminatural areas. More specifically, class 1.4 represents non-agricultural vegetated areas.

On the basis of this classification, the analysis considers:

- as urbanized areas all those areas whose land cover belongs to class 1, except the class 1.4 (namely urbanized areas are made on the sum of the classes 1.1,1.2 and 1.3);
- as soil consumption, the transformation of natural areas (namely all those areas whose land cover belongs to the classes 1.4, 2 and 3) into urbanized areas.

[3] Following the prescription of the *Comitato Interministeriale per la Programmazione Economica* (CIPE), the society who has realized the Brebemi had to conduct a monitoring on the main environmental impacts due to the construction and operation of the highway. The monitoring ended in 2018 and includes also the soil consumption. At the present the data are not freely available, but just on request and with precise limitation about their diffusion.

[4] The identification of Priority Areas for the Biodiversity in the Lombardy was inspired by the ecoregional conservation approach developed in the 1990s by WWF and The Nature Conservancy (TNC). Assuming this approach, an ecoregion is regarded as a terrestrial (or aquatic) unit relatively large that contains a distinct combination of natural communities that share most species, dynamics, and environmental conditions (Bogliani et al., 2007).

A relevant note is that soil consumption does not correspond to the net variation of the urbanized areas in a certain period. Indeed, the net variation would count both the increase of new urbanized areas (determining a positive variation) and of new natural areas (determining a negative variation). Such phenomena of re-naturalization, namely of transformation from urbanized to natural areas, are quite common in cases of infrastructures, since during the construction period the urbanized areas detected by the land cover database are wider than the final ones (for instance, they also include the building site areas). The analysis has considered the land cover features in three different years: 1999, 2007 and 2018, while the soil transformations were observed in the periods 1999-2007 (pre-Brebemi) and 2007-2018 (post-Brebemi).

The identification of the areas of study was the first step of the analysis. They are:

1. the area of the Brebemi highway (meant as "footprint" to the ground) related to the study of the direct soil consumption (Dsc);
2. the area of the infrastructures (meant as "footprint" to the ground) connected or related to the Brebemi highway, related to the study of the linear inducted soil consumption (linear Isc);
3. the area close to the Brebemi highway, namely a buffer zone of 500m from each side of the road, related to the areal inducted soil consumption (areal Isc[5]).

The area of the Brebemi was obtained starting from the linear track of OpenStreetMap. From the regional official database[6] it was possible to extract the information about the width of the highway, namely the lanes and all the other complementary elements included in the highway, as the emergency lane, the service areas or the toll booths. The area of the infrastructures refers to the new roads, built in the post-Brebemi period (2007-2018) to serve the highway or to be in connection with it. In the following, three categories are presented; they aggregate these infrastructures on the basis of the motivation for which they have been regarded as inducted by the realization of the Brebemi highway (Fig.3):

a) new roads realized to link the Brebemi highway with the territory;
b) modification of already existed roads, interrupted or deviated by the Brebemi;
c) new roads, not physically connected to the highway, but realized as Brebemi compensatory interventions.

(a) (b) (c)

Fig.3 Example of infrastructure's types: (a) West Beltway in Caravaggio (category 1); (b) interventions and deviations in Caravaggio (category 2); (c) Cassano Beltway (category 3)

[5] Note that the portions of this area outside the borders of the municipalities crossed by the highway were not consider in this classification. In any case, these portions have a little and negligible contribution on the entirety of the 1km buffer zone (500m from each side of the road).

[6] "Database Topografico (Dbt) Regionale" available on the Territorial Information System (SIT) of Lombardy Region.

Once identified the infrastructures inducted by the Brebemi, it was necessary to consider their different physical features. The linear extensions were taken from the official regional data[7], while the width was calculated by distinguishing 4 different categories based on the typology of the roads (Tab.1).

Typology of road		Dimension of road		
Name	**Description**	**Number of lanes**	**Total width [m]**	**Length [km]**
Type_1	Extra-urban main roads with two lanes in each direction	4	22	19.1
Type_2	Extra-urban secondary roads with two lanes	2	10.5	60.8
Type_3	Local roads in urban areas	2	9.5	24.1
Type_4	Road junctions	1	6	27.9

Tab.1 Classification of inducted infrastructures (linear inducted soil consumption) on the basis of their geometrical features (taken from the official roads classification introduced by the Ministry of Infrastructure and Transportation, November 2001

The two classifications introduced are overlapped in Tabl.2.

Type of roads inducted by the Brebemi	Typology of road	Length [km]
New roads connecting the Brebemi and territory	Type_1, Type_2, Type_3, Type_4	116.3
Modification of roads interrupted or deviated by the Brebemi	Type_2, Type_3	8.8
New roads of compensation interventions	Type_2, Type_3	6.8

Tab.2 Cross-classification of typologies of roads inducted by the Brebemi and of their geometrical features

Finally, the study buffer area of the Brebemi, related to the areal Isc, was identified starting from the track of the highway. The dimension of the buffer (500m from each side of the road) depends on theoretical evidence that has demonstrated how the soil consumption inducted by the presence of a new infrastructure (as in the case of logistics or productive hubs) is concentrated in a distance between 0 and 500m from it (Munafò, 2022). Since the buffer area includes also the Brebemi itself and some part of the infrastructures connected to the highway, to avoid counting twice these values the contributions derived by the Brebemi and by these other infrastructures were not included in the calculation of the indicators related to the buffer area.

After having identified the areas of study, the urbanized areas and the soil consumption were obtained by intersection with them and the land cover in the three years considered (using the "intersect" command on the GIS software). The need to identify the footprint of infrastructures (both BreBeMi and induced linear infrastructures) and then intersect them with the DUSAF data arises from the fact that the latter is not provided at a spatial scale that allows for an accurate representation of the actual dimensions of the infrastructures. Again, the same "intersect" command was used to pass from the urbanized areas in the three years considered to the soil consumption in the two periods, thus identifying areas that experienced land cover transformation and isolating those that changed from natural to urbanized areas.

From these results, two classes of indicators were constructed: synchronic, related to each of the years considered and to the relevant urbanized areas; diachronic, capturing the urbanized areas evolution during the two periods (1999-2007 and 2007-2018), namely the soil consumption registered. To be more precise and to sum up the previous considerations, the indicators considered are reported in Tab.3.

[7] "Infrastrutture della mobilità" available on the Territorial Information System (SIT) of Lombardy Region.

Synchronic indicators	Diachronic indicators
Urbanized areas – UA [ha]: soil belonging to the DUSAF 1.1, 1.2, 1.3 classes.	Soil consumption – SC [ha]: soil belonging to DUSAF 1.4, 2, 3 classes that are transformed into 1.1, 1.2, 1.3 classes within the considered time horizon.
Urbanized coefficient – UC [%]: ratio between the urbanized areas and the total municipal surface in a certain year.	-
Direct urbanized areas – Dua [ha]: urbanized area of the Brebemi highway route.	Direct soil consumption – Dsc [ha]: soil consumption due to the construction of the Brebemi highway.
Linear induced urbanized areas – linear Iua [ha]: urbanized areas belonging to the road infrastructure supporting Brebemi.	Induced linear soil consumption – linear Isc [ha]: soil consumption due to the construction of road infrastructure supporting Brebemi.
Areal induced urbanized areas – areal Iua [ha]: urbanized areas within the 1km buffer zone, excluding the direct and linear induced urbanized areas included in the buffer zone.	Induced areal soil consumption – areal Isc [ha] – soil consumption within the 1km buffer zone and the considered time horizon, excluding the direct and linear soil consumption included in the buffer zone.
Incidence coefficient of urbanized areas – (D, L, A)uI or TuI_B [%]: ratio between the direct, linear induced and/or areal induced urbanized areas and the total urbanized areas in the municipality.	Incidence coefficient of soil consumption– (D, L, A)cI or TcI_B [%]: ratio between direct, linear induced and/or areal induced soil consumption and total soil consumption in the municipality.
-	Speed of variation of urbanized areas – (D, L, A)Svar or $TSvar_B$ [ha/year]: direct, linear induced and/or areal induced soil consumption per year on average within the considered time horizon.

Tab.3 Synchronic and diachronic indicators valuated for the analysis of Brebemi direct and induced effect on land cover trasformations

4. Results: the direct and inducted soil consumption of the Brebemi highway

The analysis has brought to the quantification of soil consumption due to the realization of the Brebemi highway. Totally, it was calculated a soil consumption, namely a transformation from natural to urbanized areas in the post-Brebemi period, of 1045.1 ha, formed by: Dsc, produced by the Brebemi highway, of 278.3 ha[8]; linear Isc of 116.8 ha; areal Isc of 650 ha (Fig.4-5). It is relevant to note that to realize the new infrastructures (the Brebemi highway and the inducted roads) it was "reused" just a minimum part of already urbanized areas: just 10.5 ha in the case of the Brebemi (the 3% of the total urbanized area of the highway) and 28.7 ha in the case of the other roads (the 20% of their areal track).

The results show that the weight of the Isc corresponds to more than 275% of the soil consumption due to the highway itself. In particular, the areal Isc is the most relevant part since it weighs more than 84% on the total.

On average over the municipalities crossed, the areal Isc corresponds to 24 ha, while the linear Isc corresponds to 2.6 ha. Deepening the analysis, it is possible to note how in some municipalities the areal Isc reaches quite significant values: it is the case of Chiari, with more than 92 ha, or of Caravaggio, Antegnate, Calvenzano and Treviglio which reach respectively the values of 79 ha, 40.9 ha, 36.5 ha and 36.2 ha. The same can be seen in the linear case, for example in the municipalities of Roncadelle and Vignate, with respectively more than 9 and 12 ha, and Calcio, Casirate d'Adda and Caravaggio, with more than 7 ha. Such variability in the results

[8] This data appears quite distant from the other discussed previously in the literature where the estimated soil consumption of the Brebemi highway, even if quantified before its completion, was 309.5 ha, while the urbanized area was assumed to be 356.4 ha (Di Simine, Salata, 2014).

reflects the different distribution of new urbanized areas or of new infrastructures related to the Brebemi: this depends on the logistic and productive hubs in some municipalities, which may determine a higher value of areal Isc, or on new beltways as in Caravaggio (*West Beltway*), Calcio (*South Beltway*) and Casirate d'Adda (C*onnection between West Treviglio-Casirate d'Adda tollbooths*), which cause alone a high value of linear Isc, namely of respectively 5.4 ha, 7.8 ha and 6.6 ha.

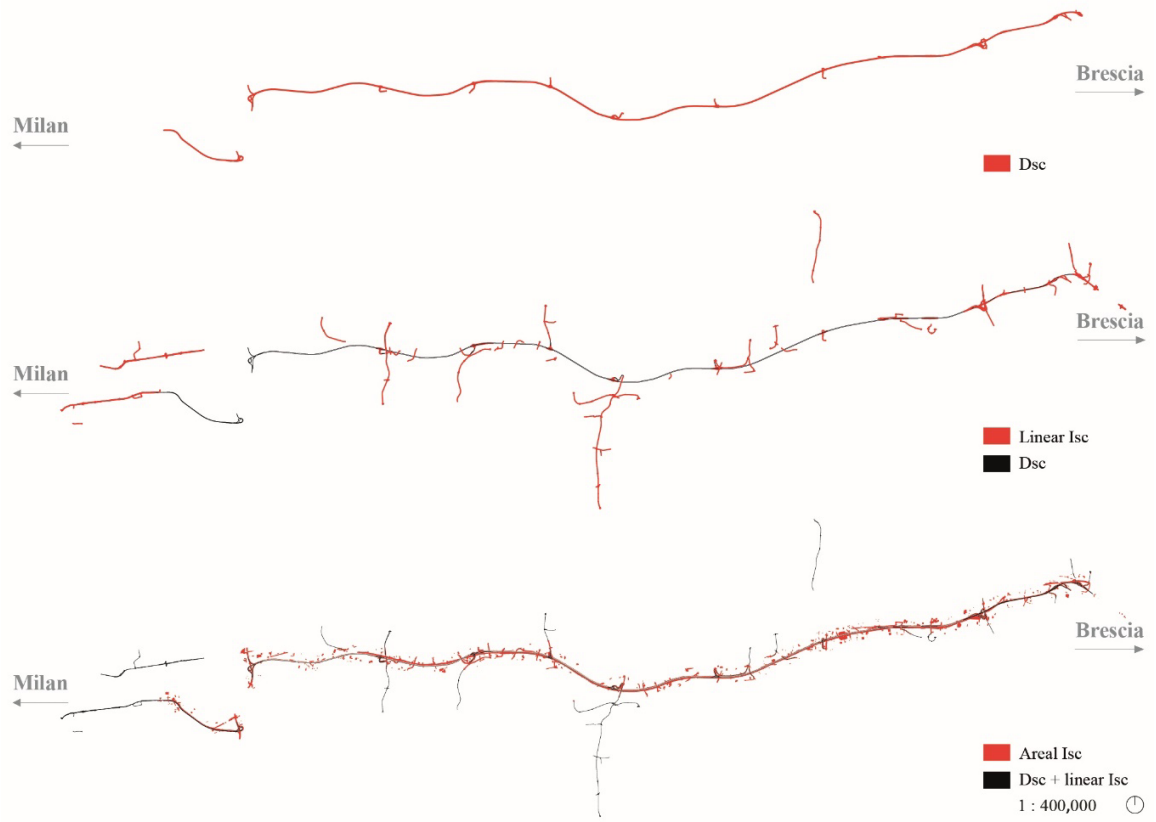

Fig.4 Soil consumption produced by the Brebemi highway divided in direct and inducted (linear and areal)

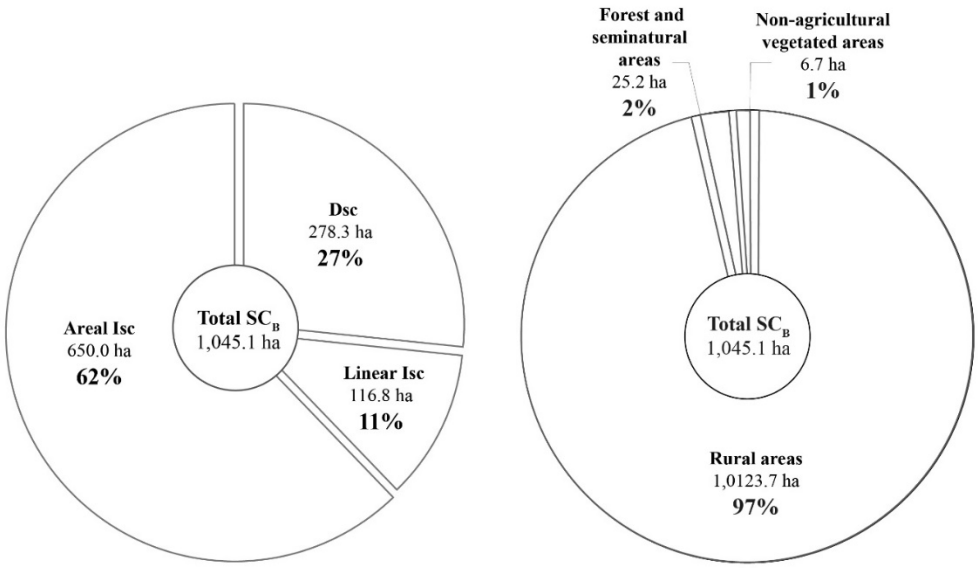

Fig.5 Main results about the soil consumption produced by the Brebemi highway. SC_B stands for Soil Consumption of Brebemi highway

A second finding emerges by analyzing the natural areas lost due to the Brebemi and its inducted transformations. In total, soil consumption has been made mainly on rural areas (1013.7 ha, almost the 97% of the total), while the rest has determined a loss of forest and seminatural areas (25.2 ha, more than 2%)

and non-agricultural vegetated areas (6.2 ha, less than 1%). Moreover, 54% of the total soil consumption affects high valued landscapes: 157.6 ha of soil consumption regard regional parks (49 ha caused by Dsc, 21.7 ha by linear and 86.9 ha by areal Isc) while 537.5 ha[9] involve regional priority areas for the biodiversity (152.1 ha caused by Dsc, 60 ha by linear and 325.4 ha by areal Isc).

In sum, the results show the relevant impacts of the Brebemi highway on the transformation of the land cover, not only for the realization of the infrastructure itself (Dsc), but also for all those inducted changes produced both by new infrastructures connected to the Brebemi (linear Isc) and by the urban sprawl along it (areal Isc) (Fig.5).

5. A reflection on the results: the weight of Brebemi highway in the soil transformations

The results just presented need to be discussed by contextualizing them in a broader frame, to better understand how much the soil consumption derived from the Brebemi, both direct and inducted, has been relevant.

A useful comparison can be done by considering the national data on soil consumption elaborated yearly by ISPRA (the Italian Institute for Environmental Protection and Research). Taking the last report, the Lombardy was the third Italian region for soil consumption in the period 2022-2023, with a value of 780 ha, while Brescia province has consumed 147 ha (Munafò, 2024). This data can provide us a referring point: the soil consumption of the Brebemi, 1,045.1 ha, corresponds to more than the 130% of the soil consumption of the whole Lombardy Region in the last year, and almost ten times the soil consumption occurred in the Brescia Province. These results appear particularly impressive if we consider the different spatial scales of the terms in the comparison[10] and if we notice that 1,045.1 ha correspond to a soil consumption generated by a single infrastructure that it is not the only realized in the Lombardy Region in the last years.

On a local scale, another interesting comparison can be done by calculating how much the Brebemi, with its direct and inducted effects, has affected the total amount of urbanized areas and soil consumption in the municipalities crossed by the highway.

As a first analysis, the increase of the urbanized area determined by the Brebemi can be measured especially by considering the areal induced urbanized areas (areal Iua) and by making a comparison between the land cover pre-Brebemi (period 1999-2007) and post-Brebemi (period 2007-2018). Considering the 1km (500m from each side of the road) buffer zone of the Brebemi highway, the total amount of areal Iua in the three different years of the analysis (1999, 2007, 2018) has changed from 671 ha in 1999, to 882 ha in 2007 (+211 ha in the period 1999-2007), reaching 1.435 ha in 2018 (+553 ha in the period 2007-2018). More specifically, as shown in Figure 6, the areal Iua in the 1km buffer zone of the Brebemi have increased in all the municipalities crossed (except for just two cases). The ratio between the areal Iua in the 1km buffer zone and the urbanized areas in the whole municipality (namely the Incidence coefficient of the areal induced urbanized areas, AuI) gives the weight of the former on the local context (Fig.7). In 1999, before the realization of the Brebemi highway, 15 municipalities on 27 presented a ratio under 10%, 10 of them between 10 and 25% and just 2 of them over 25%. In 2018, after the realization of the Brebemi highway, the situation is quite different: just 6 municipalities have maintained a ratio under 10%, while 11 municipalities display a ratio between 10 and 25% and 10 exceed the 25%. Some cases are significant since they have moved from values under 10% to values over 25%, as occurred in the municipalities of Calcio and Urago d'Oglio.

These data suggest a clear contribution of the Brebemi highway on the land transformations occurred in the municipalities considered and also describe an alarming modification of the territory.

[9] Note that this amount overlaps with soil consumption in regional parks for 130.7 ha.

[10] To give an idea, the area limited by the administrative boundaries of the municipalities crossed by the Brebemi (40,680 ha) represents only the 8.5% of the Brescia Province surface and the 1.7% of the Lombardy Region surface.

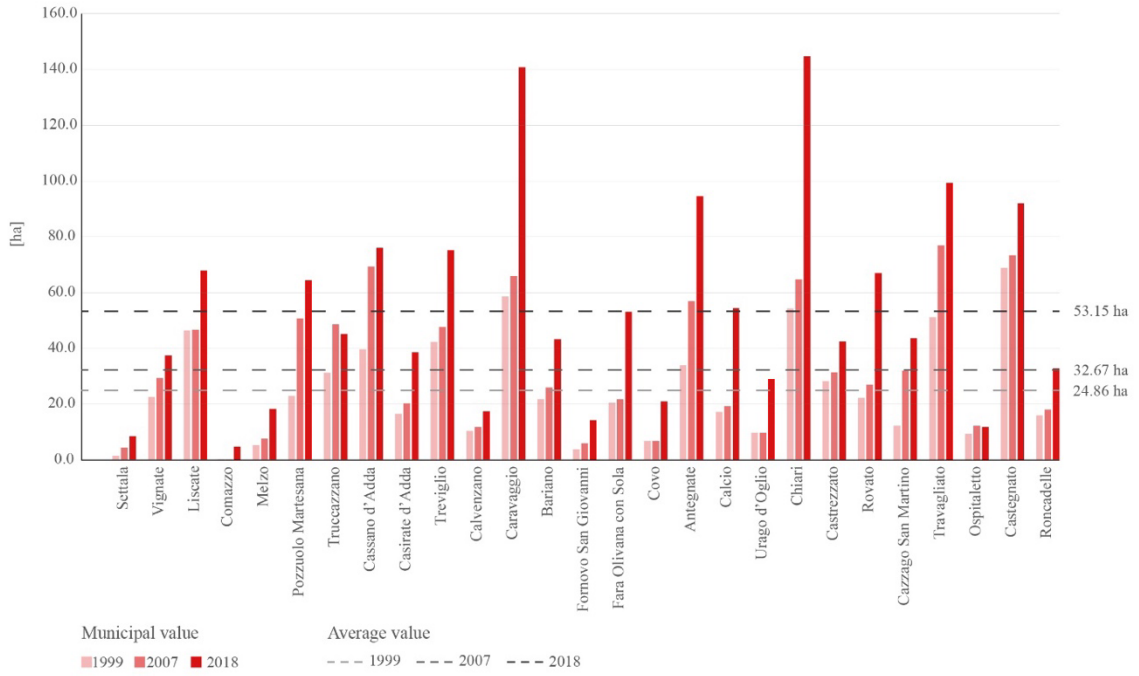

Fig.6 Areal induced urbanized areas in the 1km buffer zone of the Brebemi in 1999, 2007 and 2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

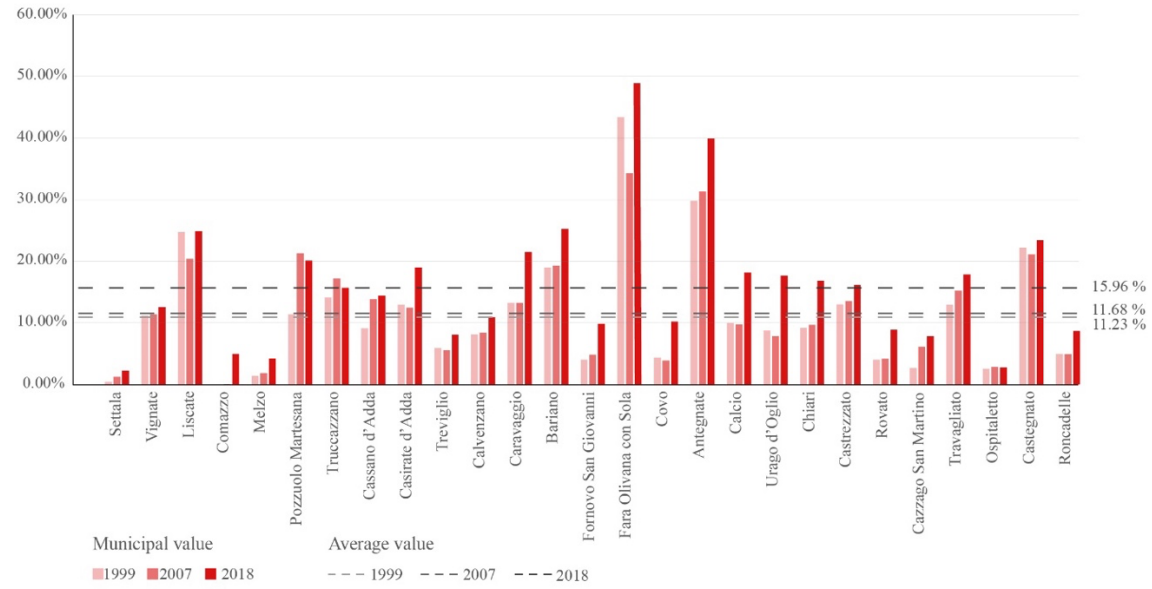

Fig.7 Incidence coefficient of areal induced urbanized areas in each municipality in 1999, 2007 and 2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

The speed of variation, namely the ratio between the value of the soil consumption in a period and the period itself, is another useful indicator that can validate how the situation has changed in the two scenarios, pre-Brebemi and post-Brebemi. Considering the Speed of variation of areal induced urbanized areas (ASvar), with reference to its average value, the indicator almost duplicates, increasing from 0.98 ha/year in 1999-2007 to 1.86 ha/year in 2007-2018. Regarding the single values, the indicator increased in the period post-Brebemi in almost all the municipalities crossed and in some cases with relevant values (Fig.8): e.g. in the municipality of Caravaggio, where the speed of variation has passed from a value of +0.91 ha/year in the period 1999-2007 to +6.8 ha/year in the period 2007-2018. Similarly, in the municipality of Chiari the indicator pre-Brebemi was +1.3 ha/year, while that one post-Brebemi arrives to 7.2 ha/year.

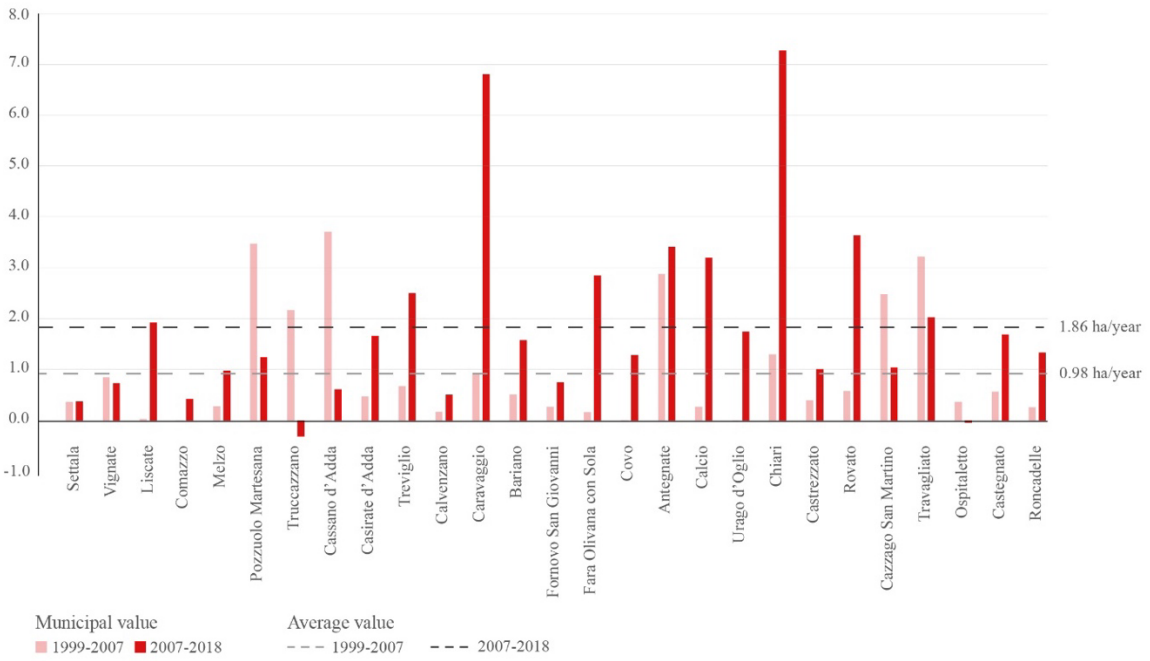

Fig.8 Speed of variation of areal induced urbanized areas in the periods 1999-2007 and 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

In the same way, the urbanization coefficient (i.e. the ratio between the urbanized surface and the total municipal surface in a certain year) has changed in each municipality in the pre and post-Brebemi period: in particular, 7 municipalities experienced an increase at least of the 30% of their urbanization coefficient from 2007 to 2018 (just two in the period 1999-2007), among which we find Calcio with an increase of the 52%, and Fara Olivana con Sola, with a +72% (Fig.9).

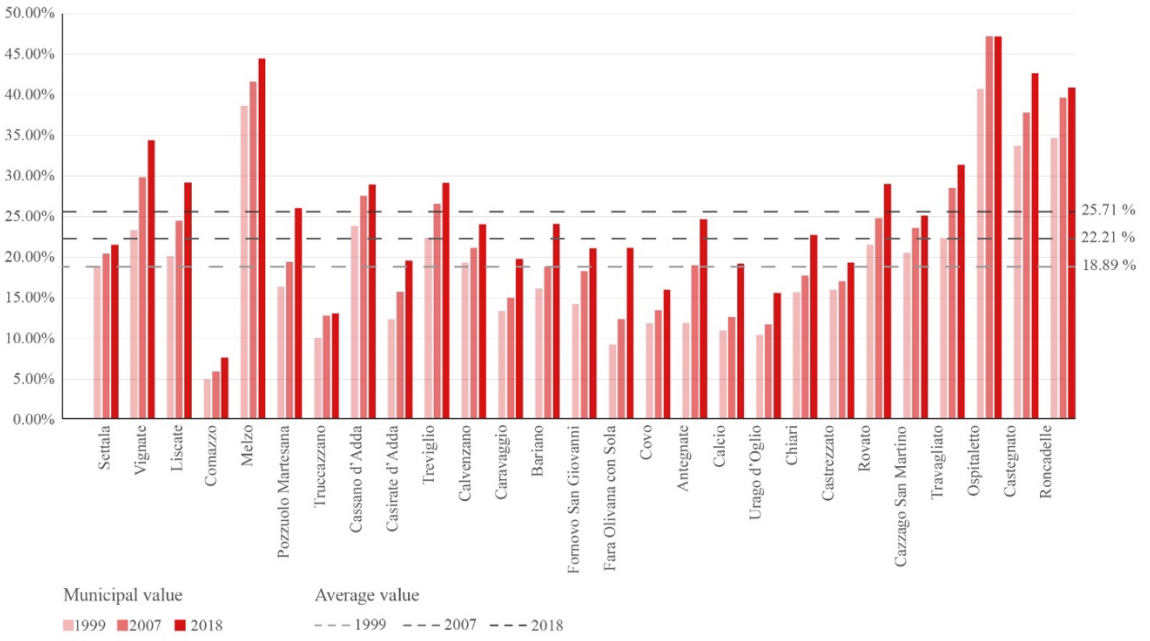

Fig.9 Urbanized coefficient of the municipalities crossed by the Brebemi in 1999, 2007 and 2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

In addition to the speed of variation, it is useful to consider now another diachronic indicator, thus moving from the values of urbanized areas in the different years to the land cover transformations in the periods 1999-2007 and 2007-2018: in this way it is possible to calculate how much the soil consumption of the Brebemi,

both direct and inducted, has affected the total amount of soil consumption in the municipalities crossed by the highway. As shown in Figure 10, the analysis has considered separately each component of soil consumption related to the Brebemi, the Dsc and the linear and areal Isc. For each of them it was calculated the respective incidence on the total amount of the municipal soil consumption, by elaborating different Incidence coefficients of soil consumption, as a Direct-consumption Index (DcI), a Linear-consumption Index (LcI) and an Areal-consumption Index (AcI).

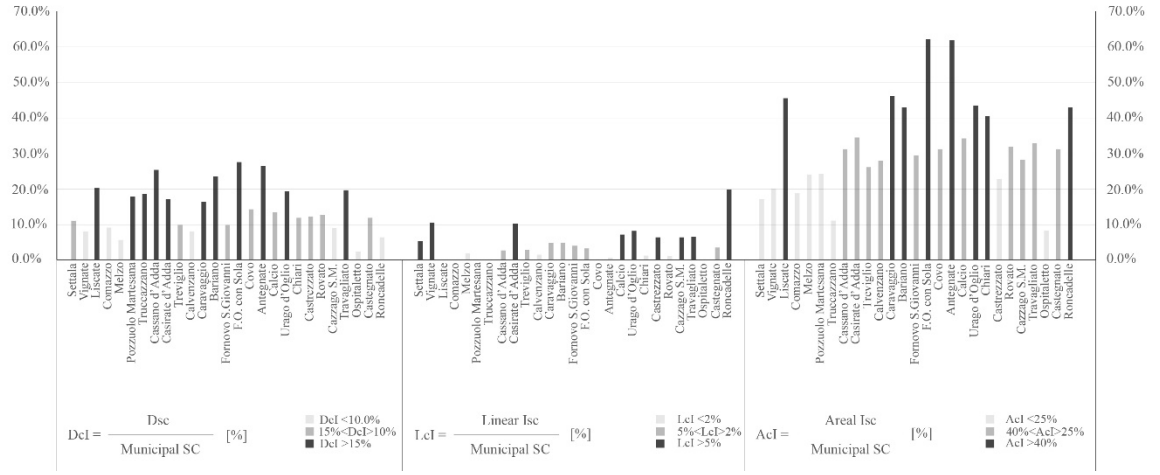

Fig.10 Incidence coefficient of soil consumption (direct and inducted) in the period 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

Starting from the DcI, in 11 municipalities (more than the 40% of the total amount) the value is quite relevant since it exceeds the 15%; in 9 municipalities (the 33%), the value appears between the 15% and the 10%; in the rest of the cases the incidence of the Brebemi on the total amount of the soil consumption registered in the period 2007-2018 is still greater than the 5% (except for Ospitaletto, which registered the 2.3%). More specifically, the most relevant values concern Cassano d'Adda (25.4%), Antegnate (26.4%) and Fara Olivana con Sola (27.5%): these values depend on the fact that the highway passes through the mentioned municipalities from side to side and not only partially as in other cases. Moreover, in the case of Fara Olivana con Sola the high value of soil consumption is also determined by the presence in the territory of the municipality, which is the smallest in terms of extension among all those considered, of a toll booth with the relative road junctions.

Considering now the LcI, the contribution is much lower (note that consistent parts of the new infrastructures fall outside the administrative limits of the municipalities crossed by the highway), but surpasses the 5% in 9 municipalities. A peak occurs in Roncadelle, where the linear Isc represents the 20% of the total soil consumption in the city for the period 2007-2018: as a matter of fact, in this municipality lots of intervention concerning the requalification of the South Beltway in Brescia had place, as part of the connecting and compensatory interventions of the Brebemi.

Regarding the AcI, the percentages appear more critical: just in 8 municipalities, almost the 30% of the total amount, this contribution is lower than the 25% of the total soil consumption registered in the territories; 11 cases have values between the 25 and 40%; finally, in 8 municipalities the values exceed the 40%, with peaks higher than the 60% for Antegnate and Fara Olivana con Sola.

The situation is even more alarming when we consider the contribution of the whole soil consumption due to the Brebemi highway (defined as Total-consumption of the Brebemi Index – TcI_B) (Fig.11): 19 municipalities, more than the 70%, reach values higher than the 40%, and 8 of them surpass the 60%. Again, the highest values are in the municipalities of Fara Olivana con Sola, 92%, and Antegnate, 88%: in other words, almost

the totality of the soil consumption occurred in these municipalities in the period 2007-2018 was made by the Brebemi itself, by the connected infrastructures and in a 1km area from the highway border.

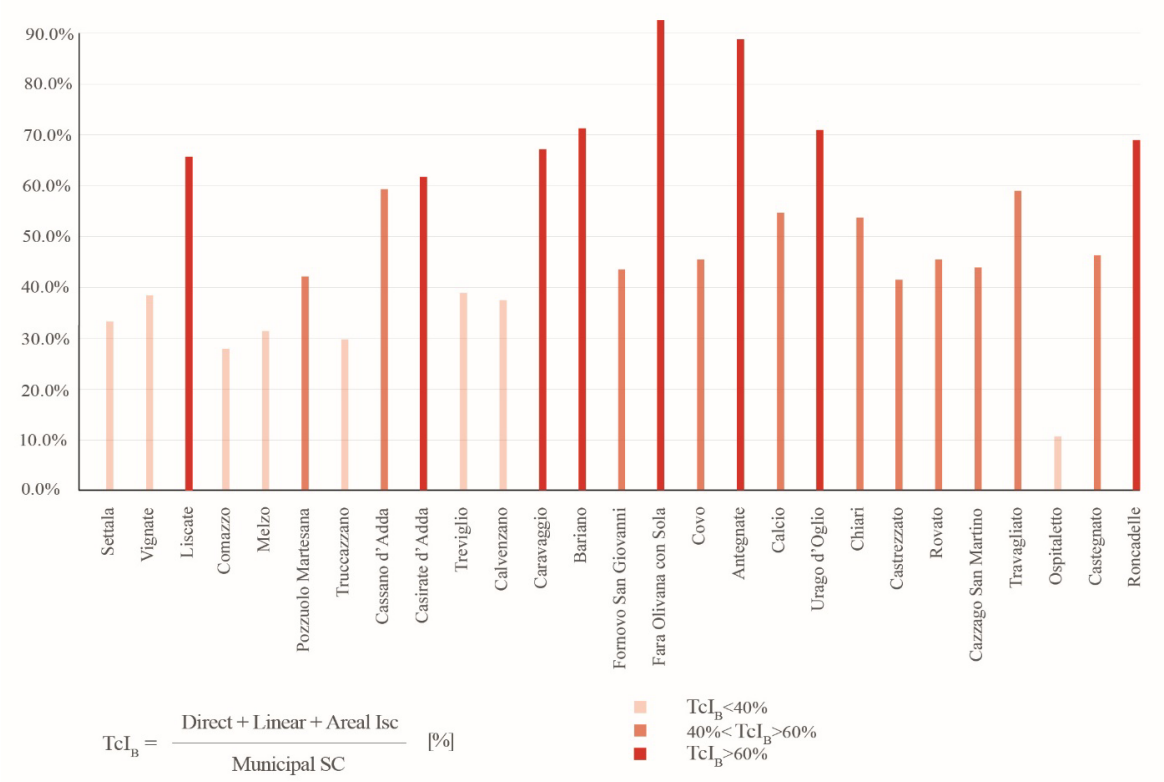

Fig.11 Incidence coefficient of soil consumption (direct + inducted) in the period 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

Given the higher contribution of the areal inducted soil consumption and since it is not possible to compare the direct and linear soil consumption in 2007-2018 to 1999-2007 (the infrastructures had not been built yet), Figure 12 reports the comparison between the AcI pre-Brebemi (period 1999-2007) and post-Brebemi (period 2007-2018). Except for few cases (Cassano d'Adda, Cazzago San Martino, Pozzuolo Martesana and Truccazzano), all the municipalities register a consistent increase in value of AcI: 11 municipalities show a more than threefold increase and among these 5 municipalities register more than five times the value of 1999-2007. Finally, three municipalities reach values at least 70 times higher than those of the previous period: more specifically, Comazzo passes from a percentage of 0.24% in 1999-2007, to a 18.70% in 2007-2018 (78 times higher); Calcio switches from 0.18% to 30.92% (168.8 times higher); Urago d'Oglio registers a 43.27% in 2007-2018 compared to the 0.16% in 1999-2007 (270.3 time higher).

In sum, we can state that the soil consumption in the 1km buffer zone has increased in the period post-Brebemi in almost all the municipalities crossed (except for four cases), passing from a total soil consumption of 225 ha in the period 1999-2007 to a value of 650 ha in the period 2007-2018 (Fig.13). A further reflection can be done by comparing areal induced soil consumption data in different buffer zones: 0-500m (already taken as Areal Isc), 500-1000m, 1000-1500m, 1500-2000m, 2000-2500m[11] (all are considered for each side of the highway). Such analysis makes us to better understand and quantify the Brebemi impact on land-use changes of the surrounding territory. The results are shown in Tab.4 and Fig.14, where it is evident how the soil consumption in the pre-Brebemi period is highest in the buffer area 1,000-1,500m. On the contrary, the lowest values are in the buffer areas 0-500m and 2,000-2,500m. This data is probably due to the distribution of the urbanized area.

[11] First results of this analysis were carried out by Fornasari, 2023.

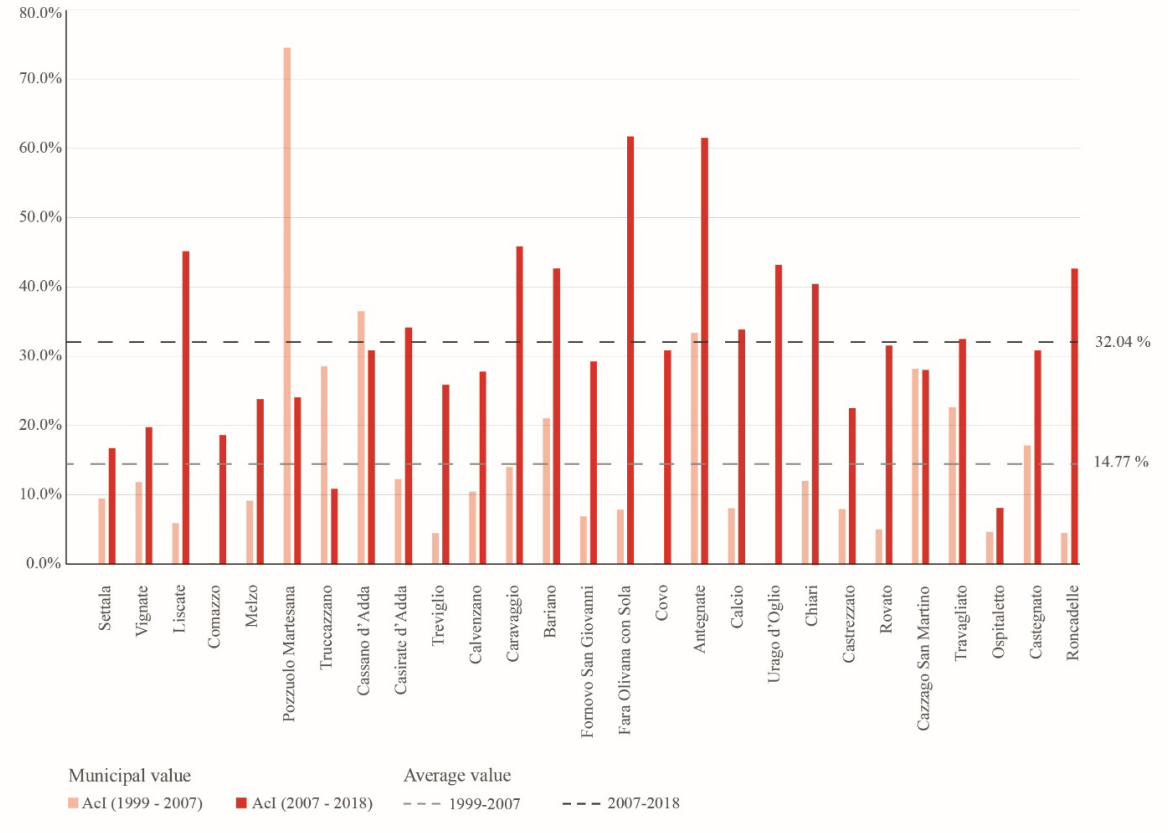

Fig.12 Incidence coefficient of ~~the~~ areal inducted soil consumption in the periods 1999-2007 and 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

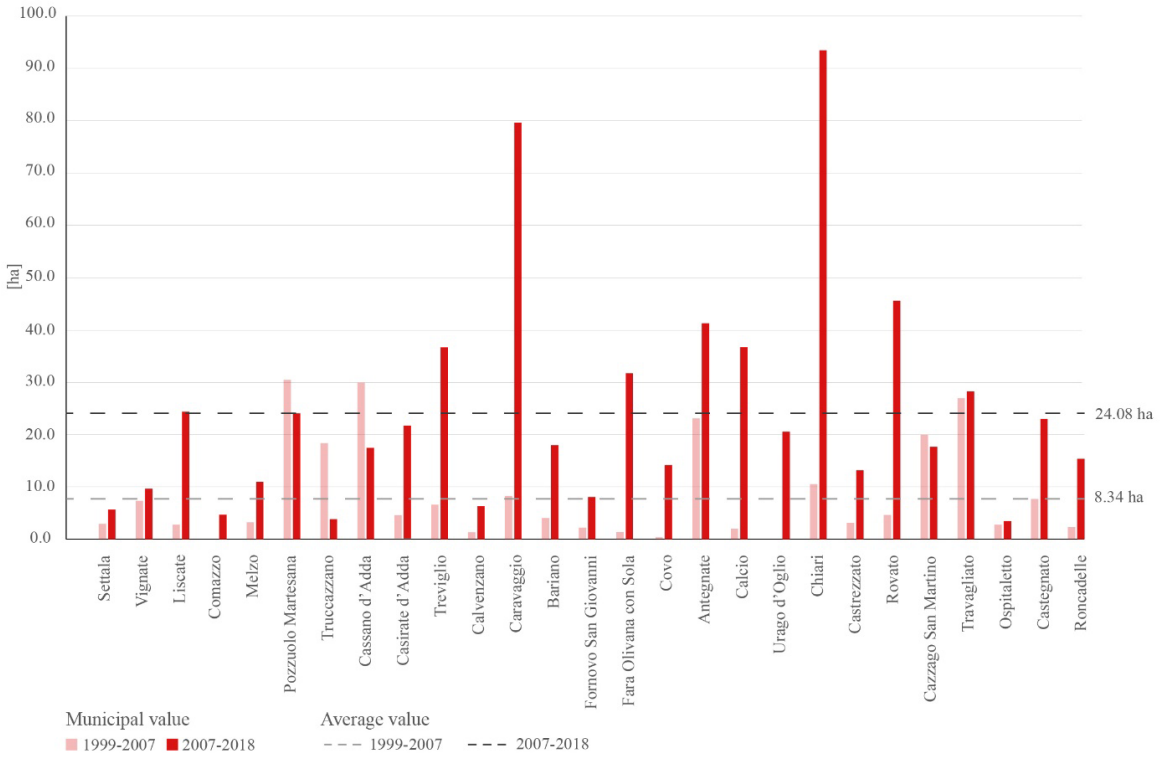

Fig.13 Areal induced soil consumption in the periods 1999-2007 and 2007-2018. The municipalities in the graph are located following the track of the Brebemi, from Milan to Brescia

As a matter of fact, in 1999, starting moment of the analysis, the coefficient of urbanized area for each buffer was quite different, varying from the 22% in the buffer of 1000-1500m (the highest value) to less than 10% in the buffer of 0-500m (the lowest one). The situation changes after the realization of the highway, in the post-Brebemi period, when the peak of soil consumption is in the buffer area 0-500m (note that in this buffer the value of the Dsc is always excluded). Such results confirm what has emerged from the previous analysis, namely that the Brebemi highway has strongly affected land-uses in its surroundings, by determining a huge inducted soil consumption.
However, it is also possible that in the future the Brebemi effect can propagate to greater distances from the highway as the closest buffers become saturated and the availability of building land decreases.

Buffer	**Soil consumption [ha]**		
	Pre-Brebemi (1999-2007)	Post-Brebemi (2007-2018)	Variation
0 - 500 m (Areal Isc)	225	650	195%
500 – 1,000 m	286	273	-5%
1,000 – 1,500 m	296	204	-31%
1,500 – 2,000 m	246	192	-22%
2,000 – 2,500 m	221	151	-32%

Tab.4 Values of soil consumption pre and post Brebemi for different buffer areas. The data do not include the values of the Brebemi highway and of the inducted infrastructures

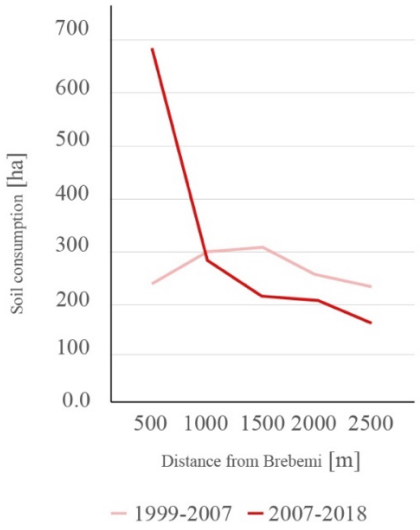

Fig.14 Areal induced soil consumption related to the distance from the Brebemi highway in the periods 1999-2007 and 2007-2018. The data do not include the values of the Brebemi highway and of the inducted infrastructures

6. Conclusion: monitoring and reducing direct and inducted soil sealing due to new road infrastructure

The paper has discussed the impacts on land transformations derived from the construction of a new highway, by focusing on the quantification of soil consumption. The analysis tackles two different kinds of transformations: one directly generated by the infrastructure itself (the natural soil lost due to the realization of the road); another inducted by the infrastructure (e.g. other new inducted infrastructures connected to the new road or new urbanized areas). The case study of the Brebemi highway in Italy was selected as a valid case to examine these double typologies of impacts on land transformations. The analysis has been carried

out in order to quantify the impacts on soil consumption caused by the infrastructure itself (defined as direct soil consumption), but also caused by the new infrastructures connected to the highway (defined as linear inducted soil consumption) and by new urbanized areas located in a buffer zone of 500m from each side of the highway (defined as areal inducted soil consumption). The results have demonstrated how the Brebemi has been a decisive lever for the land transformations: not only for its direct impact, but mainly for the inducted works. The discussion about the inducted part is one of the main results of this analysis, since it demonstrates that the construction of a new infrastructure, especially of national or over-local level, needs to be considered in its whole dimension of environmental impacts. This means acknowledging that the effects of highway construction will extend across both space and time, spanning different jurisdictions both horizontally (involving multiple municipalities, provinces, or even regions) and vertically. Indeed, for such major infrastructure projects, the approval process typically begins at the national level and subsequently involves lower levels of governance. For its approval, the Brebemi highway project by-passed the typical Environmental Impact Assessment (EIA) process in favor of a faster, more streamlined evaluation under the so-called "Obiettivo Law" (Law No. 443/2001). This acceleration, typical of large-scale and strategic public works or infrastructures, often raises justified criticism, particularly because, while they could arise significant economic and social benefits, they also tend to cause the most widespread and unpredictable environmental impacts on a large scale. The findings of this study should highlight the need for a more in-depth evaluation of highway impacts, with particular emphasis on assessing previsions on soil consumption and recognizing induced soil consumption as a potential effect. Concurrently, within planning instruments, previsions on land transformations (not only due to the infrastructure itself but also to induced soil consumption) must already today be subject to Strategic Environmental Assessment (SEA) to evaluate environmental impacts. However, at the planning stage territorial authorities should broaden and strengthen this assessment process, which is neither uniform nor consistently effective in evaluating and measuring soil consumption (Moscarelli and Pileri, 2020). This should apply both to municipal master plans, which are in most of the cases responsible for land cover transformations, and to larger territorial areas, such as provinces, which can provide a broader and cumulative perspective on the spatial effects of a single infrastructure. The correlation between the Brebemi and what has been defined as inducted transformations, linear and areal, is at the same time an added value of the analysis and a critical point of it. As a matter of fact, it not completely demonstrable that inducted transformations, especially the areal ones, were provoked by the new highway. This can be assumed as a limit of the analysis, even if the decision of considering just a 1km buffer zone can in part reduce such weakness. Moreover, the indicators presented in the discussion, especially those including the comparison between the period pre and post-Brebemi, describe almost in all the cases the high incidence of the Brebemi and, thus, its reasonable incidence in the inducted transformations of the soil. Such data are in part confirmed by the local plans, which in 12 cases (44.4% of the total municipalities crossed) explicitly declare that the new urban transformations are strongly influenced and fostered by the presence of the Brebemi[12] (Giuliani, 2023). Nevertheless, it would be interesting to deepen the analysis of the correlation between the infrastructure and other inducted works, also considering the scientific debate on the road-effect zone. In this sense, it would be necessary to carry out a more detailed study on the land cover transformations in a wider part of territory, e.g. by identifying different buffer zones. Another point that should be analyzed more deeply concerns the typology of transformations more spread in the buffer zone, whether they are productive, logistic, commercial or residential: in this way it would be possible to enrich the correlation between new infrastructures and transformations of the territory. In addition, future studies should be aimed at assessing land consumption

[12] This regards, in particular, Bariano (Municipality of Bariano, 2013), Calcio (Municipality of Calcio, 2017), Calvenzano (Municipality of Calvenzano, 2011), Caravaggio (Municipality of Caravaggio, 2013), Castrezzato (Municipality of Castrezzato, 2012), Cazzago San Martino (Cazzago San Martino, 2007), Chiari (Municipality of Chiari, 2009), Fornovo San Giovanni (Municipality of Fornovo San Giovanni, 2011), Liscate (Municipality of Liscate, 2011), Pozzuolo Martesana (Municipality of Pozzuolo Martesana, 2014), Settala (Municipality of Settala, 2011), Travagliato (Municipality of Travagliato, 2011).

after 2018 (and thus not registered by the DUSAF version considered) still connected to the construction of the highway, a link that is likely and confirmed by local plans: for example, the municipality of Chiari registered a consistent logistical expansion in 2021 declaredly connected to the presence of the Brebemi in the territory (Giuliani, 2023). Finally, it could be useful also to compare this case with other relevant infrastructures, in order to verify whether the land transformations trends appear similar or not.

Author contributions

The authors have shared the concept of the paper. R.M. has written the paragraphs 1,2 and 5. M.G. has written the paragraphs 3,4 and 6. The part written by R.M. is a result of the SPADES project, funded by the European Union (Grant Agreement No. 101146122). Views and opinions expressed are, however, those of the author only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor REA can be held responsible for them.

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Image Sources

Fig.1 – 14: own elaborations by authors

Tab. 1 – 4: own elaborations by authors

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Mobility changes occasioned by COVID-19 lockdown measures: evidence from an emerging economy

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Abstract
The unprecedented and drastic emergency responses that accompanied the declaration of COVID-19 as a pandemic have highlighted and intensified mobility injustices worldwide. Most of the global interest in the impact of COVID-19 on mobility patterns has come from developed countries, leaving a gap in literature specifically focused on Africa. This paper aims to fill that gap by examining the effects of government-imposed travel restrictions on people's attitudes and mobility behavior in urban Ghana. Using a combination of data sources, including surveys and photographic evidence, we analyze the spatial variations in mobility patterns during the lockdown. Our findings from statistical analyses and time-lapsed images indicate that many young people, informal sector workers, and individuals living in disadvantaged neighborhoods largely ignored the lockdown order. In contrast, most formal sector employees utilized internet-enabled telecommuting, e-learning opportunities, and telephone communications during the lockdown period. The paper concludes with policy recommendations aimed at enhancing mobility justice for all in the face of future public health crises and social emergencies that may require physical mobility restrictions.

Keywords
COVID-19; Lockdown; Mobility; Accra; Ghana

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1. Introduction

Transport plays a crucial role in fostering socio-economic growth and development by providing access to people, goods, and services, ultimately enhancing the quality of life and well-being of users. However, traditional approaches to urban and transport planning often overlook the unique characteristics of individual users (Carpentieri et al., 2023). Coupled with systemic inequalities, infrastructural limitations, and socio-economic disparities, this has led to persistent mobility challenges, particularly for marginalized populations, including individuals with disabilities, the elderly, youth, economically disadvantaged groups, and rural dwellers (Di Roucco, 2025). Research shows that women, for example, do not have equal access to walk to various city areas (Carpentieri et al., 2023). Meanwhile, engaging in physical activities, such as walking and relaxing in urban greenspaces, can be linked to improved therapeutic and psychological well-being (Sari et al., 2023). Consequently, Di Ruocco (2024, p. 106) argues that "the economic development of the city and the attainment of excellent quality of life indicators of the city" remain elusive. To achieve Global Goal 11 — to "make cities inclusive, safe, resilient, and sustainable" (UN, 2023) — it is imperative not to ignore the injustices in transportation. As Martens (2017, p. xiv) cautions in the preface to his book 'Transport Justice,' "governments, as representatives of all persons in their jurisdictions, have a moral obligation to act as guardians of the interests of all individuals. Their actions should thus avoid pertinent injustices while promoting justice where practically feasible." By advocating for mobility justice, we can ensure that everyone has equal access to "safe, affordable, convenient, dignified, and reliable transportation options that allow them to lead joyful, meaningful, and fulfilling lives" (Karner et al., 2023, p. 5).

The unprecedented and drastic emergency responses following the declaration of COVID-19 as a pandemic—including lockdowns, physical distancing, frequent hand washing, face mask use, remote work, and border closures—have exposed and intensified levels of mobility injustices worldwide. This is especially true in low- and middle-income countries like Ghana, where existing challenges such as erratic power supply, limited internet connectivity, gender gaps in internet access, informality in work, and over-reliance on road transport contribute to transport poverty for many residents (Wrigley-Asante & Agyemang, 2019; Mogaji, 2020).

This paper aims to highlight how the COVID-19 pandemic and the strict lockdown measures implemented by the Ghanaian government may have exacerbated socio-economic gaps in accessibility in Accra. We chose Accra because, as the national capital of Ghana, it is the most densely populated city with diverse socio-economic and residential groups. Additionally, it was the site of the first COVID-19 case in Ghana, experiencing a significant increase in deaths and illnesses that led to government-imposed restrictions. As recently as July 1, 2025, Ghana's Ministry of Health confirmed 107 new cases and an additional 316 suspected cases of the Omicron sub-variant of COVID-19 in Accra (Addae, 2025).

In this context, as the COVID-19 pandemic enters a new phase of uncertainty, some commentators have begun referring to it as 'long COVID' or 'long-haul COVID' (Soriano et al., 2022; CDC, 2022). Indeed, as Nia (2021) warns, the number of pandemics has dramatically increased over the last 200 years, raising the likelihood of future pandemics. Therefore, it is critical to reflect on the effects of past policy responses to develop nuanced and contextualized scientific knowledge for decision-makers to combat the disease and its impacts. This paper makes two key contributions. Methodologically, we triangulate various data sources, including surveys and photographs, to map spatial variations in mobility patterns. Empirically, we provide evidence of how the pandemic has affected travel behavior differently across socio-economic groups in a developing country context, highlighting policy implications for post-COVID-19 planning of inclusive mobility options.

2. Literature review

The COVID-19 pandemic had a profound impact on research activities (Sohrabi et al., 2021). Studies have specifically examined the policy implications of lockdown measures and their strict physical restrictions on

social interactions, particularly concerning transport travel behavior (de Haas et al., 2020; Rodríguez González et al., 2021; Munawar et al., 2021; Li et al., 2022; Gramsch et al., 2022; Gladwin & Duncan, 2022; Vallejo-Borda et al., 2022; Lu & Giuliano, 2023; Kroesen et al., 2023; Hintermann et al., 2023). Collectively, these studies show that transport users adapted dynamically during and after the pandemic. For example, due to concerns about contracting the virus, fewer people used public transport and instead chose less crowded, active modes of transport like cycling and walking. Telecommuting and online shopping also gained popularity among urban residents during the lockdown, particularly in high-income countries with accessible internet facilities. However, in poorer and ethnically marginalized areas, compliance with government stay-at-home orders was often lacking.

Additionally, other research highlighted how the lockdown measures reduced anthropogenic sources of pollution, including emissions from industries and transport, and their implications for public health risks (Venter et al., 2020). These studies were conducted in major European cities such as Rome, Milan, and London (Winkler et al., 2021; Aboagye et al., 2021; Llaguno-Munitxa & Bou-Zeid, 2023) and in North American cities like Boston and Atlanta (Terry et al., 2021; Huang et al., 2021). Similar studies in Asian cities, including Beijing, Nanjing, Lucknow, New Delhi, Peshawar, Karachi, Quetta, Lahore, and Islamabad (Srivastava et al., 2020; Lin et al., 2021; Tao, Diao & Cheng, 2021; Khan, 2021), unanimously concluded that transport-related NO2 and PM2.5 concentrations significantly decreased, improving ambient air quality, although indoor air quality deteriorated due to increased heating and cooking.

Some commentators have argued that much of the research on the pandemic's effects on mobility and environmental outcomes has primarily focused on high- and middle-income countries (Kutela et al., 2021). In fact, data on COVID-19 and mobility patterns in response to government interventions are scarce in low-income nations (Kim, 2021). Noteworthy studies from Africa include Sogbe (2021) in Ghana and Mogaji et al. (2022) and Mogaji (2022) in Nigeria. For instance, Mogaji et al. (2022) found that impoverished and marginalized residents of Lagos, who typically relied on jitney-type public transport known as "Danfo," faced higher costs because of limited bus space; opportunistic drivers took advantage of this scarcity to charge more. Their survey participants also indicated a willingness to change their travel behavior post-pandemic, particularly regarding telecommuting and online shopping.

Research from Ghana has primarily focused on the health and economic impacts of COVID-19 on vulnerable populations (Asante et al., 2021). Some studies have also examined the level of compliance with specific COVID-19 mitigation measures implemented by the government, such as the use of face masks and hygienic practices (Dzisi & Dei, 2020; Bonful et al., 2020; Agyemang et al., 2021). Additionally, there has been documentation regarding the mistrust in government mitigation measures (Owusu et al., 2022; Bisung et al., 2021). Nathavni et al. (2022) conducted a significant study that utilized intelligent sensing and analytics to analyze the spatial and temporal dynamics of Accra's environment, focusing on health, livability, safety, and sustainability before, during, and after the city's lockdown. However, they did not explore the social science aspects of transportation, particularly the impact of lockdown on the mobility patterns of different socio-economic groups living in various urban neighborhoods, as has been discussed in other studies (Lu & Giuliano, 2023; Daňková, & Dostál, 2011).

To address this gap in the literature, this paper aims to investigate how COVID-19-induced travel restrictions differentially affected attitudes and mobility behaviors in urban Ghana. The goal is to highlight and promote concepts such as 'urban environmental justice' (Llaguno-Munitxa & Bou-Zeid, 2023), 'socially sustainable transport' (Dankova & Dostal, 2011), 'transportation justice' (Karner et al., 2023), and 'eco-mobility justice' (Di Ruocco, 2024).

Socially sustainable transport acts as a bridge between various cultures and social groups, helping to reduce barriers to communication and fostering beneficial coexistence (Dankova & Dostal, 2011). The present authors draw inspiration from previous research, which asserts that "to achieve true justice, transportation researchers

from across the disciplinary spectrum need to continue to advance their work, engage with affected communities, and aim for transformative change" (Karner et al., 2023, p. 5).

3. Materials and methods

3.1 Research Design

In line with the research objectives of this paper, we conducted surveys to assess the lived mobility experiences and social interactions of residents in the Greater Accra Metropolitan Area (GAMA) during three distinct periods: before, during, and after the COVID-19 lockdown. With a population exceeding 5 million (GSS, 2021), GAMA comprises the Greater Accra Region and its contiguous areas, including Kasoa in the Awutu Senya East Municipality (Agyemang, 2017). For the specific age group of interest (18-80 years), the Ghana Statistical Service (2021) estimates the total population at approximately 3,046,719. For a population of over 100,000, a sample size of 400, at a 95% confidence interval and a 5% margin of error, is considered ideal and representative of the general population (Israel, 1992). To account for potential incomplete responses, we adjusted the sample size by 40%, resulting in a total of 560 participants.

Survey participants were recruited via an online questionnaire created using the KoboCollect toolbox. We utilized a convenience sampling method and shared a link among the researchers' professional and non-professional networks, similar to previous studies (Sureshkumar, 2023; Zuiderwijk, 2024). The survey was disseminated through social media platforms, notably WhatsApp, Twitter, and Instagram, between September 25th and October 13th, 2020.

To ensure that participants were residents of GAMA and responding from the appropriate geographical area, they were required to provide the name of their neighborhood. Additionally, a GPS locator was embedded at the end of the questionnaire to automatically capture participants' locational coordinates. Participants were encouraged to share the survey link with their contacts using a chain sampling approach. To include views from individuals in the informal sector, who are generally offline, we allowed participants who completed the survey to explain the instrument to adult acquaintances who could not read but wished to participate. A reminder was sent to participants and, through them, to their contacts on October 1st, 2020, to increase the response rate.

3.2 Questionnaire survey data

The survey measured various aspects of the participants' socio-economic backgrounds, including gender, age, education, and occupation. It also assessed attitudes toward COVID-19, including participants' fear of the virus, compliance with lockdown directives, and commuting behaviors before, during, and after the lockdown. Of the 560 submissions received, 77 were discarded due to being incomplete, resulting in a response rate of 86.3% (i.e., 483 valid responses). Preliminary data treatment indicated that the sampled population did not accurately represent the demographic dynamics of GAMA. This discrepancy was partly due to the method of data collection. To address this, we adjusted the data to reflect the age and gender distribution of GAMA, as published by the Ghana Statistical Service, using MATLAB R2018b (version 9.5) software. We developed an algorithm based on the concept of iterative proportional fitting to generate weights for the sampled individuals. The weights for each category (age x gender) were calculated by dividing the general population categories normalized to the sampled respondents' demographic categories. The weighted data were further analyzed for consistency and reliability, resulting in a Cronbach's Alpha score of 0.72, indicating that the data is robust, consistent, and reliable (van Griethuijsen et al., 2014).

We used IBM SPSS software (version 20) to analyze our primary survey data. In addition to descriptive statistics, we performed Pearson's chi-squared tests to evaluate variations among different groups of

respondents regarding their mobility patterns and to assess statistical significance. Furthermore, we conducted correlation analyses to understand the strength of linear relationships among the socio-economic and demographic groupings.

3.3 Remotely-sensed data

Following the approval of the study protocol (ECH147/18-19) by the University of Ghana Ethics Committee for the Humanities, and with the permission of local residents, we installed Moultrie-M50 cameras at 145 sites throughout the Greater Accra Metropolitan Area (GAMA) over a 15-month period, capturing approximately 2 million time-lapsed images. As previously described (Nathavni et al. 2022), our research team labeled a subset of 1,250 images containing 20 contextually relevant distinct objects related to mobility, safety, leisure and play, daily life activities (such as shopping), air and noise pollution, and sanitation and hygiene. We stratified the images based on the frequency and size (measured by pixel count) of each object category. Additionally, we categorized the images as color or greyscale, corresponding to daytime and nighttime images. These strata were split into subsets of 60% for training, 20% for validation, and 20% for testing an adapted convolutional neural network (CNN) model. Further details concerning our image labeling protocol, the analysis code used for our model's basic parameters, and the calculations of mean and standard deviations for the images can be found at https://zenodo.org/records/7401005#.Y44cfi-l19c.

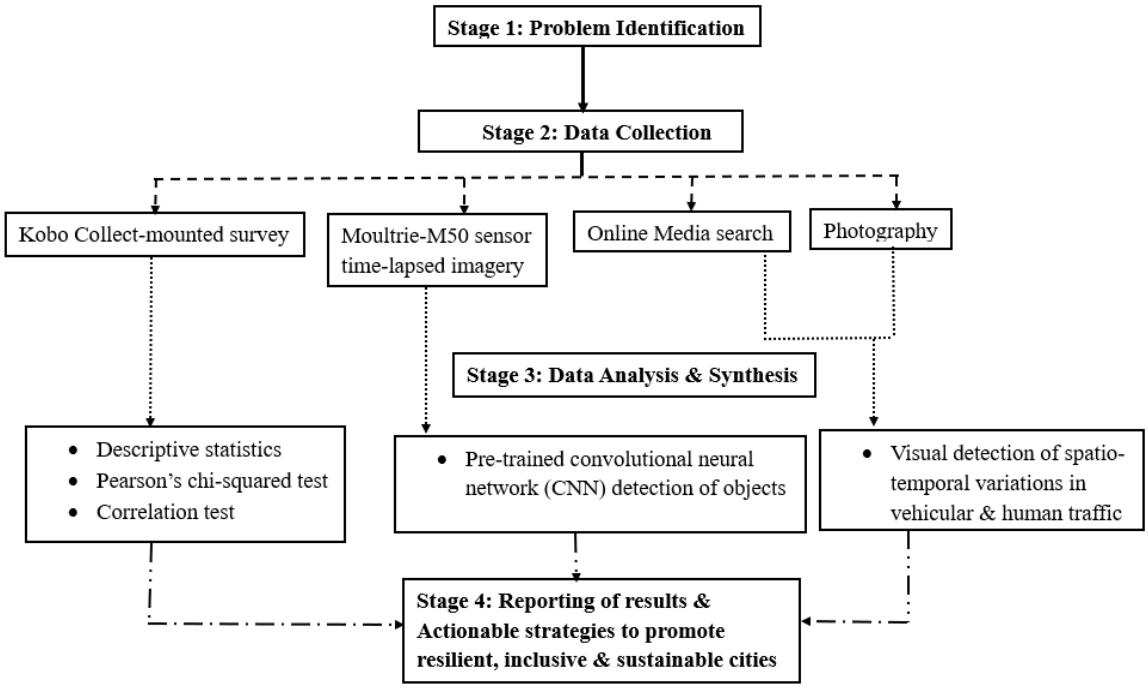

Fig.1 The research flow chart process

To study the impacts of the lockdown order in the time-lapsed images, we carefully selected data from four distinct neighborhoods in Accra: Nima, Asylum Down, East Legon, and Labadi. Nima is a densely populated and culturally diverse community featuring a mix of residential and commercial areas, located in the Ayawaso West Municipal District of Accra. Asylum Down is situated in the heart of the Accra Metropolis, characterized by a blend of old and new residential buildings and commercial activities. East Legon is an upscale residential area that includes luxury homes, apartments, and gated communities. Labadi, commonly referred to as La, is in the La Dade-Kotopon Municipal District of Accra and is known for its popular beachfront area, combining residential and commercial properties. We also included data from the University of Ghana and the Accra-Tema Motorway for our analysis. The algorithm used in our study categorized the presence of the objects of interest into three distinct time frames. The 'pre-lockdown' period is defined as the 21 days prior to the

declaration of lockdown in Accra (March 9th - March 29th, 2020). The 'lockdown' period is defined as the 21 days during which Accra and surrounding districts were under quarantine (March 30th - April 19th, 2020). The 'post-lockdown' period is defined as the 21 days following the announcement of the easing of the lockdown by the President of Ghana (April 20th - May 10th, 2020).

Finally, we gathered internet media reports and photographs taken by journalists along some major, busy corridors of Accra one day after the lockdown was announced. After the lockdown was lifted, and while following all COVID-19 safety protocols, we conducted field observations and documented the level of traffic activity in those same locations photographically.

The photographs taken during and after the lockdown were placed side-by-side for analysis to identify the settings, including geographic areas, time of day, and the surrounding environment. This analysis aimed to gauge the level of vehicular traffic and human activities during the specified periods. A summary of the research flow is presented in Fig.1.

4. Results

4.1 Data characteristics

The data indicates that just over half of the surveyed population were females, comprising 51.1%. In terms of age, the majority of participants were millennials (42.9%) and post-millennials (24.6%). These gender and age demographics reflect the population structure of Ghana and many African countries, which typically have a higher proportion of youth and females.

More than two-thirds of the sampled population were highly educated, including those who were tertiary students at the time of the survey (24.6%), those who had obtained diplomas and degrees (26.5%), and individuals with postgraduate degrees (23.2%). Regarding occupational status, over half of the participants (55.5%) reported being employed in the formal sector, while nearly a quarter (24.8%) were still students. Employees in the informal sector represented the smallest group at 19.7%.

Most survey participants (62.3%) identified themselves as regular users of public transport, with around 30% indicating they used cars. Additional information about the survey participants can be found in Tab.1.

Variable	**Category**	**Frequency**	**Percent**
Gender	Male	236	48.9
	Female	247	51.1
Age	18-24 (Post-millennials)	119	24.6
	25-39 (Millennials)	207	42.9
	40-54 (Generation X)	100	20.7
	55 + (Baby-Boomers)	57	11.8
Education	No formal education	15	3.1
	Basic (Primary & Junior High)	46	9.5
	Senior High	63	13
	Tertiary (currently enrolled)	119	24.6
	Tertiary (Completed)	128	26.5
	Postgraduate (Masters & higher)	112	23.2
Occupation status	Formal sector	268	55.5
	Informal sector	95	19.7
	Student	120	24.8
Commute Mode share	Motor taxi (Okada)	1	0.2

Bus	2	0.3
Traditional taxi	11	2.3
App-based taxi	28	5.7
Car	141	29.2
Trotro	301	62.3

Tab.1 Overview of survey participants

4.2 Attitudes towards Covid-19 and lockdown compliance

When asked, "Did you visit family and friends outside of your home during the lockdown period, and how often?" the data revealed that a majority (88%) of participants complied with the directive to stay indoors. However, a weak statistical variation (p=0.037) was observed in terms of full compliance with the lockdown directive based on the age of the participants. Fig.2 illustrates that millennials and post-millennials were more likely to violate the lockdown order compared to other age groups, having visited individuals outside their immediate households a few times. Interestingly, while individuals over 55 years largely complied with the directive, approximately 14% of them reported visiting other locations "about one or two times".

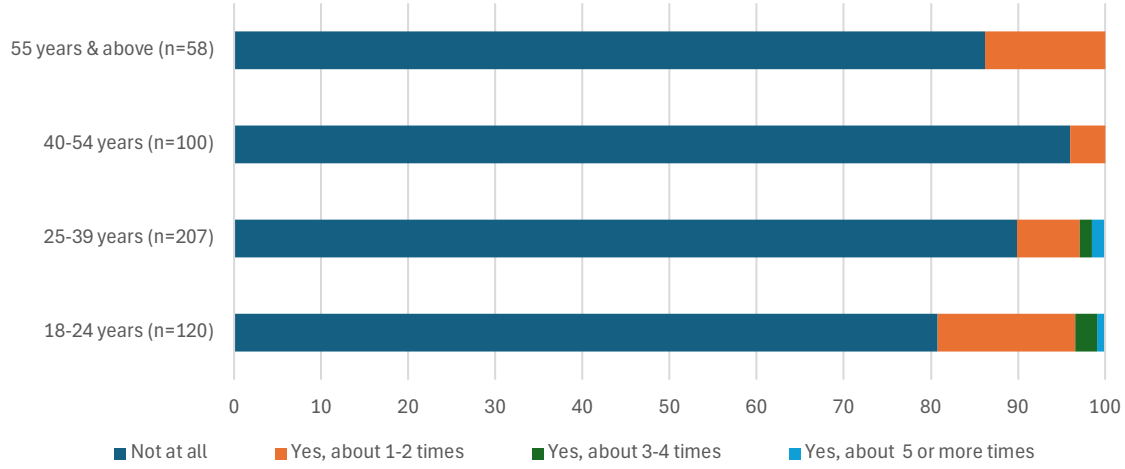

Fig.2 Compliance with lockdown directive by the age of participants

4.3 Adaptation to Covid-19 mobility restrictions

To overcome geographic barriers and stay connected during the lockdown period, many participants utilized telephone and internet-enabled services. Data revealed that a significant portion of survey participants (40%) engaged in internet-based telecommuting and e-learning opportunities during the lockdown.

However, following the relaxation of social restrictions, there was a 47.8% decrease in the use of telecommuting and e-learning. Conversely, physical movements for work-and-study-related trips increased by 31.8% after the lockdown period, as shown in Fig.3.

A Chi-square test for independence (with Yates continuity correction) indicated a statistically significant association [X^2 (5, n=484), p =0.001, phi=0.38] between the educational status of participants and their choice of mode of transport (i.e., physical or virtual) during and after the lockdown measures. The results showed that, during the lockdown, all respondents with no formal education (100%) and a majority of those with basic education (93.6%) or senior high education (88.9%) continued to physically commute to their destinations. This trend persisted even after the government lifted the ban on physical mobility. In contrast, about 50% of respondents who had completed their degrees or were pursuing degree programs primarily relied on telecommuting or e-learning during the lockdown. The data revealed that most students (51.7%)

utilized virtual technologies for e-studying or telecommuting in response to the lockdown, although there was a notable decline of about 58% in internet use for these purposes following the easing of restrictions.
Similarly, the type of occupation [X^2 (2, n = 483), p = 0.001, phi = 0.34] was statistically associated with transport mode choices during both periods under consideration. As expected, informal sector employees primarily commuted physically during the lockdown (94.7%) and continued to do so after restrictions were eased (92.6%). In contrast, 45% of formal sector employees used the internet to perform their functions during the lockdown, but this figure dropped by 44% once the lockdown was lifted.

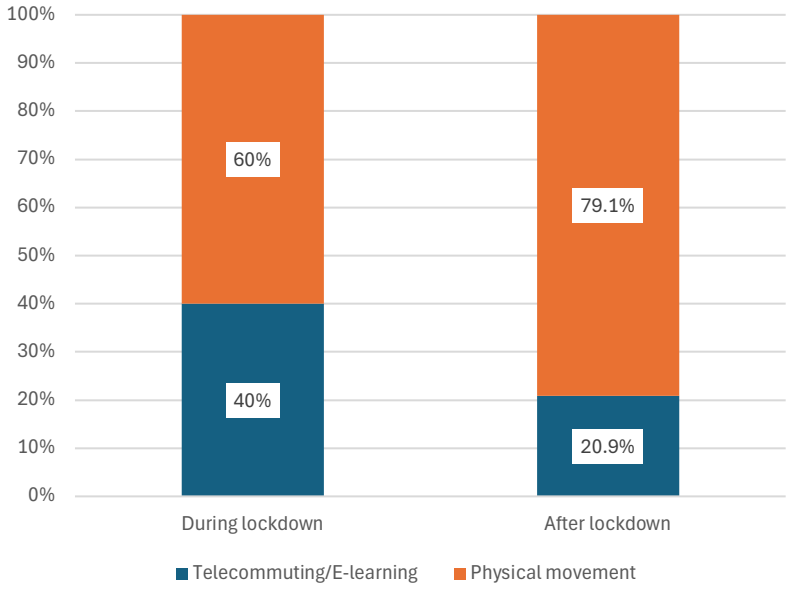

Fig.3 Modal share dynamics during and after lockdown for work/study-related trips

Furthermore, the age predictor variable was only statistically significant during the lockdown period [X^2 (3, n = 482), p = 0.001, phi = 0.34)], indicating it played a role in mode choices (i.e., physical or virtual transport) only during this time. During the lockdown, 61% of Generation X respondents reported a significant increase in their internet use for social activities. However, older individuals from the Baby Boomer generation primarily continued to commute physically and did not rely on telecommuting during the lockdown.
Interestingly, the perception of increased internet use to bridge geographic distances during the lockdown period was unexpectedly low among many younger respondents. Tab.2 provides further details on the relationship between transport mode choice and lockdown orders among various sample populations.

Variable	Category	DURING LOCKDOWN		P-value	AFTER LOCKDOWN		P-value
		Virtual Access	Physical Access		Virtual Access	Physical Access	
Age	18-24	45 (37.4%)	74 (62.2%)	0.000	21 (17.6%)	98 (82.4%)	0.187
	25-39	79 (38.3%)	127 (61.7%)		43 (20.8%)	164 (79.2%)	
	40-54	61 (61.0%)	39 (39.0%)		27 (27.0%)	73 (73.0%)	
	55 +	0 (0.0%)	57 (100%)		8 (13.8%)	50 (86.2%)	
Education	No formal education	0 (0.0%)	15 (100%)	0.000	0 (0.0%)	15 (100%)	0.000
	Basic (Primary & Junior High)	3 (6.4%)	44 (93.6%)		5 (10.6%)	42 (89.4%)	

	Senior High	7 (11.1%)	56 (88.9%)		7 (11.1%)	56 (88.9%)	
	Tertiary (currently enrolled & completed)	176 (49.0%)	183 (51.0%)		88 (24.5%)	271 (75.5%)	
Occupation status	Formal sector	118 (45.0%)	150 (55.0%)	0.000	66 (24.6%)	202 (75.4%)	0.002
	Informal sector	5 (5.3%)	90 (94.7%)		7 (7.4%)	88 (92.6%)	
	Student	62 (51.7%)	58 (48.3%)		26 (21.7%)	94 (78.3%)	

Tab.2 Modal share dynamics of participants during and after the lockdown

4.4 Spatio-temporal patterns in human and vehicular traffic in response to Accra's lockdown

Our observations indicate a general decrease in social activity, as reflected by the reduced presence of people due to lockdown measures. Fig.4 illustrates the mean daily trends in the number of people recorded through images taken before, during, and after the lockdown in Accra. The shaded bands represent the standard deviation variation at specific times of day before the lockdown, allowing for a comparison of subsequent trends relative to pre-COVID periods.

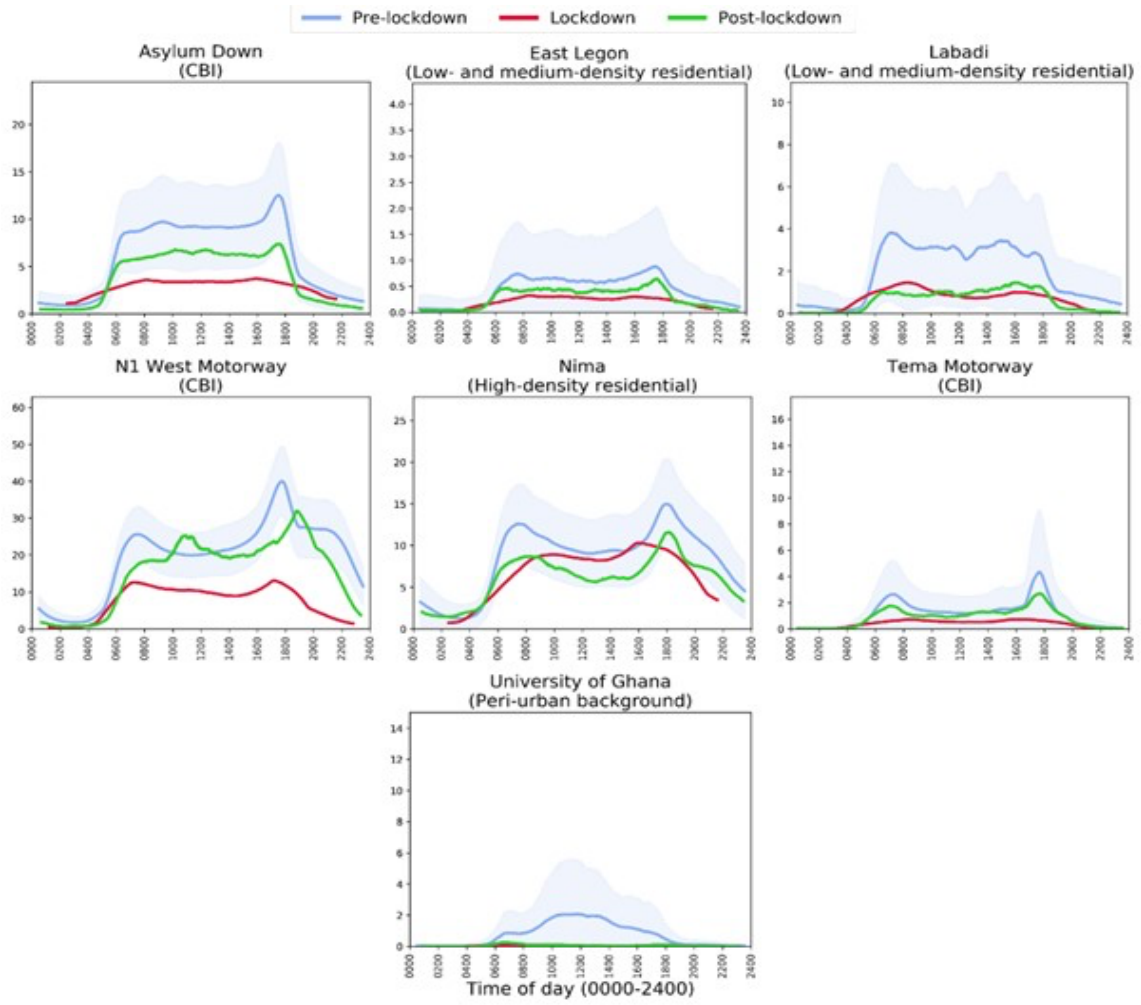

Fig.4 Average daily trends of counts of people in imagery (smoothed) in before, during and after the COVID-19 lockdown

During the lockdown, the data reveal a significant reduction in the presence of people during daylight hours (approximately 6 am to 6 pm) across all observation sites, compared to average levels before lockdown.

However, in Nima, the observed reduction was proportionally smaller. In contrast, at Asylum Down, East Legon, and Labadi, the number of people present in the early morning hours (around 12 am to 5 am) was slightly higher than during the pre-lockdown period, though still within the range of variation observed earlier. In higher-income neighborhoods like East Legon and the nearby major public university, the visible presence of people was minimal. After the lockdown was lifted, the number of people returned to just below pre-lockdown levels at all observation sites except for two locations—Labadi and the public university campus—where the presence remained at lockdown levels immediately following the easing of restrictions.

Similarly, photographs taken the day after the lockdown was enforced showed deserted streets and public transport terminals. However, shortly after the lockdown was lifted, traffic activity levels returned nearly to pre-lockdown volumes, as shown in Figs.5 (a & b) and 6 (a & b).

(a) (b)

Fig.5 Changes in vehicular and human traffic at the Kaneshie-Odorkor stretch of the Busia Highway in Accra: (a) during the lockdown (31/03/2020 at 4:50 pm; Photo credit: Adomonline, 2020) and (b) after lockdown (28/10/2020 at 4:50 pm; Photo credit: Field data, 2021)

(a) (b)

Fig.6 Changes in vehicular and human traffic at the Kaneshie Market Trotro station in Accra: (a) during the lockdown (31/03/2020 at 4:50 pm; Photo credit: Adomonline, 2020) and (b) after the lockdown (28/10/2020 at 4:50 pm; Photo credit: Field data, 2021)

5. Discussion

The role of transportation in sustainable development was first recognized at the 1992 United Nations Earth Summit (UN, 2025). Effective and efficient transportation is essential for achieving inclusive, resilient, and sustainable cities for all, as outlined in Global Goal 11 (UN, 2023). The COVID-19 pandemic and its related mobility restrictions helped keep the public safe but also exacerbated existing socio-economic disparities in accessibility for various socio-economic groups, hindering progress toward the goal of leaving no one behind.

It is critical that governments and city authorities ensure mobility justice, aiming to provide equal access to transportation benefits for all individuals during both normal and crisis situations.

Focusing specifically on Accra, our data indicates that as many as 88% of survey participants complied with the announced lockdown order. This high level of compliance may be partly due to the fact that over half of the sampled population consists of formal sector employees in government or private organizations. Aside from a few essential service providers, educational and formal institutions were ordered to shut down during the lockdown. Most academic and work-related interactions were conducted online, with a significant 40% of survey participants relying on internet-enabled telecommuting, e-learning opportunities, and telephone calls during this period. This finding aligns with an earlier study showing that workers in areas with established COVID-19 mitigation cultures, including regular health monitoring and encouragement to self-quarantine when exposed to the virus, were more likely to comply with mitigation protocols (Probst et al., 2021).

Conversely, we observed that many young people (ages 18 to 39) largely disregarded the lockdown order. This behavior is understandable, as younger individuals generally perceive themselves to be healthier and thus more resilient than older populations. Previous studies have confirmed that older individuals are more likely to follow social distancing regulations (Durizzo et al., 2021) and other COVID-19 mitigation measures (Agyemang et al., 2021). In our study, a larger percentage of older formal sector workers reported a significant increase in internet usage during the lockdown.

Moreover, most respondents from the informal sector seldom utilized the internet as a safe and efficient means of social interaction and livelihood during the lockdown in Accra. The nature of informal sector jobs, especially in food services and hospitality, requires workers' physical presence. Street vendors, market traders, and porters, who make up a substantial portion of the urban informal economy, typically earn their livings in public spaces (WIEGO, 2024). When quarantines prevented them from engaging with clients physically, they faced significant livelihood losses. Research shows that the pandemic's impacts in the global South have been severe on lower-productivity enterprises and lower-paid workers, particularly women (Mukhtarova, 2020; ILO, 2021). It is not surprising that systemic inequalities and socio-economic disparities, along with urban planning methodologies that frequently overlook the specific requirements of women, contribute to ongoing mobility challenges for marginalized populations (Di Ruocco, 2025; Carpentieri et al., 2023). Access to technology for economic purposes could have significantly contributed to the resilience of female informal sector employees during the lockdown. However, a significant gender disparity exists regarding access to and use of internet resources for economic activities (Mumporeze & Prieler, 2017). Both genders face challenges such as poor internet connectivity, high data costs, and internet fraud. Nevertheless, studies have indicated that male informal traders have a competitive advantage over their female counterparts in accessing the benefits of ICT applications, such as reaching wider market bases on social media or saving time and commuting costs via online banking (Wrigley-Asante & Agyemang, 2019, p. 45). As a result, women's economic prospects in the informal sector may have been further compromised due to a lack of affordable internet access for running their businesses during the COVID-19 lockdown. Our data also reveal spatial variations in movement across the city. Human activity was significantly reduced in wealthier neighborhoods, such as East Legon, and was entirely absent near the local public university, which had shut down after a reported COVID-19 case among students, with all educational activities moving online. In contrast, there was relatively high human movement in low-income, high-density neighborhoods like Nima. Low-income earners typically need to leave their homes almost daily to earn a living and support their often-large families. This situation underscores the critical importance of equitable access to transportation and resources for all residents during emergencies.

6. Conclusion

Over the past 200 years, there have been dramatic and frequent occurrences of major epidemics and pandemics. During such emergencies, governments often adopt strict mitigation measures that, while intended

to protect the general public, can expose and worsen existing systemic inequalities and mobility injustices. The current study found that tertiary students, formal sector employees, and wealthy residents largely remained insulated from the economic impacts of lockdown orders because they could continue using technology for socio-economic interactions and activities. However, for many young people (aged 18 to 39), residents in poor, high-density neighborhoods, and women working primarily in informal sectors, compliance with lockdown orders was nearly impossible.

To promote social justice and create pandemic-resilient urban spaces while minimizing transportation-related disparities, policymakers must intentionally bridge the digital divide in accessing essential services. We concur with Di Ruocco (2025, p.106) who argues that "addressing mobility poverty requires a comprehensive approach…that promote inclusion and equity". To this end, strategies for promoting digital inclusion in Ghana should be both pro-poor and gender-sensitive. Specifically, the government should leverage existing strategic partnerships with donors and development partners to enhance the activities of the Ghana-India Kofi Annan Centre of Excellence in ICT (AITI-KACE). This partnership aims to improve digital skills among all Ghanaians, particularly targeting marginalized groups and communities to foster their inclusion in the digital economy.

Furthermore, the government should invest directly or encourage partnerships with the private sector to strengthen broadband internet infrastructure. The Ministry of Communications and Digitalization must effectively monitor the activities of communication service providers to ensure fair competition and prevent opportunistic behaviors among operators. These measures will lower internet data prices, making it more affordable and accessible for small-scale informal business operators and marginalized groups, enabling them to engage in business activities during normal times. This will also enhance their resilience during future events that may necessitate physical mobility restrictions.

Additionally, governments in the Global South should strategically invest more resources in formal mass transit options, including bus services, to improve urban mobility while also preparing for potential future emergencies.

Unlike governments, private transport service providers showed little interest in continuing service for the public good during the height of the COVID-19 pandemic. Valuable lessons can be learned from the Ghanaian government's use of high-occupancy buses operated by GAPTE to transport frontline health workers to health facilities during the lockdown. Therefore, the government must address the bottlenecks hindering the full implementation of its mass transit policy.

Moreover, there should be intentional community engagement between authorities, opinion leaders, women groups and community-based organizations working in low-income and densely populated areas, such as Nima, as identified in the study. This engagement is crucial for building trust and prioritizing the mobility needs of community members during normal times. Such a participatory and inclusive approach will provide a relevant knowledge base that can be effectively used during crisis periods, like lockdowns, to encourage compliance from all.

While this study offers valuable insights into how the government's lockdown affected attitudes and mobility behaviors differently in urban Ghana, it has several limitations that readers should be aware of. The use of convenience sampling techniques, reliance on social media platforms to recruit and remind participants about the study, and the short observational period may limit the generalizability of the research findings. Additionally, the reliance on self-reported data may pose another limitation. Future researchers should address these limitations by using larger, more diverse samples and objective measures.

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Image Sources

Fig.1: Authors' construct

Fig.2: Field data

Fig.3: Field data

Fig.4: Field data

Fig.5: (a) Adomonline, 2020 https://www.adomonline.com/covid-19-accra-empty-as-lockdown-begins-photos/

Fig.5: (b) Field data

Fig.6: (a) Adomonline, 2020 https://www.adomonline.com/covid-19-accra-empty-as-lockdown-begins-photos/

Fig.6: (b) Field data

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An evaluation on the change of natural areas: the case of Eastern Black Sea settlements

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Abstract
Urbanization has a significant impact on social, economic and environmental sustainability. Dynamic urban development and change processes affect both the natural and built environment. Recently, with the increase in urban population and the expansion of urban areas, the pressure on natural areas has increased. Understanding the relationships between natural and built environmental elements that depend on dynamic processes is important and necessary for the future development and management of urban areas. For this reason, the study aims to analyze land use/land cover changes depending on natural environmental elements in the settlements of the Eastern Black Sea Region for a period of approximately 20 years. Considering the heterogeneous structure of the settlements, a multivariate process was followed at the district level. The data set of the study was provided by CORİNE and TUIK and Two-Step Clustering Analysis was used as the method. As a result of the study, the changes over time of the districts in similar and different clusters according to their natural environment components were evaluated by comparative discussion. The results will be useful and guiding in providing input to planning decisions regarding the similarities and differences of districts-provinces and sub-regions based on natural environmental components.

Keywords
Natural areas; Land-use pattern and change; Two-step cluster analysis; Eastern Black Sea Region-Turkey

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1. Introduction

Terrestrial ecosystems are important components of nature since they have biological and functional effects on climate regulation, the hydrologic cycle and as a source of natural resources to satisfy human needs. However, during the last 300 years, the ecosystems have been subject to accelerated processes of land use and cover changes (LUCC) (Jiménez et al., 2018). This has been identified as one of the main factors contributing to global environmental change (Magliocca et al., 2015; Turner et al., 2013; Verburg et al., 2015). Land change is the result of the interaction of political/institutional, economic, cultural, cultural, technological, natural/spatial drivers and the actors involved (Bürgi et al., 2004; Hersperger et al., 2010). The term 'land use' usually refers to the changes wrought on the surface of earth by way of increasing human activities. 'Land cover' refers to the physical manifestation of the surface of the earth; the distribution process of water, soil, vegetation or urban area arrangement (Fahad et al., 2020).

The factors influencing land use land cover change are complex and dynamic and vary from one place to another. These changes are primarily driven by natural and human-induced factors (Mobaraki, 2023). One of the most important human-induced factors is the increase in the urban population and the urbanization processes that develop due to this increase. International statistics show that the global population has increased rapidly over the last century and will continue to increase in the coming decades, albeit at a lower rate (Addae & Oppelt, 2019). And it shows that the global urban population will increase by up to 68% by 2050. With stronger urbanization expected in the coming years, cities will cover increasing areas of the earth's surface and will host the majority of the human population (Seto et al., 2012). The growth and development of urbanization in the last few decades, as well as the land use changes around and inside big cities have been considered as one of the most essential challenges of global sustainable development (Mobaraki, 2023). Land use and land cover changes following population growth and urbanization cause major current environmental problems such as widespread urban sprawl, land loss and degradation, climate change, vegetation loss, biodiversity loss, conversion of agricultural land, deforestation and ecosystems fragmentation (Jiménez, etc., 2018). As a result, ecosystems are also negatively affected by such destruction of nature and vegetation areas.

1.1 Theoretical Framework

Recent increases in urban populations and the expansion of urban areas have increased pressure on natural areas (UN, 2009). As urban areas expand, transform and envelop the surrounding landscape, they affect the environment at various spatial and temporal scales, such as climate change, loss of wildlife habitat and biodiversity, and greater demand on natural resources (Steffen et al., 2004). With the rapid increase in population and urbanization, especially since the mid-20th century, a number of ecological and environmental problems have emerged, such as the uncontrolled spread of construction lands, deterioration of habitat quality and landscape fragmentation (Han et al., 2015; He et al., 2014; Lei et al., 2016). Moreover, urban land change is not limited to the central city but includes many new urban-rural areas functionally connected to the city (Brenner & Schmid, 2015) and has many impacts on rural hinterlands (Bren d'Amour et al., 2016). This kind of changes therefore profoundly affects local and/or regional environment, which would eventually affect the global environment (Hegazy & Kaloop, 2015). At this point, open and natural/non-urbanized areas in and around the city affected by land changes are becoming increasingly important in terms of environment and quality of life. In many countries, open spaces are today regarded an integral part of land use planning decisions (Maruani & Amit-Cohen, 2007). Protection of open space is directly linked to the issue of urbanisation, making it one of the dominant planning topics in the developed World (Koomen et al., 2008). At this point, the current and future status of "open spaces" and "non-urbanized" areas, which are natural environments for sustainable urban development and development facing risks and challenges, is of great importance.

Open spaces are generally characterized by a low level of intervention that does not change their intrinsic "naturalness", and allows continuous functioning of the ecosystems and survival of nature and landscape

values. Open spaces, which are roughly divided into two different types: agricultural landscapes and natural areas, are also divided into two main categories according to their functions. These functions are the provision of recreation and other services to the community and the protection of natural values (Maruani & Amit-Cohen, 2007; Koomen et al, 2008). In addition, many natural resources provide society with ecological (e.g. protection of natural processes and resources, conservation of biodiversity) and environmental (e.g. maintaining air and water quality, improving the local microclimate) services, that are considered life-supporting systems (Maruani & Amit-Cohen, 2007).

Another natural environment feature, non-urbanised areas (NUAs) are part of agricultural and green infrastructures that provide ecosystem services (La Greca et al., 2011). These areas are semi-natural patches that represent the last remnants of nature in the urban context and play an important role in mitigating the consequences of climate change (Bowler et al., 2010; La Rosa & Privitera, 2013). As part of the agricultural and green infrastructure they provide ecosystem services, such as purification of air and water, mitigation of floods and droughts, re-generation of soil fertility, moderation of temperature extremes and enhancing of landscape quality (La Rosa & Privitera, 2013). Ecosystem services are the conditions and processes through which natural ecosystems and the species that compose them sustain and fulfill human life (Daily, 1997). Although ecosystem services are essential for sustaining the long-term well-being of societies, their quantity and quality are expected to continue to deteriorate in the coming decades (Millennium Ecosystem Assessment, 2005; Foley et al., 2005). There is growing evidence that natural environments – including green and open spaces – provide wide-ranging benefits for urban populations, referred to broadly as ecosystem services. These benefits are commonly referred to as ecosystem services (Douglas et al., 2019). Elements of the built environment represent a high level of intervention in the ecosystem, altering the landscape and interfering with natural processes, sometimes irreversibly. Interference can cause irreversible consequences or damage irreplaceable natural assets (Chavas, 2000). Therefore, under the impact of global ecosystem changes, coordinated development of all natural elements has become a top priority in maintaining ecological security (Gao et al., 2022). Therefore, as urban areas are expected to continue to grow in the future, planners and political decision-makers should carefully consider the role of non-urbanized areas in providing ecosystem services (La Greca et al., 2011). As a result, population increases, the urbanization phenomenon brought about by population growth and land use/land cover (LULC) changes seriously threaten sustainable resource use and global/regional environmental sustainability. Therefore, there is a need for appropriate interventions that can prevent the negative consequences of urbanization and ensure sustainable urban development. As Seto and Fragkias (2005) note, "characterizing and understanding the changing patterns of urban growth is critical given that urbanization will continue to be one of the major global environmental changes in the foreseeable future". In such a context, knowing the spatial-temporal pattern of urban growth, monitoring land cover change and revealing past trends will provide insights into future developments.

Based on all these, the aim of the study is to analyze the natural land cover changes of the settlements in the Eastern Black Sea Region - at the district level - depending on time and space. The study, which supports sustainable urban planning, evaluated the time-dependent changes of open spaces and non-urbanized areas. The year 2000 was set as the start year and 2018 as the end year, taking into account the availability of data. Changes in the natural environmental elements of settlements as a result of population growth and urbanization processes were examined with the help of classified maps. In such a context, knowing the spatio-temporal pattern of urban growth is crucial for formulating sustainable urban development policies that can mitigate the negative impacts of urbanization and ensure sustainable urban development.

2. Methodological framework

The physical process of urban land use change is often described as a change in the absolute area of urban space or a change in the rate at which other areas, such as agriculture, are converted to urban uses (Seto et

al., 2000). For any time period, the spatial arrangement of urban areas provides a snapshot of various economic, social, and political factors that influenced land-use decisions (Seto & Fragkias, 2005). Recently, innovative approaches to urban land use planning and management such as sustainable development and smart growth have been proposed and widely discussed (Kaiser et al., 1995; American Planning Association, 2002). Their application relies heavily on existing knowledge about the causes, chronology and impacts of urban change processes (Herold et al., 2005).

Knowledge of the land use/cover patterns of a region is one of the prerequisites for the planning and implementation of effective land use policies and schemes for sustainable regional development (Suthakar & Bui, 2008). Land use changes are a complex and dynamic processes that link together natural, economic, social and cultural factors in time and space (Koomen et al., 2008) and various tools are needed to understand and explain these processes (Hapugala, 2013). Geographic Information Systems (GIS) and remote sensing techniques provide effective tools in studying and monitoring land-use/land-cover change over space and time (Addae & Oppelt, 2019). Remote sensing can detect changes in land cover and land use and monitor the consequences of human and natural activity (Partheepan et al., 2023).

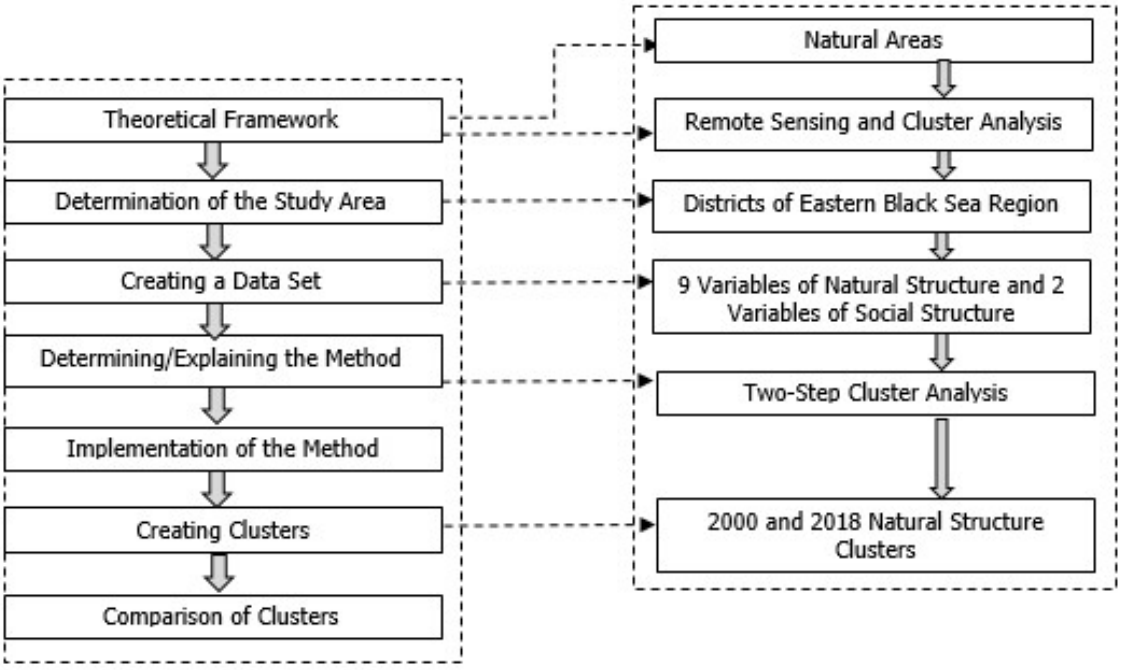

Fig.1 Study process and its application in the Eastern Black Sea Region

Remote sensing data highlight high temporal frequency land cover changes that are of great importance for earth system processes (Lambin et al., 2003). Remote sensing represents a major though still under-used source of urban data, providing spatially consistent coverage of large areas with both high geometric detail and high temporal frequency, including historical time series (Herold et al., 2005). Usually, land uses and urban growth in remote sensing involves the analysis of two registered, aerial or satellite multi-spectral bands from the same geographical area obtained at two different times (Hegazy & Kaloop, 2015). Monitoring land cover transformation can be accomplished by a simple comparison of successive land cover maps. In contrast, detection of subtle changes within land cover classes requires representation of land cover where surface attributes change continuously over time and space, at seasonal and interannual scales. Such an analysis aims at identifying changes that have occurred in the same geographical area between the two times considered (Radke et al., 2005). Remote sensing and Geographical Information Systems (GIS), when integrated with the tools of landscape ecology, can be used to investigate the changing spatial patterns of biodiversity.

A description of the shape, size and spatial arrangement of patches of vegetation in the landscape can be used to link the observed pattern with the ecological processes that may have generated it. Alongside spatial

scale, temporal scale is equally important when assessing the change of a landscape over time. Multi-temporal analysis based on remotely sensed data has played an important role in landscape ecology (Rocchini et al., 2006). The methodological framework consists of determining the study area based on the elements of the natural environment, creating the natural structure data set of the area and explaining the cluster analysis, which is the study method (Fig.1).

2.1 Study area

The Eastern Black Sea Region, one of Turkey's 12 regions according to the Statistical Regional Classification (Level-1), consists of 6 provinces (Artvin, Giresun, Gümüşhane, Ordu, Rize and Trabzon) and 79 districts. According to the 2017 Socio-Economic Development Index (SEGE) study, Trabzon ranks 26th, Rize 36th, Artvin 49th, Giresun 53rd, Ordu 60th, and Gümüşhane 64th among the provinces in the region (Fig.2).

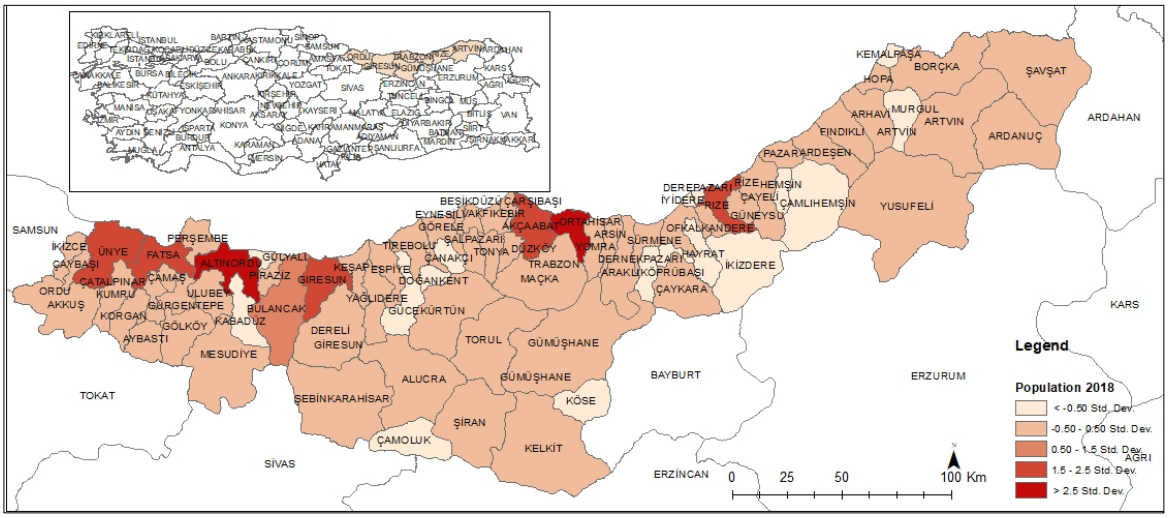

Fig.2 Location of the Eastern Black Sea Region and population size of settlements

As of 2023, 3.20% (2,733,265 people) of the country's population of approximately 85 million live in the Eastern Black Sea provinces. The country's population density, which was 77 people/km2 in 2018, became 78 people/km2 in 2023. While Artvin (23 persons/km2), Giresun (68 persons/km^2), Gümüşhane (23 persons/km^2) are below the national average, Ordu (130 persons/km^2), Rize (89 persons/km^2) and Trabzon (177 persons/km^2) are above the national average (TÜİK, 2023). According to the 2018 census; the average annual population increase in the region is 32.02 (per thousand) and the decrease in Gümüşhane province in 2018 is remarkable. All other provinces of the region are above the country average in this period. According to 2023 data the regional average is 15.94 (per thousand) and all provinces except Trabzon (7.71) are above the regional average (TÜİK, 2000-2018-2023).

The study area was chosen as the Eastern Black Sea Region due to the rich natural environmental elements of the region. According to 2000 values, 99.49% of the region consisted of "agricultural areas", "forest and semi-natural areas", "wetlands" and "water bodies" which can be defined as natural areas. With this ratio, the region ranked first in the country. The region has an important place in the country especially in terms of Forests and Semi-Natural Areas. The region also has the lowest Artificial area ratio in the country. According to 2018 data, the natural area ratio was 99.23% (4th in the country). In 2018, when evaluated in terms of natural environmental elements, there are 1,073,649 ha of agricultural areas, 2,422,571 ha of forest and semi-natural areas and 17,112 ha of water bodies in the region (Tab.1) (TÜİK, 2000-2018-2023).

	Regions	Artificial Areas(1)		Agricultural Areas (2)		Forests and Semi-Natural Areas (3)		Wetlands (4)		Water Bodies (5)		Total Ratio (%)	
		2000	2018	2000	2018	2000	2018	2000	2018	2000	2018	2000	2018
TR1	İstanbul	18.60	22.65	28.88	29.11	49.97	45.62	0.07	0.14	2.47	2.48	81.40	77.35
TR2	West Marmara	2.33	2.78	54.49	55.64	42.16	40.33	0.22	0.20	0.81	1.05	97.67	97.22
TR3	Ege	2.26	2.75	41.92	43.39	54.45	52.52	0.58	0.35	0.79	0.99	97.74	97.25
TR4	East Marmara	2.26	3.04	41.00	44.12	55.30	51.24	0.22	0.26	1.22	1.35	97.74	96.96
TR5	Western Anatolia	2.17	2.61	56.50	56.43	38.10	36.73	0.65	1.52	2.58	2.70	97.83	97.39
TR6	Mediterranean Sea	1.47	2.14	35.19	35.23	61.42	60.53	0.25	0.32	1.67	1.78	98.53	97.86
TR7	Central Anatolia	1.22	1.56	53.62	54.62	43.97	41.46	0.48	1.49	0.71	0.87	98.78	98.44
TR8	Western Black Sea	1.19	1.20	39.23	40.66	58.84	57.19	0.15	0.16	0.59	0.78	98.81	98.80
TR9	Eastern Black Sea	**0.51**	**0.77**	**28.91**	**30.32**	**70.15**	**68.42**	**0.00**	**0.00**	**0.43**	**0.48**	**99.49**	**99.23**
TRA	Northeast Anatolia	0.76	0.98	33.29	37.34	65.06	60.57	0.36	0.51	0.53	0.60	99.24	99.02
TRB	Middle East Anatolia	0.63	0.86	26.71	27.48	65.85	65.04	0.68	0.34	6.13	6.28	99.37	99.14
TRC	Southeast Anatolia	0.94	1.52	50.90	53.95	47.10	43.34	0.01	0.04	1.04	1.14	99.06	98.48

Tab.1 Land cover distribution of geographical regions of Turkey

2.2 The dataset

The dataset of the study, which aims to analyze land cover change due to natural environmental factors over time and space, consists of land cover/use variables obtained from the CORINE (Coordination of Information on the Environment) database/bank of Turkey. CORINE data includes land cover data produced by computer-aided visual interpretation method on satellite images according to the "Land Cover/Use Classification" determined by the European Environment Agency. The main objective of the CORINE Project is to establish a standardized database for the purposes of determining environmental changes in the land, rational management of natural resources and formulation of environmental policies in line with the criteria and classification system determined by the European Environment Agency (URL-1, 2024).

Within the scope of the study, the data produced by the Turkish Ministry of Agriculture and Forestry for natural structure within the scope of the CORINE project according to the European Environment Agency criteria and classification units were utilized. In order to examine changes in land cover and land use, a total of 11 data under 4 main headings (excluding artificial regions) collected under the CORINE project were used. The change in the land cover of the Eastern Black Sea Region due to natural environmental factors was comparatively analyzed and evaluated by utilizing the data set of 2000 and 2018 produced at the district level. In addition to natural environmental factors, "population size" and "urban population ratio", which are effective in land cover change, are analyzed in the analysis of land cover change over time and space. Variables were also included in the process. The data on these 2 variables of socio-demographic structure were obtained from TUIK (Tab.2).

Indicators	Variables
2. Agricultural Areas (CORİNE)	Arable Areas (21)
	Continuous Products (22)
	Pastures (23)
	Mixed Agricultural Lands (24)
3. Forests and Semi-Natural Areas (CORİNE)	Forests (31)
	Maquis or Herbaceous Plants (32)
	Areas with Low or No Vegetation (33)
4. Wetlands (CORİNE)	Inland Wetlands (41)
	Coastal Wetlands (42)
5. Water Bodies (CORİNE)	Terrestrial Waters (51)
	Sea Waters (52)
Socio-demographic indicators (TUIK)	Population size
	Urban population size

Tab.2 Selected and grouped natural environment variables (URL-1, 2024)

2.3 Methodology

The study, which aims at rational use of natural resources and sustainable development, examines the change in land cover over the years. The district level study aims to reveal the similarities of the region according to the natural structure elements and to classify the districts according to the natural structure elements. Land cover variables of the natural structure of the Eastern Black Sea districts were classified with the help of cluster analysis. After the classification according to 2000 and 2018 natural structure elements, the clusters and the settlements in the clusters were compared and evaluated.

The change of the spatial pattern of the settlements of the Eastern Black Sea Region depending on the determined natural environmental variables was carried out with the help of cluster analysis. Cluster analysis is a method used in the process of organizing and analyzing multivariate or large scientific data. It aims to divide data that may have a high degree of similarity into several clusters in the same group/classification (Everitt, 1993; Shih et al., 2010). The similarity level of each cluster is defined by the distance between it and the system that each axis represents, and communities that are close to each other are more likely to be grouped in the same cluster (Vıncze & Mezei, 2011).

In the study, which aims to examine the change of land pattern at the district level over the years in order to manage natural resources rationally and create environmental policies, the "Two-Step Cluster" method from cluster analysis was used to reveal similar settlement texture and its change over the years. Two Step Cluster Method; It is a hybrid clustering technique formed by combining "K Means", a non-hierarchical clustering technique, and "Ward's Smallest Variance", a hierarchical technique (Ceylan et al., 2017). It is a single-pass data approach that allows using quantitative and qualitative variables simultaneously, determining preliminary clusters in the first step and then performing hierarchical clustering (Wu et al., 2016; Michailidou et al., 2009). In the pre-clustering stage of the method, the data are scanned one by one and it is decided whether the current situation will be combined with previously created clusters or whether a new cluster will be started according to the distance criterion (Michailidou et al., 2009). In the cluster step; data are grouped into the desired number of clusters using the standard hierarchical clustering algorithm according to the subsets obtained from the preliminary cluster step (Satish & Bharadhwaj, 2010).The most important features of this algorithm are; it can be applied to large data sets, can process categorical and continuous variables, can automatically determine the most appropriate number of clusters, and can remove observations that do not comply with the obtained clusters from the data when desired (Ceylan et al., 2017).

In this process, in order to reach valid and meaningful results in the analysis, the priority step is to select important variables and determine the number of clusters correctly (Punj & Stevvart, 1983). One of the most basic criteria developed to determine the number of clusters is that the number of clusters can be calculated with the expression k = (N/2)1/2 to indicate the number of N observations (Tatlıdil, 1992; Çakmak et al., 2005).

3. Result

In order to compare the time-dependent changes in the natural environmental elements of the Eastern Black Sea Region, a "two-step cluster analysis" was utilized. Population size and urban population variables affecting the change of land cover related to natural structure were also included in the clustering analysis process. Within the scope of the study, two-step clustering analysis was performed with 2 standardized variables of social structure and 9 standardized variables of natural structure. The analysis of 2000 and 2018 variables was carried out with the help of SPSS 25.0 package program. "Wetlands" that are not located in the Eastern Black Sea Region were excluded from the data set (Tab.3-4-5-6). As a result of the analyzes, the spatial distribution of the time-dependent changes of the natural environmental elements of the Eastern Black Sea Region at the district level were mapped and interpreted (Fig.3-4).

3.1 Spatial reflections of natural structure land cover: year 2000

First of all, Two-Step Cluster Analysis was performed with 11 variables belonging to 6 provinces and 79 districts in the Eastern Black Sea Region. In the study, it was aimed to determine a common number of clusters in order to make comparisons between the clusters to be formed with the help of variables from different years (2000 and 2018). The optimum cluster number formula (cluster number k = (N/2)1/2) was used to determine the number of clusters. It was decided that the number of clusters to be used in the clustering analysis and to reflect the diversity of 79 districts - indicated by the cluster number formula - should be "6".

Variable (importance)	Cluster-1	Cluster-2	Cluster-3	Cluster-4	Cluster-5	Cluster-6
	%36.71	%7.59	%29.11	%12.66	%6.33	%7.59
	29 districts	6 districts	23 districts	10 districts	5 districts	6 districts
31. Forests (1)	-0.58	-0.33	-0.24	1.25	-0.37	2.27
21. Arable areas (0.99)	-0.23	-0.22	-0.23	-0.2	3.31	-0.21
Population size (0.82)	-0.44	3.06	0.05	-0.2	-0.23	-0.07
32. Maquis or Herbaceous Plants (0.75)	-0.51	-0.48	-0.43	1.11	1	1.87
24. Mixed agricultural lands (0.57)	-0.85	1.58	0.08	0.58	0.76	0.55
Urban population size (0.51)	-0.35	2.68	0.08	-0.26	-0.07	-0.37
23. Pastures (0.5)	-0.24	-0.24	-0.23	-0.16	2.74	0.25
33. Areas with Little or No Vegetation (0.44)	-0.38	-0.39	-0.35	0.36	1.49	1.74
52. Sea waters (0.38)	-0.42	1.63	0.67	-0.51	-0.55	-0.55
51. Terrestrial waters (0.18)	-0.44	0.26	0.33	-0.38	-0.32	1.36
22. Continuous products (0.09)	-0.13	1.15	-0.18	-0.2	-0.21	0.92
Ranking of mean values	Lowes					Highest

Tab.3 Importance level-mean values of variables effective in the formation of clusters (2000)

Variable (2000)	Cluster-1	Cluster-2	Cluster-3	Cluster-4	Cluster-5	Cluster-6
	36.71%	7.59%	29.11%	12.66%	6.33%	7.59%
	29 districts	6 districts	23 districts	10 districts	5 districts	6 districts
Artvin	(1) Murgul		(2) Arhavi, Hopa	(1) Ardunuç,		(4), Şavşat, Yusufeli, Merkez, Borçka
Giresun	(6) Doğankent, Eynesil, Güce, Piraziz, Yağlıdere, Çanakçı	(1) Merkez	(4) Espiye, Görele, Keşap, Tirebolu	(3) Alucra, Bulancak, Dereli	(2) Çamoluk, Şebinkarahisar	
Gümüşhane				(1) Torul	(3) Kelkit, Köse, Şiran	(2) Merkez, Kürtün
Ordu	(9) Aybastı, Gülyalı, Gürgentepe, Kabadüz, Kabataş, Çamaş, Çatalpınar, Çaybaşı, İkizce	(2) Altınordu, Fatsa, Ünye	(5) Gölköy, Korgan, Kumru, Perşembe, Ulubey	(2) Akkuş, Mesudiye		
Rize	(5) Derepazarı, Güneysu, Hemşin, Kalkandere, İyidere		(5) Ardeşen, Fındıklı, Pazar, Merkez, Çayeli	(2) Çamlıhemşin, İkizdere		
Trabzon	(8) Beşikdüzü, Çarşıbaşı, Dernekpazarı, Düzköy, Hayrat, Köprübaşı, Şalpazarı, Tonya	(2) Akçaabat, Ortahisar,	(7) Araklı, Arsin, Çaykara, Of, Sürmene, Vakfıkebir, Yomra	(1) Maçka		

Tab.4 Distribution of districts according to clusters as a result of the analysis (2000)

After determining the number of clusters as 6, natural structure clusters for the year 2000 were formed as a result of the Two-Step Clustering analysis. As a result of the analysis, it was seen that the most effective variables in the formation of similarities between the districts in 2000 were "forests" and "arable areas". The least effective variable in the analysis where natural environment components are the most effective is "continuous products" (Tab.3).

In 2000, the distribution of the variable values formed as a result of the Two-Step Clustering analysis with the variables belonging to the year 2000 to the clusters was analyzed. Cluster characteristics were determined by comparing the "Mean" values of all variables between clusters. As a result of the holistic and comparative evaluation of 11 variables and 6 clusters, the clusters were grouped according to their natural environment characteristics. As a result of the two-step clustering analysis, there are 29 districts in the Eastern Black Sea Region that show the highest number (36.7%) of Cluster-1 characteristics in 2000 (Tab.3-4) (Fig.3).

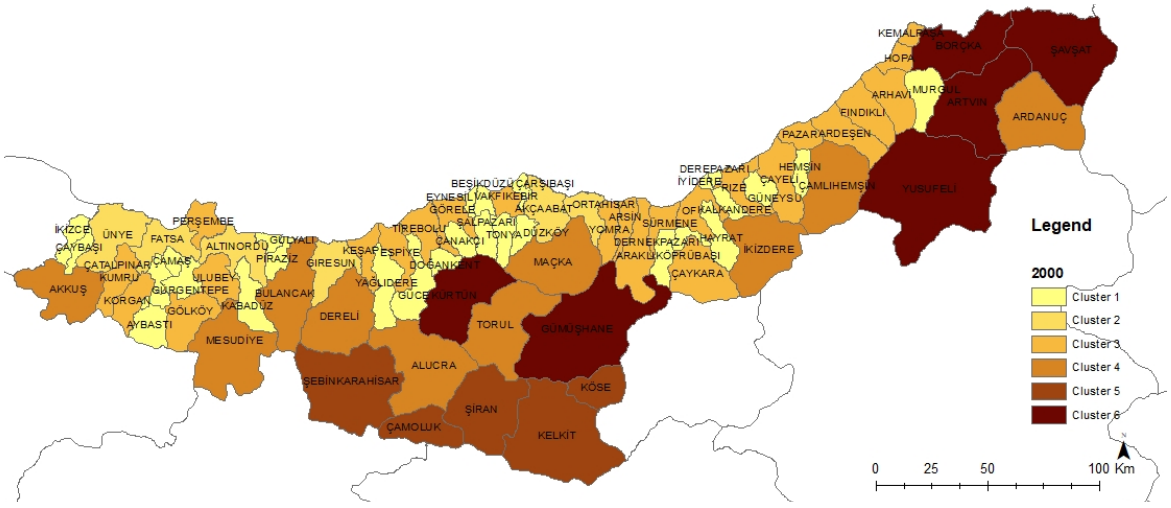

Fig.3 Spatial distribution of settlements according to natural structure components (2000)

The clusters and cluster characteristics formed as a result of the classification according to natural environment elements and socio-demographic components are as follows.

- Cluster-6 has the highest values of the variable "forest and semi-natural areas (3)", which is one of the natural environment components. And Cluster-6 consists of 6 districts of Artvin and Gümüşhane provinces. Settlements belonging to the cluster have the highest values in terms of "forests (31)", "maquis or herbaceous plants (32)", "areas with little or no vegetation cover (33)";
- Another natural environment component is "agricultural areas (2)". Cluster-5 settlements have the highest values in terms of "arable areas (21)" and "pastures (23)" within the agricultural areas indicator set. It is seen that all 5 districts of Giresun and Gümüşhane provinces are rich in natural areas;
- Following Cluster 6 and Cluster 5, Cluster-4 settlements have the highest values for "forests (31)", "frable lands (21)" and "maquis or herbaceous plants (32)";
- Cluster-2, where "population size" and "urban population size" have the highest values, consists of Akçaabat, Ortahisar, Ünye, Fatsa and Giresun central districts. This cluster shows similar characteristics in terms of population and natural structure components;
- Cluster-3 settlements have the highest "population size" and "size of urban population" values after Cluster-2 settlements. In addition, these cluster districts are also important in terms of "water bodies (5)" and "forests (31)" and show similar characteristics. This cluster, consisting of 23 districts in total, covers 29% of the region.

As a result, cluster analyse shows that in the 2000s, the natural structure - forests - was important in the classification of settlements according to their similarities and differences. It is also observed that 29 districts

with the lowest values in terms of both population and natural structure elements are included in Cluster-1, showing similar characteristics.

3.2 Spatial reflections of natural structure land cover: year 2018

Following the 2000 clustering analysis, clustering analyses were conducted with the natural structure and population variables in 2018. According to 2000 and 2018 natural structure components, the distribution of settlements into clusters was compared. The spatial reflections of the changing land cover over the past 20 years were analyzed. As a result of the two-step clustering analysis with population and natural structure variables, approximately half (53.16%) of the settlements in the Eastern Black Sea Region were located in Cluster-1. In 2018, it was observed that the most effective variables in the formation of similarities between districts were "population size" and "urban population size". In the analysis where natural environment components are the most effective, the least effective variable is "arable land" (Tab.5-6).

Variable (importance)	**Cluster-1**	**Cluster-2**	**Cluster-3**	**Cluster-4**	**Cluster-5**	**Cluster-6**
	53.16%	**8.86%**	**7.59%**	**20.25%**	**3.79%**	**6.32%**
	42 districts	7 districts	6 districts	16 districts	3 districts	5 districts
Population size (1)	-0.33	2.77	-0.02	-0.27	-0.5	0.05
Urban population size (0.92)	-0.28	2.74	-0.1	-0.3	-0.41	-0.18
32. Maquis or Herbaceous Plants (0.87)	-0.48	-0.54	-0.44	0.85	0.87	2.53
33. Areas with Low or No Vegetation (0.79)	-0.3	-0.35	-0.35	0.11	-0.13	3.11
22. Continuous Products (0.65)	-0.18	1.81	1.59	-0.48	-0.74	-0.91
23. Pastures (0.63)	-0.26	-0.13	-0.29	0.13	3.85	0
52. Sea Waters (0.46)	-0.23	1.35	1.84	-0.433	-0.49	-0.49
31. Forests (0.45)	-0.41	-0.46	-0.58	1.1	-0.22	1.39
51. Terrestrial Waters (0.35)	-0.29	0.12	-0.14	0.07	-0.36	2.44
24. Mixed Agricultural Lands (0.2)	-0.38	0.59	-0.59	0.7	-0.29	1.02
21. Arable Areas (0.13)	-0.18	-0.19	-0.19	-0.07	1.18	1.52
Ranking of mean values	Lowest					Highest

Tab.5 Importance level-mean values of variables effective in the formation of clusters (2018)

Variable (2018)	**Cluster-1**	**Cluster-2**	**Cluster-3**	**Cluster-4**	**Cluster-5**	**Cluster-6**
	53.16%	**8.86%**	**7.59%**	**20.25%**	**3.79%**	**6.32%**
	42 districts	7 districts	6 districts	16 districts	3 districts	5 districts
Artvin	(3) Arhavi, Hopa, Murgul			(3) Ardunuç, Borçka, Şavşat		(2) Merkez, Yusufeli
Giresun	(8) Doğankent, Espiye, Eynesil, Güce, Piraziz, Yağlıdere, Çamoluk, Çanakçı	(1) Merkez	(3) Görele, Keşap, Tirebolu	(3) Alucra, Bulancak, Dereli,		(1) Şebinkarahisar
Gümüşhane				(3) Kürtün, Torul, Şiran	(1) Köse	(2) Merkez, Kelkit
Ordu	(11) Gölköy, Gülyalı, Gürgentepe, Kabadüz, Kabataş, Korgan, Kumru, Çamaş, Çatalpınar, Çaybaşı, İkizce	(3) Altınordu, Fatsa, Ünye	(1) Perşembe	(4) Akkuş, Aybastı, Mesudiye Ulubey,		
Rize	(8) Ardeşen, Derepazarı, Fındıklı, Güneysu, Hemşin, Kalkandere, Çayeli, İyidere,	(1) Merkez	(1) Pazar	(2) Çamlıhemşin, İkizdere		
Trabzon	(12) Arsin, Beşikdüzü, Çarşıbaşı, Dernekpazarı, Düzköy, Hayrat, Of, Sürmene, Şalpazarı, Tonya, Vakfıkebir, Yomra	(2) Akçaabat, Ortahisar,	(1) Araklı	(1) Maçka	(2) Çaykara, Köprübaşı	

Note. Underlined settlements indicate the districts that were in the same cluster in the previous period

Tab.6 Distribution of districts according to clusters as a result of the analysis (2018)

According to the evaluation made by comparing with the 2000 data, the following results were obtained (Tab.5-6), (Fig.4):

- Cluster-6, which has the highest values of "forest and semi-natural areas (3)" among the natural environment components, consists of 5 districts of Artvin, Gümüşhane and Giresun provinces. Settlements belonging to the cluster have the highest values in terms of "forests (31)", "maquis or herbaceous plants (32)", "areas with little or no vegetation cover (33)" in this period. In 2000, Artvin Merkez, Yusufeli and Gümüşhane Merkez districts were in the same cluster in this period;
- As a result of the 2018 cluster analysis, it is seen that a new cluster with different characteristics from the previous period was formed. Cluster-5 has the highest values for the variable "pastures" and the highest values for the variable "maquis or herbaceous plants (32)". Cluster 5 consists of Çaykara and Köprübaşı districts of Trabzon province and Köse district of Gümüşhane province. In addition, the population values of this cluster are lower than the other clusters;
- It is seen that the variables "pasture areas", "forest" and "areas with little or no vegetation cover", which are agricultural area variables of the natural environment, have high values for Cluster-4 after Cluster-6. In addition, the cluster has secondary importance in terms of "mixed agricultural areas" as in the previous period. Cluster-4, which consists of different cluster settlements in 2000, is completely heterogeneous. Cluster-4 consists of 16 districts and covers 20.25% of the total settlements;
- Cluster-3, which has the highest values in terms of "sea waters", the highest values in terms of "continuous product" and "urban population size" variables and the lowest values in terms of many other variables, consists of a total of 6 districts in 2018. In the last 20 years, the number of settlements in Cluster-3 with similar characteristics has decreased. Settlements belonging to the cluster consist entirely of settlements that were in Cluster-3 in the previous period;
- Cluster-2, where "population size" and "urban population size" have the highest values, consists of Akçaabat, Ortahisar, Ünye, Fatsa and Giresun central districts as in the previous period. In addition, Altınordu and Rize Central districts also show similar characteristics (Cluster-2) in terms of population and natural structure components;
- Finally, it is observed that a heterogeneous group consisting of settlements that were in Cluster-1 and Cluster-3 in the previous period has emerged. This cluster has moderate values in terms of both population and natural structure components. This cluster consists of 42 districts and covers 53.16% of the settlements in the region.

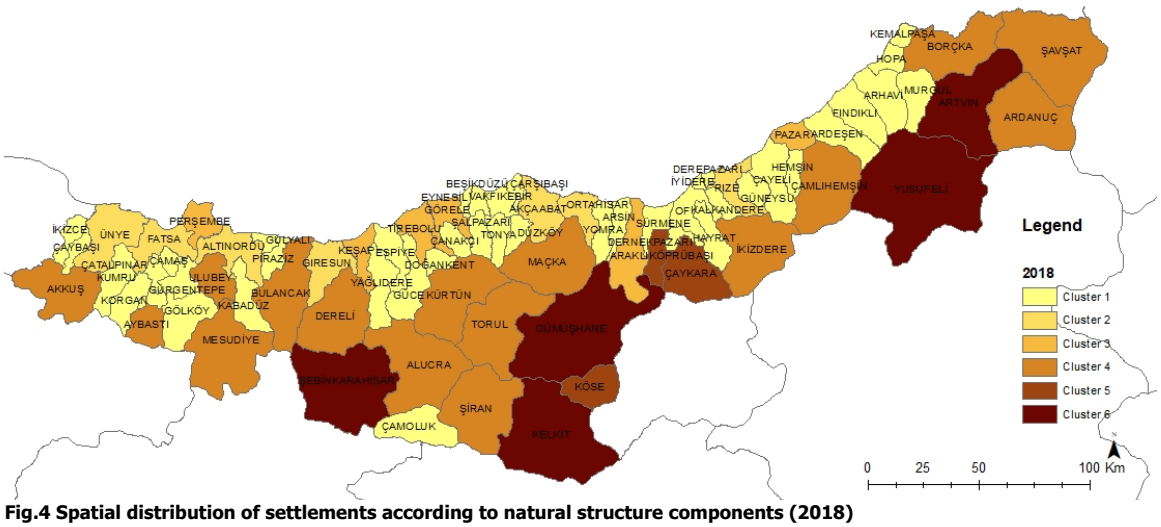

Fig.4 Spatial distribution of settlements according to natural structure components (2018)

4. Discussion

Urbanization has a significant impact on social, economic and environmental sustainability. Dynamic urban development and change processes that have occurred recently as a result of increasing urban population movements affect both the natural and built environment. Within the scope of the study, the changes of 6 provinces and 79 districts within the Eastern Black Sea region, which are considered rich in natural environmental elements, were examined depending on "agricultural areas", "forest and semi-natural areas", "water bodies" and "population size".

In 2000, the most influential variable in cluster formation was "forests". The repeated analysis at the end of approximately 20 years shows the impact of urbanization on space. Namely, the most effective variables of the clusters formed in 2018 were "population" and "urban population". It was observed that the similarities and differences of the settlements were determined by social structure dynamics, unlike the natural structure elements that were effective in the previous period.

According to the time-based comparative evaluation for the Eastern Black Sea Region, Cluster-1 and Cluster-2 have the lowest values in terms of natural structure elements, while Cluster-6 has the highest values. In 2018, it is observed that the spatial continuity of Cluster-6 settlements - natural structure continuity - has deteriorated especially in Artvin province. It is seen that Borçka and Şavşat districts, which are rich in natural environmental elements, have similar characteristics with Ardanuç district in 2018.

In 2018, the number of settlements in Cluster-4, which has high values in terms of "forest", "arable land" and "pastures", increased compared to the previous period. Especially in the south of Trabzon and Giresun provinces, there is a change and spatial continuity due to natural structure elements. In 2000, some of the Cluster 5 and Cluster 6 settlements with high natural structure elements were included in Cluster-4 in this period.

The number of Cluster-1 settlements, where "population" and "urban population size" and natural structure components have medium-low values, has increased over time. This change in the coastal and especially in the eastern part of the region is significant and remarkable. While 36.71% of the settlements in the region were in Cluster-1 in 2000, this rate increased to 53.16% in 2018.

Finally, in both periods, it is observed that the districts of Artvin and Gümüşhane provinces are concentrated in clusters rich in natural structure elements. Rize and Trabzon provinces, on the other hand, show a trend in the opposite direction. This situation is consistent with the observed changes in the region. The results of clustering analyses based on the similarities and differences of natural environment components and social structure elements show that the settlements within the provinces have a heterogeneous distribution and that there are differences between coastal and inland areas (Tab.4).

5. Conclusion

The transformation of natural areas is a vital issue for ecosystems. Over time, the protection of nature for future generations becomes even more important. In this respect, the study aims to analyze the land cover changes in the natural structures of the settlements in the Eastern Black Sea Region over time and to classify the settlements according to their natural structure similarities. The study shows that "artificial areas" and "agricultural areas" increased and "forest areas" decreased in the region from 2000 to 2018. In addition, the spatial patterns of land cover changes were also revealed with the classification studies conducted specifically for settlements. Clusters formed according to similarities in natural structure also enabled the identification of transitions between each land use. Time-dependent classification and mapping of land cover changes can serve as a valuable tool to protect environmentally sensitive areas from further damage. Another issue is that land cover changes are associated with physical and socioeconomic impacts. However, the availability of current and up-to-date physical and socioeconomic data is limited. This is a limitation of this study, which was designed to monitor spatial and temporal land cover change and reveal complex human-nature interactions.

It is recommended that future studies be conducted in a holistic manner with rich and up-to-date data sets. The results will provide important insights for planners and key actions to ensure sustainable development in the region and reduce degradation of the natural environment. This information will help in the formulation of land planning strategies and the development of land use conservation policies. Such studies will contribute to the planning discipline in terms of addressing economic and ecological decisions together, the necessity of rational resource utilization and making environmentally sensitive land use decisions.

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Image Sources

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

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Mode choice patterns and socio-spatial equity in contrasting transitional urban mobility systems

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Abstract

This study explores a comparative analysis of mode choice behavior in Bundang and Ilsan, two distinct new towns in the Seoul Metropolitan Area, using Nested Logit Model (NL) to unravel how socio-demographic, trip-specific, and land-use variables interact with urban morphology to shape mobility preferences. By addressing the methodological limitations of traditional multinomial logit models, our NL framework incorporates hierarchical decision-making structures and mitigates the Independence of Irrelevant Alternatives (IIA) assumption, offering granularity in modeling multimodal substitution patterns. The analysis reveals stark contrasts: Bundang's car dependency in low-density zones is driven by age and household dynamics, while Ilsan's income-driven preferences for taxis and efficient public transit underscore the role of infrastructure equity. Further insights include the identification of gendered mobility disparities, women's reliance on buses in Bundang versus men's motorized dominance in Ilsan, and the quantification of nonlinear thresholds (e.g., 10-minute bus access limits) that dictate mode shifts. By integrating parcel-level land-use data, this study provides actionable levers for policymakers, such as equity-centered subsidies and transit-oriented land-use integration. The findings of the research challenge universalist assumptions in transportation economics, demonstrating that urban structure and localized norms mediate mobility behaviors, thereby offering a replicable framework for cities navigating the tension between rapid urbanization and sustainable transport systems.

Keywords

Urban mobility; Mode choice; Nested logit model; Sustainability; Land use; Transportation policy

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1. Introduction

In recent years, cities globally have been actively investing in their transportation infrastructure to boost sustainability and user-friendliness, recognizing the crucial role such developments play in urban planning (Banister, 2008). As population growth and economic development continue to accelerate, the demand for travel has significantly increased, heavily influenced by consumer behavior, including preferences for specific transport modes (McCollum et al., 2017). The selection of travel modes by consumers is pivotal, with extensive implications for transportation policy and urban mobility strategies (De Vos et al., 2016). This paper undertakes a detailed empirical analysis of travel choices within Bundang and Ilsan, two newly developed in the Seoul Metropolitan Area. It explores the dichotomy between the perceived comfort of personal vehicles and their lower sustainability compared to public transport options (Pojani & Stead, 2015). While public transportation provides a practical alternative for those located near transit routes, effectively reducing personal vehicle use, it is not devoid of challenges. Factors such as inaccessibility to transit routes and the unpredictability of travel times due to delays often deter users, leading them to favor personal vehicles over public options (Beirão & Cabral, 2007). Strengthening multimodal integration and providing real-time information can foster a shift toward more sustainable travel behaviors.

The Seoul Metropolitan Area (SMA) represents a significant microcosm of South Korea's broader urban transport challenges, accommodating over half of the country's automobiles (Kang et al., 2016). Longitudinal household-travel surveys for the Seoul Metropolitan Area reveal that the car fleet ballooned from roughly one million vehicles in 1990 to more than three million by 2009, about 17 % of all cars in Korea, marking a rapid and far-reaching shift in everyday mobility patterns (Choi et al., 2014). Simultaneously, car ownership per thousand people soared from 15.6 in 1980 to 181.6 by 2000, exacerbating the ratio of road length available per passenger car and significantly contributing to urban sprawl and traffic congestion (Seoul Metropolitan Government, 2014). This congestion is further aggravated by the continuous rise in both population and vehicle numbers, necessitating expansive road construction efforts aimed at managing the escalating traffic volumes. Despite these infrastructural expansions, congestion remains a persistent issue, casting doubts on the sustainability of the current transport mobility system (Roh et al., 2017). Given these circumstances, it becomes imperative to delve into the individual factors influencing modal choices to better understand travel behaviors in urban environments. Examining consumer behavior through modeling helps uncover the preferences that shape travel mode choices. This understanding is crucial for developing more effective and sustainable transportation policies that align with the evolving dynamics of urban mobility (Paulssen et al., 2014).

Existing studies on Seoul's new towns typically examine the entire metropolitan area or concentrate on a single satellite city (Lee & Ahn, 2005; Lee et al., 2015). A comparative lens is essential because it holds constant national policy and macro-economic conditions while isolating the micro-level socio-spatial factors that drive divergent travel behaviour (Ewing & Cervero, 2010). By juxtaposing multiple new towns, this approach unveils nuanced distinctions in urban form and travel dynamics that single-case analyses often overlook, thereby providing richer insights for context-sensitive planning strategies. To close this gap, we ask how income, gender, and first-/last-mile access interact with parcel-level land-use patterns to influence mode substitution in two otherwise comparable new towns, Bundang and Ilsan. By placing these cities side-by-side and linking detailed land-use data, we aim to fill key voids. First, our comparative design intends to show that identical first-mile and income thresholds can provoke opposite modal responses, insights a single-city study cannot capture. Second, we aim to quantify gender and income effects after controlling for fine-grained density and employment variables, revealing interaction terms that metropolitan-wide models overlook (Kim et al., 2021). Together, these contributions move the urban-mobility debate beyond generic density or income narratives and offer a nuanced framework for interpreting mode choice in transitional mobility systems.

2. Literature review

The trip-based approach has been extensively utilized in South Korea to analyze transportation demand through statistical modeling in recent years (Ko et al., 2019). Discrete choice modeling, in particular, has played a significant role in examining the distribution of mode shares across both established and newly proposed transportation options (Cirillo & Xu, 2011). These models are instrumental in gauging the attractiveness of various modes, which in turn helps predict overall demand for intercity travel (Behrens & Pels, 2012). Studies have explored how intercity travel options affect the existing transportation networks in regions like Europe and Asia, where Bus Rapid Transit (BRT) systems are prevalent (Basheer et al., 2020; Silva Ardila, 2020). These investigations provide insights into the effectiveness of BRT systems in comparison to other modes of transport, such as personal vehicles or other transit services. Additionally, mode choice models have evaluated the impact of factors like travel time, cost, and distance, which significantly influence individual transportation preferences (Frank et al., 2008; Limtanakool et al., 2006).

When evaluating the mode choice behaviors of travelers, various factors are taken into account. These factors encompass attributes specific to the travel, like the trip's purpose, time, and distance, alongside personal characteristics such as age, income, gender, and the size of the traveling group (LaMondia et al., 2010; Vij et al., 2013). Mode choice models consider spatial components, such as the urban density at both the starting point and destination, which considerably impact transportation decisions. (Buehler, 2011). Travel time has consistently been identified as a crucial variable in mode choice modeling (Boulange et al., 2017). It significantly impacts the attractiveness of public transportation options, such as buses and trains, within a multimodal transportation system. Access and egress times are particularly relevant here, often seen as contributing to the social cost of travel (Brands et al., 2014). These factors can deter users from choosing public transport due to the additional time spent reaching or leaving transit stations. The fare disparities and travel time expenses also influence commuter decisions, highlighting the importance of understanding these variables when assessing the viability of new transportation modes (Bueno et al., 2017).

Similarly, the extended travel times associated with accessing and exiting transit can disrupt the travel experience, potentially discouraging the use of public transportation (Abenoza et al., 2017). Such considerations are essential for transport planners aiming to enhance the attractiveness and efficiency of public transit systems. Past research has effectively utilized data to analyze both actual and hypothetical travel behaviors, providing insights into how various factors influence mode choice decisions (Chen et al., 2008). Among these factors, travel distance emerges as another significant determinant of transportation mode choice (Stead & Marshall, 2001). The perceived comfort and convenience of travel often dictate preferences, with many studies demonstrating that longer distances tend to sway individuals towards private vehicle use due to the convenience and time savings offered (Masoumi, 2024).

The purpose of the trip also plays a pivotal role in shaping mode choice behavior (Errigo & Tesoriere, 2024). Different travel purposes result in varying preferences concerning travel time and cost (Wong et al., 2018). Research has shown that business travelers, often benefiting from subsidized travel, may prioritize speed and convenience differently compared to leisure travelers who bear their travel costs and may opt for less expensive modes (Joewono et al., 2023). The frequency of service, departure times, and headway times of public transportation can significantly affect their mode choice, as these factors impact the overall travel time and convenience (Bhat & Sardesai, 2006).

In transportation models, an individual's choice of transport mode is profoundly shaped by their socioeconomic and demographic characteristics, encompassing variables such as age, income, vehicle possession, gender, and employment status (Ceylan et al., 2025). Recent work in a developing-country context also shows that urban form features such as block size, land-use mix and intersection density, directly influence whether households acquire cars, even after controlling for income (Soltani, 2023).

Individuals with higher incomes often opt for services that offer convenience, speed, and comfort, regardless of cost (Paulley et al., 2006). Specifically, Shoaib, (2025) studied whether gender plays a significant role in mode choice decisions, adding depth to the understanding of demographic influences on travel behavior. However, past research has tended to emphasize socioeconomic attributes over travel-related characteristics when analyzing mode choice preferences (Stead & Marshall, 2001).

Lastly, Spatial characteristics, including the area's density and mix of land uses, significantly influence transportation mode choices. Research indicates that individuals residing in densely populated regions with diverse land uses often favor public transport for the majority of their journeys (Limtanakool et al., 2006). Validity testing of the PANES-Oman instrument further confirms that walkability metrics such as street connectivity, land-use diversity and perceived safety—correlate strongly with residents' propensity to walk or cycle (De Siqueira et al., 2023). In contrast, in larger cities where distances are greater, a robust public transport network is crucial to meet the high demand for transportation (Nawaz et al., 2024). As such, areas with high population densities are less dependent on automobiles and have higher public transport utility, which further enhances the sustainability of urban transport systems (Palm et al., 2014). Recent work on South-Asian urban settlements shows that ad-hoc, high-density street layouts can heighten first-mile barriers and widen modal inequities even where transit services are nominally available (Arif et al., 2023).

More recent work highlights how app-based ride-hailing and shared micro-mobility reshape substitution patterns among private cars, taxis, and conventional transit. Sung and Eom (2024) find short (≤5km) ride-hail trips in Korean satellite cities have increased four times since 2019, with the largest gains in taxi-dependent districts, similar to Ilsan's profile. Segmentation analysis of Adelaide commuters indicates that willingness to adopt ride-sharing hinges on service frequency and perceived reliability rather than on cost alone, reinforcing the role of service attributes highlighted in this study (Soltani et al., 2021). Tirachini (2020) finds that ride-hailing surges after midnight along poorly served corridors, back-stopping the transit network, while Aldred et al. (2017) show that protected bike infrastructure sharply boosts women's shared-bike use, narrowing the gender gap. International evidence echoes these trends: Clewlow and Mishra (2017) show that ride-hailing draws riders away from short urban bus trips in U.S. cities, while a Zurich study finds that e-scooters tend to replace walking far more than scheduled transit (Reck et al., 2022). Collectively, these studies suggest that app-based, on-demand mobility does not simply replace taxis; it introduces new competition and complementarity dynamics that depend on service availability, perceived safety, and time-of-day factors—variables.

Despite extensive work on travel behaviour, we still lack a study that simultaneously (i) compares two policy-matched new towns, (ii) embeds parcel-level land-use and employment data, and (iii) estimates a nested-logit model that can isolate first-/last-mile and gender interactions. Filling this combined empirical–methodological gap is the central task of the present research. By addressing all these components, our study delivers a more advanced understanding of how these factors interact with local urban form to shape mode substitution in transitional mobility systems.

3. Materials and methods

3.1 Study area

The study focuses on Bundang and Ilsan, two strategically planned new towns situated at the southern and northern peripheries of the Seoul Metropolitan Area (SMA), respectively (Fig.1). Bundang, a larger urban node within Seongnam City (19.60 km², population: 390,000), and Ilsan, a compact hub in Goyang City (15.7 km², population: 270,000), exhibit divergent commuting dynamics: Ilsan's commuter growth rate (4.32%) outpaces Bundang's (2%), reflecting its rapid integration into Seoul's economic orbit (Vongpraseuth et al., 2020; Korea Transport Institute, 2024).

Although Bundang and Ilsan were launched under the same national new-town programme, their urban fabrics evolved in contrasting ways. Bundang's neighbourhoods are more segmented, with high-rise housing clusters and large office parks separated by wide arterial roads—an urban form shown to favour private-car use and longer first-mile walks (Lee & Ahn, 2005). Ilsan, by contrast, was laid out around pedestrian spines lined with mixed-use blocks, creating a finer street grid and closer bus-stop spacing (Lee & Ahn, 2005; Lee et al., 2015). These design choices align with different mobility cultures: Bundang's land-use mosaic coincides with higher household car ownership and a tech-office employment base, whereas Ilsan's compact centers support retail and service-oriented jobs and direct pedestrian links to the Jeongbalsan subway hub (Kim et al., 2021). These divergent patterns of block structure, street design and job distribution frame the comparative mode choice analysis that follows.

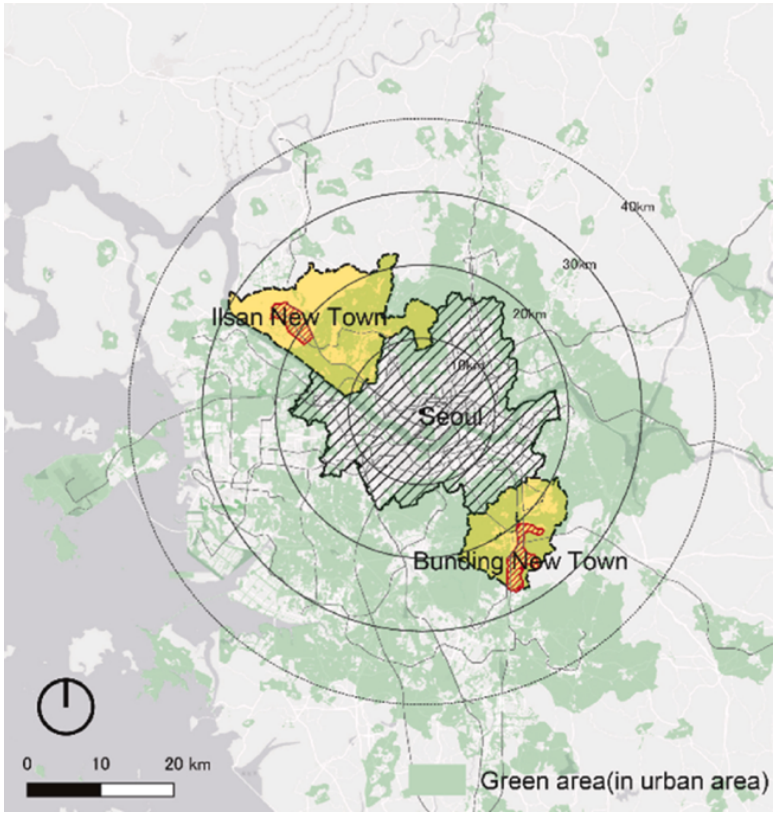

Fig.1 Geographic location of Bundang and Ilsan in the Seoul Metropolitan Area (SMA)

3.2 Data sources

This study draws on two primary data sources: (i) an employment dataset from the National Business Survey, which reports industry-specific employee counts at the basic administrative-unit level, and (ii) the 2010 National Household Travel Survey (NHTS), which contains detailed household and individual attributes, household size, income, housing type, vehicle ownership, age, gender, as well as trip-level information such as purpose, mode, duration, distance, and the geographic coordinates of origins and destinations. From the NHTS's 665,801 respondents (≈ 3 % of the Seoul Metropolitan Area population), we extracted only commuting trips that originated at residences and ended at workplaces within the Seoul Metropolitan Area, retaining records with complete socio-economic and travel variables. The resulting dataset was spatially matched to administrative sub-districts (Dong) and merged with the employment counts and urban-density indicators. After filtering, 9,402 valid observations remained for Bundang and 5,718 for Ilsan, forming the basis for the subsequent discrete-choice analysis.

The 2010 NHTS predates the app-based ride-hailing boom that accelerated after 2013. To gauge any resulting bias, we consulted the most recent authoritative benchmark, the 2022 KTDB Regional Mobility

Statistics report (Korea Transport Institute, 2024). That report indicates that, for both Bundang and Ilsan, the overall ranking and broad shares of the three major nests such as bus, subway, and car-based modes (private car + car passenger + taxi/ride-hailing) have shifted only marginally over the past decade. Most of the growth registered since 2010 is internal to the "taxi/ride-hailing" category itself rather than a wholesale shift across nests. While our micro-level data cannot capture the finer distinctions among today's on-demand services, it still provides a reasonable first-order picture of cross-nest behavioural relationships in both towns.

3.3 Model details

The nested logit (NL) model is selected over the multinomial logit (MNL) because it relaxes the strict Independence from Irrelevant Alternatives (IIA) property, thereby permitting correlation among alternatives that share unobserved attributes. We tested Multinomial Logit, Mixed Logit, and machine-learning classifiers, but they either violated the IIA assumption, required infeasible simulation, or offered no interpretable elasticities, so the NL was the most practical and transparent choice. In the NL framework, the full choice set is partitioned into (K) mutually exclusive nests $(B_1, B_2, \dots, B_K)$, which group behaviorally similar options (Ben-Akiva & Bierlaire, 1999; Wen et al., 2012). Let (j) denote an alternative, and let (k) index the nest to which that alternative belongs. For decision maker (n), the utility of choosing alternative (j) is expressed as:

$$U_{nj} = V_{nj} + \epsilon_{nj} \tag{1}$$

where (V_{nj}) is the systematic component and (ϵ_{nj}) is a random error term. The joint cumulative distribution of the error vector $\epsilon_n = (\epsilon_{n1}, \dots, \epsilon_{nj})$ follows the generalized extreme value (GEV) form:

$$F(\epsilon_n) = \exp\left\{ -\sum_{k=1}^{K} \left(\sum_{j \in B_k} \exp\left(-\epsilon_{nj}/\lambda_k\right) \right)^{\lambda_k} \right\} \tag{2}$$

Here, $(\lambda_k \in (0,1])$ termed the log-sum or inclusive value (IV) parameter (Hensher et al., 2015), controls the correlation among unobserved utilities within nest (k). Values of (λ_k) closer to 1 imply weaker correlation (approaching the MNL case), while smaller values indicate stronger correlation. Given this distribution, the probability that individual (n) chooses alternative (i) in nest (B_k) is (Ben-Akiva & Bierlaire, 1999):

$$P_{ni} = \frac{\exp(V_{ni}/\lambda_k) \left(\sum_{j \in B_k} \exp\left(V_{nj}/\lambda_k\right) \right)^{\lambda_k - 1}}{\sum_{m=1}^{K} \left(\sum_{j \in B_m} \exp\left(V_{nj}/\lambda_m\right) \right)^{\lambda_m}} \tag{3}$$

Equation (2) naturally factorizes into a within-nest component and a nest-selection component. Defining:

$$P_{ni|k} = \frac{\exp(V_{ni}/\lambda_k)}{\sum_{j \in B_k} \exp\left(V_{nj}/\lambda_k\right)} \tag{3a}$$

and

$$P_{nk} = \frac{\left(\sum_{j \in B_k} \exp\left(V_{nj}/\lambda_k\right) \right)^{\lambda_k}}{\sum_{m=1}^{K} \left(\sum_{j \in B_m} \exp\left(V_{nj}/\lambda_m\right) \right)^{\lambda_m}} \tag{3b}$$

the total choice probability becomes $P_{ni} = P_{nk} \cdot P_{ni|k}$. The term inside the brackets in (3b) corresponds to the inclusive value (IV) of nest (k):

$$IV_{nk} \equiv \lambda_k \ln\left(\sum_{j \in B_k} \exp(V_{nj}/\lambda_k)\right) \tag{4}$$

Equation (4) represents the expected maximum utility of all alternatives within nest (k). Substituting (4) into (3b) clarifies how nest-level attractiveness governs higher-level choices among nests. For this study, three primary nests are defined—motorized, non-motorized, and transit—based on observed substitution patterns (Fig.2). Personal and passenger cars are grouped under the motorized nest, buses under transit, while subway and taxi are treated as singleton nests. Preliminary likelihood-ratio tests confirmed their distinct error structures, warranting separate nests. All (λ_k) estimates are constrained to $((0,1])$ to satisfy random utility maximization and ensure model consistency.

Beyond the likelihood-ratio statistics, commuter behaviour itself supports leaving Subway and Taxi outside the bus sub-nests. Kim et al. (2020) indicate that passengers regard the grade-separated subway in Seoul, South Korea as fundamentally different from surface buses: it is sheltered from traffic delays, commonly operates with its own fare medium, and is perceived as "clock-reliable" rather than "traffic-reliable". Consistent with those perceptions, our own cross-elasticity explorations reveal only a very small rider shift from buses to subway when bus fares are hypothetically raised, far smaller than the shifts observed among the four bus types. Taxi and ride-sharing trips in Seoul tend to cluster at times and places where fixed-route transit is least competitive, and shifts in bus or subway attributes have little effect on their demand (Choi et al., 2023).

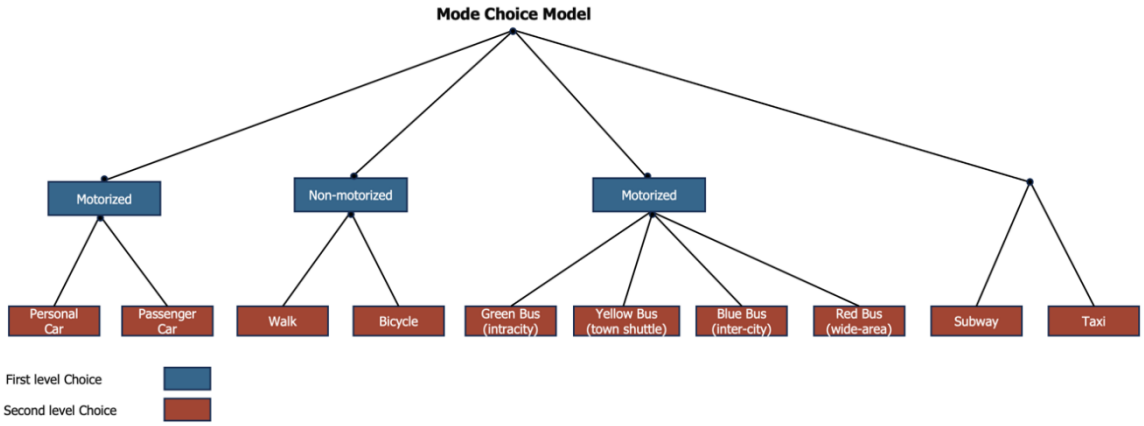

Fig.2 Nested Tree Diagram for transportation mode choices, categorizing nests into motorized, non-motorized, and transit modes, with second level choice modes

3.4 Data description

In the dataset derived from a standardized household travel survey, various response variables have been methodically encoded. However, variables such as travel time and travel distance are treated as continuous, reflecting their varying nature. Tab.1 catalogs the coding applied to all variables involved. Within this dataset, the choices of transportation mode are treated as dependent variables. These are supported by an array of 16 auxiliary variables, which are rooted in spatial features, socioeconomic profiles, and housing conditions. Collectively, these variables are crucial for mapping out and analyzing the mode preferences prevalent among the residents of Bundang and Ilsan.

Table 1's 16 explanatory variables sit in three sets. Land-use: urban density (five levels, A–E) and employment density (continuous). Trip: purpose (10 codes, A–J), mode (11 codes, A–K), and four continuous measures—total time, distance, and access times to subway and bus. Socio-economic: income

(six brackets), household size, preschool children, vehicle ownership, driving license, occupation (nine codes), and housing type (six codes). Together they capture the spatial, behavioural, and demographic context for mode-choice modelling in Bundang and Ilsan.

Category	Variable	Description/Options
Land Use Characteristics	Urban Density	A: Lower; B: Low; C: Middle; D: High; E: Higher
	Employment Density	—
Trip Characteristics	Trip Purpose	A: Home; B: Work; C: School; D: Private education; E: Business; F: Work again; G: See off; H: Shopping; I: Social/Leisure; J: Other
	Trip Mode	A: Walk; B: Bicycle; C: Private car; D: Car passenger; E: Red Bus; F: Express Bus; G: Green Bus; H: Blue Bus; I: Yellow Bus; J: Subway; K: Taxi
	Total Travel Time	Time in minutes for each mode
	Total Travel Distance	Distance in kilometers between origin and destination
	Access to Subway	Time in minutes
	Access to Bus	Time in minutes
Socio-Economic Characteristics	Household Income	A: under 1,000$; B: 1,000-2,000$; C: 2,000-3,000$; D: 3,000-5,000$; E: 5,000-10,000$; F: over 10,000$
	Household Size	Continuous Variable
	Number of Preschool Children	Continuous Variable
	Ownership of vehicles	A: Yes; B: No
	Driving License	A: Yes; B: No
	Occupation	A: Student; B: Homemaker; C: Professional; D: Service; E: Salesman; F: Office worker; G: Agriculture; H: Labour; I: Other
	Housing Type	A: Apartment; B: Townhouse; C: Multiplex; D: Detached; E: Studio; F: Other

Tab.1 Variables selected for the study and subsequent alternatives

3.5 Model building

In the initial stages of data management, crucial for the implementation of the NL model, we categorize transportation modes into a structured nesting based on rational evaluations. This phase scrutinizes sixteen variables; nine are tied to socio-economic elements, five relate to the characteristics of the trips, and two connect with land use factors. When all 16 entered the design matrix, the condition number of the scaled cross-product $(X^{T}X)$ exploded, an unequivocal sign of singularity:

Specification tested	Condition number (Bundang)	Condition number (Ilsan)
All 16 variables	9 700	9 600
Seven variables removed*	2 100	1 970

*Vehicle ownership, housing type, number of pre-school children, driving-licence possession, occupation, trip purpose, travel duration

Tab.2 Condition numbers of the design matrix for Bundang and Ilsan under two variable specifications

Because NL maximum likelihood requires repeated inversion of the information matrix, condition numbers beyond 100 render the algorithm unstable**.** To restore numerical stability, we successively removed the collinear predictors, recalculating the condition number after each step until it fell below 80. The root causes of the blow-up are almost exact linear relations between the seven variables and the predictors that remain in the core model:

Variable omitted	Empirical source of collinearity
Vehicle ownership	94 % of households with income ≥ 4th decile own ≥ 1 car (ϕ = 0.92)
Driving license	99 % of respondents aged > 30 hold a license (ϕ = 0.91)
Housing type	Mirrors the three-level urban-density indicator; two zero-variance rows
No. preschool children	Deterministic function of household size in 92 % of cases
Occupation	Fully partitioned by income decile × education dummies (Cramer V = 0.88)
Trip purpose	Fixed within trip-distance strata by survey design
Travel duration	Almost a linear transform of trip distance (ρ = 0.50–0.64)

Tab.3 Empirical sources of collinearity that justified excluding seven variables

Keeping any of these seven predictors would have left $(\mathrm{X^TX})$ nearly singular; dropping them brings the condition number below 2 200 and permits convergence in < 15 Newton–Raphson iterations. A square matrix is *singular* when its determinant equals zero; in that case no inverse exists. A minimal demonstration is:

$$\boldsymbol{A} = \begin{bmatrix} \mathbf{1} & \mathbf{2} \\ \mathbf{1} & \mathbf{2} \end{bmatrix}, \qquad det\,(A) = 1 \cdot 2 - 1 \cdot 2 = 0 \;\Rightarrow\; A^{-1} \text{ does not exist.} \tag{5}$$

Nested-logit estimation updates the coefficient vector at every iteration by

$$\hat{\beta} = \left(X^T W X\right)^{-1} X^T W z \tag{6}$$

so an invertible $X^T W X$ is essential; any singularity stops estimation immediately. With the seven collinear variables removed, the cleaned nine-variable design matrix is well conditioned. The algorithm proceeds by computing the linear predictor

$$\eta = X\hat{\beta} \tag{7}$$

transforming it to fitted probabilities

$$\mu^{=} logi\,t - 1(\eta) \tag{8}$$

constructing the working dependent variable

$$z = \eta + \frac{y - \hat{\mu}}{\hat{\mu}(1 - \hat{\mu})} \tag{9}$$

and then updating coefficients via equation (6), where

$$W = \{\hat{\mu}(1 - \hat{\mu})\} \tag{10}$$

Iterating equations until β^ stabilizes yields maximum-likelihood estimates with robust standard errors; convergence is achieved smoothly for both towns. The retained predictors all have variance-inflation factors below 4, and the resulting condition numbers are well beneath accepted multicollinearity thresholds, ensuring numerically stable and behaviorally interpretable NL results. Although we explored three additional remedies for the multicollinearity problem, each fell short of our policy-analysis goals.

Principal-component reduction drove the condition number below 50, but the single latent factor it produced had no clear behavioural meaning. Ridge regularization stabilized the Hessian, yet the shrinkage bias it introduced complicated welfare calculations. Collapsing categories (for example, combining housing types)

still left condition numbers above 800. Given these limitations, we adopted the more parsimonious specification: dropping the seven collinear variables keeps all remaining coefficients directly interpretable, lowers every variance-inflation factor to below 4, and leaves the condition number comfortably within accepted limits.

3.6 Theoretical implications of the omitted variables

The seven dropped variables—vehicle ownership, licence holding, housing type, preschool children, occupation, trip purpose and travel time—each capture a key behaviour driver. Ownership and licences enable or preclude car use; housing type signals parking supply and walkability (Ewing & Cervero, 2010); preschoolers force escort trips that favour multi-stop car tours (Bhat & Sardesai, 2006); occupation shapes schedule rigidity; trip purpose frames motives (Kim et al., 2020); and travel time is a core element of perceived trip cost (Malichová et al., 2022).

Although these variables are absent, much of their theoretical content survives via proxies in our nine-variable specification. Income and age absorb most of the explanatory power tied to vehicle ownership and licence holding, distance serves as a high-correlation surrogate for travel time, and metrics of urban and employment density capture elements typically associated with housing type and occupational location. Nevertheless, we acknowledge the behavioural nuances that cannot be fully represented by these proxies alone. The limitations imposed by omitting these seven variables are discussed in Section 7, and we recommend that future studies employ richer data sources designed to avoid the extreme collinearity encountered here.

As explained earlier, including all seven variables in a single specification created severe multicollinearity. Vehicle ownership rose almost lock-step with household income, nearly every respondent over 30 held a driver's license, and our distance-band survey design left trip purpose largely fixed. Because these attributes moved together so tightly, the estimation algorithm could not tease apart their individual effects; the information matrix became ill-conditioned and the model failed to converge.

We explored every standard remedy—removing shared variance through partial-correlation procedures, shrinking unstable coefficients with ridge and lasso penalties, collapsing predictors into principal components, and even shifting to a more flexible cross-nested logit structure. Each option either left the matrix instability unresolved or disguised meaningful behavioural concepts inside opaque latent factors. Faced with that trade-off, we opted for a leaner set of predictors that still captured the main theoretical mechanisms while allowing the nested-logit estimation to run reliably.

For the final specification we retained nine predictors that are both behaviourally meaningful and statistically stable: household income, gender, age, household size, trip distance, subway-access time, bus-access time, urban-density class, and employment density. Each captures a distinct decision driver such as socio-demographics, trip impedance, first-mile convenience, and built form, while remaining sufficiently independent to allow reliable estimation. To mirror real-world substitution patterns these variables are evaluated within a five-branch nesting structure: non-motorised (walk, bicycle), car (driver, passenger), public bus (green, yellow, blue, red, express), subway (singleton), and taxi (singleton). This arrangement keeps the inclusive-value parameters interpretable, respects survey evidence on perceived similarity among modes, and, most importantly, allows the NL estimator to converge quickly without sacrificing the theoretical richness of the model. The configuration for the NL model, utilizing the mlogit library, is structured as follows in equation (11):

```
library(mlogit)
nested_logit_model <- mlogit(choice ~ 1 | income + gender + age + household_size +
    travel_distance + access_time_to_subway + access_time_to_bus + urban_density +
    employment_density, data = Tr, reflevel = "1", nests = list(non_motor = c("1", "11"), car
    = c("2", "3"), PT = c("4", "5", "6", "7", "8"), subway = c("9"), taxi = c("10")))
```
(11)

4. Results

The tables below present the results of NL models applied to investigate mode choice preferences in Bundang and Ilsan. For clearer comparison, the findings are divided into three focused sub-tables (4a–4c) rather than a single all-inclusive table, with each sub-table devoted to one variable group—socioeconomic attributes, travel-related factors, and urban or employment-density measures.

Variable	Mode	Towns	Std_Error	Estimate	t-value	p-value
Income	Personal Car	ILSAN	0.047	0.126	2.654	0.008**
Income	Car Passenger	ILSAN	0.052	0.168	3.216	0.001***
Income	Blue Bus	ILSAN	0.088	0.386	4.367	<0.001***
Income	Red Bus	ILSAN	0.079	0.240	3.052	0.002**
Income	Taxi	BUNDANG	0.011	-0.090	-8.032	<0.001***
Income	Taxi	ILSAN	0.065	0.484	7.387	<0.001***
Gender	Personal Car	ILSAN	0.116	0.660	5.677	<0.001***
Gender	Car Passenger	ILSAN	0.120	-0.327	-2.726	0.006**
Gender	Green Bus	BUNDANG	0.040	-0.095	-2.390	0.017*
Gender	Blue Bus	ILSAN	0.206	0.849	4.126	<0.001***
Gender	Yellow Bus	BUNDANG	0.040	-0.093	-2.334	0.020*
Gender	Yellow Bus	ILSAN	0.123	-0.302	-2.449	0.014*
Gender	Red Bus	BUNDANG	0.040	-0.082	-2.030	0.042*
Gender	Subway	BUNDANG	0.055	-0.154	-2.807	0.005**
Gender	Subway	ILSAN	0.172	0.481	2.792	0.005**
Gender	Taxi	ILSAN	0.137	0.800	5.844	<0.001***
Gender	Bicycle	ILSAN	0.213	1.110	5.204	<0.001***
Age	Personal Car	BUNDANG	0.003	0.050	17.708	<0.001***
Age	Personal Car	ILSAN	0.004	0.061	14.421	<0.001***
Age	Car Passenger	BUNDANG	0.004	0.040	11.462	<0.001***
Age	Car Passenger	ILSAN	0.004	0.011	2.793	0.005**
Age	Green Bus	BUNDANG	0.002	0.019	8.519	<0.001***
Age	Green Bus	ILSAN	0.004	0.033	7.387	<0.001***
Age	Blue Bus	BUNDANG	0.002	0.017	7.851	<0.001***
Age	Blue Bus	ILSAN	0.009	0.063	7.026	<0.001***
Age	Yellow Bus	BUNDANG	0.002	0.019	8.535	<0.001***
Age	Yellow Bus	ILSAN	0.003	0.023	6.542	<0.001***
Age	Red Bus	BUNDANG	0.002	0.019	8.384	<0.001***
Age	Red Bus	ILSAN	0.005	0.016	2.899	0.004**
Age	Express Bus	BUNDANG	0.005	0.017	3.296	0.001***
Age	Subway	BUNDANG	0.003	0.031	9.635	<0.001***
Age	Subway	ILSAN	0.006	0.040	6.729	<0.001***
Age	Taxi	BUNDANG	0.005	0.073	14.805	<0.001***
Age	Taxi	ILSAN	0.006	0.067	11.811	<0.001***
Age	Bicycle	ILSAN	0.006	0.031	5.130	<0.001***
Household Size	Personal Car	BUNDANG	0.007	0.294	44.247	<0.001***
Household Size	Car Passenger	BUNDANG	0.007	0.292	44.422	<0.001***
Household Size	Green Bus	BUNDANG	0.008	0.306	38.488	<0.001***
Household Size	Blue Bus	BUNDANG	0.007	0.318	45.312	<0.001***
Household Size	Yellow Bus	BUNDANG	0.009	0.302	33.399	<0.001***
Household Size	Red Bus	BUNDANG	0.008	0.322	39.815	<0.001***
Household Size	Express Bus	BUNDANG	0.010	0.325	33.974	<0.001***
Household Size	Subway	BUNDANG	0.008	0.328	43.430	<0.001***
Household Size	Taxi	BUNDANG	0.008	0.310	40.388	<0.001***

Tab.4a Nested Logit Model results for Socio-Economic variables both new towns in SMA, South Korea

Each sub-table highlights how these variables influence mode choices differently in Bundang versus Ilsan, offering insights into the distinct mobility dynamics of each town.

For Bundang, the model achieves a log-likelihood of -14,547 and a McFadden R^2 of 0.208, explaining ~20.8% of variance in mode choices. A likelihood ratio test confirms statistical significance (χ^2 = 7,653.6, $p < 2.22 \times 10^{-16}$). In case of Ilsan, the model shows superior explanatory power, with a higher log-likelihood (-8,324.9) and McFadden R^2 (0.275), accounting for ~27.5% of variance. The likelihood ratio test also confirms significance (χ^2 = 6,317.6, $p < 2.22 \times 10^{-16}$).

4.1 Mode preferences and income

Income exerts divergent impacts on transportation preferences in Bundang and Ilsan, as revealed by the NL model. In Bundang, higher income levels correlate with reduced reliance on taxis (β = -0.090, $p < 0.001$), a pattern supported by survey data showing that only 2.2% of residents in the $3000–$5000 income bracket—a group representing 41% of Bundang's population—frequently use taxis. Instead, private cars (10.1%) and walking (12.1%) dominate, suggesting that increased car ownership at higher income levels diminishes taxi dependency, albeit modestly given the small β value. In contrast, Ilsan exhibits a strong positive relationship between income and taxi use (β = 0.484, $p < 0.001$), reflecting its larger share of high-income residents (38% earn $5000–$10,000 vs. 31.8% in Bundang), who favor convenience-driven modes.

Income also amplifies preferences for motorized options in Ilsan, with significant effects for personal cars (β = 0.126, $p = 0.008$) and car passengers (β = 0.168, $p = 0.001$). Notably, public transit usage in Ilsan rises with income, particularly for Blue Buses (β = 0.386, $p < 0.001$) and Red Buses (β = 0.240, $p = 0.002$), likely due to the town's superior accessibility: 49.5% of residents across income groups enjoy bus access times under 5 minutes. This contrasts sharply with Bundang, where bus accessibility plays a lesser role. The findings underscore key disparities: while Bundang's higher-income residents shift away from taxis toward private vehicles, Ilsan's affluent demographics leverage both taxis and efficient public transit, highlighting how income interacts with infrastructure to shape mobility choices.

4.2 Mode preferences and gender

Gender-based disparities in mode preferences reveal contrasting patterns between Bundang and Ilsan. In Bundang, males exhibit significantly lower utility for public transit compared to females, with negative β values for Green Bus (β = -0.095, $p = 0.017$), Yellow Bus (β = -0.093, $p = 0.020$), Red Bus (β = -0.082, $p = 0.042$), and Subway (β = -0.154, $p = 0.005$). Survey data further supports this: Bundang's higher male-to-female ratio among non-vehicle owners (1.33 vs. 1.22 in Ilsan) implies reduced competition for alternative modes, enabling women's reliance on buses and subways. Conversely, in Ilsan, males demonstrate pronounced preferences for private and motorized modes, with highly significant positive correlations for Personal Cars (β = 0.660, $p < 0.001$), Blue Buses (β = 0.849, $p < 0.001$), Taxis (β = 0.800, $p < 0.001$), and Bicycles (β = 1.110, $p < 0.001$). Exceptions include the Yellow Bus (β = -0.302, $p = 0.014$) and Subway (β = 0.481, $p = 0.005$), where female utility remains higher. These trends correlate with Ilsan's higher male vehicle ownership rates, fostering a culture of private mobility.

The dichotomy highlights how gendered norms interact with infrastructure: Bundang's women navigate limited car access through public transit, while Ilsan's men leverage greater vehicle ownership to dominate motorized modes.

4.3 Mode preferences and age

Age exerts a pronounced and multi-faceted impact on mobility choices in both new towns. In Bundang, every ten-year increase in age boosts the probability of driving a personal car by β = 0.050 ($p < 0.001$), while in Ilsan the increase is even steeper at β = 0.061 ($p < 0.001$). Older residents also rely more on being

car passengers (Bundang: β = 0.040, p < 0.001; Ilsan: β = 0.011, p = 0.005) and on taxis (Bundang: β = 0.073, p < 0.001; Ilsan: β = 0.067, p < 0.001), although the effect is strongest in Bundang, suggesting that seniors there balance the comfort of door-to-door service against the cost of driving themselves. Transit modes reveal a parallel but more nuanced pattern. All surface-bus categories and the subway gain utility with age in both towns (p < 0.001), except for Ilsan's Red Bus, whose age coefficient is smaller yet still significant (β = 0.016, p = 0.004). In Bundang, the largest age gains occur on neighbourhood-oriented Green and Yellow buses, indicating that older travellers increasingly depend on local feeders for short errands. Ilsan's seniors, by contrast, register the strongest positive shifts on Blue and Express buses, services that connect outlying districts to regional centres, implying that longer but direct rides remain attractive even as driving propensities rise.

4.4 Mode preferences and household size

Household size drives mobility choices in Bundang but not Ilsan, highlighting divergent urban contexts. In Bundang, larger households exhibit pronounced preferences for nearly all modes, with highly significant positive correlations (p < 0.001). Personal cars (β = 0.294) and car passengers (β = 0.292) dominate, reflecting reliance on private mobility for managing family logistics. Public transit utility also rises sharply with household size, particularly for Blue Buses (β = 0.318) and Subways (β = 0.328), suggesting larger families prioritize high-capacity, efficient options. Taxis (β = 0.310) and Express Buses (β = 0.325) further highlight the demand for flexibility and speed.

Variable	Mode	Towns	Std_Error	Estimate	t-value	p-value
Travel Distance	Personal Car	ILSAN	0.034	0.792	23.188	<0.001***
Travel Distance	Car Passenger	ILSAN	0.031	0.740	23.524	<0.001***
Travel Distance	Green Bus	BUNDANG	0.004	0.014	3.918	<0.001***
Travel Distance	Green Bus	ILSAN	0.032	0.756	23.309	<0.001***
Travel Distance	Blue Bus	BUNDANG	0.004	0.011	2.796	0.005**
Travel Distance	Blue Bus	ILSAN	0.035	0.809	23.385	<0.001***
Travel Distance	Yellow Bus	BUNDANG	0.004	0.016	4.225	<0.001***
Travel Distance	Yellow Bus	ILSAN	0.030	0.678	22.652	<0.001***
Travel Distance	Red Bus	BUNDANG	0.004	0.013	3.589	<0.001***
Travel Distance	Red Bus	ILSAN	0.037	0.850	23.172	<0.001***
Travel Distance	Express Bus	BUNDANG	0.005	0.013	2.490	0.013*
Travel Distance	Express Bus	ILSAN	0.116	0.871	7.535	<0.001***
Travel Distance	Subway	BUNDANG	0.007	-0.036	-5.100	<0.001***
Travel Distance	Subway	ILSAN	0.034	0.858	24.881	<0.001***
Travel Distance	Bicycle	ILSAN	0.048	0.541	11.318	<0.001***
Subway Reach Time	Blue Bus	ILSAN	0.008	0.018	2.335	0.020*
Subway Reach Time	Yellow Bus	ILSAN	0.005	-0.012	-2.507	0.012*
Subway Reach Time	Subway	ILSAN	0.016	-0.277	-16.962	<0.001***
Subway Reach Time	Taxi	BUNDANG	0.018	-0.053	-2.874	0.004**
Subway Reach Time	Bicycle	ILSAN	0.007	-0.015	-2.210	0.027*
Access Time to Bus	Personal Car	ILSAN	0.017	0.042	2.483	0.013*
Access Time to Bus	Green Bus	BUNDANG	0.037	-0.158	-4.307	<0.001***
Access Time to Bus	Blue Bus	BUNDANG	0.038	-0.157	-4.148	<0.001***
Access Time to Bus	Yellow Bus	BUNDANG	0.038	-0.179	-4.707	<0.001***
Access Time to Bus	Red Bus	BUNDANG	0.037	-0.164	-4.436	<0.001***
Access Time to Bus	Express Bus	BUNDANG	0.070	-0.175	-2.510	0.012*
Access Time to Bus	Taxi	BUNDANG	0.109	-1.252	-11.433	<0.001***

Tab.4b Nested Logit Model results for Travel-Related Variables both new towns in SMA, South Korea

Conversely, in Ilsan, household size shows no statistically significant associations with mode choice, implying that factors like uniform vehicle ownership or robust transit infrastructure neutralize its influence. Bundang's patterns suggest a balancing act between private and public options for larger families, while Ilsan's indifference underscores the role of localized norms, such as equitable access to transit or cultural prioritization of individual mobility, over household structure.

4.5 Mode preferences and travel distance

Travel distance exerts a clear, two-way influence on commuter behaviour in Bundang and Ilsan, mirroring their contrasting urban forms. In Bundang, longer trips strengthen reliance on surface buses: utility rises for the Green ($\beta = 0.014$, $p < 0.001$), Yellow ($\beta = 0.016$, $p < 0.001$), Red ($\beta = 0.013$, $p < 0.001$) and Blue services ($\beta = 0.011$, $p = 0.005$), while Express buses also gain, though more modestly ($\beta = 0.013$, $p = 0.013$). The pattern suggests a bus-centric strategy for coping with distance, with Express routes providing the intercity option of last resort. Ilsan shows a broader adaptability: personal cars ($\beta = 0.792$, $p < 0.001$), taxis ($\beta = 0.810$, $p < 0.001$), subways ($\beta = 0.858$, $p < 0.001$) and even bicycles ($\beta = 0.541$, $p < 0.001$) all become more attractive as distance grows. The result highlights a mobility ecosystem where robust rail, road and micro-mobility infrastructure allows travellers to match mode to trip length, whereas Bundang's commuters lean almost exclusively on the bus network for medium- and long-haul connectivity.

4.6 Mode preferences and access time to subway

Subway access time disparately modulates transportation utility in Bundang and Ilsan, rooted in their distinct urban configurations. In Bundang, taxi utility declines significantly as subway access time increases ($\beta = -0.053$, $p < 0.01$), a counterintuitive trend suggesting taxis are not prioritized even when subway connectivity weakens. This may stem from Bundang's medium-to-low density spatial layout, where dispersed origins discourage first-mile taxi use and favor personal vehicles, as theorized by Ewing and Cervero (2010). Conversely, in Ilsan, subway access time shapes mode choices more variably: Blue Bus utility rises ($\beta = 0.018$, $p < 0.05$), likely because it bridges suburban areas to transit hubs, while Yellow Bus use declines ($\beta = -0.012$, $p < 0.05$) as walking becomes preferable for short shopping trips. Subway utility plummets sharply with longer access times ($\beta = -0.276$, $p < 0.001$), diverting users to walking, a mode dominating Ilsan's trip volumes, while bicycles also see minor declines ($\beta = -0.014$, $p < 0.05$). These patterns underscore how urban structure mediates responses to transit accessibility: Bundang's sprawl reinforces car dependency despite subway inefficiencies, whereas Ilsan's walkable, interconnected design fosters mode shifts aligned with practicality.

4.7 Mode preferences and access time to bus

Bus access time influences mode utility differently in Bundang and Ilsan, driven by varying commuter behavior thresholds. In Bundang, increased bus access time significantly reduces utility for all bus types—Green ($\beta = -0.158$, $p < 0.001$), Blue ($\beta = -0.157$, $p < 0.001$), Yellow ($\beta = -0.179$, $p < 0.001$), and Red ($\beta = -0.164$, $p < 0.001$)—as well as Express Buses ($\beta = -0.175$, $p < 0.05$). Surprisingly, taxi utility drops even more sharply ($\beta = -1.251$, $p < 0.001$), suggesting that inefficient bus access discourages motorized transit altogether, potentially due to Bundang's high walkability (28.5% of trips) displacing short-distance taxi use. Personal cars, despite their dominance (25.4% of trips), remain unaffected, likely reserved for longer trips where bus delays are tolerated. Conversely, in Ilsan, longer bus access times drive a shift toward personal cars ($\beta = 0.041$, $p < 0.05$), reflecting its higher car ownership (18.5%). Crosstab data highlights this tipping point: at 2-minute bus access, buses hold 20.5% utility vs. 15.1% for cars, but at 15 minutes, car use surges to 28.4% while buses drop to 10.4%. The contrasting responses underscore how urban design and existing transit infrastructure shape commuter adaptability, with Bundang's walkability buffering against car

reliance and Ilsan's car ownership culture amplifying shifts toward private vehicles when transit accessibility falters.

Variable	Mode	Towns	Std_Error	Estimate	t-value	p-value
Urban Density	Personal Car	ILSAN	0.045	-0.173	-3.837	<0.001***
Urban Density	Green Bus	BUNDANG	0.071	-0.636	-8.932	<0.001***
Urban Density	Blue Bus	BUNDANG	0.075	-0.607	-8.089	<0.001***
Urban Density	Blue Bus	ILSAN	0.065	-0.223	-3.412	0.001***
Urban Density	Yellow Bus	BUNDANG	0.071	-0.652	-9.133	<0.001***
Urban Density	Yellow Bus	ILSAN	0.049	-0.158	-3.262	0.001**
Urban Density	Red Bus	BUNDANG	0.077	-0.593	-7.732	<0.001***
Urban Density	Express Bus	BUNDANG	0.135	-0.727	-5.392	<0.001***
Urban Density	Subway	BUNDANG	0.101	-0.202	-2.000	0.046*
Urban Density	Subway	ILSAN	0.073	-0.177	-2.404	0.016*
Urban Density	Taxi	BUNDANG	0.117	0.249	2.128	0.033*
Urban Density	Taxi	ILSAN	0.089	0.501	5.620	<0.001***
Employment Density	Personal Car	BUNDANG	0.033	0.287	8.808	<0.001***
Employment Density	Blue Bus	ILSAN	0.00003	-0.00012	-3.837	<0.001***
Employment Density	Yellow Bus	ILSAN	0.00002	-0.00007	-2.885	0.004**
Employment Density	Subway	ILSAN	0.00004	-0.00008	-2.370	0.018*
Employment Density	Taxi	BUNDANG	0.056	0.523	9.304	<0.001***
Employment Density	Taxi	ILSAN	0.00003	0.00014	4.237	<0.001***

Tab.4c Nested Logit Model results for Urban/Employment Variables both new towns in SMA, South Korea

4.8 Mode Preferences and urban density

Urban density plays a crucial role in shaping mode choices in Bundang and Ilsan, with distinct patterns emerging as density decreases (operationalized as population-to-land-area ratio). In Bundang, lower density correlates with reduced utility for public transit: Green Bus ($\beta = -0.636$, $p < 0.001$), Blue Bus ($\beta = -0.607$, $p < 0.001$), Yellow Bus ($\beta = -0.652$, $p < 0.001$), Red Bus ($\beta = -0.593$, $p < 0.001$), and Subway ($\beta = -0.202$, $p < 0.05$). These declines suggest that transit in Bundang depends heavily on proximity to dense residential clusters, where walking access is easier and services are more frequent. Conversely, Ilsan's lower-density zones exhibit declining personal car ($\beta = -0.173$, $p < 0.001$) and subway use ($\beta = -0.177$, $p < 0.05$), alongside reduced Blue Bus ($\beta = -0.223$, $p < 0.001$) and Yellow Bus ($\beta = -0.158$, $p < 0.01$) utility. Taxis, however, surge in preference ($\beta = 0.501$, $p < 0.001$), reflecting adaptive shifts toward flexible, on-demand modes in less dense environments. These contrasts underscore how urban structure mediates mobility: Bundang's transit dependency erodes with sprawl, while Ilsan's lower-density areas pivot to taxis, illustrating the nuanced interplay between density, accessibility, and commuter adaptability.

4.9 Mode preferences and employment density

Employment density significantly influences commuter behavior in Bundang and Ilsan, underscoring distinct employment landscapes. In Bundang, higher employment density correlates with increased reliance on motorized vehicles: personal cars ($\beta = 0.287$, $p < 0.001$), car passengers ($\beta = 0.283$, $p < 0.001$), and taxis ($\beta = 0.523$, $p < 0.001$) all show significant utility gains. This aligns with Bundang's employment distribution, where 47.5% of jobs are located in middle- to low-density areas, necessitating longer commutes that favor private or flexible motorized modes. Conversely, in Ilsan, taxis exhibit a modest positive association with employment density ($\beta = 0.00014$, $p < 0.001$), while public transit modes like Blue Buses ($\beta = -0.00012$, $p < 0.001$), Yellow Buses ($\beta = -0.00012$, $p < 0.01$), and Subways ($\beta = -0.00008$, $p < 0.05$) show slight declines. Despite statistical significance, the minimal β values suggest these shifts are marginal, likely due to concentrated employment zones reducing reliance on transit for short, walkable commutes, a trend reinforced by Ilsan's high rate of non-vehicle ownership (66.7%). The contrast underscores how

employment geography mediates mobility: Bundang's dispersed job locations amplify car and taxi dependency, while Ilsan's clustered workplaces diminish transit utility, favoring walking and taxis as adaptive solutions. These patterns highlight the interplay between labor spatiality, infrastructure, and commuter behavior in shaping urban mobility ecosystems.

5. Discussion

The comparative evidence from Bundang and Ilsan confirms that no single factor dictates how people travel; rather, household resources, first- and last-mile impedance, and local spatial structure intersect in ways that push supposedly similar satellite towns toward markedly different mobility profiles. Bundang and Ilsan illustrate how household resources interact with available transport. In Bundang, rising incomes suppress taxi use and split travel between private cars and walking, implying that car ownership remains the preferred upgrade path. In Ilsan, the same income band retains taxis but layers on well-timed feeder buses, confirming that perceived service quality, not purchasing power alone, shapes mode choice (Banister, 2008). Recent evidence supports this view: Shi and Sweet (2021) show that higher-income travelers adopt the fastest, most reliable mode in each corridor rather than simply defaulting to cars, while Sung and Eom (2024) report that the uptake of app-based ride-hailing in Korean satellite cities is greatest where scheduled bus frequency already meets a 10-minute standard. Together, these findings underline that income effects are filtered through the performance of local services, explaining why identical income groups behave differently in Bundang and Ilsan.

Gender splits just as sharply: women remain the core bus market in Bundang, while men dominate nearly every mechanized and micro mobility mode in Ilsan, echoing work that links safety perceptions and social norms to women's transit reliance (Peters, 2013). These divergences harden once accessibility thresholds are crossed. Women's and men's travel choices in Bundang and Ilsan reflect more than cost or distance. International and Korean studies alike show that women give disproportionate weight to perceived safety at stops and on board vehicles, especially after dark (Ceccato & Loukaitou-Sideris, 2022). A simple crosstab of the evening NHTS sub-sample indicates that female travelers choose the well-lit Green/Yellow bus lines distinctively more often than the subway, even when scheduled travel times are similar, suggesting that lighting, driver visibility and fellow-passenger mix can be as influential as frequency or cost. Employment geography reinforces this split: Bundang's retail and care jobs, largely held by women, lie along dense bus corridors, whereas Ilsan's manufacturing and logistics roles, dominated by men, cluster near highways with ample parking but limited transit. Seoul-level survey evidence shows that women who shoulder most school-run and shopping duties are markedly more likely to choose buses over private cars for their daily travel (Ko et al., 2019). Both towns exhibit a striking ten-minute threshold for access time.

In Bundang, once the walking time to a bus stop exceeds this limit, travelers abandon the bus altogether and complete the entire trip on foot; even taxis show no compensating uptake. In Ilsan, the same ten-minute walk barrier steers travelers toward private cars, an outcome typical of neighbourhoods with generous residential parking and car-oriented street grids (Kirschner & Lanzendorf, 2020); a similar break-point in walking tolerance is reported for Beijing metro users, whose likelihood of boarding drops markedly once access time exceeds ten minutes (Sun et al., 2016).The different responses in Bundang and Ilsan, walking versus driving, underline how the same temporal barrier interacts with local street design and vehicle availability to yield opposite behavioural outcomes. Density on its own does not guarantee transit use. In Bundang, declining density steadily erodes the appeal of both buses and subways; in Ilsan, the same spatial thinning boosts taxi trips instead, indicating that flexible, on-demand services can partly stand in for scheduled routes when origins are dispersed. Earlier comparative work in U.S. and European cities notes a similar pattern: below a certain residential threshold, ride-hail or informal paratransit fills the gap left by infrequent fixed-route service (Ewing & Hamidi, 2015). Job geography further tilts behaviour. Clustered

employment in Ilsan shortens average trip length and sustains walk-and-bus combinations, whereas Bundang's more dispersed workplaces perpetuate car and taxi dependence, an inversion of the high-density/high-transit synergy reported for Tokyo and Singapore (Suzuki et al., 2013). Cats and Jenelius (2015) argue that such outcomes arise from the interaction of three variables—density, service frequency, and perceived reliability—rather than from density alone. The Bundang–Ilsan contrast supports that view: similar headline densities yield different mode shares once network design and job clustering are taken into account. These findings show that blanket density-led policies can backfire once filtered through local demographics and urban form. The Bundang–Ilsan contrast reveals that the same density figure can spur transit use, taxi reliance, or car dominance depending on access times, job distribution, and household resources. Effective policy must therefore treat density, accessibility, and socio-demographics as interlocking levers and test fare, parking, or land-use interventions within that framework, relying on measured behaviour and continuous monitoring rather than headline indicators. This approach allows planners to avoid misleading generalizations and focus on the mechanisms shaping everyday travel choices. Our results are most applicable to fast-growing satellite towns with a mixed bus-rail network, rising but not universal car ownership, and neighbourhood-scale variation in density and first-mile walk times. In these settings, the ten-minute access threshold, income-mediated service-quality effects, and gendered safety perceptions should recur. Extrapolation to polycentric metros, ride-hail-dominated cities, or regions with very low driving costs requires caution, and replicating our parcel-level nested-logit approach will test whether the same behavioural mechanisms, not just coefficient magnitudes, hold elsewhere.

6. Conclusion

The comparative lens on Bundang and Ilsan shows that urban mobility outcomes hinge on the delicate alignment of land-use patterns, service accessibility, and household circumstances. By modelling travelers' hierarchical choices, the study reveals that small gaps in first-mile connectivity or shifts in employment geography can redirect entire populations toward or away from transit, even when headline density figures appear similar. It follows that density-driven growth strategies, fare subsidies, or ride-hailing initiatives will succeed only when calibrated to the specific spatial layouts, income profiles, and behavioural thresholds that define each locality, for instance, the point at which additional walking time causes riders in one town to abandon buses while those in another turn to cars.

Embracing this triadic perspective equips planners with clearer performance targets, such as maximum acceptable access times or optimal job clustering radii, and encourages iterative policy design that is responsive to local feedback rather than guided by universal formulas. In doing so, cities can move more confidently toward mobility systems that are both equitable and resilient, advancing sustainable transport goals without overlooking the contextual realities that ultimately determine whether interventions will flourish or falter.

7. Limitations and recommendations

A key limitation of this study is the exclusion of seven conceptually important variables, most particularly vehicle ownership and trip purpose, because their extreme multicollinearity made reliable estimation impossible. The exclusion of granular service attributes (e.g., bus frequency, fare variability, transfer penalties) and qualitative factors such as perceived safety or comfort constrains the explanatory power of the estimated utilities. Additionally, the use of Traffic Analysis Zone averages masks parcel-level heterogeneity in land use. Another limitation is the study's reliance on 2010 NHTS microdata. Although the 2022 KTDB Regional Mobility Statistics report shows that aggregate bus, subway, and car-based shares in Bundang and Ilsan have shifted only modestly since 2010, our analysis cannot reflect post-2013 innovations such as app-based ride-hailing or shared micro-mobility.

We recommend four targeted strategies based on our findings. First, introduce an income-linked discounted multi-ride bus pass for Bundang households earning under $3000 USD, whose homes lie more than ten minutes on foot from a stop, with uptake tracked via the existing NHTS-style survey. Second, overlay peak-period feeder shuttles on the twelve Bundang stops where walk access exceeds ten minutes, using current vehicles and a minor timetable tweak, and measure success by comparing quarterly boarding counts.
Third, pilot a demand-responsive shared-taxi corridor in Ilsan between the two late-night origin–destination pairs with the greatest taxi volumes, leveraging app-based ride data to monitor shifts from conventional taxis. Fourth, fast-track safety and comfort upgrades on the twelve Bundang routes where women dominate night-time ridership by improving lighting, installing CCTV and enabling driver-operated request stops after 22:00; conduct women-centred first-mile audits around the six Ilsan subway portals with the lowest walkability scores to add marked crossings and staffed help points; and realign Bundang's retail-corridor timetable so its last three evening departures, matching predominant female shift-end times and reducing reliance on higher-fare taxis. Each proposal remains firmly rooted in our findings and requires no new data collection or external assumptions.

Declaration of interest

The authors declare that they have no conflicts of interest.

Writing assistance disclosure

During the preparation of this work, the authors used Grammarly and AI tools to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the final content of the publication.

Data availability statement

The original data presented in the study are openly available in the Korea Transport Database at https://www.ktdb.go.kr

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Image Sources

Fig.1: Vongpraseuth & Choi, 2014

Fig.2: Illustrated by the authors

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REVIEW NOTES – International Regulation and Legislation for the Energy Transition

Positive Energy Districts for urban energy transition: regulatory challenges and implementation strategies

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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. This contribution analyzes the role of Positive Energy Districts (PEDs) in the urban energy transition, highlighting key regulatory barriers and the potential of Renewable Energy Communities (RECs) as an enabling tool. Through an examination of the European legislative framework, the text emphasizes the importance of integrated urban planning and proposes policy recommendations to facilitate the widespread implementation of PEDs in European cities.

Keywords
Energy transition; Urban Planning; Positive Energy Districts; Renewable Energy Communities.

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1. Introduction

The growing urgency of addressing climate change and promoting the energy transition imposes radical transformations on European cities, which are now the main critical nodes in terms of energy consumption and climate-changing emissions, concentrating about 70 percent of global CO_2 emissions and more than two-thirds of energy demand (Sassenou et al., 2023). In such a scenario, the concept of Positive Energy District (PED), or urban district that can produce more energy from renewable sources than it consumes annually, emerges as one of the most promising strategies for urban decarbonization (Sgambati, 2023). PEDs are not limited to mere energy efficiency at the building scale, but introduce a systemic and multilevel approach, integrating energy production, storage, management and exchange between buildings, networks and users through innovative organizational models and advanced spatial planning tools (Tuerk et al., 2021). The European Union has recognized the strategic role of PEDs in achieving climate neutrality, promoting their deployment through the Strategic Energy Technology (SET) Plan, which sets the goal of implementing at least 100 PEDs by 2025 as a pilot project for cities of the future (EC, 2018). The focus on PEDs was further consolidated with the adoption of the Clean Energy for All Europeans (CEP) legislative package, which introduced regulatory tools such as Renewable Energy Communities (RECs), making it possible to share energy produced within neighborhoods through the public grid, overcoming the limitations imposed on energy cooperation between buildings (Kozlowska, 2024). In this new regulatory context, PEDs take shape not only as technical aggregates but also as social entities capable of activating new local supply chains, generating shared value, and contributing to energy equity (Angiello, 2020). The integration between PEDs and energy communities is a crucial node for urban planning, which becomes the place where these innovations are designed, regulated and implemented. However, the effective localization of PEDs in urban settings depends on the ability to identify suitable areas according to multidimensional criteria-environmental, regulatory, socioeconomic, and morphological-and to implement coherent, flexible, and enabling land-use governance tools (Casamassima et al., 2022). In this context, urban planning assumes a central role in the design of PEDs, providing an integrated framework for spatial energy governance and fostering the emergence of sustainable, resilient and participatory urban development models. This paper aims to critically analyze the concept of PEDs, with particular reference to the role of spatial planning, the link with RECs, and the identification of the constraints, particularly regulatory ones, that limit their implementation in urban settings.

2. Definition of Positive Energy Districts

A Positive Energy District (PED) is defined as a defined urban area that, on an annual basis, generates more energy than it consumes, achieving a positive energy balance and aiming for net CO_2 emissions close to zero (Albert-Seifried et al., 2021). This concept emerges as an advanced operational tool of the urban energy transition and represents an evolution of previous energy configurations promoted by European directives, such as near-zero energy buildings (nZEBs). In this perspective, PED expands the energy approach from the individual building to the neighborhood, promoting systemic integration between distributed generation (e.g., photovoltaics, wind), storage, high-performance buildings, electric mobility, and smart grids (Chen et al., 2024). The European Union has recognized the strategic role of PEDs in achieving climate neutrality, promoting their deployment through the Strategic Energy Technology (SET) Plan, which sets a goal of implementing at least 100 PEDs by 2025 (EC, 2018). The focus on PEDs was further consolidated with the adoption of the Clean Energy for All Europeans (CEP) legislative package, which introduced regulatory tools such as RECs, making it possible to share energy produced within neighborhoods via the public grid, overcoming the limitations imposed on energy cooperation between buildings (Kozlowska et al., 2024). The Clean Energy Package enshrined the right of citizens to produce, consume, store, and share energy from renewable sources (RED II, 2018/2001/EU), paving the way for the creation of RECs, while RED III, part of the "Fit for 55" package, raised the binding renewable energy target to 42.5 % by 2030. This further reinforces the need for

integrated instruments such as RECs in PEDs for collective energy production and management at the local level. According to the JPI Urban Europe program, PEDs must be efficient and flexible, capable of actively managing a renewable energy surplus, integrating buildings, heat and power grids, sustainable mobility and digital systems, while ensuring well-being, quality of life and social inclusion (JPI Urban Europe, 2020). In this sense, PEDs stand at the crossroads of technological innovation, European energy regulation and urban spatial planning, with the potential to catalyze sustainable urban regeneration practices. In this vein, PEDs are configured not only as energy projects, but as complex spatial devices for sustainable urban transformation and the realization of climate neutrality goals to 2050 (Volpatti et al., 2024; Molinaro, 2020).

3. Spatial planning and enabling tools for PEDs

The design and location of a PED in an urban setting requires an integrated approach that connects urban and energy planning. At the design stage, it is crucial to assess the characteristics of the urban site and the built environment: an effective PED tends to combine buildings of different types (new interventions and redevelopment of existing) and mixed uses (residential, commercial, services), so as to exploit synergies in energy demand profiles and maximize self-consumption from local renewables (Alpagut et al., 2021). European studies show that many pilot PEDs are in urban expansion or regeneration districts where it is easier to integrate clean technologies and advanced building standards from the outset, or in existing districts with large-scale deep energy retrofits. Urban planning tools can guide this localization: administrative units can identify areas suited to become energy-positive districts, while through building codes requirements such as the widespread installation of photovoltaic panels, connection to renewable-source district heating networks, or nZEB standards for PED buildings can be imposed (Autonomous Province of Trento, 2021). In parallel, municipal energy planning can complement PED goals by coordinating local energy supply and demand interventions (Municipality of Bologna, 2021). In this context, a key role is played by RECs: introduced by recent European legislation to encourage local production and sharing of renewable energy, they are complementary to PEDs in that they allow citizens, businesses, and institutions to come together to collectively manage neighborhood energy facilities, sharing economic and environmental benefits (Maranesi & Santangelo, 2024). Although PEDs are not explicitly mentioned in European directives, RECs are the key legal-organizational tool for their implementation. Indeed, energy communities, as defined by RED II, enable the exchange of energy between different users and the sharing of energy infrastructure, which are essential conditions for the technical and economic functionality of a PED. The integration between PEDs and RECs thus becomes a normative synergy: PEDs define the technical and urban perimeter, while RECs enable its participatory and decentralized management (Mihailova et al., 2021).

Moreover, several demonstration projects in Europe show the effectiveness of these integrations. For example, the Horizon 2020 projects Making city, Atelier, and Pocityf are implementing PEDs in various cities (such as Groningen, Amsterdam, Bilbao, Évora) by combining innovative technological solutions (smart grid, storage, electric mobility) with participatory energy community approaches, all supported by ad hoc urban planning tools (Making city consortium, 2018; Atelier consortium, 2020; Pocityf consortium, 2019). These case studies highlight how urban planning, when properly directed, can act as a catalyst for positive energy neighborhoods, integrating energy goals into urban plans and mobilizing local actors through multilevel and collaborative governance models.

4. Conclusions

Positive Energy Districts today represent one of the most advanced paradigms for urban energy transition, synthesizing energy efficiency, climate neutrality, social inclusion and technological innovation goals into a single spatial device. However, their systemic deployment within European cities is still hampered by a multifaceted set of regulatory, normative and operational barriers that slow their implementation. In particular,

the lack of coherent and enabling legal frameworks at the European and national levels, coupled with the fragmented transposition rules of the RED II and RED III directives, limits the possibility of configuring energy-positive urban districts on a large and replicable scale. Rigid regulations, complex permitting processes, stringent spatial constraints on energy sharing, the absence of one-stop shops, and misalignments between urban and energy regulations are among the most frequently cited obstacles in the literature (Krangsås et al., 2021). These critical issues are compounded by economic-financial challenges-due to the high initial investment required by PEDs and the absence of established business models-and technical-design challenges related to the integration of generation, storage, and dynamic energy management at the neighborhood scale (Jradi et al., 2023). In this context, the integration of PED and RECs represents a key opportunity to overcome many of the obstacles mentioned above. RECs, formally recognized by European legislation as entities empowered to produce, self-consume, store and share renewable energy (RED II, RED III), provide the legal-organizational basis for the collective management of energy flows in PEDs. They enable participatory, flexible and resilient models, facilitating direct citizen involvement and redistribution of economic benefits from the transition. However, the full functionality of RECs in PED depends on consistent and enabling regulation: indeed, many European experiences show that without procedural simplifications, stable incentives, and equitable access to the grid, even the most advanced projects risk being confined to an experimental phase. To unlock the potential of PEDs, it is therefore crucial to move forward on several regulatory fronts: first, by harmonizing the criteria for defining and operating RECs in different member states, overcoming limits to energy sharing perimeters and reducing tax and tariff burdens on shared energy; second, by updating urban and land-use planning tools so that they explicitly provide for the promotion of PEDs and the structural integration of RECs into urban regeneration strategies. In addition, synergies between energy and urban policies should be strengthened through multilevel governance, local co-design processes, and experimentation with regulatory sandboxes capable of testing legislative innovations before their generalization (Mazzeo, 2023). Support from European programs such as Horizon Europe, the SET Plan, and the "100 Climate Neutral Cities Mission" remains essential to create the framework conditions conducive to the scalability of PEDs, but it must be accompanied by national and local political will to update and coordinate regulations governing energy, land, and buildings. Only through a convergence of regulatory innovation, enabling planning, and active participation will it be possible to transform PEDs from exceptions to a structural component of the European cities of the future. In this perspective, RECs are not simply complementary actors, but true regulatory and institutional catalysts of the urban energy transition.

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REVIEW NOTES – Urban strategies, programmes and tools

Digitalization in urban planning: new digital technologies for sustainable cities

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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 presents the different strategies and tools that guide the digitalization of urban planning.
This paper explores digitalization in urban transformation, with a specific focus on sustainability and how digital technologies act as catalysts for the achievement of environmental, social and economic sustainability goals.
Concrete examples are presented of strategies and plans implemented by some cities, New York, Amsterdam and Turin, that have successfully integrated digital to address complex challenges such as climate change, resource management and citizen well-being, demonstrating the potential of digitalization to influence urban governance.

Keywords
Digital cities; Sustainable; Urban strategies; Technologies; Digitalization

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1. More sustainable and digital cities

The digital revolution is profoundly transforming urbanity, redefining the way cities are designed, managed and experienced. It is not just the introduction of new technologies, but a radical shift in resource management and urban governance. More and more cities are trying to integrate digital and technological solutions to improve citizens' quality of life, optimize resource use, reduce environmental impact, and promote sustainable and inclusive urban development.

Through the use of new technologies cities can increase their "realm of possibilities"(Łaźniewska et al., 2021) in various areas, such as the economic, social, and organizational ones.

In 1987, the World Commission on Environment and Development, WCED, established in 1983, presented the report "Our Common Future" (also known as the Brundtland Report after the Commission's president), formulating a guideline for sustainable development that is still valid today.

The basic pillars of sustainability are commonly recognized in three interconnected and interdependent dimensions: environmental, social and economic. The concept of sustainable development aims precisely to balance these three dimensions and enable "the present generation to meet its own needs without compromising the ability of future generations to meet theirs" (United Nations, 1987).

For those who govern the territory, sustainability is a thread that directly links and influences a number of strategic objectives and has substantial effects on urban areas (Goldman & Gorham, 2006; Oguz & Tanyas, 2024), their functioning, their development and the quality of life of their inhabitants.

1.1 Digital for environmental sustainability

Environmental sustainability focuses on maintaining the health and productivity of our planet, safeguarding ecosystems and biodiversity so as not to jeopardize the future of the next generation. Its primary goals include the responsible management of natural resources, whether renewable such as water and soil or nonrenewable such as fossil fuels. It is also crucial to reduce air and water pollution and toxic waste generation, combat climate change through mitigation and adaptation, promote a circular economy, and protect biodiversity.

The Internet of Things (IoT), sensors and Big Data enable cities to collect a huge amount of real-time information on traffic, energy consumption, air quality, people flows and more. This data is critical for more informed and evidence-based urban planning, enabling optimization of land use, transportation networks, and infrastructure development.

The digital revolution offers powerful tools to promote environmental sustainability on multiple fronts. For better management of natural resources, the integration of digital and communication technologies (ICT) with physical infrastructure (power grids, water, transportation networks, etc...) optimizes energy distribution and consumption, integrating renewable sources and reducing waste. Intelligent monitoring systems in buildings, industry, and agriculture make it possible to cut consumption and reduce environmental impact. Carbon footprint reduction is supported by emission calculation and monitoring platforms, incentivizing more sustainable practices and tracking progress toward climate neutrality.

Technological innovations associated with the concept of the smart city are increasingly linked to the need for a "resilient city" in response to urgent urban needs. These two concepts are interrelated and contribute together to the transformation of cities into "human cities," cities on a human scale where human well-being, quality of life and the urban environment, and the preservation of resources are central to decisions regarding land management (Pirlone et al., 2022; Hoyle, 1988).

The Covid-19 crisis has had major consequences for the development of smart technology concepts and has accelerated the digitalization of life and work (Boujari et al., 2024).

The digital revolution is making urban services much more efficient and optimized. For mobility, advanced artificial intelligence-based systems are managing traffic, while multimodal mobility apps and smart car/bike sharing services, such as those offered under MaaS, combined with electric vehicle infrastructure, are helping

to dramatically reduce congestion, pollution and travel time. For sustainable waste management, IoT and artificial intelligence-based solutions improve waste collection, optimize disposal routes, and promote the circular economy.

Some cities are implementing major strategies to modernize infrastructure, bridge digital divides, and improve capital planning processes to accelerate major infrastructure upgrades such as roads, water systems, sewer systems, parks, and libraries. New York City, for example, continues to advance cutting-edge approaches to anticipate future needs, improve capital planning practices, and direct resources based on factors such as demographic changes, climate change impacts, equity improvements, and community perspectives. Another example is the city of Singapore, universally recognized as a leader in the transformation to a "Smart Nation," an ambitious initiative focused on integrating data and technology to address urban challenges typical of a densely populated city-state, such as resource management, mobility, aging population and environmental sustainability.

New York (USA) – *OneNYC 2050 Strategic Plan*

NYC CPP (New York City Climate Policy & Programs) manages OneNYC 2050, New York City's long-term strategy launched in 2019, and the Green New Deal to secure the city's future against the challenges of today and tomorrow. The ambitious plan is based on the belief that the struggles for environmental sustainability, economic equality and social justice are deeply interconnected.

OneNYC 2050 consists of 8 goals and 30 initiatives that make up a strategy to prepare new york city for the future. The goals reflect both the city's core strengths and the significant challenges it will face (OneNYC 2050, 2019):

- *a vibrant democracy*, where every New Yorker is welcomed into the civic and democratic life of the city;
- *an inclusive economy*, where economic growth creates opportunities for all New Yorkers and safeguards the American Dream;
- *thriving neighborhoods*, where all communities have safe, affordable housing and are well served by parks, cultural resources, and other shared spaces;
- *healthy lives*, where health inequities based on race and ethnicity are eliminated, and all residents have equal access to health care, clean air, and healthy food;
- *equity and excellence in education*, where diverse and fair schools provide a quality education for every student;
- *a livable climate*, where we no longer rely on fossil fuels and have mitigated the risks posed by climate change;
- *efficient mobility*, where affordable, reliable, safe, and sustainable transportation options mean no New Yorker needs to rely on a car. Because New York City's transit system and walkability are core to our identity, economic competitiveness, and quality of life;
- *modern infrastructure*, where reliable physical and digital infrastructure allows New Yorkers to flourish.

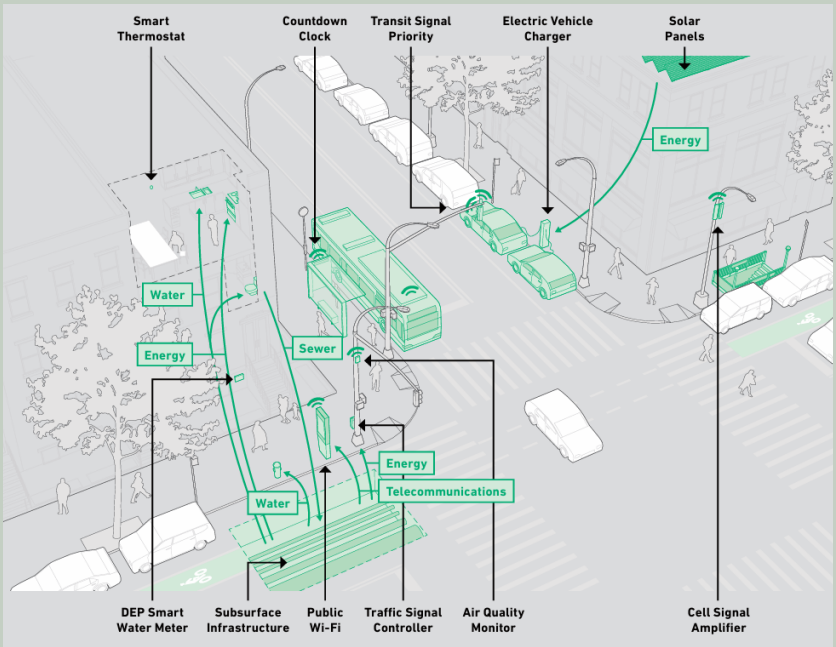

Fig.1 A connected city (OneNYC 2050, 2019)

Among many goals, the Plan promotes the use of new technologies to achieve 80 percent sustainable mode of travel by 2050. To do this, the city is deploying traffic management systems based on Artificial Intelligence and employing thousands of sensors and connected devices (IoT) to monitor flows (of people and vehicles), optimize travel times, improve safety, and reduce congestion and emissions. Another successful implementation of smart technologies has been applied in the city's automatic water meter reading system that connects residents to water consumption data, saving millions of dollars since its launch.

1.2 Digital for social sustainability

Social sustainability concerns the ability to ensure equitable and inclusive conditions of human and social well-being by promoting social justice, equality, health, education, and participation of all community members. Its primary goal is to promote social justice and equality by reducing disparities in income and in access to services and opportunities (access to employment, health, education, etc.). Also crucial are the participation and inclusion of each community in decision-making processes.

Achieving these goals can be encouraged by the use of new technologies. Digital can facilitate access to education (e-learning and digital educational resources), health (telemedicine) and public services even in remote areas or for disadvantaged segments of the population, helping to reduce the "digital divide" and promote social equity. Consider, for example, the increasingly popular "Digital Public Services," online platforms for certificates, payments, appointments and communications between citizens and the administration that make services more accessible and efficient.

The use of data and digital technologies can increase the sense of equity and social justice; digital technologies can increase transparency in public decisions and business operations, helping to combat corruption and promote more ethical practices.

The digital revolution is also transforming the way citizens participate in the life of their community. Digital platforms offer new opportunities to actively involve people in urban decision-making processes. With these tools, citizens can easily voice their opinions, report problems or disservices, and directly contribute to the design and management of public spaces. In this way, technology becomes a bridge between the administration and residents, fostering broader and more inclusive participation in civic life.

Many cities are integrating social sustainability into their strategic plans through the use of new digital technologies. A significant example is the Italian city of Turin, with its "Digital Strategy 2024/2028" by which it places digital transformation as a cross-cutting lever for sustainable, ethical and inclusive development of the city. Barcelona promotes social cohesion and inclusivity with digital by developing an online platform, "Decidim Barcelona" an open-source software that allows citizens to propose ideas, discuss and vote on issues related to the city, from urban planning to participatory budgets by incentivizing their participation in civic life and decision-making processes (Aragón et al., 2017).

At the European level, several policy directions frame the strategic actions of cities that seek to embrace and integrate digital technologies into every aspect of their governance. Among the normative references are "The New Leipzig Charter" (2020) and "The Digital Decade policy program 2030": the former, implements what has already been established in the European Urban Agenda and describes the future evolution of urban centers according to three strands: Inclusion and Cohesion, Ecology, Productivity, and Connectivity; the latter, represents the "digital compass" for EU countries and will support the prospects for Europe's digital transformation by 2030 for a people-centered, sustainable, and more prosperous digital future.

Torino (ITALY) – *Digital Strategy 2024/2028*

The Digital Strategy of the City of Turin for the five-year period 2024 - 2028 was developed with the objective of defining and sharing the directives that will guide the City's ICT initiatives towards completion of the digital transition.
The City's digital strategy defines a "Citizen-Centric" digital transformation model within which four strategic objectives are declined:

- Centrality of the person and relationship with the territory
- Value of data for the City
- Security and resilience of digital services
- Digital administration

The Strategy aims to define services that will enhance the dialogue and relationship between the city and various stakeholders, responding to the specific needs of citizens and businesses. The goal is to reduce the gap between the city and people. This will be possible thanks to digital technologies that will be enabling factors in creating value in terms of opportunities, inclusion, improved quality of life, competitiveness, innovation and simplification of administrative processes.

Fig.2 A digital city (AI generated image by author)

1.3 Digital for economic sustainability

Economic sustainability refers to the ability to generate wealth and jobs in a sustainable way, ensuring a fair income, responsible consumption and efficient management of financial resources, without depleting natural or social capital.

Our current way of producing and consuming has a huge impact on the environment and on our society. It is becoming increasingly clear that something has to change.

Economic sustainability aims at fair and inclusive growth that reduces poverty by optimising the use of natural, human and financial resources. It requires sustainable innovation to develop responsible technologies and business models, while building economic systems resilient to external shocks (financial crises, climate change). It is also crucial to promote corporate responsibility with ethical and transparent practices.

The implementation of technologies increases the efficiency of production and management processes of companies that are helped in optimising energy consumption, reducing operating costs and resources used, also to the benefit of the environment.

Digital technologies enable the creation of innovative services and products, new markets as well as new sustainable business models (such as e-commerce, digital start-ups, Mobility as a Service, etc.). Moreover, digitisation is an enabling factor for the transition towards a circular economic model with platforms that can facilitate product traceability, reuse, recycling and resource sharing.

In this context, cities play a crucial role and digital becomes a key enabler for the implementation of strategies and plans for a more sustainable urban future and economic growth. Many cities develop clear roadmaps with specific goals to achieve economic sustainability targets supported by a smart use of technology. Examples are the city of Amsterdam that has adopted the Amsterdam Circular Strategy 2020-2025 with the ambitious goal of becoming 100% circular by 20250, or the city of Milan that is developing innovative projects such as

"BOTTO" an automatic communication system that facilitates the redistribution of surplus food between wholesalers and associations fighting food waste, exploiting digital technology. The city of Lahti (Finland), European Green Capital 2021, also shines for having promoted economic sustainability with an integrated strategy that combined digitalization, circular economy and citizen involvement (Lombardini et al., 2025).

Amsterdam (NETHERLANDS) – *Amsterdam Circular Strategy 2020-2025*

Amsterdam stands out globally for its ambitious commitment to the circular economy, with the goal of becoming a fully circular city by 2050 and halving the use of new raw materials by 2030. Its main plan and tool to achieve these goals is the *Amsterdam Circular Strategy 2020-2025* (2020), a strategic roadmap based on the "Doughnut Economy" model.
The City's strategy is a pragmatic approach that combines long-term vision with concrete actions in the short and medium term that focus on three value chains:

- Food & organic waste streams, to create a robust and sustainable food system, reducing food waste and ensuring high-quality processing of organic waste;
- Consumer goods, to reduce consumption and extend the useful life of products, maximizing the value of discarded goods;
- Built environment, towards a circular development in the construction sector, reducing the use of virgin materials and promoting the reuse of existing ones.

The city of Amsterdam adopts two approaches to achieve its goals: the first is top-down, as a city, it indicates what it wants to achieve and how it wants to get there; the second is a bottom-up approach, giving space to circular projects and initiatives to be accelerated and expanded.
The Amsterdam plan for the circular economy is an ambitious and concrete example of how a city can strategically plan the transition to a more sustainable model.

Fig.3 "Amsterdam Circular 2020-2025" Strategy (2020)

2. Conclusion

The digital revolution offers unprecedented opportunities for cities to become more efficient, sustainable, resilient and citizen-friendly.
Today, innovation is considered to be at the heart of territorial regeneration and this new vision is manifested in modern planning strategies, which favour participatory, multi-level methods that exploit new digital tools.
A global approach to sustainable urbanization and energy transition is spreading (Pidalà, A. M. ,2025). Among the tools deployed by cities are PEDs (Positive Energy Districts), with which cities are trying to tackle the climate crisis and dependence on fossil fuels by becoming proactive players in clean energy production themselves, with digitisation underpinning everything to transform a collection of buildings into a smart, self-

sufficient and sustainable energy ecosystem. However, in order to realise this potential fully, there are important issues to be taken into account at the same time: such as citizens' privacy and cybersecurity; the need to invest in infrastructure and training, which are essential to be able to implement the new technologies; and to consider the sustainability of the technology itself, which itself has an environmental impact (production, energy consumption and disposal). It is important to emphasise that "digital sustainability" is not only about the application of technologies, but also the conscious and responsible use of them, to ensure that the benefits outweigh the potential negative impacts on the community.

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REVIEW NOTES - Urban practices

Competitive climate adaptation. European startups driving climate change adaptation in cities

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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 the role that innovative bottom-up initiatives can play in fostering climate adaptation while promoting urban competitiveness, and the strategic support that these entities can provide in managing urban and territorial transformations. The nature of these entities and the role they can play in the governance of urban transformation is outlined, and a brief review of European cases is carried out. Finally, the results are discussed, highlighting the potential that these social constructions have in urban climate adaptation and urban competitiveness, but also the challenges they face. Three significant case studies of start-ups promoting climate adaptation in urban areas are presented, showing the relevance of the topic and its potential role in the urban adaptation discussion.

Keywords

Climate change; Adaptation; Urban practices; Competitiveness; Climate startups

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1. Europe: warming fast, innovating faster

Since the 1980s, Europe has been warming twice as fast as the global average, making it the fastest-warming continent on Earth (Copernicus & WMO, 2025). According to the European Environment Agency's 2024 European Climate Risk Assessment Report, Europe is experiencing more frequent, intense and costly climate-related events, ranging from extreme heatwaves and droughts to floods and wildfires. These events, combined with environmental and social risk drivers, compromise food and water security, energy security, financial stability, and health of the population (EEA, 2024a). Weather- and climate-related extremes caused economic losses of assets estimated at EUR 738 billion during 1980 - 2023 in the European Union, with over EUR 162 billion (22%) between 2021 and 2023 (EEA, 2024b). Moreover, in the record-hot summer of 2022, between 60,000 and 70,000 premature deaths in Europe were attributed to heat (EEA, 2024a). Climate-related extreme events will become more frequent and severe around the world as global temperatures rise (IPCC, 2021), threatening the livability, functioning, and sustainability of urban systems across Europe.

Despite growing awareness and increasing policy commitments, the adaptation gap in Europe remains significant. In 2021 the European Commission adopted its new EU strategy on adaptation to climate change, setting out how the European Union can adapt to unavoidable impacts of climate change and become climate resilient by 2050 (European Commission, 2021a). Nevertheless, the aforementioned European Climate Risk Assessment Report warns that current adaptation measures are insufficient to cope with projected risks in key sectors such as health, infrastructure, and agriculture (EEA, 2024a). At the global level, this imbalance is mirrored by the latest Adaptation Gap Report by UNEP (2023), which highlights how – despite the rising climate change impacts – climate adaptation is slowing instead of accelerating, leaving communities, ecosystems and cities increasingly exposed.

Rapid warming trends and a growing frequency of climate extremes call for urgent investments and innovations to strengthen resilience across urban territories. Europe has embraced the undeniable centrality of urban contexts as both key targets and change engines, placing them at the center of their climate strategies such as the EU Mission on Adaptation to Climate Change and the European Urban initiative (European Commission, 2025b; Climate Adapt, 2021; European Commission, 2021b). The European Union aims to make climate adaptation smarter, swifter and more systemic, and to lead a significant uptake at the international level (European Commission, 2021a). To achieve this goal, aware of the great economic requirements needed, EU's strategies deeply link climate action to innovation, promoting the creation of digital tools supporting the transition, as well as boosting entrepreneurial opportunities.

EU member states are therefore united in the pursuit of inclusive economic growth, driven by a vision of building the conditions for businesses to thrive while the environment is protected and everyone has an equal chance of success. To do so, the European Commission placed sustainable competitiveness as its first pillar of prosperity, placing the conditions for business to be productive while environmentally friendly (European Commission, 2024). Mario Draghi's report "The future of European competitiveness" findings have informed the Commission's work on a new plan for Europe's sustainable prosperity and competitiveness: the EU Competitiveness Compass, a strategic roadmap to drive the Commission's work towards an environmentally friendly and just economic growth (European Commission, 2025a). Thanks to this innovation-driven approach, deeply rooted in the principles of sustainable development, the European Union is supplying the tools to drive a sustainable transformation that will make European cities more competitive and more resilient.

2. The EU's roadmap to competitiveness: innovative climate tech startups

While Europe is among the regions most exposed to the accelerating impacts of climate change, it is also positioning itself as a global leader in climate innovation. As the continent is experiencing the tangible consequences of a rapidly changing climate, with rising risks to health, infrastructure, and urban livability, the European Union holds a vast potential to lead the transition toward adaptive and regenerative urban futures.

This potential is rooted not only in public policies and research capacities, but also in Europe's growing network of startups capable of delivering concrete, scalable, and tech-enabled responses to adaptation challenges.

In recent years, the European Union has placed innovation at the heart of its strategic agenda, recognizing its critical role in addressing global challenges and reinforcing the Union's geopolitical and economic competitiveness. The *New European Innovation Agenda*, launched in 2022, represents the EU's most ambitious framework to date for fostering innovation across its member states (European Commission, 2022a). The Agenda outlines five flagship actions, including the scaling-up of deep tech innovation, improving access to finance, creating innovation ecosystems across the EU, attracting and retaining talent, and aligning policy tools to support innovation in strategic sectors. It explicitly aims to position Europe at the forefront of the new wave of technological advancements while ensuring that innovation translates into real societal and environmental impact. Complementing this overarching framework are targeted initiatives such as *Horizon Europe*, the EU's main research and innovation funding programme, and *InvestEU*, which channels investments into sustainable infrastructure, research, and digitization (European Commission, 2021c; European Union, 2021).

Within this broader innovation policy landscape, the *Startup Europe* initiative and the *EU Startup Nations Standard of Excellence* stand out for their dedicated support to the startup ecosystem. The *Startup Europe Strategy* promotes cross-border networking, mentorship, and funding opportunities for early-stage ventures, particularly in emerging technology sectors (European Commission, 2025c). It also aims to reduce fragmentation in the European startup landscape by harmonizing regulatory and fiscal frameworks. The EU Startup Nations Standard, endorsed by 26 member states, encourages governments to adopt best practices in startup policymaking, including streamlined visa regimes, digital-by-default services, and simplified procedures (Startup Nations Standard, 2021). These initiatives underscore the EU's acknowledgment of startups as engines of economic dynamism and climate-aligned innovation.

A cornerstone of the EU's innovation ecosystem is the *European Institute of Innovation and Technology (EIT)*, which operates through a network of Knowledge and Innovation Communities (KICs). Among them, *EIT Climate-KIC* is Europe's leading climate innovation initiative, supporting startups that address climate mitigation, adaptation, and systemic urban transitions. Through accelerator programmes, seed funding, and collaborative networks, Climate-KIC empowers early-stage ventures to scale high-impact solutions (EIT Climate-KIC, 2025). Thanks to this dense network of initiatives, startups are emerging as key agents of change in the transition toward resilient and net-zero urban futures. Their agility, openness to experimentation, and capacity to scale solutions position them as potential partners for local governments. By connecting top-down policy ambitions with grassroots innovation, startups play a strategic role in accelerating systemic transformations and ensuring the environmental, economic, and social sustainability of European cities.

3. Europe's climate tech ecosystem, a review

In recent years, the European Union has increasingly recognized climate tech startups as key enablers of its twin transition – green and digital – and as essential actors in advancing urban adaptation, sustainability, and resilience. A central pillar of this strategy is the creation of an enabling ecosystem for innovation, where startups can thrive through access to funding, networks, knowledge, and supportive regulation. Among the most prominent initiatives is EIT Climate-KIC, the EU's largest public-private innovation partnership focused on climate. Established under the European Institute of Innovation and Technology (EIT), Climate-KIC acts as a knowledge and innovation community (KIC) that brings together over 450 partners from business, academia, cities, and the public sector to accelerate systemic climate innovation across Europe.

EIT Climate-KIC provides support through education, startup incubation and acceleration programs, systems innovation labs, and large-scale experimentation. Through initiatives like the ClimateLaunchpad, ClimAccelerator, and the Deep Demonstrations program, it has helped launch and scale hundreds of startups across Europe, with a focus on solutions for climate adaptation, mitigation, and just transition. In particular,

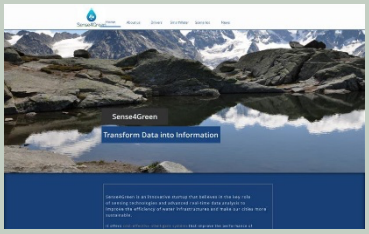
the ClimAccelerator network supported more than 1,800 startups across 65 countries between 2015 and 2023, including many working on adaptation-related themes such as water management, agriculture, disaster risk reduction, and nature-based solutions.

As a result of this ecosystemic support, Europe has witnessed a strong growth in the number and maturity of climate tech startups. According to Dealroom (2024), Europe is now home to over 3,800 climate tech startups, with a combined enterprise value of more than €100 billion. Key hubs include Germany, France, the Netherlands, and the Nordic countries, but Southern and Eastern Europe are also witnessing rapid development, especially in sectors related to energy, mobility, circular economy, and urban resilience. In 2023 alone, European climate tech startups raised around €13 billion in venture capital, marking a steady increase despite the global downturn in startup investments (Holmes & Kirchgaessner, 2024).

These trends confirm that, although Europe is facing some of the most severe and accelerating climate impacts globally, it is also at the forefront of providing innovative and effective responses. Climate tech startups, supported by a robust European policy framework, are emerging as both a strategic resource and a driver of climate-resilient urban transformation across the continent.

In this review, three exemplary cases of newborn, innovation-driven, European climate startups founded through the EIT Climate-KIC ClimAccelerator program are reported.

1.1 Sense4Green. Transform Data into Information



Sense4Green is an innovative startup that harnesses the power of sensing technologies and real-time data analytics to improve the performance and sustainability of urban water infrastructure systems. Founded on a mission to bridge ICT innovation with environmental responsibility, the company develops intelligent, cost-effective solutions designed to monitor, detect, and respond to anomalous events – such as leaks or pressure transients – in water networks, thereby reducing water losses, energy consumption, and operational costs.

The startup's flagship product, SmartWater, enables continuous, automatic monitoring of water systems and delivers several key benefits: enhanced infrastructure efficiency and control, faster response to faults, mitigation of damage, reduced non-revenue water, and improved customer engagement. By integrating Internet of Things (IoT) technologies with advanced analytics, SmartWater supports water utilities in transitioning toward more resilient, energy-efficient, and sustainable operations.

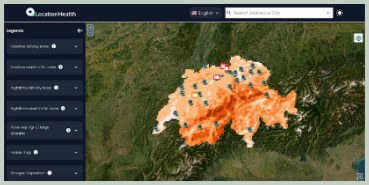
Sense4Green emerged from the research and interdisciplinary experience of founder Daniela Tulone, whose work at MIT and Bell Labs laid the foundation for the company's vision. Inspired by personal experiences of water scarcity and deteriorating infrastructure in her hometown, Tulone sought to apply cutting-edge technologies to one of the most pressing urban challenges: sustainable water management.

Since its inception, Sense4Green has been recognized by several prominent European innovation platforms, including the Climate-KIC Accelerator, TIM WCAP Accelerator, and PA Idea Challenge, and has participated in major innovation expos such as EXPO 2015 and SMAU Bologna. These milestones reflect the startup's relevance at the intersection of climate innovation, smart cities, and digital transformation.

Sense4Green's broader mission extends beyond technology. It aims to raise awareness among utilities, policymakers, and citizens about the urgency of sustainable water use. By combining technical excellence with social impact, the company positions itself as a key player in fostering resilient and intelligent urban water systems across Europe and beyond.

Startup page: https://sense4green.myfreesites.net/

1.2 LocationHealth. Countering climate risks with effective products & solutions



LocationHealth is a Swiss climate adaptation and resilience startup headquartered in Herrliberg, Switzerland, offering an advanced platform that bridges climate analytics with tailored mitigation solutions for built assets (e.g. real estate, infrastructure). As part of the EU ClimAccelerator programme, the company leverages data-driven insights to help stakeholders assess, manage, and mitigate climate-related risks.

At the core of LocationHealth's offering is its climate risk analytics engine, which delivers asset-specific projections and real-time predictions – extending as far out as the year 2100 – on key hazards such as flooding, heatwaves, wildfires, and other physical and transition risks. Equipped with intuitive mapping tools, the platform enables users to visualize climate impacts and vulnerability across their properties, helping identify areas of highest priority.

Complementing analytics, LocationHealth integrates a marketplace of climate adaptation products and services – ranging from flood barriers, cool roofing systems, heat-resistant landscaping, to runoff management infrastructure. Users can quickly find mitigation solutions tailored to geography, asset type, or specific risk profile. Central to its design is the fusion of climate data with procurement functionality: users not only assess risk, but can also act via the platform to source optimal resilience solutions.

Beyond analytics and marketplace, the platform includes collaboration tools – facilitating risk communication, document and task management, and ESG-aligned reporting workflows. This end-to-end digital environment supports coordinated climate risk strategies among asset owners, insurers, planners, and service providers.

As a startup targeting real estate developers, investors, insurers, and financial institutions, LocationHealth positions itself as a comprehensive climate-risk management solution – emphasizing high-resolution data accuracy, transparency, and modularity to support ESG-aligned decision-making and investments.

In summary, LocationHealth brings together predictive risk assessment, marketplace access to mitigation products, and collaboration tools into one platform, empowering stakeholders to proactively adapt infrastructure and built environments in line with changing climate realities.

Startup page: https://locationhealth.solutions/

1.3 PlattenBaum. We co-create prototypes for climate transition

PlattenBaum is a Berlin-based urban-agriculture and climate-adaptation startup specializing in modular and mobile infrastructure systems that transform underutilized urban spaces into productive and socially engaging landscapes. Founded in 2020 by architects Kerem Halbrecht and Maayan Strauss, the company merges built-environment expertise with social design to deliver scalable, off-grid solutions for sustainable urban food production and community cohesion.

Its core innovation is the Mini-Biosphere, a self-sufficient greenhouse roughly the size of a parking space. This compact unit collects rainwater, harvests solar energy, composts organic material, and enables year-round cultivation – all without foundations or external infrastructure. Mini-Biospheres can be rapidly deployed on paved public areas such as streets, courtyards, or brownfields, providing localized access to fresh produce while reinforcing urban biodiversity and resilience.

In addition to product development, PlattenBaum offers co-creation workshops and strategic urban regeneration services, engaging stakeholders to design community-driven, climate-adaptive urban interventions. Their hands-on workshops – ranging from one-day activations to weekend design-build intensives – are tailored to foster social capital and accelerate climate-media transition efforts at neighborhood scale.

PlattenBaum has received support from EIT Food's startup programmes and was featured at innovation platforms such as EIT accelerator events and municipal pilot projects, including early collaborations with housing associations in Berlin panel housing ("Plattenbau") estates. The founders' multidisciplinary experience, blending architecture, urban planning, design, and participatory practice, underpins the company's dual mission: to enable sustainable urban agriculture and strengthen social cohesion through accessible, decentralised infrastructure.

By bridging high-impact food production, environmental sustainability, and community building, PlattenBaum offers a novel model for urban food systems that is equitable, resilient, and scalable across standardized mass-housing contexts. Its long-term ambition is to evolve into a turnkey general contractor, providing integrated infrastructures and project management for regenerative food ecosystems in cities across Europe.

Startup page: https://www.plattenbaum.de/

4. Considerations from case studies

The examination of Sense4Green, LocationHealth and PlattenBaum illustrates the emerging role of climate tech startups as effective enablers of urban adaptation to climate change. Despite operating in different sectors – water infrastructure, climate risk intelligence and urban agriculture – each of these startups exemplifies how innovation, when grounded in local needs and supported by advanced technology, can deliver tangible solutions to complex and evolving urban challenges. Sense4Green addresses the pressing issue of water scarcity and aging infrastructure by deploying real-time monitoring systems that detect anomalies such as leaks and transients, enabling water utilities to reduce losses, optimize maintenance, and improve operational efficiency – key elements of climate-resilient infrastructure. GIScience methods and techniques are fundamental to build innovative cognitive frameworks for spatial analysis (Caprari & Malavolta, 2023). LocationHealth provides high-resolution climate risk assessments combined with an integrated marketplace for resilience solutions, allowing cities and asset managers to both anticipate and act on physical climate threats through data-driven decision-making. To ensure greater synergy between the processes of urban regeneration and containment of climatic risks it is necessary to base planning choices on a quantitative and spatial analysis of local climatic vulnerability (Palermo et al., 2024). PlattenBaum, meanwhile, reimagines urban space through mobile, self-sufficient greenhouses that foster local food production, social cohesion, and ecological regeneration in dense, vulnerable neighborhoods. These urban transformation initiatives involving citizens have been gaining recognition within the scientific literature (De Noia et al., 2024).

What unites these initiatives is their ability to mobilize hybrid, innovative financing pathways – blending public support, private investment, and entrepreneurial drive – to implement scalable and locally adapted solutions. Their responsiveness, modularity, and capacity for rapid prototyping allow them to complement public administrations by filling critical gaps in capacity, technical know-how, and community engagement. As cities face mounting climate risks with constrained budgets and urgent timelines, startups like these offer not only disruptive technologies but also new governance approaches rooted in agility, co-creation, and impact. In this context, the European Union's commitment to fostering a dynamic innovation ecosystem – through initiatives such as the *New European Innovation Agenda*, *Startup Europe*, and *EIT Climate-KIC* – provides a compelling roadmap for how climate resilience and entrepreneurship can be mutually reinforcing. By creating fertile

ground for the emergence of high-impact startups, the EU sets a practical example of how innovation ecosystems can accelerate the urban transition toward a more resilient and climate-proof future.

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REVIEW NOTES – Urban planning literature review

Exploring open and green space characteristics for climate change adaptation: a focus on flooding phoenomenon

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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 second issue of TeMA Journal volume no. 18, this section provides a comprehensive overview of the challenges and solutions related to the role of open and green spaces in climate change adaptation, with particular attention to the urban flooding risks. Using a variety of scientific sources and practical resources, this contribution aims to identify the key characteristics of these spaces that can influence adaptation strategies, examining the solutions proposed in the scientific literature, specifically in books, journals, and reports.

Keywords
Open space; Green areas; Literature review; Climate change adaptation; Flooding risks

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1. Introduction

Urban areas globally are becoming increasingly vulnerable to the effects of climate change, and among the most pressing challenges are flooding, which poses a growing threat to modern cities (Kabisch et al., 2017). The increased frequency of extreme weather events, coupled with rapid urbanisation and the expansion of impermeable surfaces, has generated favourable conditions for the occurrence of urban flooding (Duan et al., 2016). In this scenario, built open spaces and green areas emerge as key elements in climate adaptation strategies, offering multifunctional solutions capable of responding to both mitigation and adaptation needs (Lai, 2021). Numerous studies have highlighted the close relationship between urban morphology and flood risk, highlighting how the configuration, connectivity and characteristics of open spaces directly influence urban resilience in the face of flood events (Pauleit et al., 2017).

Traditional solutions based on engineering works such as drainage systems and concrete channels have often proven inadequate to cope with the increased intensity and frequency of extreme rainfall (Fletcher et al., 2015). This has encouraged a paradigm shift, directing planners and researchers towards the adoption of greening solutions, which enhance the role of green and open spaces in managing storm runoff. In this context, the concept of ecosystem services has become central to understanding how green and open spaces can effectively contribute to urban flood risk mitigation (Andersson et al., 2014; Mohamed Thariq & Mohamed Mujithaba Mohamed, 2024).

These environments provide regulating services through mechanisms such as infiltration, retention and evapotranspiration of water, while offering supply and support benefits that are critical to improving the quality of life in cities (Gómez-Baggethun & Barton, 2013). However, the effectiveness of such spaces in reducing hydraulic risk is highly dependent on: size, connectivity, soil condition and use, vegetation type and distribution within the urban fabric (Pennino, 2024).

2. Agreements and strategies developed at international level

Managing urban flooding through the strategic use of green and open spaces is increasingly recognised in major international agreements and strategies as a key component of climate change adaptation. The 2015 Paris Agreement laid the foundation for global climate action by emphasising the importance of ecosystem solutions (UNFCCC, 2015), while the UN Framework Convention on Climate Change promoted Nature-Based Solutions (NBS) as an integrated approach to address mitigation and adaptation simultaneously (UN, 2015). In parallel, the Sendai Framework for Disaster Risk Reduction (2015-2030) highlighted the role of green infrastructure in disaster risk reduction, encouraging the adoption of natural solutions in planning and reconstruction processes (UNDRR, 2015).

In the European context, the EU Green Infrastructure Strategy, defined by the 2013 Commission Communication, identified water management and flood prevention as central priorities, supported by the Floods Directive and the Water Framework Directive. The European Green Deal and the Biodiversity Strategy 2030 further consolidated these goals, promoting the creation of urban green spaces and ecological corridors to strengthen urban resilience.

Globally, the New Urban Agenda adopted during Habitat III in 2016 promoted sustainable cities through green space planning for climate adaptation, while the C40 Cities initiative provided operational guidelines for implementing green infrastructure in stormwater management (Ascione, 2025).

Finally, the UN Sustainable Development Goals, in particular SDG 11 and SDG 13, have set specific targets for universal access to urban green spaces and the implementation of ecosystem-based adaptation measures, supported by tools such as the UN-Habitat World Urban Database platform (UN-Habitat, 2016), which provides indicators to monitor the effectiveness of such interventions at a global scale.

3. Morphological characteristics of open spaces and their role during flooding events

From a hydrological perspective, green spaces act by reducing runoff through rain interception, soil infiltration and evapotranspiration (Staccione et al., 2024). Urban flooding can result from heavy rainfall, river flooding or coastal events, accentuated by the heat island effect and the presence of impermeable surfaces (Guerreiro et al., 2018).

The urban form strongly influences flooding risks, as elements such as building density, road network and distribution of green spaces modify the microclimate and water flows. The size of green spaces affects their effectiveness: large parks can retain significant volumes of water, but networks of small, well-distributed and connected spaces are often more functional (Salvadore et al., 2015).

Connectivity, whether along water flows, between urban and natural areas, or in the vertical structure of vegetation, enhances water management capacity. Studies have shown that the optimal size for flood management depends on the specific urban context and flood risk characteristics. In dense urban environments, even small pocket parks and green corridors can contribute significantly to flood risk reduction when strategically located and well connected (Liquete et al., 2016; Mora-Esteban, 2025). Vegetation also plays a crucial role: native species and trees with broad canopies can intercept large volumes of rainfall, while multiple vegetative layers improve soil stability and absorption; moreover, the strategic placement of green spaces, supported by risk mapping and hydrological modelling, maximises benefits, especially when located in upstream or flood-prone areas (Pauleit et al., 2017).

Solutions such as the renaturalisation of canals or the use of parks as temporary reservoirs show the potential of integrated and multidisciplinary planning (Shi et al., 2015). Furthermore, the effectiveness of green and open space strategies depends critically on soil characteristics, in particular infiltration capacity, water retention capacity and drainage properties. Urban soils often suffer from compaction, sealing and altered structure that reduce their natural water management functions (Morel et al., 2015). Restoring and improving soil quality is a key requirement for effective flood management.

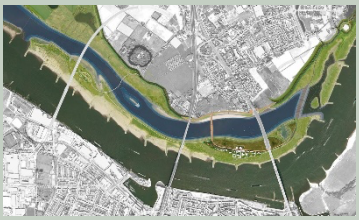
4. Conclusion

The integration of green and open spaces into urban flood management strategies is an increasingly relevant approach to adapt to climate change. The hydrological performance of these spaces can be measured through indicators such as runoff reduction, peak flow attenuation, runoff delay and water quality improvement (Mguni et al., 2016). In addition to water management, green spaces offer multiple co-benefits: air quality improvement, carbon sequestration, biodiversity support, urban cooling and human well-being (Kabisch et al., 2017).

International case studies, such as the "Room for the River" programme in the Netherlands and "Gardens by the Bay" initiative in Singapore, demonstrate the feasibility and effectiveness of these solutions in different urban contexts, and success factors include political support, community involvement, adaptive management and integration of green infrastructure into overall urban planning. However, technical challenges persist, such as low permeability of urban soils and spatial constraints, as well as economic and institutional obstacles, including high initial costs and inadequate funding (Santoro, 2024).

To overcome these limitations, investments in emerging technologies, innovative materials and more flexible planning and regulatory approaches are needed as the future requires interdisciplinary research aimed at more advanced predictive tools, integrated models and policies that incentivise primarily greening solutions (Barbarossa, 2021). Only through a systemic and collaborative transformation in urban management will it be possible to build more resilient and sustainable cities capable of effectively addressing climate challenges.

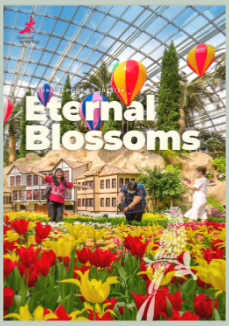
Room for the River Programme



The "Room for the River" programme in the Netherlands demonstrates the large-scale implementation of nature-based flood management, creating space for rivers to expand during flood events by providing recreational and ecological benefits (Klijn et al., 2009). This approach has influenced flood management strategies in many other countries, demonstrating the transferability of nature-based solutions across different contexts.

Retrieved from:
https://www.dutchwatersector.com/news/room-for-the-river-programme

Singapore: Gardens by the Bay



Singapore's Gardens by the Bay integrates green infrastructure throughout the urban fabric, with an emphasis on tropical rainfall management and flood risk reduction. The city's comprehensive approach includes green roofs, vertical gardens, park connectors and integrated stormwater management systems that demonstrate the potential for dense urban environments to incorporate extensive green infrastructure.

Retrieved from:
https://www.gardensbythebay.com.sg/en/about-us/about-the-gardens/annual-reports.html

Buenos Aires: De-paving/Green Streets

To combat urban flooding, Buenos Aires is converting paved streets into green spaces through its "Calles Verdes" (Green Streets) program. The approach reconnects residents with nature and enhances drainage, prioritising pedestrians over vehicles.
Launched in 2023, the project covers 49 blocks across 18 streets and integrates green infrastructure directly into the urban fabric.
Key points:

- Strong community participation;
- Designs must avoid unintended water accumulation;
- NBS foster social and environmental resilience.

Retrieved from:
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REVIEW NOTES – Urban planning literature review

Global warming reports: a critical analysis of NGOs publications

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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 second issue of TeMA Journal volume no. 18, this section provides a critical analysis of recent reports and documents on climate change, published by different types of stakeholders. This review examines the landscape of climate change reporting through a comparative lens, focusing on key findings, strengths, weaknesses, and implications of selected publications. This contribution aims to provide a comprehensive understanding of Non-Governmental Organizations (NGOs) perspectives on climate change, examining their role as intermediaries between scientific research and public awareness, while critically assessing both the strengths and potential limitations of their reporting approaches.

Keywords
Global warming, non- governmental organizations, climate change, adaptation

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1. Introduction

The phenomenon of climate change has now been identified as the most urgent and complicated challenge of the 21st century. The consequences of climate change, which include severe weather changes, the extinction of species, along with increased ocean levels and human habitation changes, are visible and well recorded in scientific journals. The scientific community worldwide has converged, with organisations such as the Intergovernmental Panel on Climate Change (IPCC), to issue warnings about the deadly consequences of inadequate or delayed measures that are irreversible (Pennino, 2025). The implementation of political initiatives has been characterised by a certain slowness and inconsistency. This can be attributed, in some cases, to the constraints imposed by the interests of disparate nations and economies (D'Onofrio et al., 2025). Nevertheless, the climate governance sphere has undergone significant transformation and is subject to ongoing change. For instance, there has been a marked increase in the number and variety of reports submitted not only by the intergovernmental authorities but also by non-governmental organisations (NGOs) and other community cohorts (Haris et al., 2021). It is evident that these actors have become increasingly engaged in the process of converting scientific information into strategic plans, thereby underscoring the necessity for action and offering counsel to various sectors. Consequently, they have assumed the role of a conduit, more commonly referred to as the science–policy gap. In the context of international relations, IGOs (International Governmental Organizations) such as the UNFCCC (United Nations Framework Convention on Climate Change) or the IPCC (Intergovernmental Panel on Climate Change) represent formal organizations comprised of member states. These IGOs possess a distinct legal status, which is conferred upon them through the treaties they conclude. The primary function of these entities is to establish a framework for intergovernmental cooperation and to deliver scientific or legal products. In contrast, NGOs are statistically autonomous of states and derive their power from sources of legitimacy, expertise, and audiences. These actors frequently emerge from the grassroots and function as advocacy platforms, intellectual think tanks, or as nexuses within urban and civil society (Hadden & Jasny, 2019).

In this landscape, characterised by its heterogeneity, non-governmental organisations (NGOs) have assumed a pivotal role in the dissemination of knowledge. These entities have been instrumental in shaping the discourse surrounding climate change, advocating for policy measures that extend beyond the scope of commitments made by governments, both in terms of their ambition and their implementation. This contribution reviews three leading NGOs, which also correspond to different framings of the climate crisis: the World Economic Forum (WEF), a global platform that assembles leaders of business, politics, and academia to evaluate systemic risks; the World Resources Institute (WRI), a think tank that produces data and monitoring instruments targeted at specific economic sectors; and C40 Cities, a network of mayors that seek to carry out climate action on the ground. Despite their divergent institutional composition and profile, all three organisations are pivotal in the translation of climate science.

The subsequent section will undertake a detailed analysis of their most recent reports, evaluating the manner in which each NGO frames the climate challenge. After the introductory section, the following section provides a comprehensive overview of three NGO reports. The third section of the report presents a comparative analysis of the reports, highlighting their strengths and weaknesses, along with the similarities and differences between them. The fourth section of the text offers a conclusion, which summarises the main findings.

2. Reports summary

This section provides a detailed analysis of three reports published by different intergovernmental organizations, offering insight into the diverse perspectives and approaches adopted at the international level. Each report focuses on a different aspect of climate adaptation and through a comparative reading of these reports, it is possible to understand how different international institutions frame and implement climate action across sectors.

The selected reports are presented in the following Tab.1

Title	Organization	Publication date
C40 Cities Annual Report 2024	C40 Cities Climate Leadership Group	2024
Global Risks Report 2024	World Economic Forum (WEF)	2024
State of Climate Action 2023	World Resources Institute (WRI)	2023

Tab.1 Overview of the reports analyzed, including their title, publishing organization and year of publications

C40 Cities Annual Report 2024

The C40 Cities Annual Report 2024 offers al collection of climate action led by cities, representing mayors as crucial actors in worldwide progress. The report's fundamental premise is that even in the event of national governments failing, cities have the capacity to deliver concrete and ambitious results in the present. Furthermore, it highlights the collective impact of the 97 member cities of the network, which collectively account for 23% of the world GDP and have generally achieved significantly greater progress in reducing emissions than their respective national governments. The report under review here sets out to highlight some of the key climate accomplishments in the areas of clean air, green jobs, and a just transition, utilising numbers to demonstrate the scale of their impact. Moreover, the document presents the narrative of the Duchess of City, with examples such as London, Paris and Rio, which are documented as having been active in the total abandonment of fossil fuels, the establishment of the renewable energy sector and, concomitantly, the reinforcement of the sustainable infrastructure sector.
It is also notable that the report outlines a clear 2025-2030 business plan, with a focus on reducing fossil fuel use by half, establishing green zones, and promoting climate justice. The report is thus a dual-purpose document, serving both as a robust instrument of verification and as an advocacy tool. It underscores the imperative to recognise the significance of urban areas and to provide them with the necessary support to facilitate the achievement of the 1.5°C target.

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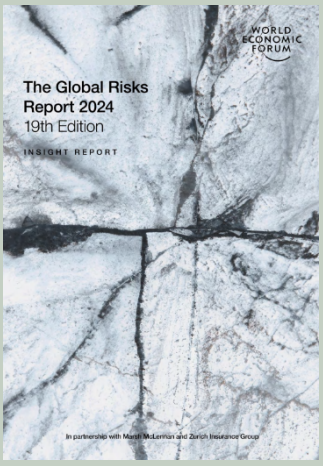
Global Risks Report 2024



The World Economic Forum's Global Risks Report 2024 provides a comprehensive and deeply unsettling assessment of global risks, including everything from geopolitical conflict to technological disruption. Nevertheless, whilst the report addresses numerous crises, the unambiguous and most urgent alert focuses on the rapidly escalating climate and environmental emergency. The document presents a compelling argument for framing climate change not as a future problem but as an intensifying driver of instability, portraying it as the most critical structural challenge to humanity's future.

In the two-year preview, extreme weather events are identified as the most significant environmental concern, surpassed only by misinformation. This phenomenon exemplifies a substantial consensus among experts worldwide concerning the repercussions of climate change, which encompasses extreme heat, deluge, and wildfires. These phenomena are already precipitating crises at a systemic level. A 10-year time perspective is presented in the report, the findings of which are even more alarming, with environmental risk featuring predominantly. The four highest risk levels are of an environmental nature, namely: extreme weather events, critical change to Earth systems, biodiversity loss and ecosystem collapse, and natural resource shortages.

This compelling ranking suggests a profound shift in risk perception, whereby the systemic collapse of natural systems on the planet is regarded as the ultimate long-term risk, surpassing all other potential hazards. This compelling ranking suggests a profound shift in risk perception, whereby the systemic collapse of natural systems on the planet is regarded as the ultimate long-term risk, surpassing all other potential hazards. The report presents a novel proposition: that Critical Change to Earth Systems should be recognised as a significant new hazard, with reference to the possibility of the crossing of "climate tipping points". The report issues a strong warning that the 1.5°C warming threshold is likely to be crossed as early as the early 2030s, with the resultant irreversible and perpetual changes including the collapse of ice sheets, rapid thawing of permafrost, and disruption of ocean currents.
Furthermore, the report effectively demonstrates that climate risks are a "threat multiplier", i.e. they are linked and exacerbating other forms of global risks. The report utilised two case studies: natural resource shortages (food and water) and involuntary migration, which are positioned among the top ten long-term risks and directly linked to the reality of climate breakdown. The report states that as climate change worsens, it will contribute to economic stress, societal polarisation, and conflict, resulting in a negative cycle of cumulative crises. The Global Risks Report 2024 offers a definitive conclusion regarding the environmental crisis. While other present dangers may be of concern, the environmental crisis is worsening to a point of no return.

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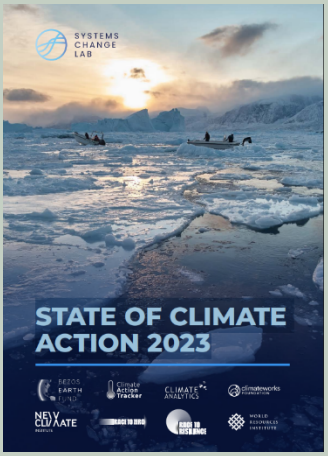
State of Climate Action 2023



The State of Climate Action 2023, a report compiled by a coalition including the World Resources Institute and Systems Change Lab, serves as a rigorous, data-driven evaluation of global efforts to limit warming to 1.5°C. The core purpose of the initiative is twofold: firstly, to translate the Paris Agreement's temperature goal into tangible, sector-specific targets for 2030; and secondly, to provide a stark, evidence-based assessment of the world's progress. The report is characterised by its quantitative methodology, which transcends perception to quantify real-world action against scientifically aligned benchmarks. The central message is characterised by a deliberate and powerful dichotomy, which is introduced in the foreword as "two seemingly irreconcilable truths." Firstly, the world is significantly falling short of its climate targets. The report's comprehensive analysis of 42 indicators across key sectors – power, buildings, industry, transport, forests, food, and finance – reveals that only one, the share of electric vehicles in passenger car sales, is "on track." The majority of these are categorised as "well off track" or, more alarmingly, "heading in the wrong direction". This is quantified through "acceleration factors," which calculate the required rate of progress to be accelerated. For instance, the phase-out of coal must be accelerated sevenfold, and deforestation rates must decline fourfold. Secondly, despite this bleak evaluation, the report underscores "remarkable advancements" and indications of exponential transformation in specific domains. The accelerated, S-curve growth of solar power and electric vehicles indicates that transformational, non-linear change is not only feasible but already occurring. The employment of dual narratives in this manner serves a strategic purpose, utilising hard data to convey the extreme urgency of the crisis while concurrently offering evidence-based hope that rapid acceleration is achievable, thereby countering fatalism. The report presents a detailed methodology, defining 1.5°C-aligned 2030 targets for each indicator. A set of colour-coded indicators is utilised to provide a concise overview of performance for each sector. Each indicator is supported by a chart that visualizes historical data against the required trajectory, thereby rendering the "action gap" immediately apparent. The analysis also contextualises these trends by discussing recent policy developments, such as the Inflation Reduction Act, and market shifts that could influence future progress.

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3. Critical overview and comparative analysis

Despite the common general goal of promoting action on climate change across the three reports, the World Economic Forum's Global Risks Report 2024, C40's Annual Report 2024, and the World Resources Institute's State of Climate Action 2023, each approach is characterised by its own distinct approach, tone and framing. Each title has been uniquely designed to align with its intended audience and the institutional mandate of the publisher. When considered collectively, these elements offer a comprehensive and persuasive depiction of the global climate problem.

The World Economic Forum's Global Risks Report provides a comprehensive picture of the systemic risks posed to the global economy and stability by climate change. The report does not strictly fall within the remit of a climate report; rather, it is a general risk report in which climate change has been identified as the most significant long-term risk. The methodology adopted in conducting this research comprised the administration of surveys to nearly 1,500 executives of global organisations.

The tone of this research is characterised by a sense of gravitas, which is intended to address the audience of chief executive officers, finance ministers, and insurers. The report's most notable strength lies in its credibility, which allows it to establish a link between climate change and other pressing concerns, such as misinformation, geopolitical conflict, and economic collapse. This phenomenon conveys a salient message to the Davos elite: the existential threat they have been alerted to has now materialised and is inextricably intertwined with the myriad of other dangers that keep them awake at night. The primary focus of the report is the macro-level interconnections of threats, and it presents a picture of a world whose adaptive capacity is being stretched to the limit.

In contradistinction the C40 report is characterised by an emphasis on agency and hope. The core imperative goal of this report is to assert proactive city resolutions, driven by a sense of optimism in city-led solutions. The mayor’s actions have been commended for their success in surpassing significant milestones in the realm of climate action, which have been attributed to their pragmatic heroism. These accomplishments are commendably complemented by the report's illustrious narratives. It is evident that the city of Cambridge has taken significant strides in its commitment to environmental sustainability, as evidenced by the establishment of designated air zones within its boundaries. In contrast, the city of Rio has demonstrated a progressive stance on the matter, with its proactive adoption of clean energy sources.

The report is replete with concise case studies and thematic illustrations. It is politically motivated and is directed towards nation-state governments. The report contends that policy implementation cities 'sustain' the Paris Agreement. The scaling of urban funding appeals, autonomy, case workings, cited actions, achievable milestones, proven effective methods and most critical issues were discussed. The latter included a granular focus. Finally, the WRI is subject to scrutiny with regard to its climate accounting.

The report's defining characteristic is the "acceleration factor," which is defined as the discrepancy between the efforts required and the actions taken.

To illustrate this, consider the following example: "coal must be phased out seven times faster." The article adopts a neutral stance, refraining from any undue emphasis on the pessimism espoused by the WEG or the optimism expressed by C40. The target demographic of this text consists of individuals who are referred to as "technocrats" in the context of WEG. Technocrats are defined as policy makers, think tanks and non-governmental organisations. The necessity for technocrats to have access to an urgent, impartial and verifiable benchmark is crucial in order to hold leaders accountable. While it offers insights into the factors contributing to our underperformance, it does not delve into the successes of other parties. Instead, it provides an estimation of our shortcomings and subsequently emphasises the necessary efforts required to enhance our performance.

A summary of all the considerations discussed is provided in Tab.2.

Report	Focus	Approach	Target Audience
Cities Annual Report 2024	City-Led Solutions and best practice	Bottom-up. Highlights concrete actions	National governments, international organizations funders, and the media.
Global Risks Report 2024	Systemic Risk and Interconnected Threats	Top-down; based on a survey of global leaders' perceptions.	Global elite (CEOs, finance ministers, insurers, and policymakers).
State of Climate Action 2023	Performance Tracking and Accountability	Data-driven and diagnostic. Measures global progress against 1.5°C-aligned sectoral targets	Technical experts, policy advisors, government agencies, and civil society organizations.

Tab.2 Summary of key findings, similarities, and differences among the reports

4. Conclusions

A comprehensive review of the three reports reveals a pivotal element of contemporary globalisation: the escalating involvement and the mounting sophistication of non-governmental and non-state actors. These actors have moved beyond the periphery and become central to the action in the debate (Haris et al., 2020). This initiative has emerged as a response to the perceived deficiencies in the global governance system, which is often characterised by a lack of dynamism and effectiveness. This demonstrates that non-state actors are assuming responsibility not only to raise the alarm but also to invent responses to the problems and, most importantly, to measure the shortcomings (Nasiritousi et al., 2016). A salient observation that emerges from this comprehensive overview is the profound and unsettling paradox of the considerable discrepancy between public awareness, available opportunities, and the tangible measures implemented to address the issue.

The Global Risks Report, published by the World Economic Forum (WEF), demonstrates that climate risk awareness has now reached the highest level of decision-making. It is regarded as one of the most significant existential challenges of our age. By way of contrast, the C40 Cities Report functions as a showcase for "the possible", thereby demonstrating the existence of bold, creative, and genuinely scalable solutions. Moreover, it is evident that these solutions are already being locally adopted by pragmatic mayors.

In conclusion, the World Resources Institute's (WRI) publication, entitled 'State of Climate Action', provides a comprehensive evaluation of the global progress made in the realm of climate action. It is somewhat perplexing that the global community has seemingly chosen to disregard the potential dangers and the available solutions to these dangers. The term 'implementation deficit' is employed to denote the inadequate implementation of policies, which is considered by the State of Climate Action to be a significant shortcoming in the actions of policymakers worldwide. Paradoxically, a more profound comprehension of climate science, or the development of novel inventions in this field, does not represent the core of the problem. Indeed, there are already rapid and reliable climate solutions available which have been invented.

The climate crisis has been identified as the primary driver of this transformation in global governance (Stiuso, 2025). As the impacts of climate change intensify and its systemic nature becomes indisputable, it is this phenomenon, with its attendant risks, urgency, and cross-cutting implications, that has compelled non-governmental actors to intervene (Brenda et al., 2008) These actors are not merely marginal contributors to the debate, but rather occupy a central role in the advocacy, implementation, and accountability processes (Pandey, 2015). In this sense, the climate emergency has become not only an environmental and socio-economic challenge, but also a powerful driver of institutional innovation beyond the state.

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