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by Barbara Marchetti, Guido Castelli and Francesco Corvaro

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Article

# Evaluation of Environmental Impacts Related to Land Use Modification in the Central Apennines of Italy

**Barbara Marchetti** [1,*], **Guido Castelli** [2] and **Francesco Corvaro** [3]

[1] DISTA, Università degli Studi eCampus, 22060 Novedrate, Italy
[2] Struttura Commissariale Sisma 2016, 00187 Roma, Italy
[3] DIISM, Università Politecnica delle Marche, 60131 Ancona, Italy
[*] For correspondence: barbara.marchetti@uniecampus.it

**Abstract** Land use modification in mountain regions represents a fundamental driver of socio-ecological transformation, reflecting the continuous negotiation between natural processes and human agency. Rather than merely describing degradation or recovery, this study aims to quantify how multiple ecological dimensions interact through land use change, proposing a synthetic framework capable of operationalizing these trade-offs at the landscape scale. While there is a widespread narrative that associates land use modifications with ecological degradation, there is also a growing recognition of the positive role that human activities can play in shaping and sustaining biodiversity. Traditional practices such as transhumance pastoralism, agriculture, and agroforestry have historically contributed to a sustainable management of the territories and to the creation of mosaic landscapes that support a wide array of species and habitats. Within Mediterranean mountain systems, sustainable outcomes have in fact historically arisen from a specific subset of human-land use accommodations that maintain functional heterogeneity, such as rotational agro-pastoralism sustaining nutrient cycling and grassland renewal; terraced and mixed agroforestry systems mitigating erosion and regulating hydrology; low-intensity cropping and mosaic management maintaining edge habitats and pollinator networks. This study investigates the long-term environmental impacts of land use change in the Central Apennines (Italy) from 1950 to 2020. We develop and apply a Composite Environmental Index (ΔEI) integrating five indicators: biodiversity, carbon sequestration, water availability, fire risk, and soil degradation, to assess the ecological effects of landscape transformation. The results show that unmanaged reforestation following land abandonment has led to a net decline in environmental quality (ΔEI = −0.27), particularly in low- to mid-elevation zones, since the gain in $CO_2$ sequestration potential due to increased forest cover outweighed by declines in biodiversity, reduced water availability, heightened fire risk, and marked soil degradation. Spatial heterogeneity is significant: while carbon storage improved, negative trends in biodiversity and ecosystem function dominate. It also outlines that passive rewilding strategies may be insufficient in historically managed landscapes in comparison with active, context-specific management aligned with Nature-based Solutions. The ΔEI framework offers a replicable model for integrated land planning and ecological restoration in Mediterranean mountain systems. Recognizing that both extractive intensification and complete abandonment disrupt the ecological equilibrium allows us to distinguish between adaptive and maladaptive pathways of landscape evolution, a key step toward generalizing lessons beyond the Apennine context.

**Keywords** land use change; environmental impact; composite index; rewilding; Mediterranean mountains; cultural landscapes; Nature-based Solutions

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## 1. Introduction

The effect of human activities in fragile ecosystems has been widely addressed, and it still presents controversial views. There are many papers emphasizing the negative ecological effects of anthropogenic interaction, particularly in mountainous and peripheral regions [1,2] as well as many others that recognize both the threats and potential ecological benefits associated with human-managed landscapes.

The abandonment of marginal rural areas has been interpreted by some as beneficial for ecosystem recovery, primarily through reductions in agricultural intensity, livestock pressure, and pollution. Such dynamics are often associated with improvements in water quality, reforestation, and a decline in erosion processes [3–6]. These developments have informed large-scale rewilding strategies aimed at restoring ecological processes and reducing human impact across Europe's less populated regions [7].

However, the unmanaged reforestation of historically managed cultural landscapes is increasingly contested. In regions such as the Central Apennines, landscapes have co-evolved with centuries of agro-pastoral activity. The sudden removal of these human-environment interactions can lead not to ecological recovery, but to new forms of ecological degradation. Dense forest regrowth on previously managed pastures and fields has caused landscape homogenization, a sharp reduction in open habitat availability, and the decline of grassland-dependent and edge-dwelling species [8–10]. The abandonment of those areas can also contribute to the accumulation of highly flammable biomass, leading to wildfire and the colonization of invasive species [11–13].

The loss of traditional land-use practices has also direct consequences related to hydrological aspects due to the abandonment of land by local communities, causing the collapse of the terrace systems and drainage infrastructures that they once maintained, leading also to increased surface runoff, soil erosion, and downstream sedimentation [14,15]. The consequences of impacts on overall watershed instability are increased by the steep mountain environments of the Apennines.

It is also important to consider that the rewilding process needs adequate planning and the engagement of the communities living in the territory to avoid the creation of a vast wild space with no cultural, ecological, or economic functions. This loss of landscape functionality not only affects biodiversity but also degrades cultural heritage, traditional knowledge systems, and rural tourism potential [16].

Conversely, human presence, if organized around sustainable, low-impact practices, can play a crucial role in maintaining ecosystem functionality. Forestry and agro-silvo-pastoral systems, when properly managed, contribute to landscape diversity, soil protection, fire prevention, and biodiversity enhancement [17,18]. For example, thinning operations and controlled grazing reduce understory biomass and fire risk while promoting habitat heterogeneity [19]. Similarly, rural tourism, extensive livestock grazing, and traditional land stewardship practices can support ecological restoration goals while preserving local livelihoods and cultural landscapes [20].

A very good example of positive interaction between humans and the environment is found in the Plain of Castelluccio di Norcia, where farmers have cultivated lentils for many decades, contributing significantly to the preservation and enhancement of local biodiversity. Traditional and low-intensity agricultural practices are characterized by minimal use of synthetic fertilizers, crop rotation, and suitable fallow periods; together with the maintenance of heterogeneous landscape structures, it has supported the development of a wide range of plant and animal species. This approach, carried out for many years, has resulted in the creation of an ecosystem that allows pollinators, ground-nesting birds, and other fauna to thrive, particularly during the spring and early summer flowering period, due to the great floral diversity in the fields. Given these dynamics, public policies targeting inner areas should not treat land abandonment as a neutral or ecologically beneficial process. Instead, they must recognize the value of maintaining human-managed landscapes through community-based land use strategies, economic incentives, and participatory planning. Inaction or unplanned rewilding can lead to long-term degradation of ecosystems and landscapes. Therefore, proactive intervention is required to preserve both biodiversity and the social-ecological resilience of mountain regions such as the Central Apennines [21,22].

This territory, as many others in rural Europe, has indeed experienced, in the last decades, a significant abandonment of traditional land-use practices with a consequent change in the region's ecological equilibrium and cultural identity. The decline of rural populations promoted a wide forest regrowth where agricultural and pastoral lands have been left unmanaged [23]. If the reforestation process could be beneficial to increase carbon sequestration, it also has many negative ecological effects, such as the overall reduction of biodiversity due to the disappearance of open habitats that contribute to a significant decline of species reliant on semi-natural grasslands and patchy, mosaic landscapes, reducing overall biodiversity. Another side effect is the increased vulnerability of abandoned lands to invasive plant species and the risk of wildfire due to uncontrolled fuel accumulation and the absence of human intervention. Additionally, the loss of active land management has exacerbated hydrological imbalances, with increased surface runoff and erosion contributing to soil degradation and affecting downstream water quality [24]. These environmental challenges underscore the importance of sustaining active, low-impact human presence as a cornerstone of landscape and biodiversity conservation in the Apennines.

The term "rewilding" in this study specifically refers to unmanaged ecological succession on abandoned lands, in contrast with planned ecological restoration projects aligned with Nature-based Solutions (NbS). This paper hypothesizes that unmanaged reforestation in the Central Apennines has had a net negative impact on environmental quality when multiple ecological indicators are jointly considered. We test this hypothesis using a composite environmental index constructed from five normalized environmental variables across six time points, from 1950 to 2020.

The paper reconstructs land use dynamics from 1950 to 2020 in the Central Apennines, assesses the multi-dimensional environmental impacts through a synthetic indicator, and provides recommendations for integrated landscape management and NbS-oriented policies in Mediterranean mountains.

## 2. Land Use Evolution in the Central Apennines

In 2021, in the town of Tolentino in the Umbria-Marche Apennines of central Italy, a prehistoric camp dating back to approximately 11,000–10,000 years ago was discovered. It belonged to the early phase of the Mesolithic, the prehistoric period during which the transition to an economy based on agriculture and livestock farming took place, leading to the creation of hunter-gatherer groups [25]. Since then, there has been a continuous evolution trending toward the creation of stable settlements with their related influence on land usage that can be dated back to about 6000 years ago. These early settlers began shaping the ecological characteristics of the area by clearing parts of the local forest to create space for cultivation, initiating an agriculturally based society.

A significant subsequent interaction between humans and this territory was induced by the practice of transhumance, which began in the first millennium BC following the arrival of Osco-Umbrian populations and led to an increase in open areas and the establishment of routes to support the seasonal migration of livestock.

These groups, originating from Eastern Europe and considered the ancestors of the Piceni, Umbri, and Sabelli, settled along the Central Apennines ridge. Despite these changes, the mountain ecosystems remained predominantly forested, even during the flourishing of Umbri and Piceni cultures (500–100 BC) and the subsequent rise of Roman civilization. Land occupation remained stable during medieval times, with some variation due to climate and demographic changes.

After the year 1000, the integration of agro-silvo-pastoral economies with artisanal production led to a period of great prosperity for Apennine populations, leading to the establishment of a more structured relationship between humans and their territory during the Renaissance period, characterized by small villages relying on agriculture and pastoral activities, maintaining a balance between cultivable land and forests.

However, the huge increase in the population in Italy during the 19th and early 20th centuries, which went from 22 million to 47 million inhabitants, led to widespread deforestation and the conversion of pastures into arable land. In mountainous areas, the pressure of overpopulation caused significant soil degradation, prompting the use of a rotational farming system called "maggese", where fields were cultivated for one or two years and then left fallow for four or five years to recover as pastures.

The socio-economic conditions that followed World War II resulted in a dramatic migration from the Mediterranean mountain regions to industrial centers and urban areas. The consequent depopulation of those territories was the primary cause for the conversion of the abandoned lands to forests through secondary succession, altering significantly the landscape and the relative ecological dynamics [26–28].

Other major events that shaped the Italian Apennines are related to the fact that it is the most seismically dangerous area in Europe and, in recent years, has been affected by numerous seismic events of significant intensity that caused significant damage to historical centers, and reorganization of urban structures highly dependent on the demographic and urban dimensions of the municipalities involved. The earthquakes that occurred from 2009 to 2016 affected several important urban centers (L'Aquila 2009; Amatrice 2016; Norcia 2017). Figure 1 represents the seismic crater of the Central Apennines: the list of Municipalities affected by the Earthquakes is reported in Appendix A. For each earthquake, several regulatory measures were issued to define the municipalities concerned, within which the reconstruction processes were defined. The seismic crises of 2009 and 2016–2017 further accelerated the transformation dynamics of the Central Apennines, intensifying both demographic decline and land abandonment already underway in these inner areas. Beyond the physical destruction of the built environment, the earthquakes triggered deep environmental and socio-territorial repercussions, influencing settlement patterns, land management practices, and ecological connectivity. Recent analyses highlight the complex interplay between geological setting, urban morphology, and post-seismic reorganization processes, which often lead to changes in land use and spatial planning priorities. They also illustrate how centuries of adaptive construction techniques have contributed to shaping the landscape's cultural resilience, offering important lessons for sustainable reconstruction strategies that integrate heritage conservation, ecological stability, and community reactivation [29,30]. The effects of the earthquakes directly impacted economic activities, housing stock, and local communities, with indirect effects on the environmental system, including landscape fragmentation, loss of crops and food resources, deteriorating water quality and availability, soil erosion leading to reduced agricultural production, loss or deterioration of natural habitats, and threatened or reduced biodiversity [31–33]. The seismic events have exacerbated the already ongoing population shrinkage, a phenomenon that affects many developed countries but is particularly intense in inner peripheries, covering 80% of rural areas in Europe, where it has become a key social and economic issue. The depopulation of mountain areas, which started in the second half of the 20th century, has now reached a critical crossroads. Globalization and ICT progress have increased the polarization of factors and exacerbated the vulnerabilities of settings poor in market-related territorial capital, although rich in non-market assets. Recently, the slow decline affecting inner areas has been emphasized by exogenous shocks, such as the 2007–2008 Great Crisis and the subsequent recession it caused, the 2009 and 2016–2017 earthquakes, and the COVID-19 pandemic [34,35].

Quantitative analysis confirms that between 1950 and 2020, forest cover expanded by approximately 78% (+7114 ha), while cropland and grassland declined by 48.5% (−3621 ha) and 19.1% (−2982 ha), respectively. Urban and built-up areas increased by 301.5% (+427 ha), while orchards decreased by 29.6% (−622 ha). This shift corresponds to a loss of nearly half of the traditionally managed agricultural mosaic that historically maintained high habitat heterogeneity and ecological functionality in the region.

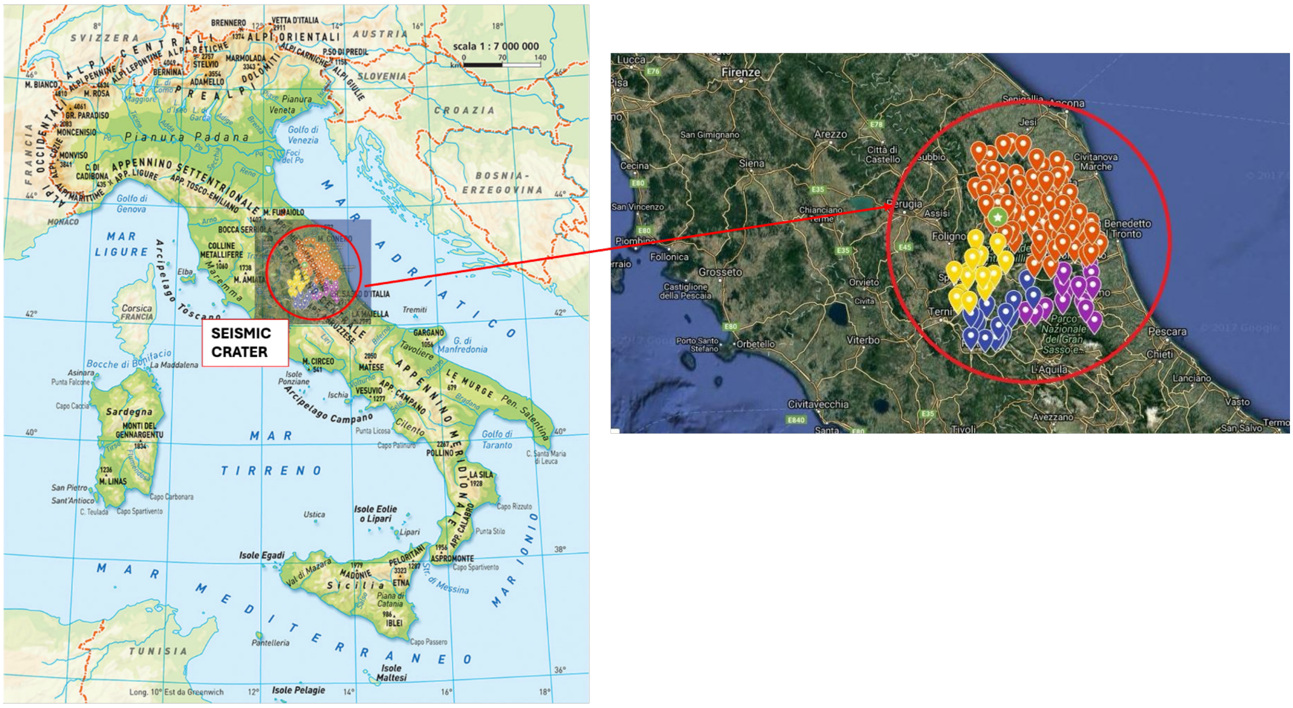


**Figure 1.** The seismic crater in the Central Apennines of Italy.

## 3. Conservation and Adaptation Measures: The Experience of NextAppennino

The measures identified by territorial policies and conservation strategies at the European level, including those aimed at adapting soils to climate change, are predominantly focused on Nature-based Solutions that aim to restore natural conditions through the limitation or absence of human activities. However, this approach may not be effective in contexts such as the Central Apennines, as described in the previous section, where soils, habitats, and species have evolved over millennia under the influence of human presence and land use. Even the recent *Activity Report of the EU Mission on Adaptation to Climate Change* fails to consider the growing evidence that in several European mountain areas, including the Apennines, the resilience of soils and biodiversity is strongly dependent on NbS that are based on traditional, place-based human activities.

A significant case is represented by the post-2016 earthquake reconstruction initiative in the Central Apennines, led by the National Commissioner's Office. Alongside the rebuilding of infrastructure and housing, a broader program was launched to support the active stewardship of these territories, known as "NextAppennino". The program aims not only to support the economic and social recovery of this heavily impacted inner area, as an example, important economic incentives have been made available for public bodies to promote the proliferation of renewable energy through the creation of renewable energy communities (CER) [36,37], but also to promote territorial rebalancing. This is essential in a landscape undergoing a critical transition: from a historically stable human-nature relationship to emerging scenarios in which human presence is declining, and natural resources must find a new equilibrium.

Counteracting land abandonment is thus a key justification for rebuilding villages and settlements destroyed by the earthquake. The NextAppennino program consists of a series of incentives and services grounded in innovation, aimed at supporting economic activities that draw on local skills and resources. Its goal is to ensure stable and lasting territorial stewardship through sustainable processes of transformation and innovation, adding value to local resources and expertise.

The urgency of territorial rebalancing is also dictated by increasingly frequent extreme weather events linked to climate change, which now affect an unprecedented situation in the Apennines: a 70% expansion in forested land use and a 25% decline in cropland and pastures. This new reality has already caused damage and fatalities downstream and in coastal areas, as highlighted in the report of the Technical-Scientific Commission on the extreme weather events of May 2023 in Romagna. The report notes: "Many abandoned forest and agricultural lands have led to reduced ordinary land management and neglect of minor water drainage networks. The resulting increase in forest cover due to land abandonment, contrary to expectations of enhanced vegetation-based hydrological regulation, does not lead to improved outcomes. In unmanaged forests, increased stand density leads to greater competition among trees, reducing mechanical stability (including root anchorage) and increasing mortality. Furthermore, abandonment encourages root-plate overturns, particularly in neglected coppices, and the death of trees and sprouts contributes to debris flow risks, threatening infrastructure along river courses."

The NextAppennino program aims to establish the conditions for active and informed stewardship of these territories through a comprehensive set of interventions and financial incentives. Preventing land abandonment is not merely a moral obligation, linked to the loss of centuries-old cultures, traditions, biodiversity, and landscapes, but is also the only viable strategy for adapting these areas to the impacts of climate change. This is a landscape shaped over millennia by human activity, what the famous Italian poet Giacomo Leopardi once referred to as "artificialized nature", which now risks losing not only its human presence but also the ecosystem balance and services it has provided for centuries [38,39].

## 4. Materials and Methods

A combination of spatial data sources was used to analyze land use change and its environmental impacts across the Central Apennines from 1950 to 2020. Land cover maps were reconstructed for six time points (1950, 1960, 1990, 2000, 2018, 2020) using historical cartography, HILDA+ harmonized datasets, and CORINE Land Cover data [40,41]. The 1950 maps were digitized from IGM topographic sources and validated via local expert interviews and air photo interpretation.

To assess ecological impacts, a Composite Environmental Index ($\Delta EI$) was developed, integrating five key indicators: biodiversity ($\Delta B$), carbon sequestration ($\Delta C$), water availability ($\Delta W$), fire risk ($\Delta F$), and soil degradation ($\Delta S$). Each component was standardized on a 0–1 scale and weighted using the Analytic Hierarchy Process (AHP), with expert input from regional ecologists and planners. Consistency ratios for pairwise matrices were all below 0.1.

$\Delta B$ was calculated using landscape heterogeneity metrics (Shannon Index) and validated with Natura 2000 biodiversity monitoring data [42]. $\Delta C$ estimates were based on IPCC Tier 1 default values calibrated for local forest types using Italian National Forest Inventory growth rates. $\Delta W$ incorporated runoff coefficients linked to land cover, and $\Delta F$ relied on MODIS fire occurrence data and vegetation structure metrics. ΔS was derived from literature-based estimates of erosion risk tied to slope, vegetation cover, and management practices.

Interpolation between years and spatial harmonization were performed via raster resampling and cross-tabulation methods in QGIS and R. Uncertainty was assessed via Monte Carlo simulations on weight ranges.

All data sources and assumptions are detailed in Table 1.

The considered time frame (1950 to 2020) experienced both the progressive abandonment of agropastoral land use and the subsequent spontaneous rewilding of the landscape.

**Table 1.** Data source and assumptions for Composite Environmental Index (ΔEI) parameters.

| Indicator | Data Source | Resolution | Temporal Coverage | Assumptions/Notes |
|---|---|---|---|---|
| ΔB (Biodiversity) | CORINE, HILDA+, Natura 2000 Monitoring, Shannon Index (QGIS) | 100 m | 1950, 1960, 1990, 2000, 2018, 2020 | Landscape heterogeneity as a biodiversity proxy |
| ΔC (Carbon Sequestration) | IPCC Tier 1 Default Factors, Italian Forest Inventory | 100 m | 1950, 1960, 1990, 2000, 2018, 2020 | Broadleaf/conifer adjusted using local biomass rates |
| ΔW (Water Availability) | Runoff coefficients from hydrological literature linked to land cover | 100 m | 1950, 1960, 1990, 2000, 2018, 2020 | Changes linked to vegetation and soil infiltration |
| ΔF (Fire Risk) | MODIS Fire Occurrence Data, Vegetation Metrics | 100 m | 2000–2020 | Fire risk proxy based on drought + fuel build-up |
| ΔS (Soil Degradation) | Slope-Erosion models, Land Management Practices, Literature Estimates | 100 m | 1950–2020 | Terrace abandonment, erosion modeled from slope & vegetation |

Conceptually, the ΔEI was designed not merely as a descriptive index but as a trade-off framework capable of capturing simultaneous gains and losses among environmental components. Each sub-indicator (biodiversity, carbon, water, fire, soil) was normalized and weighted to reflect its contribution to overall ecosystem performance. This formulation enables both temporal comparison and cross-regional transferability: the same structure can be adapted to other Mediterranean, Alpine, or Andean systems by recalibrating weightings to local ecological priorities and data availability. Hence, the ΔEI represents a methodological template for operationalizing sustainability trade-offs where complex interactions among ecosystem services occur.

### 4.1. Land Change Analysis

According to Malandra et al. [43] and based on the integration of data from the HILDA+ and CORINE Land Cover (CLC) datasets, land use changes in the Central Apennines of Italy from approximately 1950 to 2020, expressed by the following categories: pasture, cropland, managed and unmanaged forest, scrubland, urban built up and abandoned land are presented in Figure 2 [44–46].

### 4.2. Environmental Impact Assessment Framework

The change in land use represents a factor that can significantly influence the carbon sequestration characteristics of a territory such as the Central Apennines. If, intuitively, an increase in forested land has the power to improve $CO_2$ sequestration capability, in reality, there are other aspects to be considered to have a reliable picture.

An important factor to account for is the period of time: in order for a forest to act as a significant carbon sink, it must be a mature one since to reach the peak of carbon absorption potential, a tree needs to be often several decades old. The passage from abandoned land to dense mature forests involves a great amount of time during which the net carbon balance can be neutral or even negative due to the decomposition of residual organic matter, such as roots, crop residues, and unmanaged brush, that releases $CO_2$ into the atmosphere.

Another aspect to consider is related to the accumulation of deadwood and flammable material that happens in unmanaged land and significantly increases the risk of wildfires that release vast amounts of stored carbon and compromise the regrowth capacity of forest ecosystems, creating a negative feedback loop. Therefore, unmanaged afforestation often becomes a liability rather than a carbon sink.

Moreover, the change in land cover characteristics can have a significant impact on water availability. Forested landscapes, particularly the dense and unmanaged ones, generally have

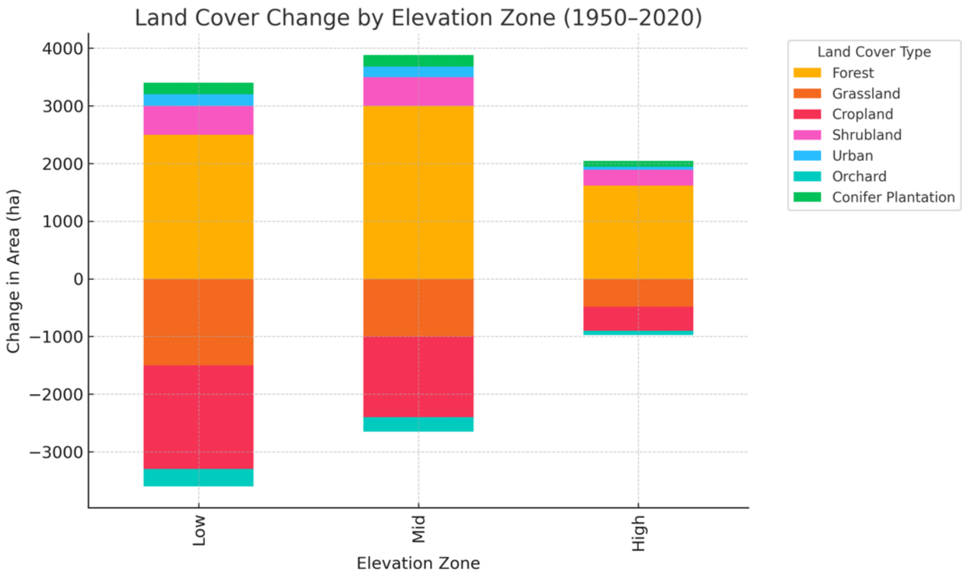


**Figure 2.** Change of land cover by elevation zone in the Central Apennines region between 1950 and 2020.

higher evapotranspiration rates compared to agricultural or pasture lands. This characteristic decreases the recharge of groundwater and streamflow, especially in the Mediterranean area, where summer droughts are intensifying. This effect can reduce the availability of water for agricultural purposes and the related biodiversity that depends on the stability of water sources, in the territories of the Central Apennines, that can also experience seasonal water scarcity.

Finally, the process of land abandonment and unmanaged reforestation produces a certain degree of soil degradation. The decrease of vegetation cover at the beginning of land cover transition exposes soils to erosion by wind and heavy rains that also carry away topsoil rich in nutrients and reduce organic matter content. Compaction from past tillage and the absence of root systems in fallow fields can also impair infiltration, leading to increased surface runoff, sedimentation of waterways, and further loss of fertile soil horizons. Over time, these processes diminish soil structure and fertility, undermining the productivity of both natural and managed systems and limiting the soil's capacity to store carbon and retain moisture.

To include all these aspects in the assessment of the overall environmental impact of land use change, a composite environmental index was developed. This index integrates five key ecosystem parameters:

$$\Delta EI = wb \cdot \Delta B + wc \cdot \Delta C - ww \cdot \Delta W - wf \cdot \Delta F - ws \cdot \Delta S,$$

where:

- ΔB = Change in biodiversity,
- ΔC = Change in $CO_2$ sequestration potential,
- ΔW = Change in water availability,
- ΔF = Change in fire risk,
- ΔS = Change in soil condition (degradation), and
- w = weight for each factor, normalized to reflect ecological relevance in the Central Apennines context.

### 4.3. Proxy Datasets and Methods for Environmental Indicators

To quantify the environmental impact of land use change in the Central Apennines, we used proxy datasets and established methodologies for each environmental indicator. These were selected based on scientific robustness, regional applicability, and consistency with previous studies in Mediterranean mountain ecosystems.

#### 4.3.1. ΔB—Change in Biodiversity

Biodiversity change was estimated using land cover heterogeneity as a proxy. CORINE Land Cover data from 1990, 2000, and 2018 were combined with historical topographic maps (1950s) and recent Sentinel-2 imagery. We used habitat diversity indices (e.g., Shannon Index) and the proportion of semi-natural versus anthropogenic habitats to infer trends in species richness. This approach was supported by literature highlighting the loss of open habitats and mosaic landscapes in the Central Apennines due to land abandonment. Local field observations and Natura 2000 monitoring reports were reviewed to contextualize biodiversity changes.

The study shows a moderate decline or stagnation due to habitat homogenization (conversion of mosaic habitats into dense forests), loss of open habitats, and species tied to agropastoral land use [21,47].

The value has been established considering the loss of mosaic landscape (meadows, pastures, woodlots) that supports high habitat heterogeneity and a greater number of species from abandonment of agropastoral practices; the reduction of edge habitats, open space specialists, and species tied to human-managed systems from the transition to uniform secondary forest. However, since a complete biodiversity collapse does not occur, some forest species benefit, and recolonization happens. This gives an estimated normalized value reflecting a mild to moderate degradation, $\Delta B \approx -0.3$ (on a scale from $-1$ to $+1$).

#### 4.3.2. ΔC—Change in $CO_2$ Sequestration Potential

$CO_2$ sequestration potential was estimated using IPCC Tier 1 factors for biomass growth and carbon accumulation, calibrated with data from the Italian National Forest Inventory (INFC 2015) [48]. Land cover transitions from pasture to secondary forest were assigned typical sequestration rates (in tC/ha/year) based on forest maturity and dominant species. Delays in sequestration due to forest succession, biomass decomposition, and potential $CO_2$ release from fires were accounted for following methodologies by Luyssaert et al. [49] and Mäkelä et al. [50].

The study shows a slight increase in potential $CO_2$ sequestration from increased forest cover, but is delayed due to forest maturity time lag and biomass decomposition, giving an estimated normalized value, $\Delta C \approx +0.2$.

#### 4.3.3. ΔW—Change in Water Availability

Water availability was assessed using evapotranspiration estimates from MODIS (MOD16 product) and streamflow data from the Italian Hydrographic Service (ISPRA). We incorporated land use data into a SWAT (Soil and Water Assessment Tool) model to estimate runoff and infiltration changes over time. Literature on the hydrological impacts of reforestation in Mediterranean mountains guided the interpretation of evapotranspiration increases and groundwater recharge reductions linked to land abandonment [51–53].

The study shows a moderate decline due to higher evapotranspiration from expanding dense forests and reduced infiltration in unmanaged lands, giving an estimated normalized value: $\Delta W \approx -0.4$.

#### 4.3.4. ΔF—Change in Fire Risk

Fire risk was evaluated using fuel load data derived from Copernicus high-resolution biomass layers and NDVI-based vegetation indices. Historical fire occurrence data were evaluated using the European Forest Fire Information System (EFFIS) [54]. To assess fire risk trends, climatic variables including drought indices and temperature anomalies from the ERA5 dataset were used. The study focused on how fuel accumulation, lack of land management, and climate stress contribute to wildfire susceptibility, as in Moreira et al. [55], showing a significant increase leading to an estimated normalized value, $\Delta F \approx -0.5$.

#### 4.3.5. ΔS—Change in Soil Condition (Degradation)

Soil degradation was analyzed using European Soil Data Centre (ESDAC) erosion risk maps and indicators of organic carbon decline [56]. Areas showing land use transitions from pasture to unmanaged shrubland or dense forest, especially on steep terrain, were associated with increased erosion potential, compaction, and nutrient loss. Soil texture and depth data were obtained from the FAO HWSD-Harmonized World Soil Database, overlaid with LULC trajectories to identify degradation hotspots [57]. Findings were aligned with global erosion assessments by Borrelli et al. [58] and Mediterranean-specific studies.

The study shows a significant increase in erosion risk observed on steep slopes after terrace collapse, combined with significant declines in soil organic carbon following abandonment, giving an estimated normalized value, $\Delta S \approx -0.6$.

4.4. Weight Assignment (w)

Weights were attributed to each component based on their relative ecological and socio-environmental importance in the Central Apennines context. Biodiversity was considered the most critical due to the region's high habitat heterogeneity and endemism. $CO_2$ sequestration and soil condition followed, reflecting the role of forests and soils in climate regulation and ecosystem functioning. Water availability and fire risk were included as key disturbance and resource stress factors, particularly under climate change.

## 5. Results

The analysis of data derived from the HILDA+ and CORINE Land Cover datasets in the Central Apennines reveals a marked transition in land use patterns over the 70-year period (1950–2020), with notable acceleration following the 2016 earthquake. Forest cover has increased by 78.0% (+7114 ha) and agricultural land has decreased significantly, grasslands by 19.1% (−2982 ha) and croplands by 48.5% (−3621 ha). Urban areas tripled (+301.5%), while orchards declined (−29.6%) and conifer plantations expanded by 47.9%. Notably, shrublands exhibited a 125.4% increase, indicating transitional successional dynamics (Figure 2).

The reasons behind this transformation have been found in the rural depopulation that, together with demographic crisis, has led to land abandonment with the consequent spontaneous rewilding processes across the landscape.

These land use dynamics resulted in a composite environmental impact (ΔEI) of −0.27, signaling a net degradation when integrating biodiversity, carbon, water, fire, and soil indicators. While ΔC (carbon) improved due to increased forest biomass, ΔB (biodiversity) and ΔS (soil) declined markedly. ΔB suffered from landscape homogenization, while ΔS reflected erosion linked to abandoned terrace systems and unmanaged slopes.

ΔF (fire risk) showed moderate deterioration, particularly in areas where fuel accumulation and climate-driven drought conditions co-occur. ΔW (water availability) declined due to changes in evapotranspiration regimes and altered infiltration following forest expansion into former grassland and cropland areas.

Spatial analysis highlights heterogeneity across elevation bands: low- and mid-elevation areas suffered greater ΔEI losses, while high-altitude areas showed modest improvement or stability. These differences underscore the need for zone-specific policy interventions.

The synthetic index (ΔEI) correlates well with the mapped ecological conditions, validating its use as an integrative assessment tool. However, its limitations include the exclusion of socio-economic indicators and reliance on proxies for biodiversity and soil degradation.

Weights were assigned to each parameter to reflect their ecological and socio-environmental relevance in the Central Apennines: biodiversity (0.30), $CO_2$ sequestration (0.25), and the remaining three factors, water availability, fire risk, and soil condition, each received a weight of 0.15 (Table 2). The weighted contribution is reported in Table 3 and shown in Figure 3.

**Table 2.** Weight assignment for Composite Environmental Index (ΔEI) parameters.

| Component | Symbol | Weight |
|---|---|---|
| Biodiversity | wb | 0.30 |
| $CO_2$ Sequestration | wc | 0.25 |
| Water Availability | ww | 0.15 |
| Fire Risk | wf | 0.15 |
| Soil Degradation | ws | 0.15 |

**Table 3.** Weighted contribution of the different parameters.

| Component | Δ Value | Weight | Weighted Contribution |
|---|---|---|---|
| Biodiversity | −0.30 | 0.30 | −0.09 |
| $CO_2$ Sequestration | +0.20 | 0.25 | +0.05 |
| Water Availability | −0.40 | 0.15 | −0.06 |
| Fire Risk | −0.50 | 0.15 | −0.08 |
| Soil Degradation | −0.60 | 0.15 | −0.09 |
| TOTAL | | 1 | −0.265 |

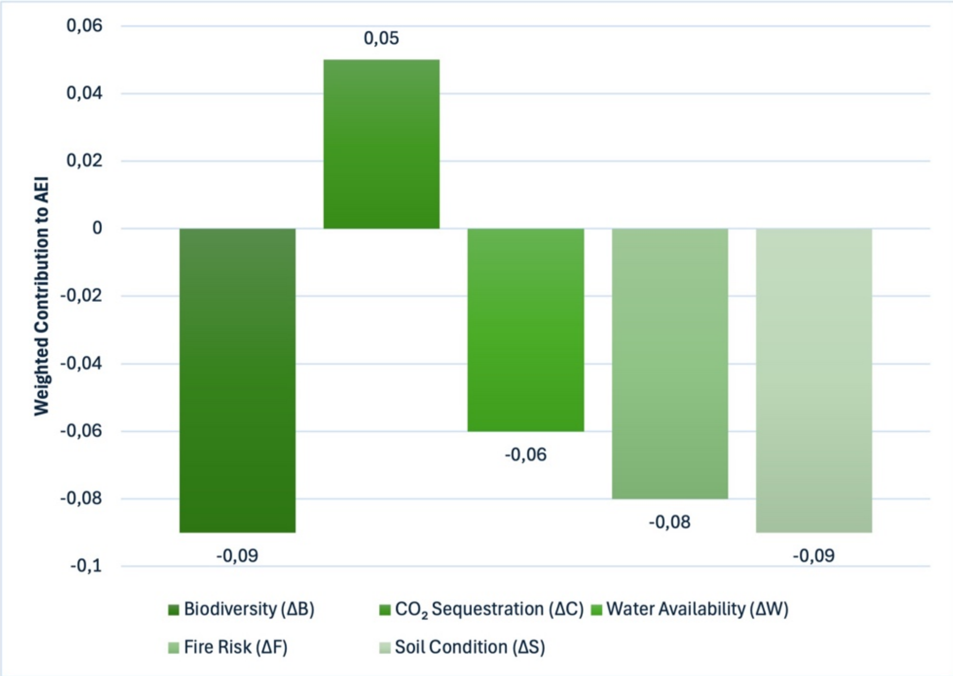


**Figure 3.** Environmental impact components (Composite ΔEI = −0.265).

The composite index ΔEI thus captures a net negative environmental impact of land use change, driven largely by unmanaged transitions that, while increasing forest cover, introduce new ecological vulnerabilities.

Policy implications call for hybrid strategies combining passive rewilding with active management, grazing, controlled burning, and agroforestry, to maintain semi-open habitats and biodiversity. The findings align with EU Nature-based Solutions principles but emphasize the role of culturally adapted practices in Mediterranean mountains.

Comparison with other European mountain systems (e.g., Pyrenees, Sierra de Gredos) confirms that land abandonment alone is insufficient to restore ecological integrity. Co-produced management strategies are essential to achieve resilience and multifunctionality in post-agricultural landscapes.

The outcomes of the ΔEI assessment hold direct operational relevance for the sustainable reconstruction of the seismic crater in the Central Apennines. By spatially identifying areas where unmanaged rewilding has caused a net environmental decline, the index provides an evidence-based foundation for territorial planning within the NextAppennino framework. It enables policy makers and local administrations to prioritize interventions aimed at restoring landscape functionality—such as controlled grazing, agroforestry, and terrace recovery—while enhancing ecosystem services critical to climate adaptation.

Integrating the ΔEI approach into reconstruction policies can thus facilitate a shift from reactive restoration to proactive landscape management, ensuring that rebuilding efforts not only recover physical infrastructure but also strengthen ecological resilience and the cultural identity of mountain communities. The index can be operationalized within local planning instruments, guiding investments under the National Recovery and Resilience Plan (PNRR) and cohesion policy measures to foster long-term sustainability in earthquake-affected territories.

### 5.1. Broader Implications and Transferability

While the ΔEI results are grounded in the Central Apennines, the analytical logic is generalizable to other mountain territories undergoing demographic and land-use transition. The observed dominance of unmanaged reforestation and consequent environmental decline illustrates a broader Mediterranean paradox: increased naturalness does not always correspond to improved ecological functionality.

Application of the ΔEI to other contexts could support scenario analysis under different land management regimes, such as active grazing reintroduction, selective forest thinning, or terrace restoration, quantifying their multi-criteria impacts on carbon, water, and biodiversity. By translating qualitative trade-offs into a quantitative composite score, the ΔEI can assist planners in evaluating competing land-use strategies, aligning them with regional adaptation and resilience policies.

### 5.2. Spatial Variability of ΔEI and Policy Relevance

The application of the ΔEI index to sub-areas within the Central Apennines reveals a clear spatial differentiation of environmental performance. The northern sector (Umbria–Marche ridge) shows moderate degradation (ΔEI ≈ −0.18), linked mainly to land abandonment and reduced grazing. The central sector, encompassing the 2016–2017 seismic crater (Norcia–Amatrice–Arquata), records the lowest ΔEI (≈ −0.31) due to the combined effects of depopulation, unmanaged forest regrowth, and post-seismic disruption of traditional land-use patterns. In contrast, the southern sector (Abruzzo highlands) exhibits partial stability (ΔEI ≈ −0.12) thanks to continued extensive pastoralism and agroforestry management in certain areas.

These results demonstrate that the ΔEI framework can be used not only for global evaluation but also for spatial prioritization of interventions. Sub-areas with the lowest ΔEI correspond to those where active land stewardship, terrace rehabilitation, and controlled grazing should be encouraged as part of post-seismic recovery programs such as NextAppennino. By mapping ΔEI variation, local governments can identify where environmental investments are most urgently needed and coordinate ecological restoration with socio-economic revitalization measures.

## 6. Discussions and Conclusions

This study demonstrates that long-term land use change in the Central Apennines, characterized by demographic crisis, earthquakes, and depopulation that happened in the period between 1950 and 2020, has greatly influenced the ecological equilibrium of these territories and resulted in spontaneous rewilding processes leading to substantial ecological transformations, many of which are detrimental when assessed through a synthetic composite index (ΔEI).

Through the ΔEI index that accounts for biodiversity, carbon sequestration, water availability, fire risk, and soil condition, it was possible to assess a net negative environmental impact (ΔEI ≈ −0.27). Despite a modest gain in $CO_2$ sequestration potential due to increased forest cover, this benefit is surpassed by declines in biodiversity, reduced water availability, higher fire risk, and more intense soil degradation. The homogenization of the traditional agroecosystem's mosaics into unmanaged forest and scrubland has reduced ecological heterogeneity, decreased habitat quality, and intensified vulnerability to climate change.

The ΔEI framework proved effective in integrating multiple ecological dimensions into a single metric, offering a replicable tool for evaluating land change impacts at the landscape scale. However, its application also revealed important trade-offs and highlighted the limitations of relying solely on natural reforestation as a restoration strategy in historically managed cultural landscapes.

These findings demonstrated the need to complement passive rewilding by active, place-based management practices that preserve open habitats and prevent further homogenization. Integrating grazing, low-intensity farming, and ecological engineering practices within the framework of Nature-based Solutions is essential to achieving environmental and socio-economic resilience in Mediterranean mountain regions.

The study's findings also have strong implications for post-seismic reconstruction and territorial rebalancing policies. The ΔEI framework can assist in identifying zones where ecological degradation and socio-economic fragility coincide, supporting the design of integrated Nature-based Solutions that align with the objectives of the NextAppennino program.

By linking environmental performance to land management trajectories, the index can inform funding priorities, encourage the reactivation of traditional agro-silvo-pastoral practices, and promote the adaptive reuse of abandoned areas as multifunctional landscapes. In this sense, the ΔEI serves as both a diagnostic and a planning instrument for sustainable recovery in the Central Apennines and comparable European mountain systems.

Beyond the Central Apennines, the ΔEI framework offers a replicable analytical structure for other Mediterranean and temperate mountain systems facing similar patterns of rural abandonment and ecological transition. By integrating five key indicators into a unified metric, the approach provides an operational pathway to assess and balance ecosystem service trade-offs. This helps decision-makers to identify where active management is preferable to passive rewilding and to simulate the long-term ecological outcomes of alternative land policies.

The generalizable value of the ΔEI therefore lies not in the specific numerical result (ΔEI = −0.27) but in the method's capacity to convert complex environmental interactions into a transparent and comparable decision-support framework.

From a broader perspective, the ΔEI provides a replicable methodological template for quantifying ecosystem trade-offs in other European mountain systems. Its application to varying scales, regional, municipal, or landscape, allows decision-makers to translate complex ecological data into actionable spatial priorities. The framework thus bridges the gap between environmental assessment and territorial governance, contributing to evidence-based strategies for resilient, multifunctional landscapes.

Future research should expand the ΔEI index to include socio-economic variables and apply the framework to other regions experiencing similar abandonment trajectories.

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**Data Availability**

Data supporting this study are available on request from the corresponding author due to privacy reasons.

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**Author Contributions**

Conceptualization: B.M., F.C., & G.C.; Methodology: B.M.; Formal analysis: B.M.; Data curation: B.M., F.C., & G.C; Writing – original draft: B.M.; Writing – review & editing: B.M., G.C., & F.C.

**Conflicts of Interest**

The authors have no conflict of interest to declare.

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## Appendix A

**List of 140 municipalities affected by the 2009–2016 Earquake.**

### Abruzzo

Barete (Aq); Cagnano Amiterno (Aq); Campli (TE) Campotosto (AQ); Capitignano (AQ); Castelcastagna (Te); Castelli (TE); Civitella del Tronto (TE); Colledara (Te); Cortino (TE); Crognaleto (TE); Fano Adriano (Te). Farindola (Pe); Isola del Gran Sasso (Te); Montereale (AQ); Montorio al Vomano (TE); Pietracamela (Te) Pizzoli (Aq); Rocca Santa Maria (TE); Teramo; Torricella Sicura (TE); Tossicia (TE); Valle Castellana (TE).

### Lazio

Accumoli (RI); Amatrice (RI); Antrodoco (RI); Borbona (RI); Borgo Velino (RI); Cantalice (RI); Castel Sant'Angelo (RI); Cittaducale (RI); Cittareale (RI); Leonessa (RI); Micigliano (RI); Poggio Bustone (RI) Posta (RI); Rieti; Rivodutri (RI).

### Marche

Acquacanina (MC); Acquasanta Terme (AP); Amandola (FM); Apiro (MC); Appignano del Tronto (AP); Arquata del Tronto (AP); Ascoli Piceno; Belforte del Chienti (MC); Belmonte Piceno (FM); Bolognola (MC); Caldarola (MC); Camerino (MC); Camporotondo di Fiastrone (MC); Castel di Lama (AP); Castelraimondo (MC); Castelsantangelo sul Nera (MC); Castignano (AP); Castorano (AP); Cerreto D'esi (AN); Cessapalombo (MC); Cingoli (MC); Colli del Tronto (AP); Colmurano (MC); Comunanza (AP); Corridonia (MC); Cossignano (AP); Esanatoglia (MC); Fabriano (AN); Falerone (FM); Fiastra (MC); Fiordimonte (MC); Fiuminata (MC); Folignano (AP); Force (AP); Gagliole (MC); Gualdo (MC); Loro Piceno (MC); Macerata; Maltignano (AP); Massa Fermana (FM); Matelica (MC); Mogliano (MC); Monsapietro Morico (FM); Montalto delle Marche (AP); Montappone (FM); Monte Rinaldo (FM); Monte San Martino (MC); Monte Vidon Corrado (FM); Montecavallo (MC); Montedinove (AP); Montefalcone Appennino (FM); Montefortino (FM); Montegallo (AP); Montegiorgio (FM); Monteleone (FM); Montelparo (FM); Montemonaco (AP); Muccia (MC); Offida (AP); Ortezzano (FM); Palmiano (AP); Penna San Giovanni (MC); Petriolo (MC); Pieve Torina (MC); Pievebovigliana (MC); Pioraco (MC); Poggio San Vicino (MC); Pollenza (MC); Ripe San Ginesio (MC); Roccafluvione (AP); Rotella (AP); San Ginesio (MC); San Severino Marche (MC); Santa Vittoria in Matenano (FM); Sant'Angelo in Pontano (MC); Sarnano (MC); Sefro (MC); Serrapetrona (MC); Serravalle del Chienti (MC); Servigliano (FM); Smerillo (FM); Tolentino (MC); Treia (MC); Urbisaglia (MC); Ussita (MC); Venarotta (AP); Visso (MC).

### Umbria

Arrone (TR); Cascia (PG); Cerreto di Spoleto (PG); Ferentillo (TR); Montefranco (TR); Monteleone di Spoleto (PG); Norcia (PG); Poggiodomo (PG); Polino (TR); Preci (PG); Sant'Anatolia di Narco (PG); Scheggino (PG); Sellano (PG); Spoleto (PG); Vallo di Nera (PG).

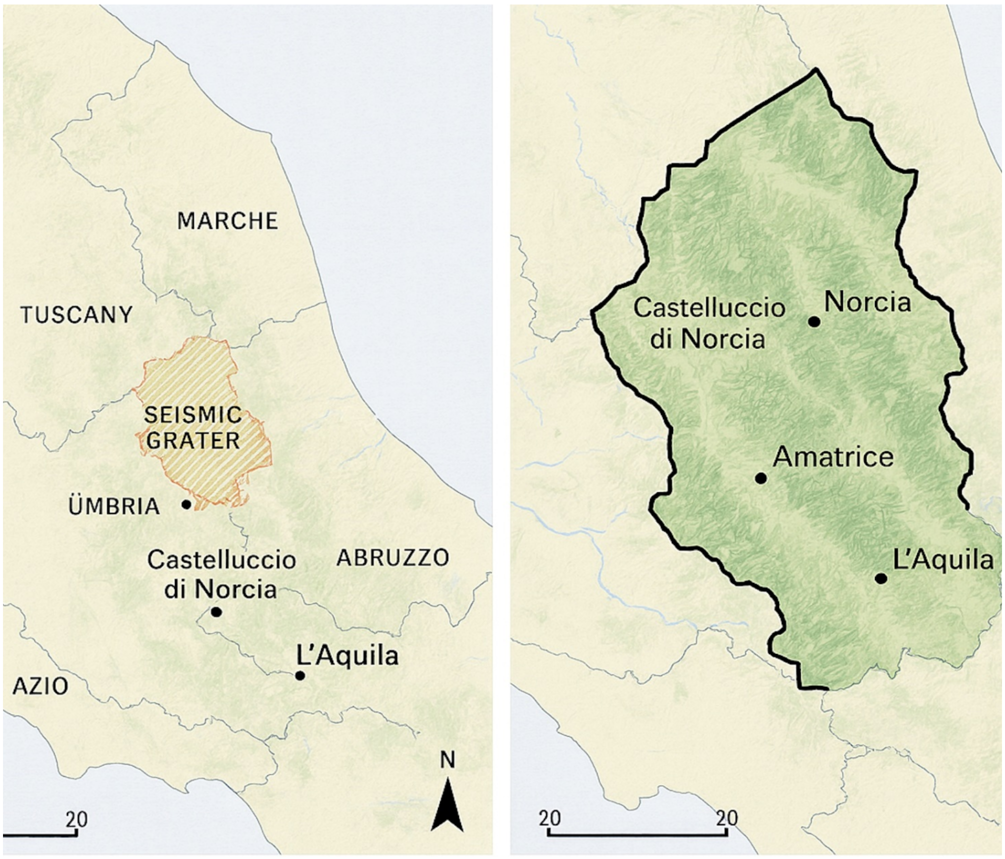


**Figure A1.** Overview of the Central Apennines study area. Left: Regional context map showing the position of the Central Apennines within Italy, including the 2016–2017 seismic crater and key reference toponyms (Umbria, Marche, Lazio, Abruzzo, Castelluccio di Norcia, L'Aquila). Right: Detailed extent of the core ΔEI assessment area, highlighting the municipalities most affected by land-use transition and seismic disturbance (Norcia, Castelluccio di Norcia, Amatrice, L'Aquila). The map provides spatial orientation for the environmental analysis presented in the manuscript.