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Case Report

Desperately Seeking Sustainability: Urban Shrinkage, Land Consumption and Regional Planning in a Mediterranean Metropolitan Area

Luca Salvati [1], Agostino Ferrara [2], Ilaria Tombolini [1,*], Roberta Gemmiti [3], Andrea Colantoni [4], and Luigi Perini [5]

1 Italian Council of Agricultural Research and Economics (CREA), Via della Navicella 2, I-00184 Rome, Italy; E-Mail: luca.salvati@entecra.it
2 School of Agricultural, Forest, Food and Environmental Sciences, University of Basilicata, Via dell'Ateneo Lucano 10, I-85100 Potenza, Italy; E-Mail: agostino.ferrara@unibas.it
3 Department of Methods and Models for Territory, Economy and Finance, Sapienza University of Rome, Via del Castro Laurenziano 9, I-00161 Rome, Italy; E-Mail: roberta.gemmiti@uniroma1.it
4 Department of Agriculture, Forest, Nature and Energy (DAFNE), University of Tuscia, Via S. Camillo de Lellis snc Viterbo, Italy; E-Mail: colantoni@unitus.it
5 Italian Council of Agricultural Research and Economics (CREA), Via del Caravita 7a, I-00186 Rome, Italy; E-Mail: luigi.perini@entecra.it

* Author to whom correspondence should be addressed; E-Mail: tombolini.ilaria@gmail.com; Tel.: +39-06-700-5413; Fax: +39-06-700-5711.

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Abstract: Land degradation has expanded in the Mediterranean region as a result of a variety of factors, including economic and population growth, land-use changes and climate variations. The level of land vulnerability to degradation and its growth over time are distributed heterogeneously over space, concentrating on landscapes exposed to high human pressure. The present study investigates the level of land vulnerability to degradation in a shrinking urban area (Rome, Italy) at four points in time (1960, 1990, 2000 and 2010) and it identifies relevant factors negatively impacting the quality of land and the level of landscape fragmentation. A multi-domain assessment of land vulnerability incorporating indicators of climate quality, soil quality, vegetation quality and land management quality was carried out based on the Environmentally Sensitive Area (ESA) framework. The highest rate of growth in the level of land vulnerability was observed in low-density suburban areas. The peri-urban mosaic formed by coastal woodlands and traditional cropland preserved high-quality land with a stable degree of vulnerability over time. Evidence suggests that the agro-forest mosaic surrounding Mediterranean cities act as a "buffer zone" mitigating on-site and off-site land degradation. The conservation of relict natural landscapes is a crucial target for multi-scale policies combating land degradation in suburban dry regions.

Keywords: Mediterranean basin; land quality; indicators; vulnerability; urban expansion

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1. Introduction

In recent decades, population and economic performance grew rapidly in wealthier countries with a negative impact on both natural landscapes (e.g., forests, shrublands, pastures) and agricultural-specialized areas [1–3]. Human misuse of land generating spatial disparities in environmental and anthropogenic factors is thought to be an important cause of degradation of the land resource base [4], enlarging the ecological gap between peri-urban and rural areas [5]. Environmental degradation depends largely on the synergic impact of biophysical and socioeconomic variables [6] showing complex and difficult-to-predict on-site and off-site dynamics [7]. Interpreting environmental complexity requires conceptual frameworks, theoretical models and empirical analyses supported by up-to-date quantitative (and possibly geo-referenced) information [8–10].

Land degradation (LD) in the Mediterranean region is a clear example of the multifaceted and spatially-varying interaction between the environmental sphere and the socioeconomic system [11]. It corresponds to a long-term loss of ecosystem functions and productivity [2]; the ability to deal with it depends on the technical, economic and human resources of a country, taking into account the fact that "land degradation can only be judged in its spatial, temporal, economic and cultural context" [12]. It is well known how LD processes are changing rapidly over time and space in both direction and intensity [8], reducing the overall quality of land [13] and creating a higher risk of desertification [14].

LD can be temporary or permanent, but even in the former case, degradation processes affect soil, hydro-geological cycles and the whole ecosystem over long periods with negative consequences for the environment [15], depending on the intensity and duration of the cause, site-specific drivers and costs involved in a recovery action. Spatial planning strategies should take into account the difference between passive degradation (derived from the past environmental dynamics and often requiring land restoration) and active degradation, which requires permanent monitoring and control measures [3].

Regional planning is increasingly required to contain the impact of urbanization on soil quality, land fragmentation and ecosystem functioning, e.g., by controlling soil sealing or by limiting land consumption in terms of per-capita built-up area. A soil is considered "sealed" when showing more than 80% impervious surface. This percentage is observed in the case of high-density residential use, while the lowest percentages were identified, according to Nowak and Greenfield [16], for commercial areas (64%), industrial areas (55%), low-density residential uses of land (18%–45%) and, finally, cropland, pastures and forests (<5%). Soil sealing negatively affects the vulnerability of land to ecosystem service loss and flood risk, as a consequence of the decrease in vegetation cover [3,17,18].

While it is difficult to assess land degradation because of the variety of factors shaping it, permanent monitoring is a crucial step when developing control and recovery strategies [19]. This is especially the case for Mediterranean areas characterized by fragile ecosystems showing spatially varying levels of land vulnerability and needing differentiated planning strategies [20–22]. A number of evaluation approaches (both quantitative and narrative) have been proposed to classify land according to the level of vulnerability to degradation in southern Europe [10]. With this in mind, the Environmental Sensitive Area (ESA) procedure, based on a large number of economic and ecological variables, is one of the approaches most frequently used to identify vulnerable land and degradation drivers in the Mediterranean region [23]. Lavado Contador *et al*. [24] and Ferrara *et al*. [25] provided evidence on the reliability of the ESA in monitoring land vulnerability at the local scale.

Using evidence that corroborates previous studies by Portnov and Safriel [5] and Otto *et al*. [26], Barbero Sierra *et al*. [3] argued that suburbanization and urban sprawl expanding into non-urban fringe landscapes are powerful drivers of desertification risk in southern Europe. In most cases, urban sprawl is coupled with rural abandonment or even with the intensification of agriculture leading to fragmentation of the traditional landscape mosaic with the subsequent loss of biodiversity and cultural heritage [21,27]. However, few studies have been devoted to the multi-temporal classification of vulnerable land in agro-forest landscapes at the urban-wildland interface [18].

Salvati *et al*. [28] hypothesized that the recent growth in the level of land vulnerability is distributed heterogeneously over time and space in the Mediterranean region and impacts areas with specific land-use composition and socioeconomic attributes, such as the mixed, agro-forest landscapes surrounding urban agglomerations and especially shrinking cities [29]. At the same time, Le Houerou [30] argued that complex cultivation patterns intermixed with forest patches are one of the most effective land-use classes in containing the expansion of degraded land in the Mediterranean basin. However, Le Houerou's statement was not directly tested at the local scale in anthropogenic contexts with relict agro-forest systems threatened by urban sprawl.

Based on these premises, the objective of the present study is to verify the role of relict agro-forest landscapes as "buffer zones" containing the expansion of vulnerable land to degradation in a shrinking urban region. Although agro-forest landscapes are broadly conceived and defined in different ways, this study focused on traditional rural areas where long-established cropland/pastures and forest/shrubland patches coexist in a dynamic equilibrium affected by urban expansion and anthropogenic pressure [31]. By investigating the dynamics of climate, soil, vegetation and land-use over a long time-interval (1960–2010), a comprehensive assessment of land vulnerability to degradation in Rome, central Italy, was developed over different uses of land (urban, agriculture, forest). The final goal of the study is to identify territorial factors most likely impacting land quality in suburban areas. Four indicators (climate quality, soil quality, vegetation quality and land management quality) were calculated at four points in time (1960, 1990, 2000 and 2010) according to the standard Environmentally Sensitive Area (ESA) framework with the aim of assessing long-term changes in the level of land vulnerability for selected land-use classes. Our results contribute to the understanding of complex spatial patterns of land quality and vulnerability in urban regions, informing, at the same time, the design of conservation strategies for relict agro-forest landscapes as a response to desertification risk in potentially affected areas.

2. Methodology

2.1. Study Area

The present study investigates changes in selected environmental and socioeconomic variables in the Rome metropolitan area, one of the largest urban regions in Mediterranean Europe. The investigated area encompasses the boundaries of the Urban Atlas region (3600 km^2) coinciding with the travel-to-work district around Rome (defined according to the 2001 population census data). A relatively flat topography consisting of 70% lowlands and 30% uplands and widespread urban settlements of various density, contiguity and form characterize Rome's region [32]. The traditional agro-forest mosaic landscape of the "Agro Romano" flat area around Rome—a long-established rural area devoted to cereal, horticulture, olives, vineyard crop and pastures—is preserved especially in the western part of the urban area. Figure 1 illustrates the spatial distribution of three basic uses of land in Rome, indicating the high fragmentation of both natural and agricultural uses of land due to the scattered expansion of residential settlements.

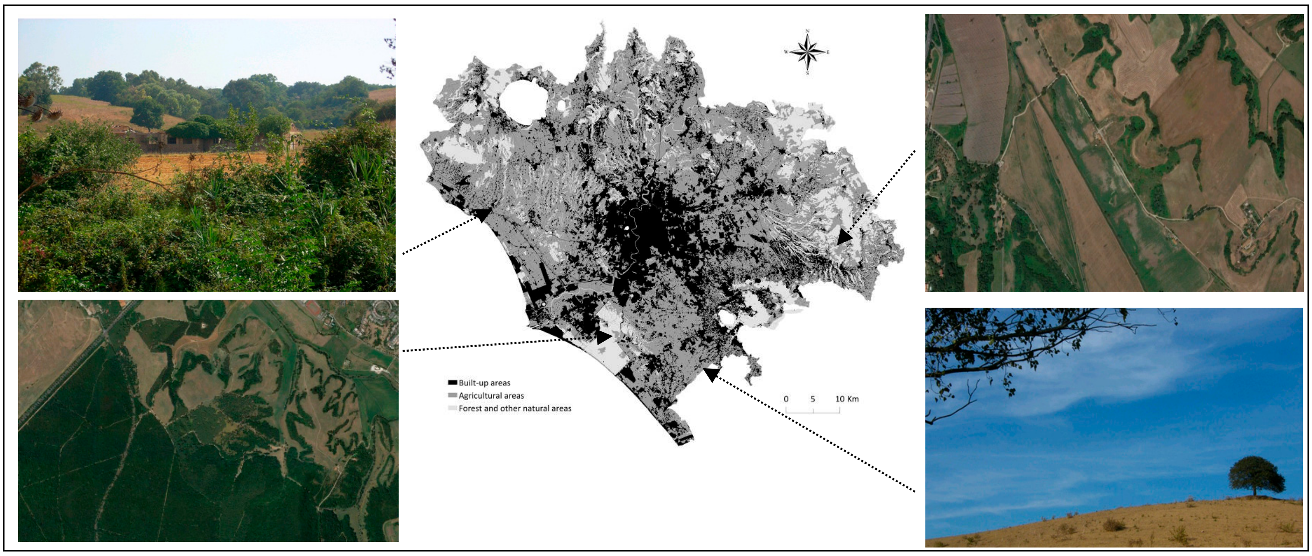

Figure 1. Urban Atlas land-use map (**middle**) of Rome metropolitan area (2008) and selected pictures illustrating the peri-urban landscape around Rome.

The pristine forest vegetation formed by sclerophyllous and mesophilous *Quercus* species, macchia and mixed shrubland intermixed with natural grassland typical of dry Mediterranean landscapes is still conserved in (more or less) isolated patches along the coast and in some inland areas especially around the Bracciano lake. The study area includes Castelfusano-Castelporziano woodland, one of the largest coastal forests in Italy (58 km^2) and threatened by urban sprawl, climate change and soil deterioration driven by sealing, salinization and compaction processes [28]. The climate is typically Mediterranean, with rainfalls concentrated in autumn and spring and mild air temperatures in winter. The average long-term (1961–1990) annual rainfall and mean daily temperature in Rome were 700 mm and 16 °C respectively, with a moderate decrease in rainfall and increased temperatures recorded in the last two decades [32].

2.2. Land-Use Maps

Land-use data were derived from a high-resolution digital map developed as part of the Urban Atlas (UA) initiative in 2008. The UA service offers 1:10,000 land-use maps of European urban areas considering 20 land-use classes based on a simplified Corine Land Cover (CLC) nomenclature. In this study, UA classes were analyzed separately and then aggregated into three basic CLC-first level classes (urban areas, agricultural areas and forests). An additional map scaled between 1:10,000 (urban areas) and 1:50,000 (rural areas) and illustrating land destination prescribed by the most recent master plan enforced in law by each municipality was considered in the present study. The map was recently set up in vector format by the cartographical service of Rome's provincial authority and is freely disseminated to stakeholders. Land destination was classified according to a nomenclature based on nine uses of land: (i) urban dense settlements; (ii) suburban (sparse) settlements to be consolidated into urban areas and brownfield recovery (taken as an indicator of self-contained urban growth); (iii) settlement expansion into non-urban land (areas where construction is allowed on previously non-developed land); (iv) industrial, service and commercial settlements; (v) agro-forest areas with moderate to high land protection regime (including natural land under strict environmental legislation such as national or regional parks); (vi) green urban areas and sport-leisure installations (belonging to already established urban areas); (vii) infrastructures including roads and railways; (viii) mixed human settlements and non-urban uses with moderate land protection regime; and, finally, (ix) out-of-plan rural areas.

2.3. Contextual Indicators

The Environmentally Sensitive Area (ESA) framework was used to evaluate land quality and to identify the spatial and temporal evolution of "critical" and "fragile" vulnerable land to degradation in Rome. Four research domains (climate, soil, vegetation/land-use and human pressure) were evaluated using 14 elementary variables that match a number of requirements including the availability and regularity of time series and the quality and reliability of data sources for each studied variable. The ESA procedure allowed to rank each spatial unit according to a score based on the estimated degree of correlation with LD processes [24]. The weighting system introduced by Bajocco *et al*. [33] was adopted to the specificity of the local context and supplemented with information taken from Salvati *et al*. [10,28], Lavado Contador *et al*. [24] and Ferrara *et al*. [25]. Despite its acknowledged importance as a tool to detect vulnerability of land to degradation, the ESA approach presents some shortcomings: the assessment of the importance of the individual variables or thematic indicators is quite simple [25] and the input variables are oriented towards the in-depth description of biophysical conditions of the area, leaving out some important socio-political and cultural factors [10]. Small changes in the input variables from the original formulation of the ESAI introduced by Basso *et al*. [23] were proposed to overcome the drawbacks mentioned above and to address place-specific factors [10,28,33]. Lavado Contador *et al*. [24] and Ferrara *et al*. [25] demonstrated that the ESA algorithm is rather stable over changes in the input variables.

The outcomes of the ESA model have been extensively validated on the ground [10,23,33]. A specific assessment [24] based on heterogeneous datasets with different reliability, confirms that the

ESA indicators are reliable *proxies* for land quality and vulnerability to degradation in the Mediterranean region [28]. Significant correlations were found between the ESA indicators and a number of soil degradation variables in several Mediterranean sites [23,24,34]. Lastly, Ferrara *et al*. [25] evaluated the stability of the ESA indicators demonstrating that the main output of the model, *i.e.*, the composite index called ESAI, is particularly stable over spatio-temporal heterogeneity in the four elementary components (Climate Quality Index, Soil Quality Index, Vegetation Quality Index and land Management Quality Index).

2.3.1. Climate Quality

The Climate Quality Index (CQI) was based on the average annual rainfall rate (RAIN), the aridity index (ARID: defined as the ratio between long term averages of rainfall and reference evapotranspiration), and slope aspect (SASP). The CQI classifies arid, dry and humid climate types affecting the level of land vulnerability to degradation and was computed through the geometric mean of three elementary variables [24]:

$$\text{CQI} = (\text{RAIN} \times \text{ARID} \times \text{SASP})^{1/3} \quad (1)$$

The selected variables were derived from the Agro-meteorological Database available from the Italian Ministry of Agriculture. The data bank contains data collected since 1951 from about 3000 gauging stations distributed along the whole Italian territory [35]. The reference evapotranspiration rate was calculated through the Penman-Monteith formula [36]. Annual precipitation and air temperatures were regionalized respectively using kriging and co-kriging procedures to ensure a homogeneous and complete territorial coverage. Elevation, latitude and distance to the sea were considered as ancillary co-kriging variables. To assess climatic variations in the area, average precipitation, temperature and aridity index were calculated for distinct time intervals (1951–1960, 1981–1990, 1991–2000 and 2001–2010).

2.3.2. Soil Quality

Soil data were derived from the soil map developed in the DISMED project covering the whole Italy based on the JRC European Soil Database [28]. The “Map of the water capacity in agricultural soils”, developed by the Ministry of Agriculture, and other thematic maps (the ecopedological map realized by JRC, the geological maps of Italy prepared by the Italian Geological Service (Rome), the map of National Land Systems produced by the National Centre of Pedological Cartography (Florence), a 20 m Digital Elevation Model and a 1:50,000 soil map covering Rome and Fiumicino municipalities) were used as ancillary information. As concerns the variability of soil over time, land attributes such as parent material, depth, texture and slope were regarded as static over the investigated time span, because they change slowly and for this reason they are infrequently measured or mapped [10]. According to the ESA methodology, the variables used were soil texture (TEXT), depth (DEPT), slope (SLOP) and parent material (PMAT). A Soil Quality Indicator (SQI) was obtained by computing the geometric mean of the selected variables as follows:

$$\text{SQI} = (\text{TEXT} \times \text{DEPT} \times \text{SLOP} \times \text{PMAT})^{1/4} \quad (2)$$

2.3.3. Vegetation Quality

The influence of vegetation on LD was evaluated through four elementary variables: fire risk (FIRI), vegetation protection (VEGP), drought resistance (DRRE) and plant cover (PLAC) [23]. These variables were derived from the CLC maps produced by the Italian Environmental Protection and Research Institute (Ispra) at different points in time (1990, 2000 and 2006) and from the Corine-like land-use map produced by Touring Club Italiano (1960). Ancillary land-use maps (*i.e.*, the topographic map provided by Italian Istituto Geografico Militare produced during 1949–1962, the agro-forest map set up by the Cartographical Service of Rome's provincial authority for 1974 and the land cover map developed by the Cartographical Service of Latium region for 1999) were used to check for internal coherence in the selected CLC data sources. To classify land at different levels of vulnerability to degradation, a score system was developed ranking each vegetation and land-use type according to the weights proposed by Ferrara *et al*. [25]. A Vegetation Quality Indicator (VQI) was calculated as the geometric mean of the scores assigned to each spatial unit for every selected variable as follows:

$$\mathrm{VQI} = (\mathrm{FIRI} \times \mathrm{VEGP} \times \mathrm{DRRE} \times \mathrm{PLAC})^{1/4} \quad (3)$$

2.3.4. Land Management Quality Index

Anthropogenic pressure was assessed by considering population density and growth and the intensity of the use of land. Population density at the municipal level (PDEN) was determined in 1961, 1991, 2001 and 2011 on data collected on the behalf of National Censuses of Population and Buildings carried out by the Italian National Institute of Statistics [10]. Annual population growth rate (PGRO) was calculated at the same spatial scale for 1951–1961, 1981–1991, 1991–2001 and 2001–2011. Finally, an indicator of land-use intensity (LINT) was obtained by ranking each land-use class based on the intensity of use and potential level of vulnerability to LD [28]. LINT was obtained from elaboration on the four land-use maps previously cited. According to the ESA framework, a partial indicator of land management quality (MQI) was derived by computation of the geometric mean of the three selected variables:

$$\mathrm{MQI} = (\mathrm{PDEN} \times \mathrm{PGRO} \times \mathrm{LINT})^{1/3} \quad (4)$$

2.3.5. A Composite Index of Land Vulnerability

The ESA model evaluates land quality by assessing place-specific conditions predisposing land to potential degradation [33]. Land vulnerability results from a combination of inadequate land management together with a particular set of environmental factors, including soil, climate and vegetation [24]. A composite index quantifying the level of vulnerability to land degradation (ESAI) in each spatial domain was calculated for the *i*-th unit and the *j*-th year (1960, 1990, 2000, 2010) as the geometric mean of the different scores of each indicator as follows:

$$\mathrm{ESAI}_{i,j} = (\mathrm{SQI}_{i,j} \times \mathrm{CQI}_{i,j} \times \mathrm{VQI}_{i,j} \times \mathrm{MQI}_{i,j})^{1/4} \quad (5)$$

The ESAI score ranges between 1 (the lowest level of vulnerability) and 2 (the highest level of vulnerability). Four classes were identified that reflect the most used classification thresholds [10]: (i) areas unaffected by LD (ESAI < 1.17); (ii) areas potentially affected by LD (1.17 < ESAI < 1.225);

(iii) "fragile" areas (1.225 < ESAI < 1.375); and (iv) "critical" areas (ESAI > 1.375). A 1 km^2 grid unit was set up as the minimum spatial domain of both the intermediate and the final maps according to the spatial resolution of the geo-referenced data used in this study [23].

2.4. Spatial Analysis

Following the analytical procedure illustrated above, the average ESAI score was estimated at four points in time (1960, 1990, 2000 and 2010) for each elementary spatial unit. An average score for each of the four partial indicators was calculated by year. The average ESAI and changes over time (1960–2010) in the percent area of each land-use class (see Section 2.2.) were derived from the overlap of the ESAI raster maps (1960, 1990, 2000, 2010) with the UA shapefile on the basis of the "zonal statistics" tool provided with the ArcGIS package (ESRI Inc, Redwoods, CF, USA). This procedure computes a surface-weighted average of the ESAI values belonging to the i-th spatial domain. An average ESAI score was also estimated at each land parcel destined for one of the nine classes of planned use of land by overlapping the ESAI 2010 raster map to the master plan vector map described in Section 2.2.

3. Results

3.1. Spatial and Temporal Distribution of Land Vulnerability to Degradation

Based on trends in the selected indicators reported in Table 1, non-urban land in the Rome metropolitan area experienced a progressive increase in the degree of vulnerability to degradation associated to the expansion of urban settlements—especially low-density, discontinuous settlements. The average index of land vulnerability (ESAI) was higher than 1.375—the threshold identifying highly vulnerable land—over the whole time period. "Critical" areas—covering only 29% of the investigated area in 1960—expanded to 58% in 2010 (Figure 2). The increase in the ESAI was primarily due to anthropogenic pressures related to land management and climate change, as indicated by the specific trends in the MQI and CQI, growing respectively by 8.8% and 7.2%. By contrast, vegetation quality (increasing during 1960–2010) and soil quality contributed less to the ESAI dynamics. Relict natural ecosystems formed a natural belt around Rome with the lowest ESAI values observed in relict forest patches and natural parks.

Table 1. The distribution of selected indicators of land quality and the ESAI composite index in the study area by year.

Variable	1960	1990	2000	2010	% Score Change (1960–2010)
Average ESAI	1.47	1.45	1.48	1.49	1.7
"Critical" Land (%) *	29	43	46	58	–
		Partial Indicators			
Climate Quality Index	1.10	1.16	1.21	1.20	9.1
Vegetation Quality index	1.63	1.69	1.69	1.56	–4.3
Land Management Quality Index	1.80	1.56	1.64	1.72	10.7
Soil Quality Index **	1.47	1.47	1.47	1.47	–

Table 1. *Cont.*

Variable	1960	1990	2000	2010	% Score Change (1960–2010)
			Ratio of Each Partial Indicator to the ESAI		
Climate Quality Index	0.75	0.79	0.82	0.82	7.2
Vegetation Quality index	1.11	1.09	1.07	1.05	–5.9
Land Management Quality Index	1.06	1.06	1.11	1.15	8.8
Soil Quality Index	1.00	1.00	0.99	0.99	–1.7

Note: * Percentage of land with ESAI > 1.375. ** SQI was considered stable over time.

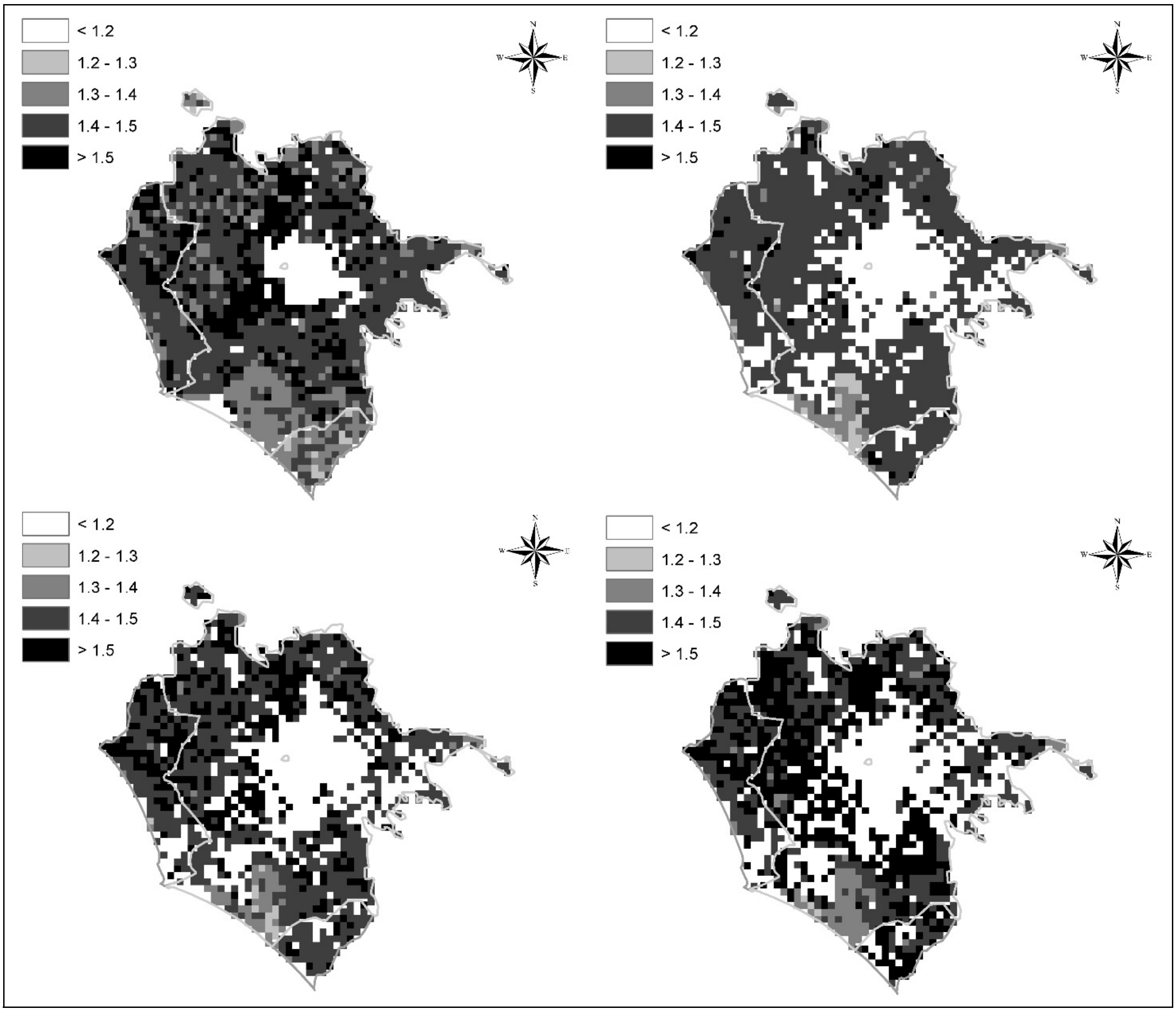

Figure 2. Spatial distribution of the average ESAI score (**upper left**: 1960; **upper right**: 1990; **lower left**: 2000; **lower right**: 2010) in Rome and the surrounding "Agro Romano" flat area (white pixels indicate strictly urban areas not evaluated in the present study).

3.2. Use of Land, Urbanization and Land Degradation

Specific trends in the ESAI score over time by UA land-use class are shown in Table 2. The highest increase in the ESAI between 1960 and 1990 (0.13% per year) was recorded for the class "discontinuous very low density urban fabric". A significant increase in the ESAI was also observed for "discontinuous low density urban fabric", "discontinuous medium density urban fabric" (both 0.07%) and "railways and associated land" (0.11%). During 1990–2000, land vulnerability increased especially for "discontinuous dense urban fabric" (0.20%), "continuous urban fabric" and "discontinuous medium density urban fabric" (both 0.17%). Significant increases in the ESAI were recorded also for other urban uses of land including "railways and associated land" (0.31%), "mineral extraction and dump sites" (0.24%), "airports" (0.21%), "green urban areas" (0.20%), "other roads and associated land" (0.19%) and "industrial, commercial, public, military and private units" (0.17%). During 2000–2010 land vulnerability increased in "discontinuous very low density urban fabric" (0.15%), "discontinuous low density urban fabric" (0.14%) and "isolated settlements" (0.16%). Significant increases in the ESAI were also recorded for "airports" (0.18%), "construction sites" (0.14%), "green urban areas" (0.20%) and "land without current use" (0.47%). These findings suggest that classes with a potentially high environmental value (e.g., "green urban areas" and "land without current use")—but exposed to high real estate speculation due to poorly defined land destination—may undergo dispersed urban expansion with more rapid land degradation than classes with a defined natural or agricultural status (e.g., codes "2000" and "3000").

Table 2. Average ESAI score by year and annual percent change in the ESAI by time interval and Urban Atlas land-use class (2008) in Rome.

Code	Class	Average ESAI Score				% Change †			
		1960	1990	2000	2010	1960–1990	1990–2000	2000–2010	1960–2010
1110	Continuous urban fabric (S.L. > 80%)	1.436	1.443	1.468	1.478	0.02	0.17 *	0.07	0.06
1121	Discontinuous dense urban fabric (S.L. 50%–80%)	1.449	1.445	1.473	1.487	–0.01	0.20 *	0.10	0.06
1122	Discontinuous medium density urban fabric (S.L. 30%–50%)	1.418	1.446	1.471	1.476	0.07 *	0.17 *	0.03	0.08 *
1123	Discontinuous low density urban fabric (S.L. 10%–30%)	1.395	1.426	1.434	1.454	0.07 *	0.06	0.14 *	0.08 *
1124	Discontinuous very low density urban fabric (S.L. < 10%)	1.359	1.412	1.415	1.436	0.13 *	0.03	0.15 *	0.11 *
1130	Isolated settlements	1.408	1.432	1.449	1.472	0.06	0.11	0.16 *	0.09 *
1210	Industrial, commercial, public, military and private units	1.455	1.459	1.484	1.500	0.01	0.17 *	0.11	0.06
1221	Fast transit roads and associated land	1.451	1.448	1.465	1.475	–0.01	0.11	0.07	0.05
1222	Other roads and associated land	1.434	1.422	1.450	1.467	–0.03	0.19 *	0.12	0.05
1223	Railways and associated land	1.403	1.449	1.494	1.455	0.11 *	0.31 *	–0.26	0.08 *
1240	Airports	1.447	1.449	1.479	1.505	0.00	0.21 *	0.18 *	0.08 *
1310	Mineral extraction and dump sites	1.450	1.451	1.486	1.502	0.00	0.24 *	0.11	0.07
1330	Construction sites	1.440	1.448	1.469	1.490	0.02	0.13	0.14 *	0.07
1340	Land without current use	1.415	1.401	1.412	1.478	–0.03	0.07	0.47 *	0.09 *
1410	Green urban areas	1.476	1.442	1.471	1.500	–0.08	0.20 *	0.20 *	0.05
1420	Sports and leisure facilities	1.457	1.451	1.470	1.485	–0.01	0.13	0.10	0.05
2000	Agricultural areas	1.406	1.420	1.439	1.454	0.03	0.13	0.11	0.07
3000	Forests	1.334	1.340	1.354	1.369	0.02	0.11	0.11	0.05

Note: † Annual percent change in the ESAI. * Highest increases in the ESAI percent change by time interval.

When considering the whole study period (Figure 3), land vulnerability increased more in "discontinuous very low density urban fabric" (0.11%), "discontinuous low density urban fabric", "discontinuous medium density urban fabric" (both 0.08%) and "isolated settlements" (0.09%). Significant increases in the ESAI were also observed for the classes "railways and associated land" (0.08%) and "airports" (0.08%). The results indicate how fringe landscapes experienced multiple patterns of land vulnerability and reflect distinct expansion waves in Rome. The highest increase of land vulnerability in areas with medium-low density settlements was observed between 1960 and 1990 while compact and dense urban expansion impacted more the level of land vulnerability during 1990–2000. This decade corresponds with a phase of urban consolidation and settlement re-polarization. The higher impact of discontinuous, very low density residential settlements on the degree of land vulnerability was observed in the last decade, when the city expanded into rural areas with discontinuous settlements (Figure 4). The overall level of land vulnerability increased with sealing rate and the opposite pattern was observed for the rate of growth (1960–2010): the highest rate of growth (1960–2010) in the ESAI was observed for land with <30% impervious land.

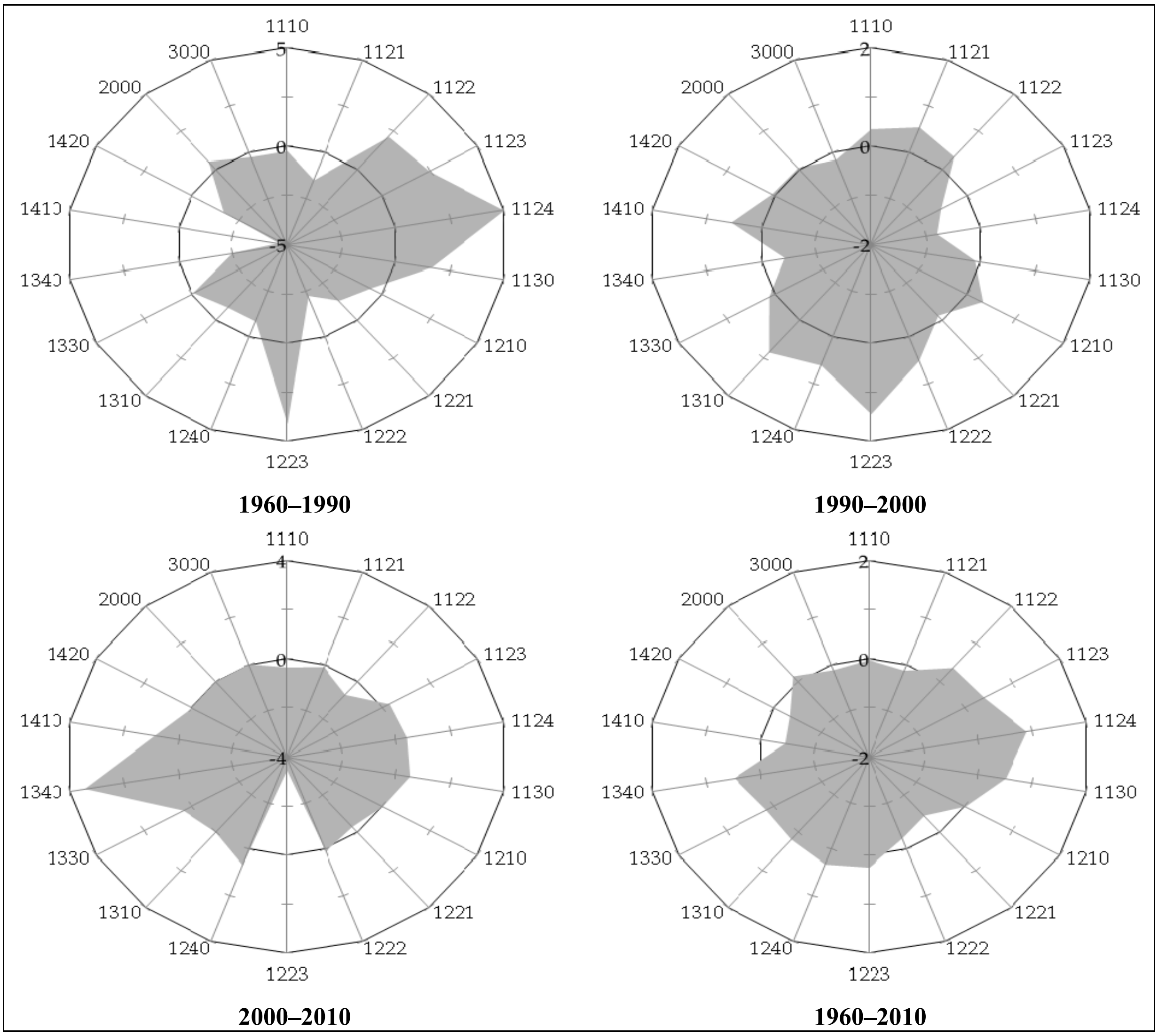

Figure 3. Percent increase in the ESAI by time interval and land-use class (for land-use nomenclature, see Table 2).

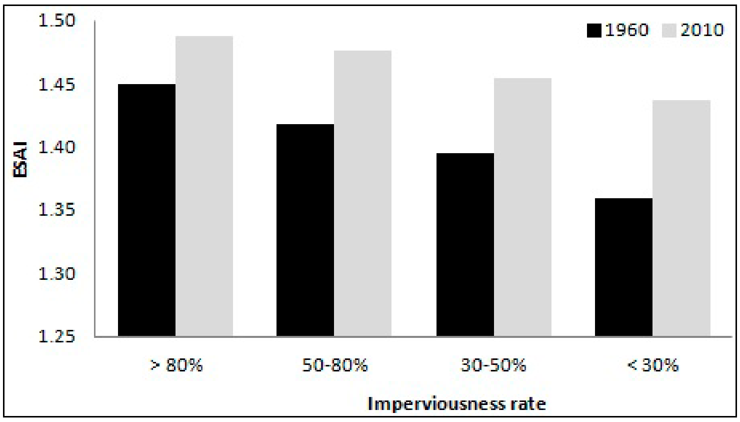

Figure 4. The average ESAI score observed in selected classes of discontinuous settlements with different imperviousness rate by year.

3.3. Urban Planning, Land Destination and Land Vulnerability to Degradation

An assessment of land vulnerability over time was carried out by classifying land according to the planned use. This approach allows investigating latent relationships between (sustainable) land management and land vulnerability to degradation, contributing to design strategies aimed at (i) improving land quality and (ii) containing urban expansion into natural environments. Table 3 shows descriptive statistics for the ESAI (2010) by planned land use.

Table 3. Descriptive statistics for the ESAI score (2010) by planned land destination.

Planned Land Destination	Class Area (%)	Average	Max	CV	Change (%)
Inner dense settlements	0.17	1.375	1.52	0.076	0.06
Low-density urban expansion	2.53	1.418	1.57	0.059	0.10
Mixed-density peri-urban residential settlements	2.72	1.428	1.57	0.054	0.08
Industrial, service and commerce settlements	0.82	1.406	1.54	0.058	0.08
Green urban areas and sport-leisure installations	14.19	1.426	1.60	0.060	0.07
Infrastructures including roads and railways	1.86	1.429	1.62	0.064	0.07
Agricultural and agro-forest areas	63.65	1.379	1.61	0.072	0.05
Mixed zones	13.17	1.366	1.61	0.083	0.05
Out-of-planning rural areas	0.63	1.335	1.58	0.075	0.04

Land parcels belonging to classes such as “mixed density peri-urban residential settlements”, “low-density urban expansion into greenfield” and “industrial, service and commerce settlements”, show a high level of vulnerability (ESAI > 1.4) and the highest observed increase over time (respectively by 0.08%, 0.1% and 0.08%). Land vulnerability increased to a lesser extent for already urbanized areas with sparse voids such as “inner dense settlements” (0.06%). A moderate growth in the ESAI (0.07%) was also observed for “green urban areas and sport-leisure installations” and “infrastructures including roads and railways”. A high land quality with moderate increase over time (around 0.04%–0.05%) was observed for undeveloped “agricultural and agro-forest areas”, “mixed zones”—with restricted construction rights—and “out-of-planning rural areas”. The last two classes require specific measures for land conservation since they are especially exposed to house speculation.

3.4. Convergence in Land Vulnerability Spatial Patterns

As reported in Table 4, which shows the correlation between indicators of statistical distribution (mean, standard deviation and class area) of the ESAI, a process of convergence in land vulnerability occurred within the land-use classes investigated. Natural areas constituted by complex agro-forest mosaics represent a buffer to the expansion of land degradation in suburban areas. The relationship between percent annual change in the ESAI and the average ESAI at the beginning of each time interval (Figure 5) underlines the specific trend observed for forests and, in part, agricultural areas compared with the remaining land-use classes. Taken together, a negative relationship was observed between 1960 and 1990 ($r_s = –0.56$, $p < 0.01$) indicating a process of convergence between land-use classes. This may reflect the fact that high-quality land was mostly affected by medium-density urban expansion along this period. A positive relationship was observed during 1990–2000 ($r_s = 0.52$, $p < 0.05$) with land vulnerability increasing in mostly affected areas. In the last decade, land vulnerability increased irrespective of the initial level of vulnerability ($r_s = –0.05$, $p > 0.05$). Figure 5 finally illustrates the relationship between the growth rate in the ESAI and soil sealing rate in both 1960 and 2010. Differences in the ESAI (1960–2010) were significant but the gap was reduced at higher sealing rates. This finding indicates how fringe land with a low soil sealing rate underwent a higher increase in land vulnerability during the investigated time interval.

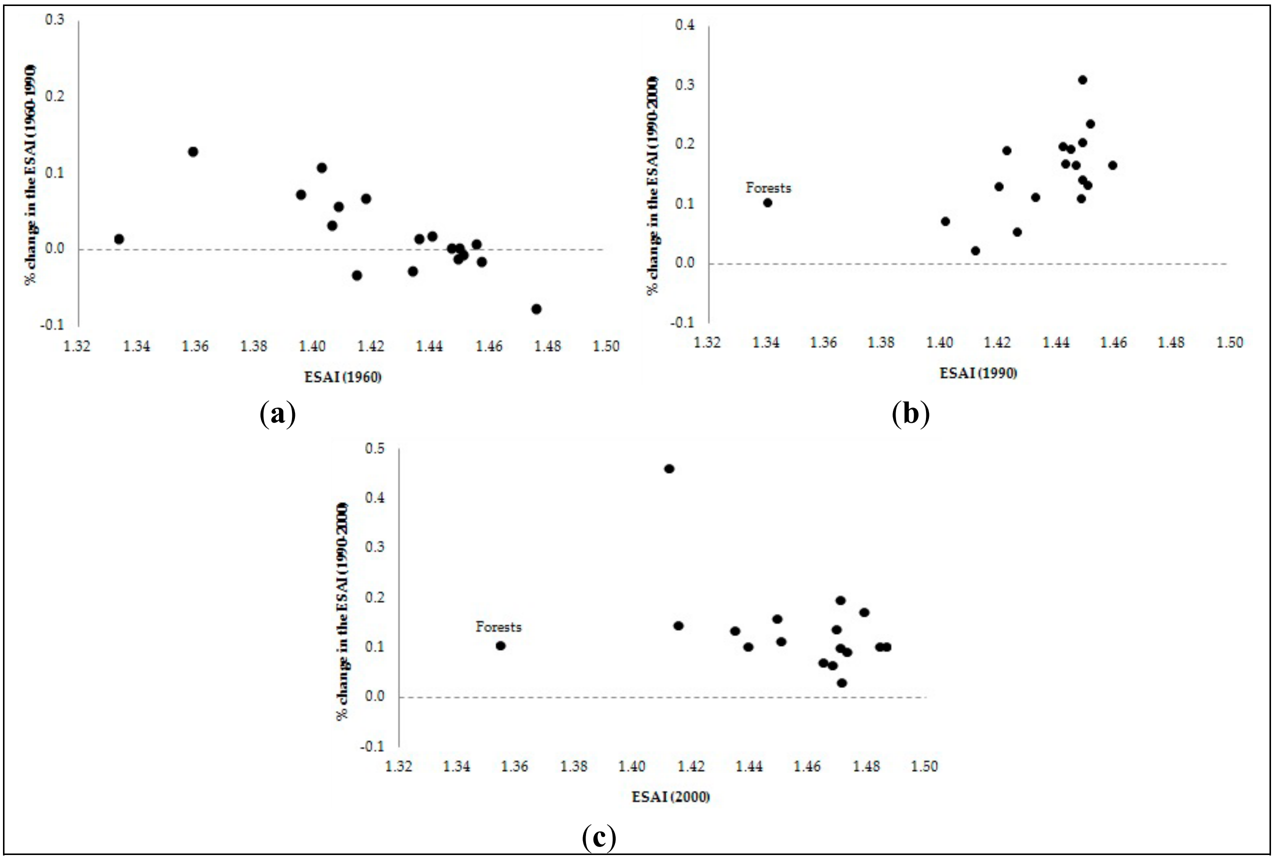

Figure 5. The relationship between percent annual change in the ESAI and average ESAI at the beginning of each time interval in Rome (**a**) 1960–1990, (**b**) 1990–2000 and (**c**) 2000–2010.

Table 4. Pair-wise correlation between the average ESAI and other selected statistical indicators of the ESAI distribution.

	1960	1990	2000	2010
Mean *vs* standard deviation	–0.23	–0.73 *	–0.77 *	–0.69 *
Mean *vs* class area	–0.29	–0.34	–0.32	–0.36
Standard deviations *vs* class area	0.39	0.43	0.44	0.49

Note: * Significant correlation ($p < 0.01$, d.f. = 19) based on Spearman linear correlation coefficient.

4. Discussion

Processes affecting land quality and vulnerability to degradation are regarded as highly dynamic over time and space [37]. Various studies [28,38,39] pointed out the relationship between environmental and socioeconomic variables affecting land degradation, especially for what concerns the Mediterranean region. The approach developed here allows for a multi-temporal assessment of land quality in metropolitan areas, providing comprehensive information to policy strategies combating land degradation. In this context, the ESA framework is well-suited to identify factors responsible for the vulnerability of a given area [23] and to develop future scenarios [24].

Based on the results illustrated in the present study and in previous papers [1,3,5,10], human misuse of land was found to be a relevant cause of land degradation along the wildland-urban interface. Mismanagement of the land, mainly due to an unplanned urban expansion, generated spatial disparities in the environmental variables and in the quality of natural resources, possibly influencing the local socio-ecological context [28]. Urban expansion in Rome was associated with the increase of land vulnerability, although different spatial patterns were observed during the investigated time interval. While compact urban growth negatively impacted land quality, especially between 1990 and 2000, the reverse pattern was observed in the subsequent decade when land undergoing dispersed urban expansion had the highest increase in the level of land vulnerability. This complex spatial pattern reflects the distinct urbanization waves observed in Rome [32] and underlines the role played by scattered urban expansion in shaping vulnerability of fringe land. This confirms the trend already observed in Spain [3].

Taken together, the highest rate of growth in the level of land vulnerability was observed in discontinuous, low-density urban areas. Scattered urbanization, sometimes coupled with rural abandonment or crop intensification [15,40,41], expanded into natural habitats was a powerful driver of land degradation. Soil sealing is responsible for the increase in land vulnerability to degradation by preventing e.g., the absorption of water from the ground. This results in the alteration of the hydrological cycle, ecosystem services loss and flooding risks as a consequence of the decrease in vegetation cover [1]. An in-depth understanding of spatial patterns of land degradation and ecosystem services loss in sensitive regions is especially required [7]. How landscape transformations and specific paths of land-use change triggering LD can affect ecosystem services provision is an issue that merits future investigation.

Our study suggests that green belts surrounding large Mediterranean cities may act as “buffer zones” mitigating land degradation because they form a physical barrier against urban dispersion and reduce the off-site impact of soil sealing on the hydrological cycle and ecosystem services loss [27,34,42]. The agro-forest mosaic surrounding Rome has preserved high land quality, maintaining a relatively stable level of vulnerability over time and playing an important role in the mitigation of climate changes at the local scale [32]. Moreover, as indicated in some studies [37,43], degraded (or highly vulnerable) land in suburban districts appears to be more prone to fire occurrence due to the extreme fire susceptibility of the vegetation [44].

Conserving relict natural ecosystems is a key issue in the sustainable land management of suburban areas [33]. Our results suggest that planning strategies against land degradation have to distinguish passive degradation deriving from the past environmental dynamics—and often requiring land restoration—from active degradation, needing permanent assessment and specific policy response [28]. Response to land degradation in suburban areas include the containment of dispersed urban expansion and landscape fragmentation, the preservation of relict agro-forest mosaic, the enhancement of traditional agricultural areas with typical farming practices and strategic planning for land controlling real estate speculation.

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Author Contributions

The authors L. Salvati, A. Ferrara, I. Tombolini and L. Perini have contributed to the design, data collection and analysis, and writing of the manuscript. R. Gemmiti and A. Colantoni have contributed to the writing of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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