SimulSoil: Ecosystem Service Modelling for Sustainability-Oriented Planning in the Metropolitan City of Turin"

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Abstract
Mountain territories provide essential ecosystem services (ES) to metropolitan areas, yet their contributions are often overlooked in spatial planning. This paper presents an updated application of the open-source SimulSoil plugin to model two key ES—Carbon Storage and Habitat Quality—in the Metropolitan City of Turin, a complex mountain-metropolitan system in northern Italy.

Using the high-resolution 2023 Land Cover Piemonte dataset, the models were applied across 11 Homogeneous Zones to map ES distribution and ecological asymmetries. Results show that mountain areas act as "ecological donors", offering critical services to densely populated urban zones.

This study demonstrates how spatially explicit ES analyses can support rebalancing-oriented governance. The updated models provide actionable knowledge for integrating ecological functions into territorial planning and reveal the need to address spatial imbalances and territorial justice.

Keywords: Metro-mountain Interdependencies, Ecosystem services, SimulSoil Modelling; Metropolitan governance, Spatial planning

1. Introduction

In recent years, ecosystem services (ES) integration into spatial planning has gained increasing attention among scholars and practitioners aiming to reorient territorial governance toward sustainability and climate resilience (Mosso, Nino and Salata 2025). Ecosystem services—broadly defined as the benefits humans obtain from nature—have emerged as a conceptual and operational framework for bridging ecological processes with human well-being (MEA, 2005; TEEB, 2010; (Egegard *et al*., 2024). Despite this growing interest, the effective operationalisation of the ES paradigm in planning remains a significant challenge, especially in multi-scalar, ecologically diverse, and institutionally fragmented contexts such as metropolitan areas.

Urban and metropolitan areas are often perceived primarily as population, consumption, and economic activity centres. However many such areas—particularly across southern and alpine Europe—include extensive mountain systems within their territorial boundaries. While often peripheral in terms of infrastructure and political attention, these upland areas are critical suppliers of key ecosystem services such as carbon sequestration, biodiversity conservation, water regulation, and landscape stability. Recognising this role requires a conceptual shift in understanding metropolitan systems (Dematteis, 2018 and 2020): not as urban-centric spaces but as socio-ecological territories shaped by complex interdependencies between human settlements and natural ecosystems.

The Metropolitan City of Turin (CmTo) offers a compelling case for exploring this shift. Located in northwestern Italy, the CmTo encompasses 312 municipalities across a spatially diverse territory that extends from the densely urbanised plain surrounding the city of Turin to the sparsely populated Alpine valleys to the west and north. This includes over 50% of its territory, classified as a mountain area. The institutional structure is based on 11 Homogeneous Zones (HZs), designed to facilitate territorial coordination, yet significant disparities in population, economic capacity, and ecological functionality remain.

Within this mountain-metropolitan system, the provisioning of ecosystem services is highly uneven. Mountainous municipalities contribute disproportionately to ecological regulation—through forested land, protected areas, and low-intensity land use—yet they often lack the institutional power and financial resources to influence metropolitan planning processes.

Conversely, lowland and urban municipalities concentrate demand for ES, infrastructure investment, and political representation while contributing relatively little to ecological functions. This asymmetry reflects a broader challenge in contemporary spatial planning: recognise and govern ecological interdependencies across heterogeneous territorial systems. The CmTo has taken up this challenge by basing the vision of its third Metropolitan Strategic Plan 2024-2026 on the this vision, incorporating elements from the Metropolitan Agenda for Sustainable Development and focusing on a new polycentric and "metromountain" development model. In this model, urban and mountain areas contribute to the competitiveness and attractiveness of the entire territorial ecosystem (Città metropolitana di Torino 2024).

One promising avenue lies in spatially explicit modelling tools that visualise ES flows and highlight ecological performance across territorial units.

This paper addresses this challenge by applying an updated version of the open-source SimulSoil plugin. Originally developed within the EU LIFE SAM4CP Project (http://www.SAM4CP.eu), SimulSoil integrates biophysical models from the InVEST software suite with locally adapted land use and ecological data (Barbieri&Giaimo, 2015; Giaimo&Barbieri, 2018; Giaimo, Barbieri&Salata, 2019). The project aimed to promote local-scale, sustainability-oriented models of land governance by providing tools to assess the costs and benefits of the free ecosystem services provided by soil; SimulSoil allows for the analysis of specific ecosystem services across planning-relevant spatial units, offering outputs compatible with strategic planning and governance frameworks.

We focus on two services: Carbon Storage and Sequestration (CS) and Habitat Quality (HQ) selected for their high relevance to climate and biodiversity goals, their mappability using available data, and their capacity to reflect underlying ecological conditions. CS and HQ serve as proxies for broader regulatory services and provide insight into the spatial logic of ecological provision in the CmTo.

Our objectives are threefold: i) to generate spatialised evidence of ES provision in the CmTo using updated and locally calibrated models; ii) to interpret the spatial patterns of CS and HQ across the 11 HZs and assess territorial imbalances in ES supply; iii) to reflect on how such evidence can inform rebalancing-oriented planning, particularly by recognising the role of mountain territories as ecological donors within the metropolitan system. The paper is structured as follows. Section 2 presents the regional context of the CmTo and discusses key socio-ecological characteristics of the HZs. Section 3 introduces the SimulSoil plugin, tracing its development and recent updates to data sources and model assumptions. Section 4 describes the methodology used to operationalise the InVEST Carbon Storage and Habitat Quality models within SimulSoil. Section 5 presents and interprets the modelling results, while Section 6 critically examines limitations of the approach and identifies potential avenues for integration into planning practice. The final section offers conclusions and policy recommendations.

This study makes three main contributions by applying updated ES models to a mountain-metropolitan case. First, it provides empirical evidence for the ecological centrality of upland territories within a metropolitan context. Second, it illustrates how open-source tools can be adapted and applied to produce planning-relevant outputs. Third, it contributes to debates on spatial justice by highlighting the need to account for territorial imbalances in ES supply and demand. Ultimately, we argue that ecosystem service modelling, when grounded in local data and critical territorial interpretation, can serve not only as a technical aid, but as a transformative planning lens—one capable of advancing ecological transition and promoting a more equitable distribution of responsibilities, resources, and recognition across metropolitan landscapes.

2. Case study: The Metropolitan City of Turin and Its Mountain-Metropolitan System

The Metropolitan City of Turin, located in the northwestern region of Piedmont, Italy, is a paradigmatic example of a mountain-metropolitan system where ecological, socio-economic, and institutional dynamics intersect. Established in 2015 as part of Italy's metropolitan reform (L. 56/2014), the CmTo replaced the former Province of Turin and is one of the ten metropolitan cities officially recognised by the Italian state. Its territory encompasses 312 municipalities, making it one of Europe's most fragmented metropolitan areas. This region's spatial heterogeneity poses challenges and opportunities for the governance of ecosystem services and territorial sustainability.

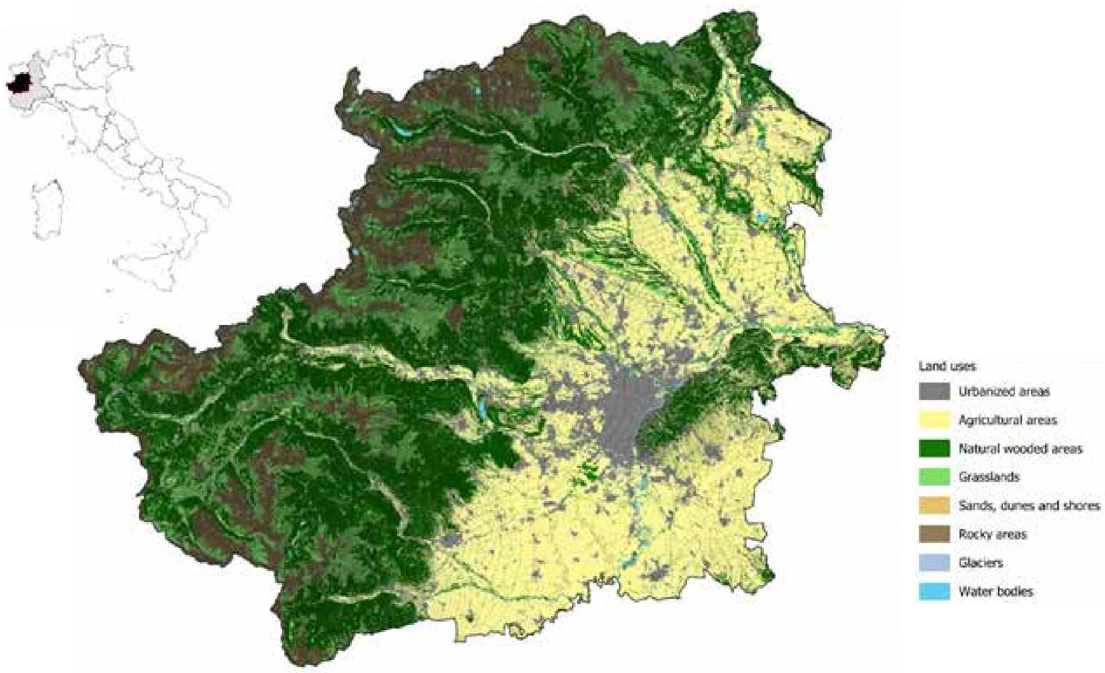

Figure 1 The Metropolitan City of Turin. Framing and Morphological-Settlement Structure (source: authors' elaboration)

Covering an area of approximately 6,800 square kilometres, the CmTo is geographically diverse and climatically varied. More than half of its territory is classified as mountain or upland area, with the western and northern parts defined by prominent alpine systems such as the Graian Alps, Cottian Alps, and the Lanzo, Susa, Chisone, and Pellice valleys. These mountain regions border France and include several national parks, protected areas, and Natura 2000 sites, collectively representing critical ecological infrastructure for carbon sequestration, biodiversity conservation, and climate regulation (Città metropolitana di Torino, 2021).

In contrast, the central and southeastern portions of the CmTo composed mainly of plains and hilly terrain, forming part of the upper Po Valley. This area hosts the urban core of Turin and its surrounding municipalities, where economic activities, transport infrastructures, and residential development are heavily concentrated. As such, the CmTo encapsulates a marked spatial asymmetry: mountainous zones are low-density, ecologically rich, and institutionally peripheral; lowland zones are high-density, socio-economically dominant, and ecologically stressed.

To foster more effective and participatory management of municipalities in metropolitan governance and government, the CmTo has adopted an internal subdivision into 11 Homogeneous Zones (HZs), each grouping municipalities with shared geographical and functional characteristics. This sub-metropolitan geography is not merely statistical but plays a role in policy coordination, funding allocation, and planning. For such reason it also serves as a practical framework for applying ecosystem service models and interpreting their results regarding planning relevance.

Figure 1 illustrates the spatial configuration of the CmTo and the major physical features of the area, including mountain ridgelines, river basins, and urban concentrations. The figure highlights the metropolitan region's concentric structure, with Turin's urbanised core surrounded by progressively more natural and mountainous belts. This spatial organisation is central to understanding the flows and gradients of ecosystem services across the territory.

Within this spatial framework, mountain territories' ecological functions are vital and under-recognised. Forests and semi-natural landscapes in the alpine valleys represent key carbon sinks and habitats of high ecological integrity. Due to limited land transformation, low-intensity agriculture, and restricted infrastructure development, these areas maintain high ecosystem service provision capacity, particularly in Carbon Storage and Habitat Quality. Simultaneously, they face socio-economic pressures such as population decline, ageing, service retrenchment, and low institutional capacity—factors that undermine their visibility and influence in metropolitan governance (Alberti et al., 2019).

Conversely, the lowland and peri-urban areas concentrate anthropogenic pressures, including land sealing, habitat fragmentation, pollution, and transportation emissions. Urban expansion into formerly agricultural land has reduced the plain's ecological connectivity, while the intensity of land use has diminished both carbon sequestration and habitat potential. While dominant in population and economic terms, these zones are ecologically dependent on the surrounding uplands for regulatory functions such as flood control, temperature moderation, and air quality improvement.

This functional asymmetry reinforces the concept of mountain municipalities as "ecological donors" in the metropolitan system, providing environmental benefits that are largely consumed elsewhere. Despite this role, ES-based reasoning is not yet institutionalised within the CmTo's planning practice. The General Metropolitan Territorial Plan (GMTP), though still in development, has only partially integrated ecological indicators, and coordination among HZs remains uneven. From a policy standpoint, the fragmentation of administrative competencies across municipalities creates obstacles to coordinated ES management. While the CmTo provides a metropolitan umbrella, actual planning competences are still largely exercised at the municipal level, with variable technical capacity and resources. This poses challenges for the integration of ES modelling tools, which require a shared vision, consistent data, and inter-institutional cooperation.

In this context, updating SimulSoil offers a valuable opportunity to visualise and quantify ecosystem services at the HZ level, providing empirical support for more equitable and sustainability-oriented planning strategies. The selection of Carbon Storage and Habitat Quality as focal ESs reflects their relevance to territorial resilience and the data availability within the regional land use framework.

The recent availability of the 2023 Land Cover Piemonte (LCP) dataset—developed by Regione Piemonte—has significantly improved the region's thematic resolution and reliability of land use information. This dataset enables a more accurate representation of forest types, agricultural mosaics, and anthropogenic land cover, essential for ES modelling. By integrating this dataset into the SimulSoil plugin, we achieve a more context-sensitive representation of ecological processes and service provision potential.

Moreover, using the HZs as the primary units of analysis allows for a better alignment between ES outputs and institutional planning scales. It helps overcome the disconnect between ecological data and planning implementation, a gap frequently highlighted in the literature on landscape governance (Primmer et al., 2015.

In sum, the Metropolitan City of Turin provides a relevant and rich case study for exploring ecosystem service dynamics in a mountain-metropolitan setting. Its territorial heterogeneity, administrative complexity, and ongoing planning reform processes make it an ideal laboratory for testing tools like SimulSoil. By linking spatialised ES modelling to institutional geography, this study aims to demonstrate how planning can move beyond urban-centric logic and embrace more ecological and equitable understandings of metropolitan space.

3. The Open Source SimulSoil Plugin: Origins and How to Update

SimulSoil is an open-source plugin for the QGIS (version 2.18.15) software, developed to support the qualitative and quantitative assessment of soil's ecosystem services. The tool aims to make mathematical and statistical models accessible to non-expert users by automating the complex calculation algorithms of the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) software.

SimulSoil provides access to repositories and databases that enable the mapping of the biophysical performance of soils at a spatial scale, as well as the identification of quantitative biophysical parameters that measure the potential of soils to deliver ecosystem services. It is achieved by relying on scientific literature and the availability of shared map bases. Additionally, the software enables the measurement of changes in ecosystem balance at the municipal scale through the simulation of alternative scenarios. The simulator was developed based on the assumption that constructing a cognitive framework for mapping ES would support more informed and shared decision-making processes regarding soil, spatial planning and management.

The tool includes eight ecosystem models selected by InVEST. This U.S.-based, open-source software uses computational models to map and assess ecosystem goods and services in biophysical and economic terms, quantifying their contribution to meeting essential human needs (Costanza *et al*., 1997; MEA, 2005). SimulSoil leverages QGIS capabilities for managing raster and vector data, integrating WMS/WFS services and using base maps (e.g. Google Maps, OpenStreetMap) to provide an intuitive, user-friendly interface. Its modular architecture and the open-source nature of the data facilitate adoption and continuous enrichment by a large, diverse user community.

SimulSoil aims to contribute developing methods and tools for integrating the ES paradigm into land-use governance activities by spatialising new knowledge on the distribution and flows of ecological and environmental performance. This methodology enables the development of a multi-scalar approach to be developed, allowing local applications to assess urban transformation scenarios and conduct spatial analyses to explore the complex interrelationships related to ecosystem flows, thus supporting decision-making processes (Corrado *et al*., 2019). It enables to prioritise scenarios in which investment in natural capital can balance human development and ecosystem conservation (Natural Capital Project, last accessed 27/05/2025).

The models produce map outputs in raster format with a pixel size of 5x5 metres, wich constitute valuable cognitive tools for studying the performance of ecosystems in soils.

At the local level, a significant potential application of the SimulSoil simulator lies in its use within the Strategic Environmental Assessment (SEA) process, a mandatory procedure for spatial planning. Analyses of ES associated with land use and land cover classes represent a concrete opportunity to quantify the impacts generated by ex-ante plan choices as well as using ES calculation models through SimulSoil allows alternative scenarios to be evaluated by modifying the cartographic input data that defines land uses and land cover.

At the scale of the metropolitan area, studying ecological and environmental performance supports spatial governance in distinct and evolving ways. For instance, studying ecological and environmental performance can address the need to consider and implement policies affecting the entire metropolitan area, which is characterised by significant morphological and settlement heterogeneity. In this context, SimulSoil is a valuable tool for analysing the exchanges and flows of ecosystem services between different spatial contexts, from the most peripheral municipalities to those close to the capital, highlighting the interdependent relationship between plains and mountains in particular. It allows to recognise the relationships between ecosystem demand and supply, identifying areas of provision and beneficiaries. Mountain territories play a strategic role in this system: they represent the entire metropolitan area's ecosystem pull, compensating for the impacts generated by the more densely urbanised lowland areas. Mountain areas provide essential regulatory services, demonstrating that ecosystem performance stems from spatial patterns generating a system of spatial interdependencies that are functional for the well-being of the entire metropolitan area.

Compared to the previous version of Simulsoil, which included eight ecosystem models, the ongoing update process aims to release a new version of the application consisting of five models: Carbon Sequestration (CS), Habitat Quality (HQ), Agricultural Production (CPR), Wood Production (TPR) and Sediment Retention (SDR). As these ecosystem models all require Land Use Land Cover (LULC) mapping as their main input data, the update process began with revising this mapping. Additionally, the update to SimulSoil will enable it to be used with QGIS versions 3.0 and above, making it more accessible to users and allowing them to take full advantage of the latest software features.

With reference to mapping, the Piedmont Region periodically produces updates to this cartographic base under the name 'Land Cover Piemonte' (LCP). As SimulSoil was developed using the available LCP base dated 2010, one of the first activities conducted as part of its update was to check how to integrate the latest version of the LCP base 2023 and study their contents to ensure consistency with the previously used LCP base for automating SimulSoil's calculation models.

The LCP 2023 database contains more geometric and descriptive detail than its predecessor, moving from a four-level classification system with 74 classes to a five-level system with 99 classes. Due to this increased detail, we decided not to use the original input data from the SAM4CP project (2014–2018) directly, as this project relied on the 2010 LCP legend. A notable example of this change is the classification of urbanised areas intended for residential use. The 2010 LCP divided these into 8 classes based on building density criteria made explicit through qualifying adjectives (e.g. continuous and dense, medium dense, discontinuous and sparse). The 2023 version, on the other hand, adopts a classification based on zones that are differentiated through percentage thresholds of soil sealing (>80%, 50-80%, 30-50%, 10-30%, <10%) and a specific class for isolated residential areas. The improved detail of the 2023 map base allows for a clearer distinction between input values associated with LULC classes. Despite the advantages of geometric accuracy and descriptive detail, the new LCP base map has some critical structural issues. Notably, despite being derived from high-resolution sources such as the Piedmont Entities Spatial Reference Database (BDTRE), the mapping does not distinguish between buildings and contiguous spaces. This limits the ability to associate specific input values with certain land use types. Additionally, while the adopted LULC classification is inspired by Corine Land Cover (CLC), it introduces descriptive language that partially diverges from the 2010 version. This necessitates the reconstruction of input repertoires. (Giaimo, Pantaloni and Farina, 2025).
The update also involved revising the reference geometries and enriching them with thematic information from various sources, such as the Forest Map, the Regional Landscape Plan, the Agriculture Census, Copernicus data, Piedmont Remote Sensing data and ISPRA land consumption data. We integrated all of this information into the parcels of the Mosaic Cadastral Survey. While this combination of sources enabled the creation of a more robust mapping base, it also necessitated substantial adaptation of the SimulSoil models in terms of content and data structure. In summary, adopting the new LCP base was a pivotal step in ensuring the continuity and reliability of the ecosystem service assessment models implemented in SimulSoil, though it did require significant work to harmonise and update the input data.

4. Methodology: updating the Habitat Quality and Carbon Storage and Sequestration models

This study employs two ecosystem service models—Habitat Quality (HQ) and Carbon Storage and Sequestration (CS)—from the InVEST software suite, integrated into the open-source SimulSoil simulator.

Carbon Storage and Sequestration refers to two distinct regulatory ES, which describe the processes by which carbon is sequestered and stored in soil, subsoil, and surface vegetation. These processes play a crucial role in balancing atmospheric greenhouse gases (Nowak&Crane, 2002). Specifically, the sequestration model quantifies the amount of carbon dioxide removed from the atmosphere by terrestrial ecosystems, while storage indicates the amount of carbon retained in organic form until the plant dies (Larcher, 1975). Therefore, Carbon Storage is linked to the entire life cycle of vegetation, whereas sequestration is generally assessed on an annual basis, corresponding to a single seasonal growth phase (McPherson&Simpson, 1999).

Habitat Quality is a life-supporting ecosystem service and a key indicator for assessing the ecological and environmental status of habitats (Assennato *et al*., 2018). The ecosystem quality index reflects the extent to which biological and genetic diversity, and the evolutionary processes that underpin the regulatory, provisioning and cultural functions of ecosystems, are preserved. Assessing HQ at a local level is essential for understanding the ecological condition of urban areas and identifying critical areas and spaces with potential for increasing vegetation biodiversity. The latter is defined as the variability of all living organisms in terrestrial, aquatic, and marine ecosystems, as well as the ecological complexes of which they form part (ISPRA-CATAP, 2012). In the literature, HQ is recognised as a key proxy value for representing regulatory ecosystem services. Assessing HQ in urban areas is particularly important because the interactions between living organisms and the physical environment generate functional relationships that determine the resilience of ecosystems, their conservation status and their ability to provide other ecosystem services (ISPRA-CATAP, 2012). This issue is becoming increasingly important in European metropolitan areas, where the ability to adapt to climate change is closely linked to the state of ecosystems and their biodiversity. Indeed, high biological diversity increases species' resilience to new environmental conditions induced by climate change (National Biodiversity Strategy, 2010).

In detail, the CS model proposed by the InVEST software and updated within the SimulSoil simulator provides quantitative estimates of the amount of carbon sequestered in soil. The model is based on associating predefined sequestration capacity values with LULC categories. Specifically, the model requires five types of input data in order to provide an output of the quantity of sequestered carbon expressed in tons/pixels. The first input is the map base, which spatially represents the different land uses and land covers. Four values representing the Carbon Storage capacity of the main reservoirs, namely litter, hypogean phytomass and epigeal phytomass, must be associated with the LULC classes. As the model is based on a direct association between these values and LULC classes, it can be considered static, as interactions between different habitats do not influence the output. Consequently, the output represents a strong simplification of the carbon cycle, as neither the plant component nor soil management is considered (Giaimo, Pantaloni and Farina, 2025): for example, agricultural processes that involve ploughing. Therefore, the model's goal is to provide shared and common parameters useful for recognising changes in LULC, rather than absolute data.

The HQ model is also based on LULC base mapping; each class is assumed to represent a different ecosystem. Unlike the CS model described above, the HQ output value calculation algorithm is more complex. The latter assesses the naturalness of land uses according to the spatial distribution of threats to them, such as infrastructure, agricultural areas and built-up areas, by cross-referencing LULC data with information on threats to habitats, including land-use changes, sealing, urbanisation, compaction, salinisation and invasive alien species, which lead to degradation, dystrophy, and the alteration of eco-biological processes. This results in a reduction in ecological resilience and ecosystem fragmentation (Seto *et al*., 2012; Romano&Zullo, 2014). The model operates dynamically, assessing interactions between different habitats and threats, which are also spatially defined within the range of LULC classes available. In detail, the input values needed by the model are seven as follows: the cartographic base of Land Use and Land Cover (on which habitats are defined); the level of naturalness, expressed by a 0-1 index, referred to each habitat; threat factors (LULC classes that determine threat to habitats); the sensitivity value of habitats to recognised threats (0-1 index); the weight associated with each threat (0-1 index); the maximum distance of interaction between threat and habitat (expressed in km); and the decay function of the threat factor in the interaction area (linear or exponential). These input values interact in a complex way to generate a parametric indicator associated with each pixel of the base map. This indicator has a value between 0 and 1 and provides a useful reference for identifying areas that are more or less prone to hosting biodiversity.

The CS model benefits from the higher quality of the updated map base in 2023, as its outputs depend on Carbon Storage values being directly associated with LCP classes. The research team chose to update the Carbon Storage values according to the new classification proposed in the LCP 2023, rather than changing the calculation algorithms proposed by the InVEST software on which Simul Soil relies. Therefore, the methodology adopted in the LIFE SAM4CP project was retraced and, where possible, the input values were updated through literature research. It should be noted that the 2023 LCP classification, particularly with regard to urbanised land, required a more substantial update to the input values concerning the storage data of the four carbon pools. Specifically, no useful bibliography could be found to define such biophysical values for urbanised territory. Consequently, a proxy storage value was adopted for the Meadows LULC class (ISPRA, 2024). This value was weighted by averaging the imperviousness threshold values derived from remote sensing data (Copernicus Sentinel-2), which define and differentiate the various urbanised classes. This is a significant revision, as in the previous version of SimulSoil, it was assumed that all urbanised land was incapable of storing carbon.

The data used to determine the carbon pools in agricultural and natural areas were searched in the bibliography. This update was based on the most recent national and regional databases, which allow Carbon Storage values to be associated with each LULC class.

As for CS, only the input data of HQ model were revised, without modifying the original algorithm. In fact, as previously described, the 2023 LULC base differs from the 2010 version in terms of both geometric accuracy and descriptive content. Consequently, the new LULC base was substituted for the one previously used by SimulSoil. The other input data required for statistical processing by the model were also revised, both to adapt to the new mapping base and to update them in light of new knowledge brought to light by the scientific literature.

5. Results and interpretation of the outcomes

The HQ and CS models produce raster maps which can be represented adopting a colour ramp, ranging from red to green, to display soil ecological and environmental performance levels. These maps therefore offer quantifiable, spatially explicit information, identifying areas, administrative boundaries, and minimum ecological and environmental units.

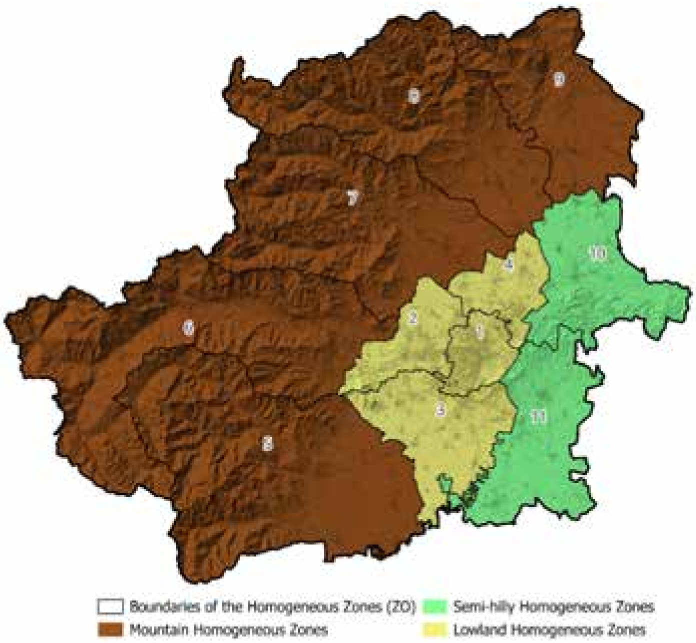

Figure 2 The 11 Homogeneous Zones. Morphological-settlement classification (source: author's elaboration).

Starting from these cartographic outputs, values expressing the average ecological-environmental performance of each OZ has been collected, both for CS and HQ ecosystem services. Doing that, the 11 OZ has been , divided into mountainous, hilly, and plain areas (Figure 2), and the mean ecological value has been compared with the one calculated considering the entire metropolitan territory.

The data illustrated in the two graphs (Figure 3) highlight that mountainous areas are the principal contributors to the ecosystem performance of the CmTo, with semi-hilly and lowland zones playing secondary roles. Among these zones, the highest value was observed in the one that includes the Turin Hill and a complex system of territorial parks and natural areas, with a relatively limited presence of heavily anthropised land uses and covers. In fact, comparing the biophysical values of HZ with those of CmTo helps us recognise which areas of the metropolitan territory contribute most to the territory's overall positive environmental performance. Furthermore, the positioning of the HZ values within the graphs shows that, although the same Land Use And Land Cover have a different contributing capacity in the provision of the two ecosystem services investigated, mountain territories constitute areas where the values recorded are always the highest, as they contain the largest amount of CmTo's natural capital.

Figure 3 From left: average Habitat Quality value per Homogeneous Zone; average Carbon Sequestration value per homogeneous zone (authors' elaboration).

Considering that, the mountainous component of the metropolitan area plays an essential ecosystem role, providing most of the ecological and environmental benefits. However, this does not mean that areas in hilly or flat contexts cannot deliver significant ecological and environmental performance. Nevertheless, analysis at this scale suggests that anthropogenic pressures and the strong presence of urbanised soils in flat and hilly HZs lead to lower ecological and environmental performance being identified. A notable example is HZ number 11, which, despite including part of the Turin hills, exhibits ecosystem values comparable to those in the HZs of the flat terrain.

This example illustrates how both the morphological and settlement structure, as well as the spatial interaction between ecologically functional soils and anthropogenic pressures, shape the ecosystem values observed across the different Homogeneous Zones (HZs).

Importantly, the ecosystem values recorded in the hilly and lowland areas of the CmTo should not be interpreted solely as indicators of environmental degradation. Ecosystem service assessment requires a multi-scalar approach that allows for more nuanced interpretation of results. When analysed at a finer spatial scale, each HZ may reveal sub-areas with varying capacities to deliver ecosystem services.

In this light, the interpretation of biophysical data and maps can provide valuable insights for enhancing ecological connectivity or guiding the restoration of degraded areas.

The results of this study contribute to raising awareness of the critical role of ecosystem services in supporting sustainable metropolitan governance and planning. By applying updated biophysical models within the SimulSoil platform to the Metropolitan City of Turin, we have demonstrated how spatially explicit mapping and analyses of CS and HQ can generate valuable insights into ecological performance and territorial asymmetries. These insights are especially pertinent in a context such as the CmTo, where natural systems, demographic dynamics, and administrative fragmentation intersect in complex ways.

A key contribution of this research lies in its empirical demonstration of the functional dualism between mountainous and lowland areas in terms of ES provision and demand. The analysis shows that mountain territories act as ecological "donors" within the broader metropolitan system, supplying essential regulatory services that are largely consumed or degraded in more urbanised, lowland zones. This spatial imbalance has been acknowledged in the literature but is rarely documented through high-resolution, model-based evidence at the metropolitan scale. In this sense, the study bridges a gap between theoretical insights on territorial interdependencies and applied planning knowledge.

Moreover, the research adds methodological value by demonstrating how open-source tools such as SimulSoil, when appropriately updated and contextualised, can operationalise the ES paradigm in a practical and locally adapted way. While many studies rely on global or standardised model parameters, we show that region-specific data and assumptions can significantly enhance the relevance and credibility of outputs. This contributes to the ongoing debate on the scalability of ES modelling frameworks in diverse planning contexts.

Another important dimension is the articulation of the models with planning-relevant spatial units—namely, the 11 Homogeneous Zones (HZs) defined by the CmTo. By structuring the analysis according to these institutional geographies, we facilitate a potential alignment between ecological knowledge and decision-making boundaries. This is particularly relevant in metropolitan governance contexts marked by fragmentation and asymmetry, where the absence of shared spatial frames often undermines cooperation. Our results suggest that ES assessments can function not only as technical tools but also as discursive instruments for framing territorial challenges and negotiating shared priorities.

Nonetheless, the discussion of results also highlights certain challenges. The models employed, while useful for quantifying ecological functions, do not fully capture the socio-political realities that mediate ES access, governance, and valuation. As such, they must be interpreted as partial representations of complex socio-ecological systems. There is a risk that planners may overestimate the neutrality and objectivity of model outputs, or fail to integrate local knowledge and stakeholder perspectives into subsequent decision-making processes. For this reason, we stress the importance of combining model-based assessments with participatory approaches and qualitative investigations.

From a broader perspective, this study reinforces the relevance of ES-based planning in the face of global challenges such as climate change, biodiversity loss, and socio-territorial inequalities. Mountain regions, often peripheral in administrative and political terms, emerge here as central actors in ecological resilience and territorial sustainability. Recognising this role has profound implications for how resources, responsibilities, and planning competences are distributed across metropolitan systems.

This discussion underscores both the promise and the limits of ES modelling in metropolitan planning. The evidence presented here supports the call for more integrated, systemic, and evidence-based approaches, while also recognising that such transitions are not purely technical but institutional and political. The path forward will require not only better models but also new forms of governance, interdisciplinary collaboration, and shared ethical commitments to territorial equity and ecological integrity.

6. Limitations and potential of ES models and updating

Although the SimulSoil tool—based on updated InVEST models—represents a promising methodology for mapping and analysing ES in metropolitan contexts, it is important to acknowledge a number of limitations that constrain its current effectiveness and applicability. A critical appraisal of these issues is essential not only for scientific transparency but also to pave the way for future refinement and operational use of the tool in planning practice. A first limitation concerns the quality, classification criteria, and temporal resolution of the land use and land cover (LULC) datasets used as input. The 2023 LCP dataset represents a substantial improvement over previous versions, particularly in terms of thematic detail and spatial resolution. However, several issues persist. Certain land cover categories remain too generalised to capture the heterogeneity of real landscapes. For example, the classification of “forest” does not distinguish between mixed deciduous forests, coniferous stands, or agroforestry systems—each of which has different ecological functions and capacities for Carbon Storage or biodiversity support. Similarly, cropland areas are treated as homogeneous blocks, even though the ecological impact of monoculture maize fields differs markedly from that of organic or polyculture farming.

Moreover, the data used represent a static snapshot in time. The ES models assume that the landscape remains unchanged throughout the analytical period. This limitation may lead to distortions in dynamic contexts where land use is rapidly evolving—whether due to urbanisation, abandonment, natural succession, or policy-driven transformations (e.g., greening subsidies, forest incentives, agricultural zoning changes). As such, the outputs should be interpreted with caution when applied to medium- or long-term planning decisions.

Second, while the visual outputs of the models are spatially detailed and potentially useful for communication and decision-making, their uptake into planning and governance frameworks remains limited. Most municipal planning offices, particularly in smaller or mountainous areas, lack the technical skills, GIS infrastructure, or staff capacity needed to interpret and operationalise model results. Furthermore, the legal and procedural frameworks that govern spatial planning in many regions—including Piedmont—do not yet mandate or structurally integrate ES consideration. Without institutional anchoring, the models risk being perceived as optional or academic exercises, rather than as actionable tools.

Third, the models operate under assumptions that may not hold in every local context. For example, the InVEST Habitat Quality model assumes that all threats act linearly and that their impacts diminish with distance according to fixed decay functions. In complex urban-rural landscapes, these relationships may be more nuanced: some infrastructure corridors may have disproportionate ecological impacts due to edge effects or barrier functions, while others may support biodiversity if managed appropriately (e.g., green railway verges or low-traffic rural roads). Customising these decay functions and threat-response parameters requires detailed local knowledge and empirical data, which are not always available or incorporated.

Despite these limitations, the updated SimulSoil framework also exhibits substantial strengths and potential. From a technical standpoint, its open-source architecture allows for continuous improvement, localisation, and user-driven modification. The model is compatible with most GIS environments, can be run on ordinary hardware, and does not require proprietary software licenses—making it particularly suited for application in low-resource settings. The use of regionally specific data and parameterisation increases its contextual relevance, while its transparent structure enhances scientific credibility and reproducibility.

From a policy perspective, the tool offers several advantages. It enables planning authorities to move beyond abstract sustainability goals and base their decisions on spatially explicit evidence. For example, the model can be used to identify ES-rich zones that should be protected, or to detect ecological deficits in peri-urban areas where restoration is needed. It supports inter-municipal dialogue by offering a shared visual language and baseline for territorial coordination. Furthermore, by making the spatial interdependencies between upland ES providers and lowland beneficiaries visible, the model can support the development of compensation mechanisms, ecological fiscal transfers, or co-management agreements.

7. Conclusions

The results of this study confirm the strategic ecological role of mountain territories in the Metropolitan City of Turin, particularly in their capacity to provide Carbon Storage and habitat-related ecosystem services. The updated implementation of SimulSoil, based on high-resolution land cover data and spatially explicit modelling, has proven to be an effective tool for supporting evidence-based planning in complex metropolitan contexts.
The case study demonstrates that digital tools and open-access geospatial datasets can significantly improve the quality and accessibility of ecosystem service assessments. However, their integration into institutional planning processes remains limited. Bridging the gap between knowledge production and governance requires embedding these models into planning instruments through legislative frameworks, technical guidelines, and training for local authorities.

The ecosystem services paradigm offers a robust lens through which to understand ecological conditions and flows across heterogeneous territories. Importantly, this approach does not replace other forms of territorial analysis, but complements them by providing a shared methodological foundation based on data produced by institutional actors such as Regione Piemonte and the Metropolitan City of Turin. In this sense, the continued updating and application of SimulSoil is not only useful but necessary, ensuring that planning tools remain aligned with current land use dynamics and ecological knowledge.

Furthermore, this study shows that Homogeneous Zones (HZs) should not be interpreted as rigid ecological units, but rather as functional subdivisions that allow for tailored, site-specific planning responses. Their use supports a more integrated reading of metropolitan space, accounting for both ecological function and administrative relevance.

A key insight emerging from this work is the importance of spatial scale. Ecosystem service provision and demand are not evenly distributed, and assessments must be sensitive to variable geographies and territorial configurations. The revised models provide a framework for interpreting such patterns and for informing governance strategies aimed at improving ecological conditions and rebalancing flows between service providers and beneficiaries.

Ultimately, the application of SimulSoil in this context demonstrates the potential of ecosystem service modelling to enhance strategic planning. By offering spatially explicit, scientifically grounded information, this approach contributes to more sustainable, equitable, and context-sensitive territorial governance—particularly in metropolitan regions facing environmental and climatic transitions.

Acknowledgements
It should be noted that in October 2022, the Directorate-General for the Environment of the European Commission sent an official letter of appreciation to the Metropolitan City of Turin (CmTo) for the results achieved through the LIFE SAM4CP project, with particular reference to the SimulSoil tool. The Commission encouraged the continued use and promotion of the tools developed by the project, recognizing their value in supporting land-use planning and management.

In 2023, LIFE SAM4CP was included in the "Knowledge Platform" developed by the Department for Sustainable Development of the Italian Ministry for the Environment and Energy Security, as an example of good practice for the environment and climate, and as an experience to be widely disseminated at both national and local levels.

This paper presents part of the results of the assignment entrusted by the Metropolitan City of Turin to DIST–Politecnico di Torino for the update of SimulSoil. The work was coordinated by Carolina Giaimo (scientific supervisor). Specifically, Sections 1 and 7 are attributed to C. Giaimo; Sections 2, 3, and 4 to G.G. Pantaloni, F. Farina, and A. Nino in equal parts; Sections 5 and 6 were jointly written by all authors

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