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An Integrated Isochrone-Based Geospatial Analysis of Mobility Policies and Vulnerability Hotspots in the Lazio Region, Italy

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Abstract

Areas characterised by high ecological and cultural value are increasingly exposed to overtourism and intensifying land-use pressures, often exacerbated by mobility policies aimed at enhancing regional accessibility and promoting tourism. These dynamics create spatial tensions, particularly in environmentally sensitive areas such as those within the Natura 2000 network and Sites of Community Importance (SCIs), where intensified visitor flows, and infrastructure expansion can disrupt the balance between conservation and development. This study offers a geospatial analysis of the current state (2024) of such dynamics in the Lazio Region (Italy), evaluating the effects of mobility strategies on ecological vulnerability and tourism pressure. By applying isochrone-based accessibility modelling, GIS buffer analysis, and spatial overlays, the research maps the intersection of accessibility, heritage value, and environmental sensitivity. The methodology enables the identification of critical zones where accessibility improvements coincide with heightened ecological risk and tourism-related stress. The original contribution of this work lies in its integrated spatial framework, which combines accessibility metrics with indicators of ecological and heritage significance to visualise and assess emerging risk areas. The Lazio Region, distinguished by its heterogeneous landscapes and ambitious mobility planning initiatives, constitutes a significant case study for examining how policy-driven improvements in transport infrastructure may inadvertently exacerbate spatial disparities and intensify ecological vulnerabilities in peripheral and sensitive territorial contexts. The findings support the formulation of adaptive, place-based policy recommendations aimed at mitigating the unintended consequences of accessibility-led tourism strategies. These include prioritising soft mobility, enhancing regulatory protection in high-risk zones, and fostering coordinated governance across sectors. Ultimately, the study advances a replicable methodology to inform sustainable territorial governance and balance tourism development with environmental preservation.

Keywords: land-use pressures; spatial analysis; accessibility; environmentally sensitive areas

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1. Introduction

Peripheral and inner regions endowed with both ecological value and cultural heritage are increasingly exposed to converging pressures from overtourism and land-use transformation. These dynamics are frequently intensified by mobility policies that aim to enhance

accessibility and stimulate regional development. While such strategies are often framed within the paradigm of sustainability and territorial cohesion, they can produce unintended spatial tensions—particularly in environmentally sensitive areas, where improved access correlates with increased visitor flows and infrastructural encroachment.

This dilemma is especially evident in landscapes containing Natura 2000 sites and Sites of Community Importance (SCIs), where even modest infrastructure expansion can compromise habitat connectivity, disrupt ecological functions, and degrade landscape integrity [1,2]. As observed by scholars such as Sánchez-Fernández et al. [3] and Scolozzi et al. [4], mobility-driven development, unless ecologically grounded, risks reinforcing spatial inequalities and environmental fragmentation—particularly in regions where territorial governance is spatially fragmented or inconsistently implemented.

This study addresses one of these challenges by presenting an integrated spatial framework to assess the cumulative impacts of accessibility-driven mobility travel on ecological vulnerability, using the Lazio Region (Italy) as a case study. Lazio Region offers a particularly fertile ground for such analysis as it combines extensive protected landscapes and UNESCO-designated cultural assets with an evolving agenda for sustainable transport. Initiatives such as the Rome GRAB (Grande Raccordo Anulare delle Bici–a circular cycling infrastructure designed to connect Rome's historical, cultural, and natural landmark), the PUMS (urban Plan for Sustainable Mobility) of the Metropolitan City of Rome, the Regional Biciplan, the planned EuroVelo corridors the Regional Plan for Mobility, Transportation and Logistic (which provides for a preliminary network of cyclovies) and the Regional Cycling Mobility Plan (currently in progress) collectively reflect a shift toward soft mobility planning. Yet, these efforts unfold within a complex spatial matrix of ecological fragility and cultural richness, where infrastructure development can unintentionally amplify environmental risks.

Existing studies in this field have extensively analysed the environmental implications of transport infrastructure and the socio-economic effects of tourism flows, yet these dimensions are often investigated in isolation. Few contributions provide an integrated geospatial framework that simultaneously addresses accessibility, ecological vulnerability, and cultural heritage exposure within peripheral and inner areas. This lack of integration limits the capacity of planning authorities to identify "vulnerability hotspots" where mobility policies may inadvertently exacerbate spatial inequalities and environmental risks.

The novelty of this research lies in the development of a replicable analytical framework that combines isochrone-based accessibility analysis with ecological and cultural overlays. Based on the Geographic Information System (GIS) approach, the method clarifies spatial inequalities and critical gaps in regional mobility systems, while supporting a more strategic alignment between transport networks and the territorial values they are meant to serve and preserve. Ultimately, this research contributes to the emerging field of evidence-based, place-sensitive territorial governance, offering actionable insights for reconciling sustainable accessibility with long-term environmental and cultural stewardship. Its methodological framework is designed to be replicable in other contexts, particularly in peri-urban and heritage-rich regions facing similar development pressures.

State of the Art and Research Question

Multiple studies have confirmed that even sustainability-oriented transport infrastructure can lead to significant ecological disturbances, including habitat fragmentation, landscape discontinuity, and loss of ecosystem services [5]. This is particularly true for protected areas within the Natura 2000 network, which are often situated near high-value heritage and natural sites that attract concentrated tourism.

Scolozzi et al. [4] used an ecosystem services-based SWOT analysis to evaluate external pressures on protected areas by employing buffer zones around conservation sites. Similarly, Carlier and Moran [6] proposed a landscape typology based on ecological connectivity to inform the design of greenways, advocating for the alignment of mobility infrastructure with functional ecological networks. These contributions underscore the necessity of incorporating ecological criteria into the early stages of mobility planning.

However, the literature still lacks integrated spatial frameworks that simultaneously assess tourism-induced pressure, mobility-driven accessibility, and ecological vulnerability. Most studies address these dimensions in isolation, limiting their capacity to inform cross-sectoral governance. An important exception is the work by Spasiano and Nardi [7], who applied a fuzzy GIS approach to map tourism potential in the Lazio Region. Their findings highlighted spatial mismatches between areas of high tourism accessibility and those requiring conservation. Yet, their approach does not fully integrate transport network analysis or offer a systematic method for detecting spatial hotspots of cumulative risk.

Lazio Region represents an especially relevant case for such a framework, as it is actively engaged in several mobility planning initiatives aligned with European soft mobility goals [8]. These mobility projects, while promoting sustainable transport, also intensify spatial exposure in already sensitive regions such as coastal belts, the Pontine Plain, and archaeological corridors [9,10]. Moreover, scholars such as Corazza [11] emphasize that fragmented governance across municipalities often hampers the integration of ecological criteria into transport planning, exacerbating spatial inequalities.

Accordingly, this study seeks to address the following guiding research question:

1. to what extent can an integrated spatial analysis—combining accessibility modelling, ecological sensitivity, and
2. cultural heritage indicators—support the identification and governance of vulnerability hotspots in peripheral and inner areas subject to mobility- and tourism-driven transformations?

The study's approach sits within contemporary accessibility literature evidence at least in two ways. First, it adopts isochrone-based GIS approach [12]. Second, the study uses the mobility-isochrone benchmark to reason about where marginal improvements create disproportionately large catchments—critical around Natura 2000 edges or heritage clusters [13]. Population catchments within isochrones constitute a defensible proxy for potential pressure, consistent with empirical evidence on visitation drivers [14]. EU and IUCN "International Union for Conservation of Nature and Natural Resources" guidance demand exactly this anticipatory lens—early identification of where access gains could translate into ecological risk, followed by proportionate, evidence-based visitor management [15].

The paper's novelty is the application to the Lazio Region, Italy—characterized by both rapid mobility planning and a dense network of protected and heritage sites. The framework enables planners to detect spatial inequalities in accessibility, assess ecological risk under tourism pressure, and formulate territorially sensitive, evidence-based policy interventions aimed at balancing infrastructure development with landscape preservation.

The paper is structured as follows, after this introduction, the methodology is described in the second section to examine how mobility strategies affect ecological and cultural vulnerability in peripheral and inner areas, using the Lazio Region as a case study. The results and discussion section are described in Section 3 and they interpret spatial disparities in accessibility, highlights vulnerable hotspots, and reflects on the implications for sustainable planning, offering policy recommendations to balance accessibility enhancement with ecological and cultural conservation. Conclusions are highlighted in Section 4.

2. Materials and Methods

2.1. Case Study

The Lazio Region in central Italy offers a revealing case of how peripheral and inner areas rich in ecological and cultural heritage are increasingly exposed to the impacts of overtourism and tourism-driven land-use change. While the city of Rome, the capital, remains the region's iconic tourist magnet, its surrounding landscapes—featuring archaeological parks, historic towns, and protected natural environments—have seen intensified promotion as alternative tourist destinations under regional development and mobility strategies [16,17].

An analysis of the spatial distribution of protected areas in the Lazio Region reveals a clear predominance of sites designated under the European ecological network. Of the 174 total classified areas, 64.4% fall under Natura 2000 designations—either as Special Protection Areas (ZPS), Sites of Community Importance (ZSC), or dual ZPS/ZSC listings. In contrast, 35.6% are national or regional parks and nature reserves established under Italian law.

Several sites in Lazio Region, such as the Lago di Bolsena, the Monte Rufeno Reserve, the Sughereta di Castel di Decima, and the Lago di Vico–Monte Venere e Monte Fogliano area, fall within the Natura 2000 network in Lazio and are recognized as Sites of Community Importance (SCI) or Special Protection Areas (SPA). Notable examples also include the Circeo National Park, the coastal dunes of Sabaudia, and the lake systems of Fogliano, Caprolace, and Monaci. These areas are ecologically fragile and home to endemic species and unique habitats. However, they are increasingly pressured by tourism and mobility infrastructure [18] that enables easier access to remote destinations. Infrastructure upgrades, such as expanded road networks, new parking facilities, and improved train connections, have contributed to rising tourist numbers in areas previously considered marginal [19]. This transformation comes with costs: housing prices have surged, traditional residents have been displaced [20], and the physical infrastructure is under strain. Similar patterns can be observed in Tarquinia and Cerveteri, two UNESCO-listed Etruscan necropolises, where increasing visitor flows threaten the integrity of archaeological remains and overwhelm local facilities [21]. Environmental consequences are also evident in natural reserves such as Lake Bolsena and the Monti della Tolfa, where pollution, noise, and unsustainable trail use have become increasingly problematic.

Meanwhile, other areas of Lazio, such as parts of the Simbruini Mountains or the Valle del Salto in Rieti province, remain largely excluded from these dynamics, reflecting a highly uneven spatial distribution of tourism benefits and environmental burdens. These inland areas often lack adequate transport services and are underrepresented in tourism promotion strategies, despite hosting significant heritage and natural assets [22].

Some local governments and park authorities have begun to implement mitigation measures—such as limiting visitor numbers, creating thematic trails, and promoting low-impact tourism practices. For instance, the Circeo Park Authority has introduced seasonal access controls and environmental education initiatives [23]. Nevertheless, these efforts are often fragmented and insufficient to counteract the broader trends encouraged by regional mobility and tourism policies.

The Lazio case highlights the challenges of aligning accessibility improvements with ecological preservation as indicated in Figure 1. It underscores the need for integrated governance frameworks and spatial planning tools that can reconcile tourism development with the conservation of environmental and cultural resources. As evidenced in other Mediterranean contexts [24], the absence of coordinated and integrated governance can lead to overtourism in heritage-rich peripheral and inner areas to compromise the very

ecological and cultural assets it aims to valorise, thereby generating long-term socio-environmental imbalances.

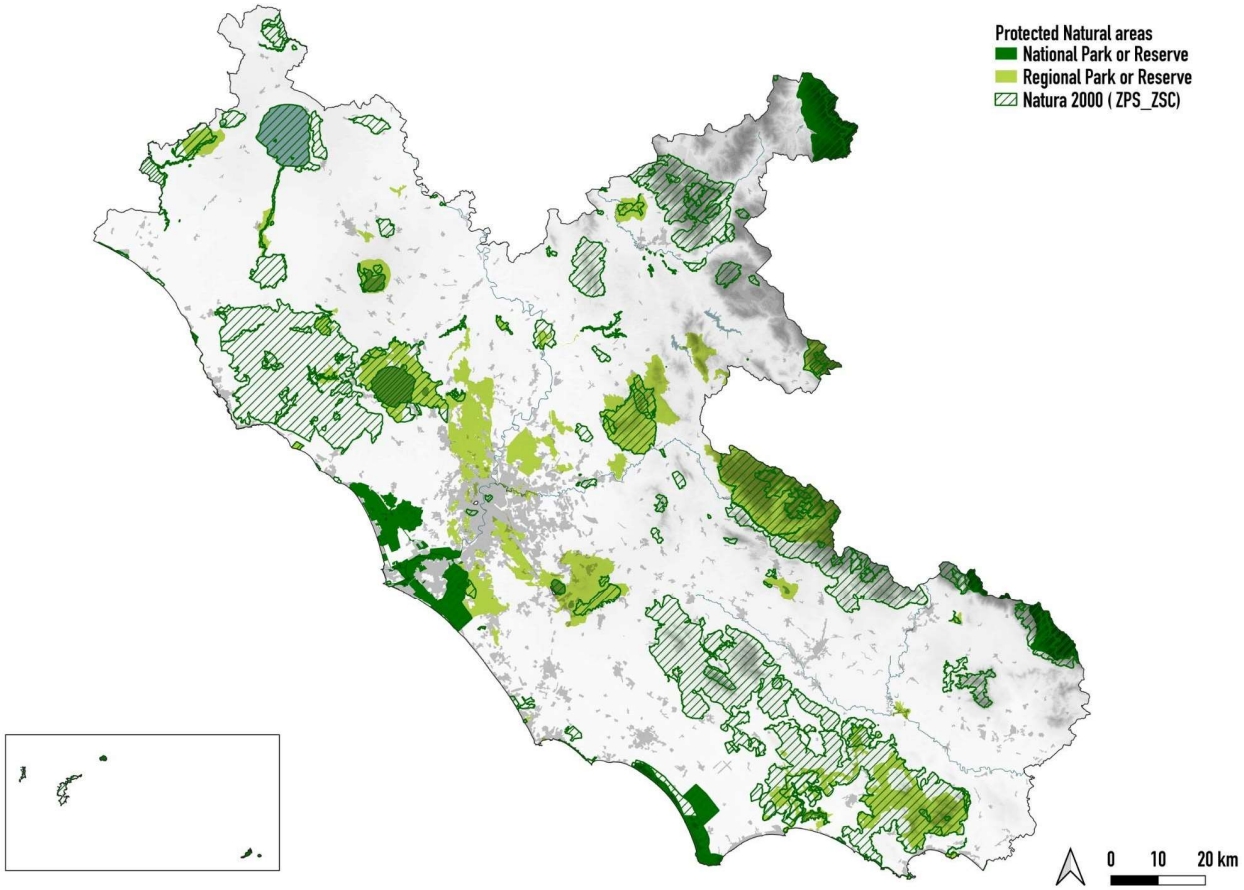

Figure 1. Natura 2000, National and regional protected areas. Source: Elaboration of authors. Note: in the left box are represented the island of the Region.

2.2. Methodology

The methodological framework combines geospatial modelling with isochrone-based accessibility analysis, applied to the Lazio Region. The goal is to identify vulnerability hotspots where accessibility gains overlap with ecological sensitivity and tourism-related stress. The process is divided into main parts, as explained as follows in the next paragraphs. As stated in the literature evidence, accessibility and mobility have become central to debates around landscape transformation [25].

According to Geurs and van Wee [26], accessibility should not only be measured in terms of spatial proximity and travel time but also in terms of the quality of opportunities and the sustainability of access. In Lazio, road improvements, increased bus connections, rail accessibility and the archaeological zones have undoubtedly made peripheral and inner areas more reachable.

The relationship between mobility and landscape is particularly complex in regions where the physical and symbolic value of the territory is high. As noted by Antrop [27], landscapes are not static backdrops but dynamic systems that evolve with social practices, including movement and infrastructure development.

Literature from landscape planning emphasizes the need for an integrated vision of mobility that respects the carrying capacity and identity of the places traversed [28]. In the Lazio Region, some areas have responded with local planning tools that attempt to balance

access and conservation, such as restricted driving zones in heritage towns or seasonal closures in national parks.

Moreover, the "landscape of mobility" [29] is not only a question of infrastructure but also of perceived accessibility and tourist imaginaries. The methodological approach is based on the development of a conceptual framework (Figure 2) organised into three dimensions:

- Accessibility: through the construction of multimodal isochrones, contrasting car and sustainable transport;
- Ecological vulnerability: intended as propensity of protected landscapes to incur ecological harm from use, as a function of exposure, sensitivity, and adaptive capacity; operationalised via Natura 2000 features, protected-area designations, and sensitivity layers [30,31];
- Tourism pressure: intended usually as intensity and concentration of visitor use on sites, typically assessed with observed flows (arrivals/presences), accommodation/bed density, and seasonality indices for visitor-management purposes [32].

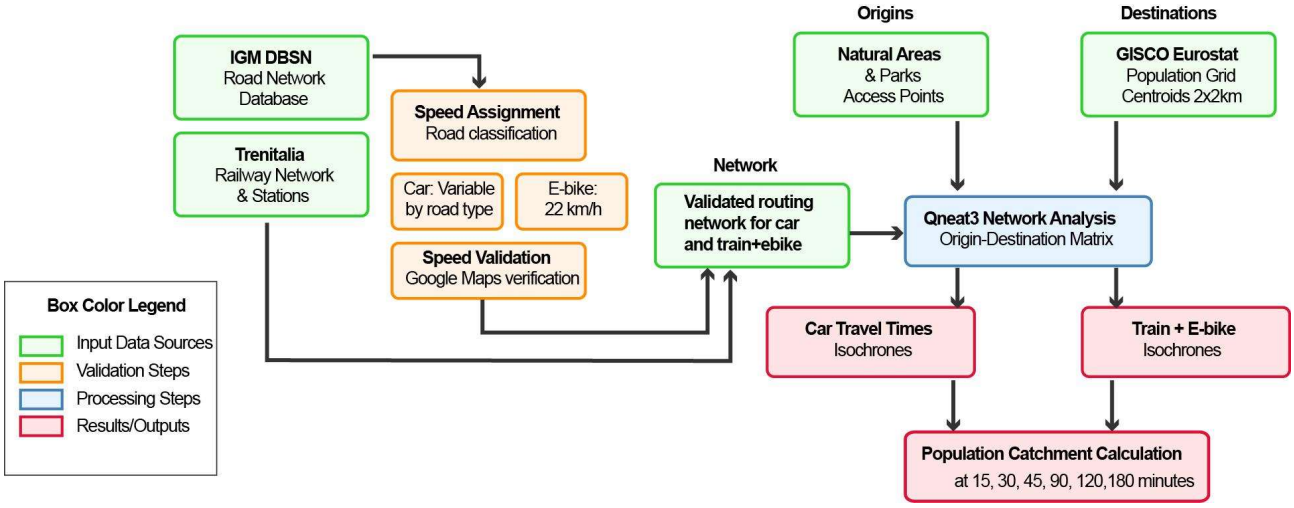

Figure 2. Travel Times and Population Catchment calculation Workflow. Elaboration of authors.

It is important to stress that in this paper, only the "accessibility dimension" has been implemented through reproducible isochrone modelling; both "ecological vulnerability" and "tourism pressure" dimensions are specified at a conceptual level to delimit scope and guide interpretation but are not developed in the present analysis. The framework therefore serves as a guide: it structures the methodology and clarifies how, in future extensions, these dimensions would interact in a geospatial environment to detect "vulnerability hotspots" where enhanced accessibility overlaps with ecological sensitivity and tourism-related stress.

The rationale underlying the accessibility analysis can be summarized as follows. First, to simulate vulnerability, we considered both valuable natural areas and national parks, as well as the presence of cities with strong tourist appeal and high visitor flows. A key limitation in this regard was the lack of consistent data on accommodation capacity and overnight stays for all urban centres. To overcome this, we adopted an alternative approach, using resident population as a proxy to model isochrones.

This methodological choice rests on two considerations. On the one hand, it was necessary to exclude the segment of the population that cannot reasonably be regarded as active tourists—those who do not generate mobility or exert pressure on natural and cultural sites. On the other hand, we therefore focused on a "mobile population," derived from an origin–destination (O/D) travel matrix between cities and parks, to approximate

actual flows from residents to protected areas and tourist villages. This approach is replicable in other studies addressing similar issues and allows for a preliminary assessment of anthropogenic pressure on high-value sites. However, it also entails a limitation: not all trips captured by O/D matrices are tourism-related, as reported in the discussion section.

Compared with fragmented and seasonally inconsistent visitor statistics—which are seldom aligned with protected area boundaries—isochrones offer a transferable and replicable method at the regional scale [12]. As highlighted in the literature, substantial evidence indicates that nearby population density and distance or friction to sites are key predictors of nature-based visitation, making resident catchments a defensible proxy for domestic tourism demand in screening analyses [14,33,34]. Conservation science further recognizes the value of coarse-grained proxies for anthropogenic pressure when fine-grained monitoring data are unavailable, provided their scope and limitations are made explicit, as in this study [35,36].

Consequently, we conceptualize "tourism pressure" here as the potential exposure of natural and cultural sites to demand generated by recreational and amateur tourism. Specifically, we consider the resident population reachable within the cycling isochrones (catchment area), rather than observed visits from official tourism statistics (e.g., arrivals, overnight stays, or day visitors). Tourism pressure is thus used in an interpretive sense, as an indicator of the likelihood that protected areas—particularly Natura 2000 sites and regional parks—may face high accessibility-driven pressure due to their spatial proximity to densely populated areas. This enables the identification of hotspots of relative vulnerability without relying on incomplete or inconsistent visitor data at the regional scale.

Therefore, using resident population within cycling isochrones as a proxy for tourism pressure is a deliberate and internally consistent design choice aligned with the paper's scope and scale. Our objective is a screening-level, ex-ante assessment that identifies places where improved accessibility could plausibly translate into higher human pressure. For this purpose, a harmonised, region-wide denominator is essential. Resident population grids, coupled with network-based isochrones, provide exactly that: (i) comparability across all sites (including those lacking robust visitor statistics), (ii) replicability of the workflow with transparent parameters, and (iii) stability against seasonal volatility and reporting gaps that affect observed flows (domestic, international, and day visitors).

Accessibility-Isochrone Approach

The second step of the methodology and in line with recent research that emphasizes the need for assessments of accessibility in peripheral and landscape-rich regions [37,38], this study adopts a statistical GIS-based isochrone approach to evaluate how accessibility to ecologically and culturally valuable areas in the Lazio Region varies across different transport modes. This methodological choice is motivated by the need to move beyond simplified representations of spatial access considering the approach and findings of Baum et al. [39] and Bhellar et al. [40].

GIS-enabled analyses of protected areas employ georeferenced layers and multi-criteria methods to map spatial heterogeneity, compare gradients, and inform access and management decisions—supporting our accessibility screening with complementary spatial evidence [41].

The analysis concentrates on destinations classified as "high-value landscapes" including national and regional parks (such as Circeo, Appia Antica, and Monti Simbruini), UNESCO heritage sites, and designated areas within the Natura 2000 network. These areas serve as critical nodes for ecological preservation and cultural tourism, but their accessibility remains uneven depending on the transport infrastructure and modal availability.

Accessibility was modelled through a multimodal isochrone analysis within a GIS environment with Qneat3, the study visualizes and compares travel times required to reach valuable ecological and cultural sites from selected origins across the Lazio Region. Isochrones were generated for seven-time thresholds—15, 30, 45, 60, 90, 120, and 180 min—considering two transport modes: private car, and the combination of train and e-bicycle. This time-based mapping allows for a more accurate representation of real-world accessibility, revealing who can reach which destinations and how quickly. Walking was excluded from the analysis due to its limited applicability over short distances, particularly in rural and peri-urban contexts.

The decision to focus on these two transport modes is grounded in recent research highlighting substantial disparities in accessibility across different user profiles. Studies show that while car users can access most high-value landscapes within 30–45 min from major urban centres, access via sustainable modes remains severely restricted—especially in the southern and inland areas of Lazio, considering the approach of other studies [42–44]. This reflects the exclusionary effects of car-centric infrastructure on active mobility and equitable territorial access.

In areas such as the Simbruini Mountains, Lago di Posta Fibreno, or Monti della Tolfa, valuable landscape resources are in close physical proximity to small settlements. However, the absence of adequate pedestrian and cycling infrastructure leads to a situation of de facto inaccessibility for non-motorized users. This mismatch is particularly concerning considering regional sustainability goals and policies aimed at promoting soft mobility and environmental protection [45]. The gap between formal proximity and functional access undermines both social inclusion and environmental stewardship [46,47], calling for integrated mobility and land-use planning strategies that address these spatial inequalities. Ecological vulnerability is defined as the propensity of protected landscapes to incur ecological harm, based on Natura 2000 features and sensitivity layers. Tourism pressure is conceptualised as the potential demographic mass (resident population within isochrones) that could generate recreational use of sites. While this study operationalises only the accessibility dimension, the framework is designed to integrate these three dimensions in future extensions.

2.3. Dataset and Variables

The analysis relied on multiple datasets: the National Synthesis Database (DBSN) by the Italian Military Geographic Institute for road networks; Trenitalia timetables for regional rail services; Eurostat GISCO 2 × 2 km grids (2021) for population data; and Lazio Open Data for protected areas (Natura 2000, parks, reserves). Travel times were validated against Google Maps routing services. Table 1 summarises the core sources and tools employed. No direct tourist flow data—whether domestic or international—were incorporated into the spatial model. This methodological choice reflects the study's focus on potential accessibility rather than observed visitation. Resident population is used as a proxy to estimate the demographic magnitude that could exert pressure on natural and cultural sites if made more accessible through transport infrastructure. While actual tourist flows may influence absolute levels of pressure, such data are often fragmented, inconsistent, or unavailable across all Natura 2000 sites and regional parks. For this reason, the results should be interpreted as relative indicators of vulnerability, highlighting areas where increased accessibility coincides with ecological sensitivity and large surrounding population catchments, rather than as direct predictions of tourist visitation volumes.

Table 1. Database and source. Elaboration of authors.

Dataset/Variable	Information/Source
Street network and classification	National Synthesis Database (DBSN-DataBase di Sintesi Nazionale) provided by the Italian Military Geographic Institute (Istituto Geografico Militare, IGM). https://www.igmi.org/it/dbsn-database-di-sintesi-nazionale (last accessed on 7 October 2025)
Regional Rail services	Travel times and connections: Trenitalia https://www.trenitalia.com/ (last accessed on 7 October 2025)
Population data	2 × 2 km grid form GISCO (Geographic Information System of the Commission) database, Eurostat, 2021
Protected areas	Rete Natura 2000, National and regional parks and reserve: from Lazio Open geographic data portal https://geoportale.regione.lazio.it/ (last accessed on 7 October 2025)
Processing tools	QGIS https://qgis.org/ (last accessed on 7 October 2025) Qneat3 https://root676.github.io/ (last accessed on 7 October 2025)

In the context of cycling access to protected areas, "vulnerability" is the relative likelihood of ecological degradation arising from increased exposure (population reachable by new/expanded cycle routes), given the sensitivity of local habitats/species and the site's adaptive capacity to manage use; it is best treated as a relative risk indicator for prioritising management rather than a forecast of visitor numbers [30].

In this phase, the study has not embedded observed tourist flows (international, domestic, overnight, or daytrip) into the accessibility model. This decision reflects both the screening purpose of the study and persistent data constraints: flow statistics are often spatially incomplete or reported at coarse administrative levels; day visitors and non-registered accommodation are systematically undercounted; temporal granularity and seasonality are not comparable across sites; and harmonisation to Natura 2000 and park boundaries is limited. Accordingly, we interpret "tourism pressure" in a potential sense: the reachable demographic mass (as captured by resident population within cycling isochrones) that could translate into recreational use under enhanced accessibility, rather than a measurement of realised visitation [48,49].

The integration of tourism flows, visitor densities, and travel times into a unified Origin-Destination (O/D) framework responds to the emerging need for multidimensional indicators in accessibility planning [50,51].

The core dataset (see Section 3) integrates multiple variables: visitor flows to major natural and cultural sites (e.g., Circeo National Park, Appia Antica), land surface data for calculating visitor density per square kilometre, and the distribution of accommodation facilities, all sourced from ISTAT, regional tourism observatories, and protected area authorities. Travel times—calculated separately for private car and e-bicycle using network analysis algorithms and IGM road network data—allow the estimation of potential accessibility from population grid centroids. Seasonal visitor load is also included to reflect temporal pressure dynamics [52].

The natural areas analysed in this study are systematically classified in Table 1 by legal and governance typology, distinguishing between Regional Parks, National Parks, State

and Regional Nature Reserves, and Natura 2000 sites (ZSC, ZPS, or dual designations). This legal framing is essential for understanding the levels of protection and management obligations involved, particularly for Natura 2000 sites that require compliance with EU directives and conservation plans.

A second level of categorisation, summarised in Table 2, distinguishes natural areas by functional and morphological characteristics—from natural-archaeological parks and Apennine ecological corridors to suburban and urban parks. These distinctions clarify not only legal designations but also patterns of use, accessibility, and exposure to tourism impacts. For example, parchi regionali urbani (urban regional parks) are typically located near metropolitan areas and offer higher recreational accessibility, while riserve parziali naturali (partial nature reserves) enforce stricter access regulation, reflecting differentiated conservation priorities.

Table 2. The natural areas considered in the case study. Elaboration of authors.

Type of Natural Areas	Description
Parco Naturale Regionale: Regional Natural Park	Designated by regional governments to preserve areas of environmental, cultural, and recreational value. They often include forests, lakes, and archaeological zones and allow regulated human use.
Parco Nazionale: National Park	Managed at the national level by the Ministry of Environment. They protect highly valuable ecosystems or landscapes of national importance (e.g., Gran Sasso, Circeo). Strictest form of protection.
Riserva Naturale Regionale: Regional Nature Reserve	Smaller in scale than parks, these are regionally protected areas often focusing on specific natural features, species, or habitats. They have more limited human access.
Riserva Naturale Statale: State Nature Reserve	Similar to regional reserves but managed and financed by national authorities. Typically established for scientific, historical, or conservation purposes.
ZSC (Zona Speciale di Conservazione): Special Area of Conservation	EU-designated site under the Habitats Directive (Natura 2000 network), aimed at maintaining or restoring biodiversity. Managed according to site-specific conservation plans.
ZPS (Zona di Protezione Speciale): Special Protection Area	EU-designated under the Birds Directive (also Natura 2000), focusing on the conservation of bird species and their habitats.
ZPS/ZSC: Dual Natura 2000 designation	Areas that serve both as ZSC and ZPS, combining habitat and bird conservation priorities.

By combining the classification framework in Tables 2 and 3 with spatial modelling, the paper enables an interpretation of tourism accessibility patterns. The integrated dataset and typological breakdown ensure that vulnerability assessments are context-sensitive, aligned with the protection level and functional role of each site, thereby enhancing policy relevance for land-use planning, environmental governance, and sustainable tourism strategies.

The category helps specify how the site is used or perceived—urban park vs. nature reserve vs. archaeological zone—even within the same type.

The 50 selected sites (Table 4) span a diverse range of geographical contexts within the Lazio Region, allowing for a robust evaluation of accessibility patterns across different territorial typologies. A classification of sites based on their locational characteristics reveals four main categories: inland/rural, mountainous, urban/peri-urban, and coastal areas.

Table 3. Category of natural areas. Elaboration of authors.

Category of Natural Areas	Key Characteristics
Parco naturale-archeologico: Natural-Archaeological Park	Combines natural preservation with archaeological heritage (e.g., ruins, ancient cities). Often a tourism magnet.
Parco naturale regionale dell'Appennino: Appennine Regional Natural Park	Large parks preserving ecological systems within a regional framework. Some focus on specific mountain ecosystems.
Parco suburbano: Suburban Park	Located near urban areas; they serve ecological, social, and educational functions. Often accessible for recreation.
Parco regionale urbano: Urban Regional Park	Integrated within city systems; balance between nature conservation and urban green infrastructure.
Parco regionale suburbano: Regional Suburban Park	Transitional areas between rural and urban zones; often part of green belts or metropolitan park systems.
Riserva naturale/parziale/provinciale/statale/regionale: Nature Reserve (with variations)	Varying levels of restriction and jurisdiction (e.g., partial reserve, provincial, etc.). Aim to protect sensitive habitats or species.
Riserva naturale di popolamento animale: Animal Population Reserve	Focused on maintaining specific animal populations, such as bird habitats or endemic fauna.
Riserva parziale naturale: Partial Nature Reserve	Some human activities permitted under strict regulation. Conservation goals prioritized.

Table 4. The selected sites of the case study. Elaboration of authors.

Territorial Category	Protection Type	Site Names	Number of Sites
Coastal	Parco Naturale Regionale	Gianola e Monte di Scauri, Monte Orlando, Monti Ausoni e Lago di Fondi	3
Coastal	Parco Nazionale	Circeo	1
Coastal	Riserva Naturale Regionale	Macchiatonda, Tor Caldara	2
Coastal	Riserva Naturale Statale	Isole di Ventotene e S. Stefano, Litorale Romano, Salina di Tarquinia, Tenuta di Castelporziano	4
Inland/rural	Parco Naturale Regionale	Bracciano-Martignano, Marturanum, Valle del Treja	3
Inland/rural	Riserva Naturale Regionale	Antiche Città di Fregellae e Fabrateria Nova, Lago di Canterno, Lago di Posta Fibreno, Lago di Vico, Monte Soratte, Monterano, Nazzano, Tevere-Farfa, Selva del Lamone, Sughereta di Pomezia, Tuscania, Valle dell'Arcionello	11
Inland/rural	ZPS/ZSC	Bosco del Sasseto	1
Mountainous	Parco Naturale Regionale	Monti Aurunci, Monti Simbruini	2
Mountainous	Parco Nazionale	Abruzzo, Lazio e Molise, Gran Sasso e Monti della Laga	2
Mountainous	Riserva Naturale Regionale	Montagne della Duchessa, Monte Catillo, Monte Navegna e Monte Cervia, Valle dell'Aniene	4
Urban/peri-urban	Parco Naturale Regionale	Aguzzano, Appia Antica, Castelli Romani, Inviolata, Pineto, Veio	6
Urban/peri-urban	Riserva Naturale Regionale	Decima Malafede, Insugherata, Laurentino Acqua Acetosa, Macchia di Gattaceca, Marcigliana, Monte Mario, Nomentum, Tenuta dei Massimi, Tenuta di Acquafredda, Valle dei Casali, Villa Borghese	11

Most sites (48%) are located in inland or rural contexts, often encompassing archaeological parks, nature reserves, and cultural landscapes situated away from major urban

centres. These areas typically exhibit fragmented infrastructure and low-density settlement patterns, which influence both their accessibility and vulnerability to overtourism.

A substantial portion (22%) of sites is situated in mountainous zones, such as the Simbruini and Reatini ranges, representing ecologically sensitive and logistically complex environments. These sites highlight challenges related to terrain, seasonal accessibility, and the balance between preservation and public enjoyment.

Urban and peri-urban landscapes account for approximately 16% of the sample, including sites such as Villa Borghese, Tenuta dei Massimi, and the Appia Antica Park. These areas are often more accessible but face higher pressures from everyday recreational use and metropolitan expansion.

Finally, coastal sites represent 14% of the sample, such as Circeo, Litorale Romano, and the Isole di Ventotene. These areas are particularly vulnerable to seasonal tourism peaks and land-use tensions between conservation and development. This typological breakdown ensures that the analysis reflects a comprehensive range of landscape configurations, each with distinct accessibility dynamics, governance challenges, and exposure to environmental pressure.

Analytical Framework and O-D Matrix Construction

To evaluate spatial accessibility and the pressures on valuable landscapes in the Lazio Region, this study develops an integrated Origin-Destination (OD) model based on georeferenced data regarding the population expressed in inhabitants per km square. The combined use of OD matrices, isochrone mapping, and multimodal indicators is widely recognised as an effective strategy to assess both transport equity and landscape usability [26,48,49].

In particular, the semi-automated GIS-based methodology presented by (Palermo et al. [49] for the Calabria region—based on isochrone thresholds in 7 time slots from transport nodes and a demographic classification of municipalities—offers a relevant precedent. This approach has proven useful in fragmented service contexts and polycentric territorial structures, characteristics that also define many areas of Lazio. The methodological framework is based on the construction of an Origin–Destination (OD) matrix designed to model accessibility from a set of urban and rural origins, defined as the centroids of a 2×2 km population grid, to the landscape nodes corresponding to the entry points of protected areas. Each OD pair, for a total of 169, contains a set of attributes including travel times by car and by train combined with e-bike from railway stations, the normalized tourism pressure at the destination (measured in visits per day per square kilometre), the number of available accommodation units within a 2 km buffer, and the population of cities located within natural and protected areas. The OD matrix supports two main iterations of the accessibility analysis: the first based exclusively on car travel, and the second integrating train services with e-bike connections from railway stations. These scenarios allow a direct comparison between private motorised accessibility and multimodal, more sustainable forms of mobility.

The analysis is developed along two complementary dimensions. The first concerns accessibility mapping through isochrone calculations, which illustrate the spatial extent of reachable destinations within defined time thresholds. This makes it possible to highlight disparities between transport modes and their relative efficiency in connecting population catchments to sensitive landscapes. The second dimension concerns the relationship between accessibility and environmental pressure, focusing on areas where landscape assets are simultaneously highly reachable and exposed to risks of overtourism and ecological stress. The statistical assessment of isochrone results demonstrates a marked growth in the population potentially able to reach the selected sites as travel times increase. The

average accessible population rises from around 462,000 people within 15 min to more than 3.2 million within 90 min, reflecting both the geographical expansion of the catchment and the higher population densities of the urban areas progressively included.

Figure 3 illustrates the differences in population catchment between private car and the train + e-bike mode. The blue areas indicate sites where accessibility is comparable across modes, while the red areas highlight locations that can be reached significantly faster by train + e-bike. This spatial pattern underscores the uneven distribution of sustainable accessibility, revealing both opportunities (red zones) and persistent car-dependency (blue zones). Particularly significant is the value of the standard deviation, which also increases with time: from ±280,000 at the 15 min threshold to over ±1.3 million at 90 min. This indicates a profound territorial unevenness: some sites—especially those located in peri-urban areas or along major infrastructure corridors—can be accessed by millions of inhabitants in relatively short times, whereas others—located in mountainous, peripheral, or poorly served areas—are accessible to a far smaller number of people.

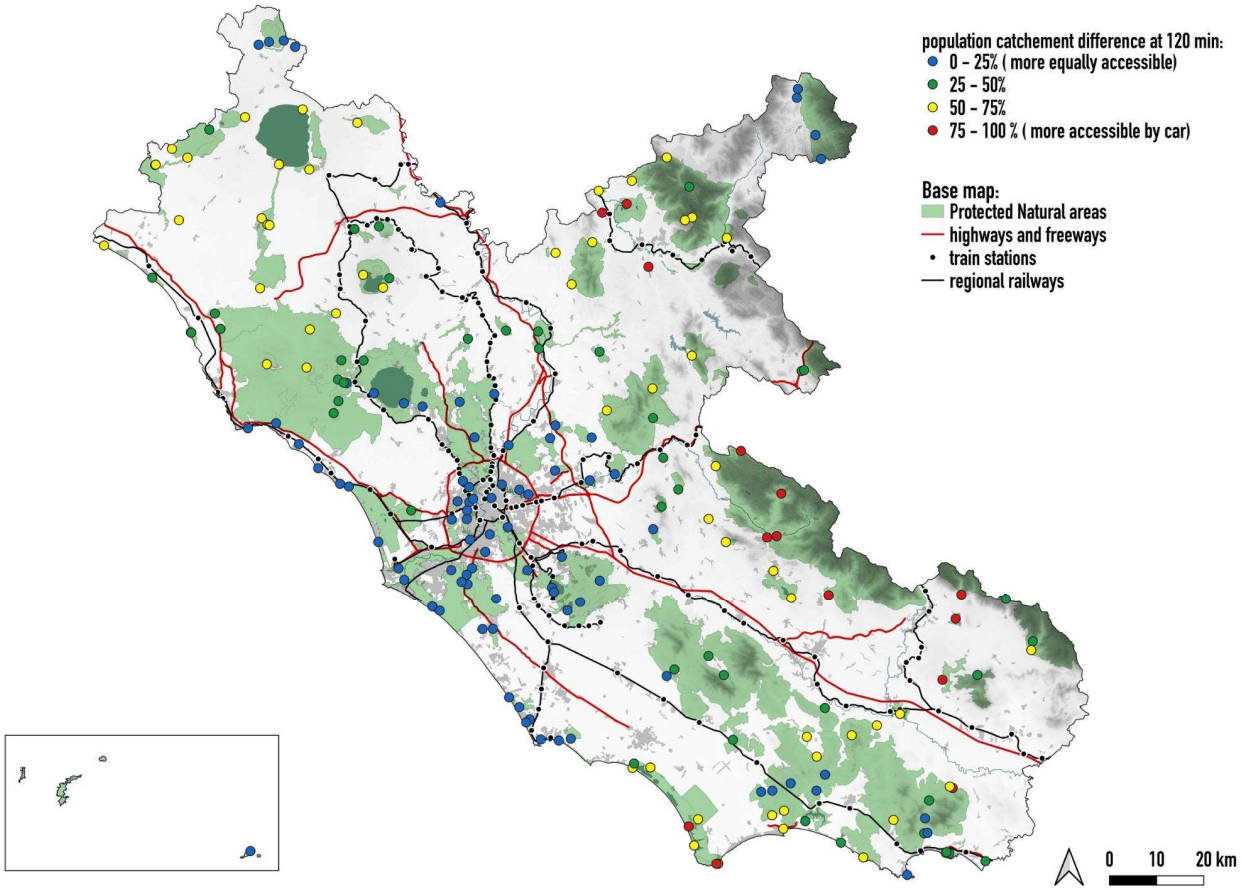

Figure 3. Catchment area and population. Elaboration of authors.

The wide range (up to 4.5 million people) between the minimum and maximum population values for each time threshold highlights that neither distance nor time alone are sufficient to ensure equitable access. Instead, infrastructural, morphological, and demographic distribution factors must be considered in both mobility planning and the protection of landscape and natural heritage sites.

In the 180 min threshold, the only low accessibility values are observed for the Pontine Islands, where longer ferry travel times are considered. For all other destinations, car accessibility approaches nearly 100%. However, the differences between transport modes remain clearly visible at the 120 min threshold.

The values presented in Table 5 underscore the need to adopt differentiated and context-sensitive approaches when managing accessibility to ecological and cultural sites, to avoid both the risk of concentrated overtourism and the systemic exclusion of inner and marginal areas.

Table 5. Descriptive statistics catchment area of car use. Elaboration of authors.

Time in Minute	Avg Pop.	Dev. Standard	Min. Pop	Max. Pop	Range
pop_15_min	~462,000	~462,000	~462,000	~462,000	~462,000
pop_30_min	±280,000	±280,000	±280,000	±280,000	±280,000
pop_45_min	~42,000	~42,000	~42,000	~42,000	~42,000
pop_60_min	~990,000	~990,000	~990,000	~990,000	~990,000
pop_90_min	~948,000	~948,000	~948,000	~948,000	~948,000

In Table 6, the average population reached in 15 min: about 14,700 people, but with a very wide range (from 1009 to 35,859), indicating strong differences between central and peripheral sites.

Table 6. Descriptive statistics catchment area of bike and train use. Elaboration of authors.

Time in Minute	Avg Pop.	Dev. Standard	Min. Pop	Max. Pop	Range
pop_15_min	24,874	26,876	1009	75,078	74,069
pop_30_min	71,486	53,043	3783	161,404	157,621
pop_45_min	221,016	237,269	5370	737,672	732,302
pop_60_min	514,432	596,531	6379	1,674,375	1,667,996
pop_90_min	1,424,330	1,410,845	7778	3,278,588	3,270,810

At 30 min, the average rises to over 65,000 people, with a maximum of over 160,000. At 45 min, the average reachable population doubles (over 200,000) and the variability increase significantly (std = ±238,000). At 60 min, an average of almost 470,000 people is reached, but with a range of over 1.5 million: this indicates a strong imbalance between highly connected sites (e.g., near Rome) and remote ones. At 90 min, the average population exceeds 1.1 million, but values vary from around 300,000 to over 3.2 million people, showing an even more marked gap. The results confirm a highly unequal distribution of accessibility between the different sites in Lazio. The increasing standard deviations and the very wide ranges suggest that the planning of mobility infrastructures and tourism services must be territorially targeted. These inequalities can fuel phenomena of overtourism concentrated in some sites and marginalization in others.

The O-D matrix allows for the identification of high-accessibility/high-pressure combinations, which signal potential conflict zones where improved accessibility may amplify environmental and social stress. Conversely, low accessibility/low-pressure areas may indicate opportunities for sustainable tourism decentralization.

3. Results and Discussion

The results from the isochrone-based Origin-Destination (O-D) analysis, summarised in Tables 5 and 6, highlight significant spatial disparities in population accessibility to protected natural and cultural areas across the Lazio Region. Areas within a 15 min range show relatively limited accessibility, reflecting the remoteness of many Natura 2000

and park-designated sites. In contrast, accessibility sharply increases beyond the 45 and 60 min thresholds, underscoring the growing pressure that improved regional mobility infrastructure may exert on previously isolated ecological zones.

Figure 4 further illustrates these differences by mapping the spatial distribution of the population grid. Denser urban cores like Rome and the coastal belt exhibit a higher concentration of accessible population, suggesting a stronger potential for tourism flows into sensitive areas located along urban–rural and coastal–inland transitions. This spatial mismatch between ecological fragility and increasing demographic reach presents a key governance challenge for sustainable territorial planning.

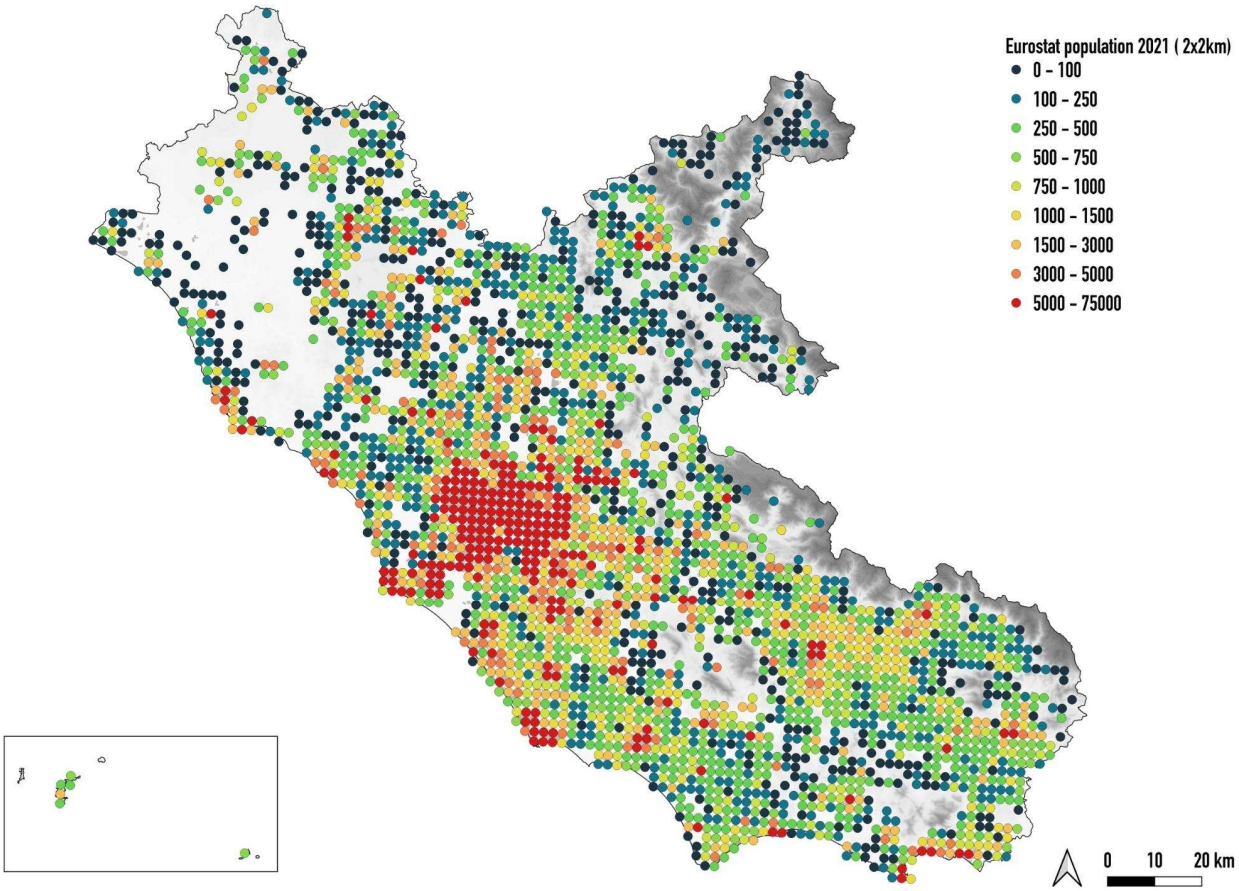

Figure 4. Population grid (2 × 2 km). Elaboration of authors based on GISCO–European Commission, 2021.

Table 7 highlights how car travel provides extensive coverage across the Lazio Region, with a sharp increase in accessible population after 30 min. The wide range values underscore disparities in infrastructural integration between central and peripheral sites.

When considering the average population reachable within various travel time thresholds, we observe that on average, over 108,808 person can access a site within 15 min, rising to over 3.38 million within 90 min. Secondly, the range values—spanning from sites accessible to virtually no population (minimums around 600–700 people) to those reachable by over 5 million people—indicate stark contrasts in the spatial integration of these landscapes into the regional transport network. This heterogeneity reflects the varying degrees of centrality and infrastructure provision across the region. Sites closer to the Rome metropolitan area (e.g., Appia Antica street) naturally exhibit higher population catchments, while peripheral or mountainous areas (e.g., Simbruini or Lake Vico) show significantly lower access figures.

Table 7. Results of isochrone-based Origin-Destination (O-D) for car use. Elaboration of authors.

Travel Time	Avg Pop.	Min Pop.	Max Pop.	Range
15 min	108,808.83	0.00	1,115,465.00	1,115,465.00
30 min	516,231.36	622.00	2,885,610.00	2,884,988.00
45 min	1,167,622.02	691.00	3,856,403.00	3,855,712.00
60 min	1,910,159.18	691.00	4,551,660.00	4,550,969.00
90 min	3,387,389.32	691.00	5,348,873.00	5,348,182.00
120 min	4,657,200.66	139,212.00	5,615,488.00	5,476,276.00
180 min	5,486,386.17	947,118.00	5,620,341.00	4,673,223.00

From a territorial equity and planning perspective, such discrepancies raise critical concerns. Landscapes with high ecological or cultural value but low accessibility may be under-visited or face isolation, impeding both local development and effective stewardship. Conversely, highly accessible sites face risks of overtourism and environmental degradation, especially when accessibility improvements are not accompanied by capacity controls or preservation policies.

These results support the need for differentiated mobility strategies, directing the plans towards measures that are more attentive to niche and naturalistic tourism and to the fight against territorial vulnerability along soft mobility transport networks. Among the suggestions emerging from this study, it is possible to propose: (i) Redistribution of flows through targeted promotion of under-accessed sites; (ii) Mitigation measures in high-accessibility zones, such as seasonal quotas or green transport incentives; (iii) Infrastructure enhancements aimed at expanding non-motorized access to currently car-dominated sites, ensuring that accessibility does not come at the cost of environmental sustainability.

The analysis of accessibility, in Table 4, using a combined train and e-bike mode reveals significantly lower population catchment values compared to private car access, particularly in short to medium travel time thresholds. On average, only 35,859 people can reach a site within 15 min, rising to just over 3.27 million within 90 min, compared to over 1.08 million and 3.38 million, respectively, for car users. This gap reflects both the infrastructural limitations of active intermodality and the geographic concentration of rail stations relative to protected landscape areas.

Table 8 illustrates the limited reach of sustainable transport, especially at short distances. Even at 60–90 min, average population accessibility remains below car levels, signalling underdeveloped multimodal infrastructure in rural zones.

Table 8. Results of isochrone-based Origin-Destination (OD) for train & e-bike use.

Travel Time	Avg Pop.	Min Pop.	Max Pop.	Range
pop 15 min	33,840.04	0.00	540,743.00	540,743.00
pop 30 min	127,434.38	0.00	1,650,602.00	1,650,602.00
pop 45 min	294,223.41	201.00	2,717,510.00	2,717,309.00
pop 60 min	583,853.21	691.00	3,543,298.00	3,542,607.00
pop 90 min	1,424,795.65	691.00	4,519,491.00	4,518,800.00
pop 120 min	2,449,338.71	691.00	5,093,318.00	5,092,627.00
pop 180 min	4,187,182.07	60,317.00	5,562,861.00	5,502,544.00

Moreover, the maximum reachability of certain sites remains high at longer thresholds (e.g., up to 5.37 million within 180 min), indicating that integrated rail/e-bike systems can, in principle, provide broad access—albeit with greater travel times and likely requiring multiple modal shifts. The minimum values are extremely low at all thresholds, with some sites remaining almost inaccessible via this mode, confirming a highly uneven distribution of accessibility and a potential barrier to equitable enjoyment of ecological and heritage assets.

This evidence reinforces the need for strategic investments in last-mile cycling infrastructure, bike-sharing systems at rural train stations, and improved multimodal connectivity to enhance the feasibility and attractiveness of low-impact tourism. Furthermore, from a sustainability perspective, the train + e-bike mode offers a critical pathway for reducing car dependency, yet it currently serves a much narrower population base. Bridging this accessibility divide is essential for aligning mobility goals with both environmental and territorial equity principles.

The results of the multimodal isochrone analysis clearly reflect the broader dynamics of accessibility and spatial transformation in the Lazio Region. As highlighted in earlier sections, peripheral landscapes such as regional parks, Natura 2000 sites, and UNESCO-listed archaeological zones have become focal points of regional mobility and tourism promotion strategies. However, our findings underscore a pronounced modal divide: car accessibility vastly outperforms that of sustainable modes—including train + e-bike—in terms of population reachability across all time thresholds.

Within 30 min, car users can access a substantial portion of the region's valuable landscapes, with average catchments exceeding half a million residents. This ease of access contributes to increasing tourist flows into environmentally sensitive areas, often without corresponding safeguards or infrastructural controls. In contrast, train + e-bike access remains limited and uneven, particularly in areas distant from railway lines or lacking last-mile cycling infrastructure. Some sites remain virtually unreachable within reasonable time frames, exposing stark territorial inequalities.

This spatial imbalance reinforces concerns about the car-centric orientation of regional development policies. As prior research has shown [42,44], infrastructure designed primarily for private vehicles tends to exacerbate exclusion for those without access to a car, while simultaneously placing fragile landscapes under disproportionate pressure.

The implications of this are particularly acute in ecologically and symbolically significant zones, such as Lake Vico, Circeo National Park, and the Monti della Tolfa, where improved vehicular access has coincided with rising pollution, overuse of trails, and degradation of both natural and cultural heritage [18,21]. In contrast, inland destinations such as the Simbruini Mountains and Valle del Salto remain marginalized—both in terms of tourism promotion and infrastructural investment—despite their strong potential for low-impact tourism.

Furthermore, the mismatch between formal proximity and functional accessibility—i.e., between the physical closeness of heritage sites and the lack of viable, sustainable access—emerges as a key barrier to achieving regional mobility and equity objectives. This aligns with the landscape planning literature, which stresses the importance of carrying capacity, sense of place, and experiential quality in defining sustainable access [27,28].

In this context, train and bike accessibility, while currently limited, offers a promising yet underutilized pathway for redistributing tourist flows and promoting climate-resilient mobility. Our findings suggest that targeted interventions—such as e-bike sharing at rural stations, cycling trail upgrades, and co-marketing of rail-linked heritage routes—could significantly enhance the reach and equity of sustainable transport systems.

Table 9 indicates that, within the 45 min threshold, Special Areas of Conservation (ZSCs) account for the majority of accessible sites across both transport modes. By contrast, Regional Parks and State Nature Reserves remain less represented, highlighting the limited short-range accessibility of sustainable transport to these critical conservation areas.

Table 9. Results for 45 min by car and train.

Type Number of Sites Percentage	Type Number of Sites Percentage	Type Number of Sites Percentage
Regional Natural Park	21	9.86
Regional Natural Reserve	30	14.08
ZSC	115	53.99
ZPS	9	4.23
ZPS/ZSC	28	13.15
National Park	5	23.47
State Natural Reserve	5	23.47

Figure 5 contrasts the spatial imprint of both modes. Car travel reaches a broader area, whereas train and bike remain more fragmented, revealing mobility inequities and potential blind spots in current accessibility policies.

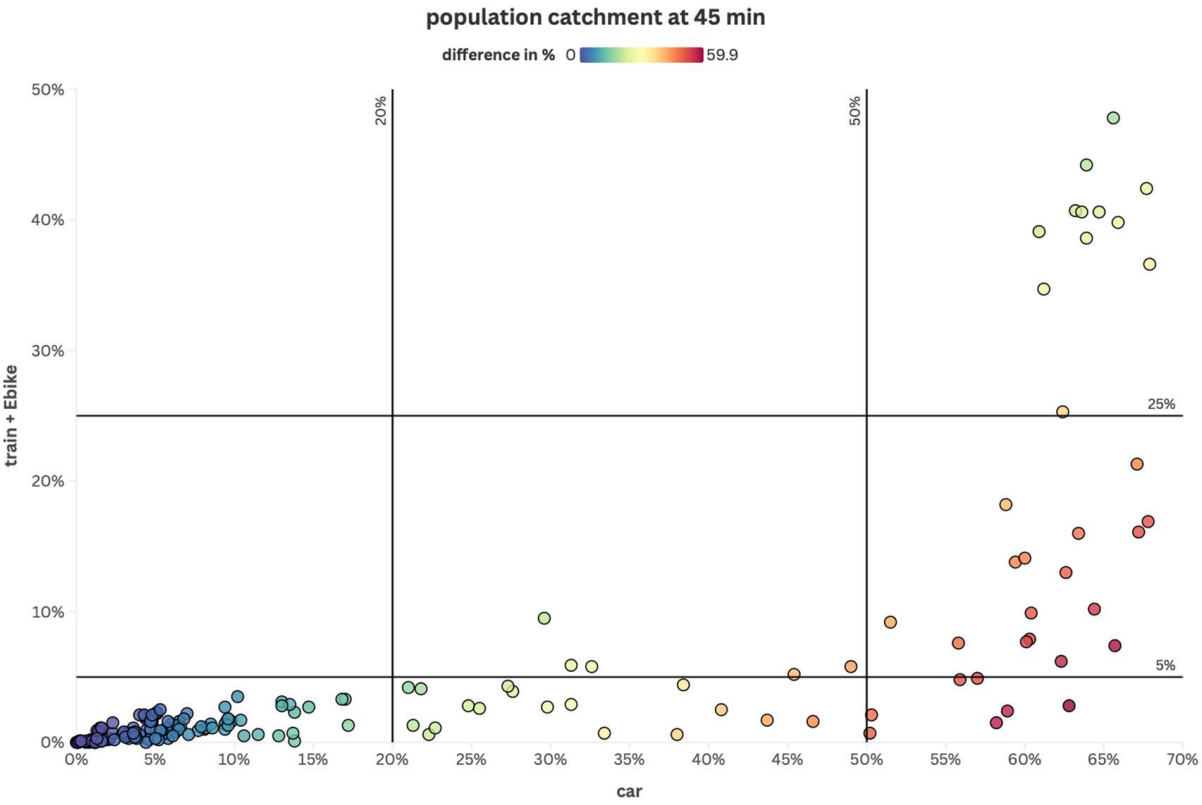

Figure 5. Distribution of population catchment when travelling by car and train + ebike on the isochrone 45 min. Elaboration of authors.

In Table 10, at the 120 min threshold the population that can access the site in 120 min or under to ZSCs and ZPSs increases significantly, reflecting their spread across the region. The continued lower share of Parks and State Reserves reinforces their relative isolation from the current transport network.

Table 10. Results for 120 min by car and train. Elaboration of authors.

Type Number of Sites Percentage (%)	Type Number of Sites Percentage (%)	Type Number of Sites Percentage (%)
ZSC	70	58.33
ZPS/ZSC	13	10.83
ZPS	12	10.00
Regional Nature Reserve	11	9.17
Regional Nature Park	9	7.50
National Park	3	2.50
State Nature Reserve	2	1.67

In Figure 6, the comparison reveals a closing gap in modal coverage, yet car use still dominates in number of accessible sites. The figure emphasizes the need for improved intermodal strategies to enhance low-impact access.

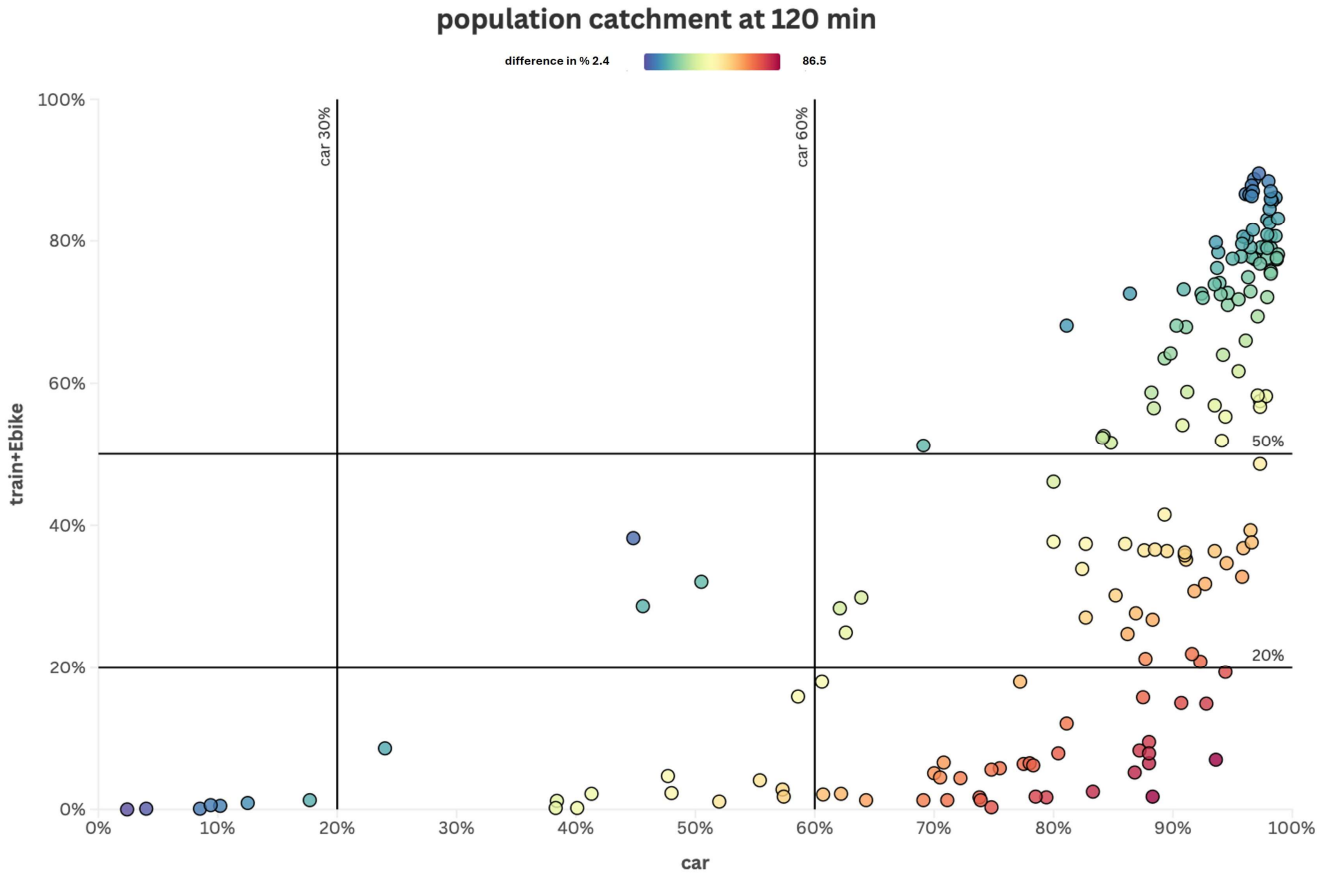

Figure 6. Distribution of population catchment when travelling by car and train + ebike on the isochrone 120 min. Elaboration of authors.

As shown in Figure 7, Isochrone patterns highlight a more fragmented accessibility, with some parks well-served and others cut off. This indicates an uneven distribution of access infrastructure and tourism potential.

Figure 8 confirms that State Reserves remain the least accessible category, especially by sustainable transport. Their ecological sensitivity makes them vulnerable to even modest tourism pressure, demanding cautious planning. While Figure 9 describes the time travel by car towards the Natural areas.

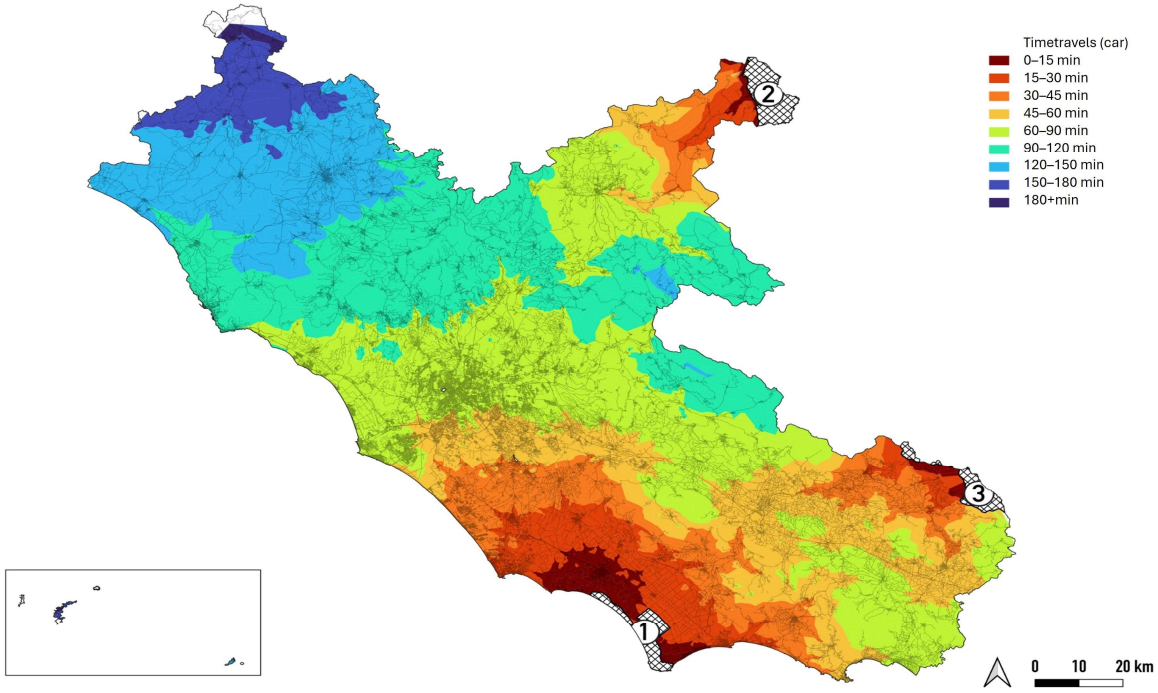

Figure 7. Isochrones of time travels of National Parks and distance in minutes by car. Elaboration of authors. Legend: (1): Parco Nazionale del Circeo, (2): Parco Nazionale Gran Sasso e Monti della Laga, 2, (3): Parco Nazionale di Abruzzo, Lazio e Molise.

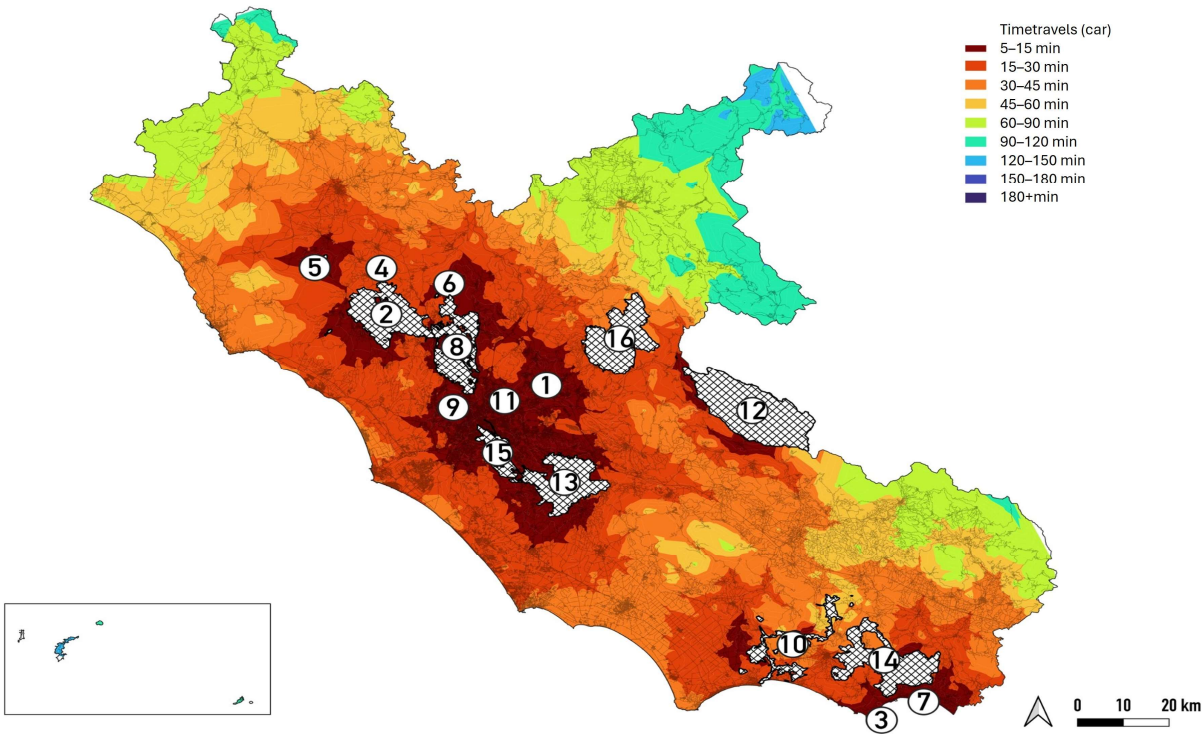

Figure 8. Isochrones of time travels of Regional Natural Park and distance in minutes by car. Elaboration of authors. Legend: Inviolata (1), Bracciano-Martignano (2), Monte Orlando (3), Parco dell'antichissima Citta' di Sutri (4), Marturanum (5), Valle del Treja (6), Gianola e Monte di Scauri (7), Veio (8), Pineto (9), Monti Ausoni e Lago di Fondi (10), Aguzzano (11), Monti Simbruini (12), Castelli Romani (13), Monti Aurunci (14), Appia Antica (15), Monti Lucretili (16).

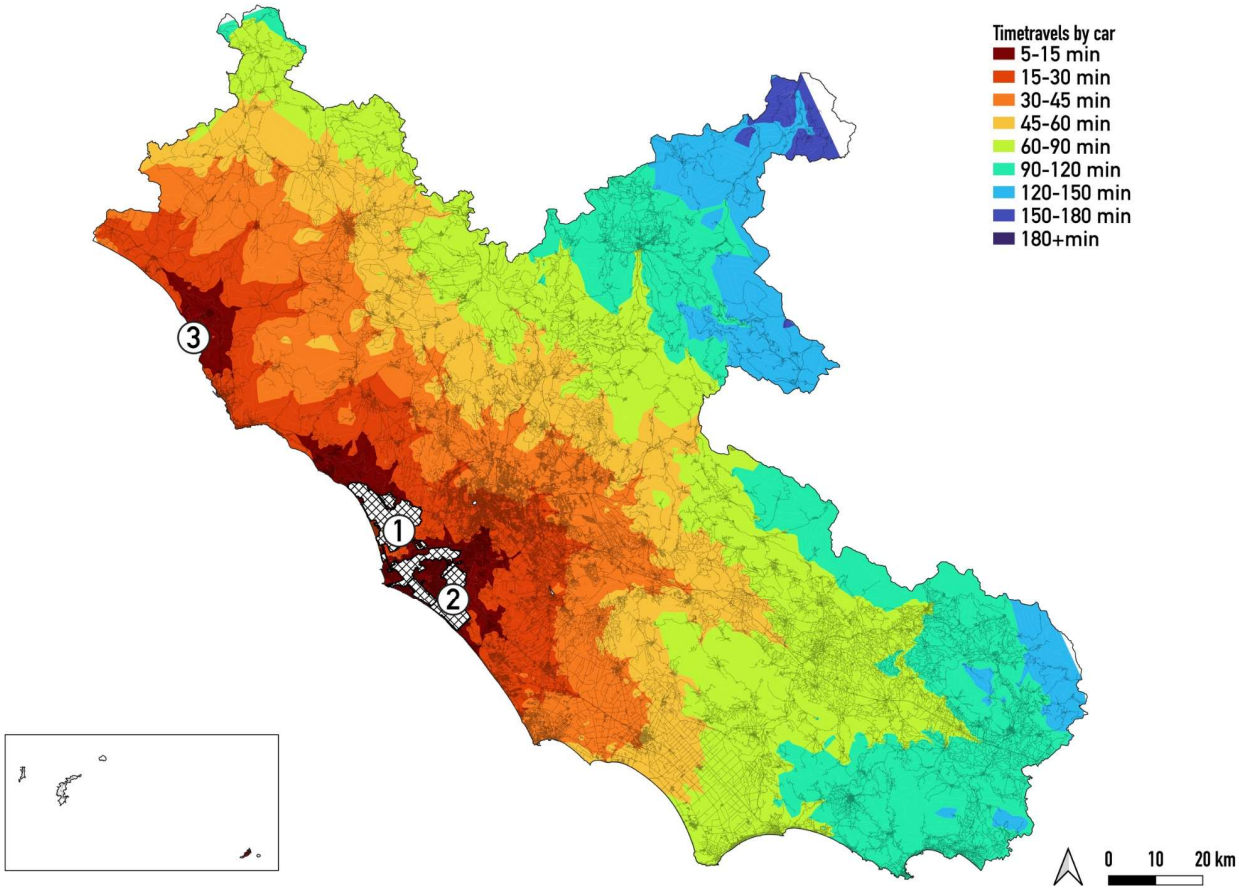

Figure 9. Isochrones of time travels of State Nature Reserve and distance in minutes. Elaboration of authors. Legend: (1): Litorale Romano, (2): Tenuta di Castel Porziano, (3): Salina di Tarquinia.

The results of the isochronous analysis shown in Figures 7–9 clearly highlight what has been reported in the most recent literature on tourism sustainability and territorial planning: the increasing accessibility of natural and cultural areas, if not accompanied by control and governance measures, tends to amplify the risks of environmental overload and degradation [50]. The case of Lazio confirms the observation of Vitale Brovarone and Cotella [51] according to which there is a structural misalignment between the geographical proximity of an area and its sustainable functional accessibility [52]. Many sites, although physically close to urban centres, are reachable almost exclusively by private car, with significant impacts in terms of congestion, emissions and land consumption.

The observed modal gap between accessibility by car and that via a combination of train + e-bike confirms the results of Lahoorpoor and Levinson [50], which highlight how intermodal systems require targeted investments in last-mile infrastructures to become truly competitive [53]. The integration between tourist pressure, population density and site classification suggest the need for multidimensional indicators, as advocated by Śleszyński et al. [13].

Figure 10 illustrates comparative accessibility between car and train + e-bike travel across the Lazio region. The colour gradients highlight areas where one mode is significantly faster than the other: blue shades show a clear advantage for car travel (up to over two hours faster), while orange to red shades indicate better performance of train + e-bike, particularly along rail corridors and in southern areas. The central belt shows more balanced travel times, reflecting multimodal accessibility. The overlay of highways, railways, and protected areas provides further spatial context for interpreting mobility patterns.

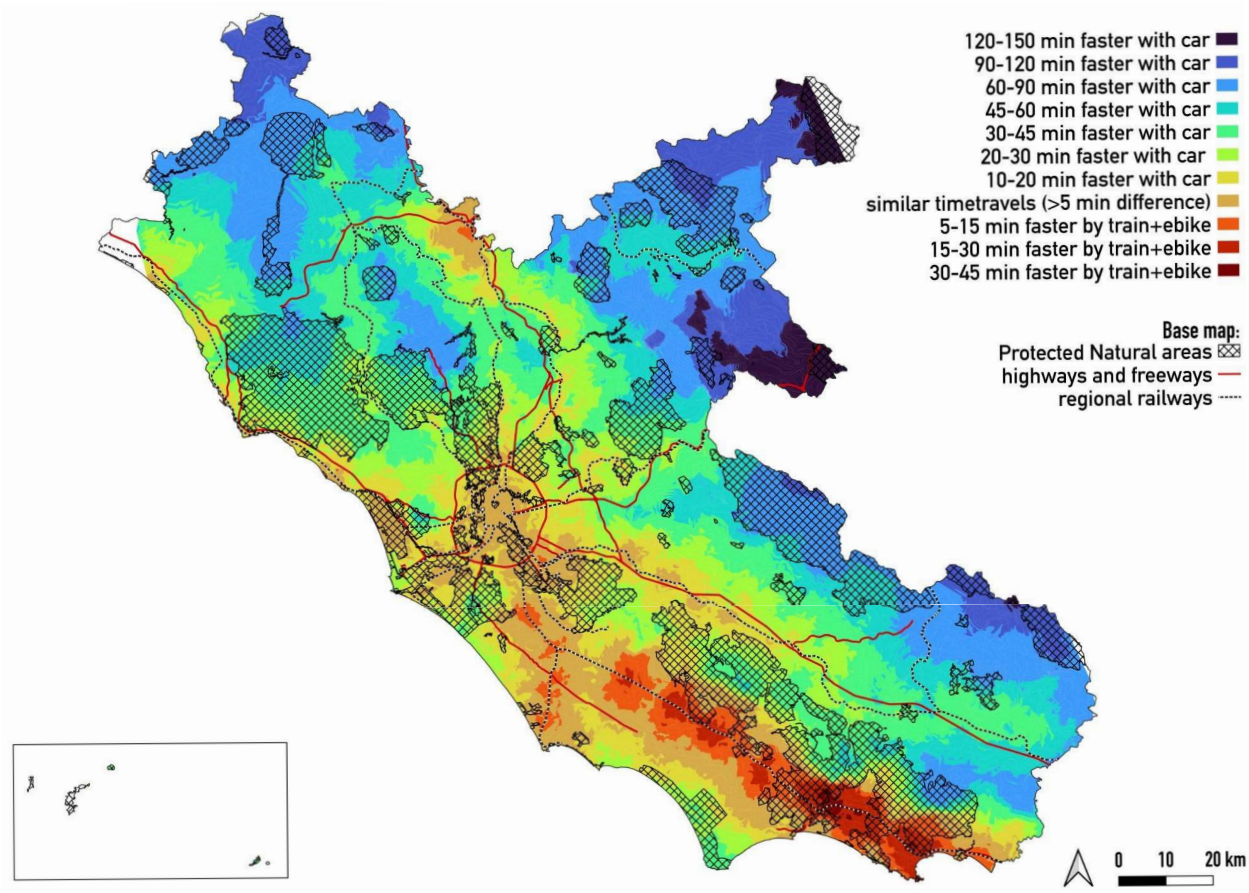

Figure 10. Difference in time travels between car and train + ebike to protected areas from central Rome. Elaboration of authors.

Vulnerable areas, especially those that combine ecological and cultural values, represent a strategic asset for the sustainable development of peripheral territories. However, the current configuration of mobility and tourism promotion policies tends to favour the maximization of accessibility and attractiveness, often to the detriment of the environmental carrying capacity and social resilience of such contexts. Lazio, with its network of regional parks, reserves and Natura 2000 sites, offers a paradigmatic example: formally protected areas become increasingly accessible to an expanding urban population basin (e.g., the Roman metropolitan area), accentuating territorial imbalances and risks of overtourism.

One of the main problems lies in the imbalance between the potential reachable population and the actual capacity of places to absorb flows. Some natural and cultural areas show a dangerous combination of high accessibility by millions of people in private cars and low sustainable infrastructure, making them particularly exposed to congestion, degradation and erosion of the landscape. On the contrary, other peripheral and inner areas, although rich in resources, remain marginal due to the absence of multimodal connections or targeted enhancement policies.

To address these critical issues, an integrated approach of adaptive governance of tourism and mobility is needed, capable of differentiating strategies based on territorial vulnerability. First, it is appropriate to introduce policies for the distribution of tourist flows, through the selective promotion of less accessible but less pressured sites. Communication campaigns, economic incentives and combined mobility packages can encourage forms of widespread tourism, decentralizing the pressure from the most iconic places to lesser-known but equally significant areas.

Second, it is necessary to strengthen light and sustainable infrastructures in medium-accessible areas: rural bike-sharing, cycle routes interconnected with railway stations, seasonal ecological shuttles can improve access while reducing environmental impact [19]. Where tourist pressure is already high, however, load capacity control systems should be implemented: seasonal tickets with limited numbers, online bookings, variable rates based on crowding, and regulation of private vehicle access.

It is also necessary to coordinate territorial planning strategies with tourism and mobility policies. Landscape plans and Management Plans of Natura 2000 sites should integrate indicators of accessibility and demographic pressure, to identify critical areas and guide decisions on infrastructure, promotion and conservation. In this sense, the use of geospatial models based on isochrones and Origin-Destination matrices can support evidence-based decisions, facilitating dialogue between local authorities, park managers and tourism stakeholders. Finally, strategies should promote forms of community and regenerative tourism, involving local populations in participatory processes of territorial valorisation, strengthening the sense of belonging and limiting the risk of gentrification or depopulation.

The results exposed confirm that vulnerability in Lazio's protected landscapes emerges from a combination of structural and contextual drivers. Coastal belts such as Circeo and the Pontine Islands experience seasonal overtourism and fragile ecosystems highly exposed to accessibility improvements. Mountainous areas like the Simbruini and Reatini are shaped by morphological constraints and limited multimodal access, which concentrate flows on a few saturated corridors. Inland sites such as Lake Vico and Bracciano illustrate the impact of fragmented governance, where overlapping jurisdictions between regional parks, municipalities, and Natura 2000 management weaken coordinated responses. Finally, peri-urban areas such as Appia Antica or Valle dei Casali suffer from continuous pressure linked to high population density and recreational use, resulting in permanent rather than seasonal stress. These differentiated dynamics highlight that vulnerability is not merely the outcome of accessibility patterns, but of the interplay between ecological fragility, governance capacity, and demographic drivers. Recognizing these layered causes is fundamental for designing adaptive, context-sensitive strategies for sustainable mobility and tourism management.

Policy Implications and Future Research Avenue

The findings of this study provide actionable insights for stakeholders engaged in territorial governance. First, regional and municipal governments can use the vulnerability maps to prioritize investments in low-impact mobility infrastructure, such as bicycle-sharing systems near railway nodes or ecological shuttle services, to reduce pressure on car-dependent areas. Second, park authorities and site managers can employ the geospatial outputs to establish capacity thresholds, regulate visitor flows, and monitor seasonal pressures, thereby ensuring that accessibility improvements do not compromise ecological resilience. Third, urban and transport planners can incorporate the integrated framework into planning tools, aligning infrastructure projects with ecological sensitivity indicators and tourism demand patterns. Finally, policy-makers at regional and national levels can draw on these results to promote inter-municipal cooperation and strengthen the integration of Natura 2000 management plans with mobility strategies.

By linking accessibility, ecological vulnerability, and tourism exposure, the proposed framework supports evidence-based decision-making, enabling stakeholders to anticipate risks, target interventions, and foster a more balanced form of territorial development.

Comparable dynamics can be observed in other European contexts, reinforcing the broader applicability of our methodology. In France, studies on the Loire Valley and

Provence regions highlight how improved accessibility through high-speed rail and regional road upgrades has intensified pressure on heritage landscapes [8,28]. In Spain, research on coastal Andalusia and Catalonia shows similar conflicts between tourism flows, Natura 2000 conservation goals, and fragmented governance [3]. In Germany, planning frameworks around the Rhine Valley and Bavarian Alps demonstrate how integrated accessibility modelling can guide mobility policies that respect ecological thresholds [13]. These parallels indicate that the Lazio case is not an isolated example but part of a wider European challenge. The geospatial framework presented here therefore offers a transferable tool to inform adaptive territorial governance across heritage-rich and environmentally sensitive regions. Moreover, this study presents several methodological and technical limitations that should be considered when interpreting the results. First, the analysis is geographically constrained to Lazio region residents only, excluding potential users from neighbouring regions who may access these natural areas, thus potentially underestimating the total potential accessibility. Second, our calculations focus exclusively on potential accessibility based on travel time thresholds and population distribution. This approach provides theoretical catchment areas without incorporating behavioural factors, preferences, or actual usage patterns. The results should be interpreted as a spatial assessment of accessibility opportunities rather than predictions of actual visitation flows. From a technical perspective, while the road network graph has been validated against major routing providers (Google Maps), certain limitations persist. The static speed assignment does not account for real-time traffic conditions, seasonal variations, or time-of-day fluctuations. Additionally, the e-bike speed assumption of 22 km/h represents an average value that may not reflect terrain variations, individual cycling abilities, or weather conditions. The population data represents residential locations derived from statistical grids, which may not capture temporary population variations or seasonal demographic shifts. Furthermore, the 2×2 km grid resolution, though detailed, may mask localized population concentrations or accessibility variations within grid cells, albeit these effects are negligible at the regional scale.

The analysis assumes direct, optimal routing for car transport and considering only direct trains for railway connections, and without considering parking availability at access points, traffic limitations (ZTL-Zona a Traffico Limitato), or infrastructure constraints that may affect actual accessibility. Additionally, the railway connectivity analysis is based on station locations and scheduled services as of the current date (June 2025) without accounting for service frequency variations or operational disruptions.

Finally, while these calculations provide valuable insights into the spatial distribution of potential accessibility, they represent a preliminary assessment that establishes baseline conditions for future comparative studies examining different accessibility scenarios or policy interventions.

4. Conclusions

This study stems from the forthcoming adoption of the Regional Plan for Cycling Mobility in Lazio, which is expected to foster the diffusion of soft mobility. While such policies bring clear benefits, they also require careful monitoring of flows directed towards natural parks, protected areas, and less-frequented destinations, where the risks of ecological stress and overtourism remain insufficiently addressed in Italy and, more specifically, in Lazio.

Our results demonstrate that accessibility gains are highly uneven across the region, as some areas—particularly coastal belts, peri-urban parks, and inland lakes—are subject to intense accessibility-driven pressure, while others, such as mountainous and peripheral sites, remain marginalised. This spatial imbalance confirms findings in the literature [13,26,45] regarding the misalignment between physical proximity and sustainable accessibility.

The main contribution of the paper lies in its integrated geospatial framework, which combines isochrone-based accessibility, ecological sensitivity, and heritage value to identify vulnerability hotspots. This approach is replicable in other regions and offers added value for policy design, providing evidence-based insights for adaptive, place-sensitive mobility planning.

At the same time, several limitations should be acknowledged. The analysis is based on resident population data as a proxy for potential pressure, without incorporating actual tourist flows, overnight stays, or behavioural dynamics. Moreover, the model does not fully capture seasonal variations or last-mile constraints (e.g., parking availability, frequency of rail services).

Future research should address these aspects by integrating tourism statistics, behavioural surveys, and seasonal mobility scenarios, as well as by linking accessibility models with accommodation capacity and carrying capacity assessments. Additionally, stronger coordination with Natura 2000 management plans and landscape planning frameworks will be crucial for operationalising these results.

Overall, this study contributes to the ongoing debate on sustainable territorial governance, offering both methodological innovation and policy-relevant evidence for balancing accessibility, tourism development, and ecological resilience.

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