The impact of collaboration on research about rural buildings and landscape: A case study in Italy

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Olive Grove Landscape Change: A Spatial Analysis Using Multitemporal Geospatial Datasets

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Abstract: This research examines the evolution of olive landscapes in Cartoceto, Italy, post-World War II. This study investigates the structural and functional attributes of two distinct olive cultivation models, mixed olive groves with a low tree density and high-density olive groves. The research employs remote sensing aerial imagery and land use cartography to reconstruct the past terrain and classify distinct categories of olive orchards. Landscape metrics are utilised to evaluate the impact of human and natural factors on the temporal development of olive landscapes across multiple spatial configurations, defined as Landscape-scale and sub-units or Landscape Units. The results indicate that olive landscapes have experienced noteworthy alterations, characterised by a reduction in the conventional large-scale system and an increase in specialised planting models of smaller sizes, classified as "high intensity". The region surrounding Cartoceto's historic centre has conserved a greater variety of mixed olive heritage and has witnessed the emergence of novel high densities of trees compared to other areas. Obtaining these results has been facilitated solely by utilising diverse spatial configurations of smaller sub-units than the entire landscape. The outcomes of this investigation provide a foundation for forthcoming enquiries into olive terrains and the development of sustainable rural landscape strategies.

Keywords: olive groves; rural landscape; LU/LC; landscape metrics; Sankey diagrams

1. Introduction

The olive tree (*Olea europaea* L.) has been a longstanding feature of the Mediterranean landscape. Olive groves have played a significant role in shaping rural landscapes and have become symbols of local identity. In Italy – the focus of our study – olive groves contribute to the landscape and provide valuable goods, such as oil, table olives and essence, while offering ecosystem services, such as biodiversity conservation, erosion control and soil fertility improvement (Bogunovic et al., 2020; Gómez et al., 2009, 2014; Mao et al., 2021; Wu & Hobbs, 2002).

These groves hold social and cultural importance as they carry the traditions of olive cultivation and processing across generations (Hürol, 2018). They also contribute to combating the decline in rural populations in areas less suitable for intensive farming (Duarte et al., 2008). Furthermore, olive-growing landscapes have become new attractions for various forms of tourism, including ecotourism, agritourism, rural tourism, cultural tourism,

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gastronomic tourism, and oleotourism. These landscapes offer services related to relaxation, scenic beauty, traditional culture and an escape from mass tourism (Pulido-Fernández et al., 2019).

The development of olive tourism, especially oleo tourism, follows the food and wine tourism routes in many countries, where vineyards have greatly enhanced prestigious wine-producing landscapes (Millán et al., 2018; Moreno et al., 2011). Research suggests that Geographical Indications (GI) and traditions play a significant role in making high-quality products with distinct attributes, which are crucial for the socio-economic development of olive-growing regions (Gómez et al., 2014; Millán et al., 2018). In this context, the Protected Designation of Origin highlights the link between food quality and landscape (Di Vita et al., 2013; Erraach et al., 2014).

The work of Forman and colleagues on landscape ecology supports the idea that landscapes are complex and adaptive systems that require an integrated approach to managing social and ecological functions(Forman, 2014). Understanding the spatial and temporal dynamics of landscapes and the interactions between human and natural systems is essential and needed for managing and conserving landscapes effectively(Forman, 2014). In recognising the vital link between human and biophysical components and processes across various scales, the idea of landscapes as complex and adaptive systems highlights the need to view them as coupled social-ecological systems (Rao et al., 2023; Rescia & Ortega, 2018; Rodríguez Sousa et al., 2019).

In this context, olive-growing landscapes are also affected by various driving forces, such as demographic dynamics, urban development, and market-oriented behaviours of farmers (Palazzo & Aristone, 2017). These changes can replace traditional olive cultivation models, which are well integrated into the local environment, with intensive monocultures (Guerrero-casado et al., 2021). The extensive growth of densely planted olive groves reduces the diversity and complexity of habitats, consequently degrading the biodiversity of the agroecosystems (Fahrig et al., 2011).

However, an integrated approach consisting of the level of intervention and the well-being of local populations could ensure a sustainable agricultural production system aligning with biodiversity conservation. This will also entail strategies tailored to the unique characteristics of local and regional contexts, transcending the dichotomy between "land sharing" and "land sparing" concerning a diversified land management practice (Pompeu et al., 2018). At the same time, particular areas have managed to preserve traditional olive cultivation practices, contributing to the vitality of local communities and historic villages. Although it has been shown that intensive and highly intensive olive orchards are better for the environment than traditional olive orchards in terms of water use efficiency, soil organic carbon sequestration, and less evaporation and runoff, the ecosystem services that olive-growing landscapes provide can change (Guerrero-Casado et al., 2021).

The primary goals of our research are to describe and provide an understanding of how and where the olive grove landscape has been transformed in the area under study – Cartoceto, Italy – specifically during the post-World War II period. We focus on the structural and functional characteristics of different olive cultivation models, starting from the traditional typology of olive trees mixed with other crops at a low tree density. This cultivation model, an extensive system, had been prevalent in the studied area from the 19th century to the first half of the 20th century (Orciani et al., 2007).

However, due to low profitability, farmers have shifted to new farming practices to meet the global demand. These include specialised "high-intensity" planting patterns, leading to mechanisation and increased inputs (Díez et al., 2016). Between these extremes, there exist various cultivation types, including specialised (up to 400 trees ha^{-1}), intensive (up to 350 - 700 trees ha^{-1}) and super high-density olive orchards (up to 1200 - 2500 trees ha^{-1}) (De Gennaro et al., 2012; Mairech et al., 2020; Rallo et al., 2013; Tous et al., 2007).

Studying and quantifying the transformations of olive groves over time is essential for planning a sustainable rural landscape and preserving ecological properties (Angold et al., 2006; De la Hera et al., 2009; Taguas et al., 2021). Geographic information systems (GISs) play a crucial role in integrating different data sources and methodologies, enabling the analysis of landscape changes over time.

However, historical landscape reconstructions face challenges due to the lack of reliability and detail of spatial databases, especially in the past, before the availability of high-resolution remote sensing (RS) imagery (Bielecka, 2020; Delogu et al., 2023; Garden et al., 2007). Official maps used in past periods often generalised the represented classes, limiting the accurate representation of different forms of olive cultivation. In our study, we have modified the available maps to adapt their resolution to a detailed scale, allowing us to identify the dynamics between the physiology of the territory and natural and anthropogenic effects. Detailed Land Use Maps (LUMs) are essential for reliably quantifying land use and land cover (LU/LC) changes (Alberti et al., 2008). Moreover, the accuracy and resolution of LUMs are crucial for analysing landscapes because many metrics are influenced by the shape and topology of patches of land (McGarigal & Marks, 1995; Shannon & Weaver, 1949).

This study is part of a larger project, Olive–Get (CONSORZIO OLIO DOP CARTOCETO, 2021), funded by the European Union's European Agricultural Fund for Rural Development (EAFRD), which aims to promote innovation (remote and proximal sensing and data sharing) in traditional or monumental olive groves while preserving high-quality standards and skilled management. In this context, our research seeks to provide objective territorial evidence to support farmers and decision-makers based on multitemporal analysis of historical data, landscape metrics and local driving forces. We will extend current practices in landscape analysis and provide a comprehensive analysis of land use/land cover (LU/LC) and their impacts on olive landscapes, revealing the complex dynamics and transformations that have occurred over time in the GI's PDO of Cartoceto. Furthermore, the combined use of different spatial configurations, defined as Entire Landscape and Landscape Units, better reflects the combination of indices adopted, as they capture both the complexity of the landscape and the drive of changes that have influenced the attribution of land use. This approach will provide a more solid understanding of the trajectories of change in olive grove landscapes and their broader socio-ecological implications, based on the different landscape patterns.

2. Materials and Methods

2.1. Studied area

Cartoceto is a picturesque town in central Italy, specifically in the Marche region. The municipality covers an area of 24 km^2 (43° 46' 4" north, 12° 52' 54" east) and has a population of 7,926 as of 2023. The population density of Cartoceto is approximately 341.7 inhabitants per square kilometre, nearly double the regional average (ISTAT, 2023). The town is near the Metauro River's hydrographic basin, which flows from west to east until reaching the Adriatic Sea. The altitude in Cartoceto ranges from 27 to 377 m above sea level (Fig. 1).

One of the remarkable features of Cartoceto is its captivating landscape, dominated by traditional olive groves. The area has been recognised as a GI (European Commission, 2021) in Italy since 2004 (Official Journal of the Italian Republic n. 291, 13/12/2004 (Italian Republic, 2004)). The distinctive Mediterranean landscape of Cartoceto was shaped during the 16th and 17th centuries through a farming system called "sharecropping". This system involved cultivating mixed arable land with olive trees and vineyards and practising polyculture on small farms spanning a few hectares. While many other Mediterranean regions have transitioned to olive monoculture, Cartoceto has preserved a diverse landscape pattern. Today, the area exhibits high heterogeneity, with specialised olive orchards coexisting with various LU dynamics, such as intensified arable lands, urban expansion, and protected areas of the Natura 2000 (Ostermann, 1998) is a network of protected areas. It provides essential habitat for many species (European. Commission, 1992) and human settlements.

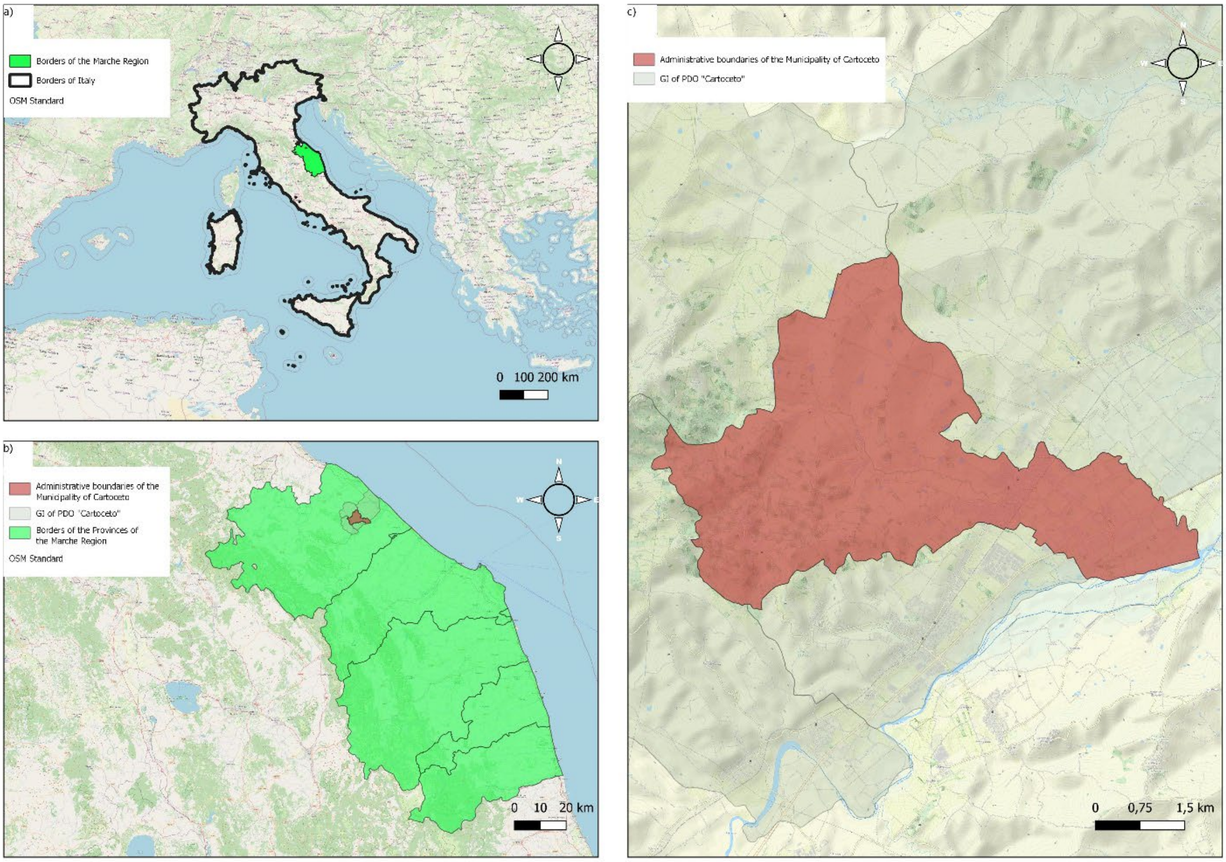


Fig. 1. a) The location of the Marche Region in central Italy, b) the geographical indication of the Protected Designation of Origin (PDO) Cartoceto area, c) Cartoceto Municipality limits.

The rural landscape of Cartoceto has been shaped by several factors, including climatic and anthropogenic events, as well as the decline of the rural population. A timeline (Fig.2) of these events can be used to understand how the landscape has changed over time. For example, in the late 1950s and the mid-1980s, two extreme climatic frost events caused olive tree deaths. The first event also caused the end of sharecropping, while from the mid-1960s onward, the Common Agricultural Policy (CAP) (European Commission, 2023)was introduced. The postwar economic recovery also encouraged intense, uneven urbanisation in the municipality of Cartoceto, which started in the late 1960s and continued until the early 2000s.

Cartoceto's rural population has been declining for many years due to some factors, including economic opportunities in urban areas, an ageing population and agricultural specialisation. Additionally, rural specialisation causes minimal use of farmers, with a simplification of adapted crops in the rural landscape. This descriptive approach was also utilised by Dimopoulos and Kizos in 2020 (Dimopoulos & Kizos, 2020).

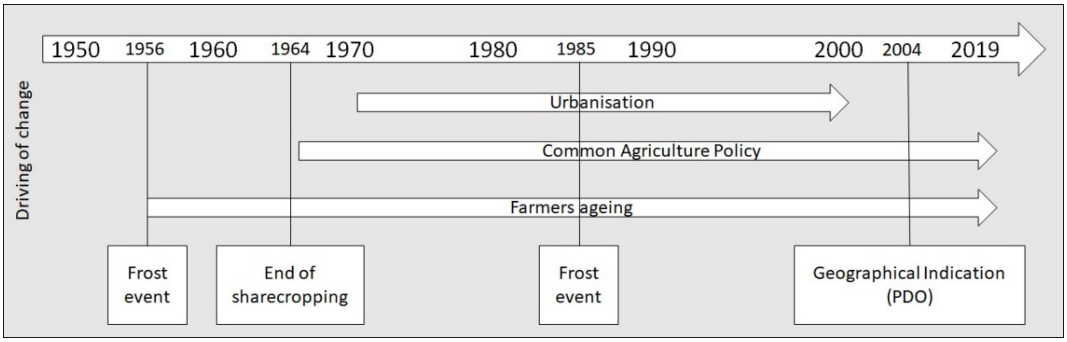


Fig. 2. Chronological overview of the development of olive cultivation in Cartoceto since the 1950s

2.2. Methodology

As shown in Fig.3, the workflow consists of three phases. First, various sources are used to gather data, including LUMs, aerial pictures and orthophotos (refer to Table 1), to create updated thematic maps through photo interpretation. Second, data analysis examines spatial statistics and metrics related to land use/land cover (LU/LC) changes. This analysis is performed on two spatial scales: the Entire Landscape and the territorial sub-units, known as Landscape Units. Third, the results of the statistical analysis and landscape metrics are interpreted, and the key findings are discussed to gain insights into the factors that drive changes in the rural landscape.

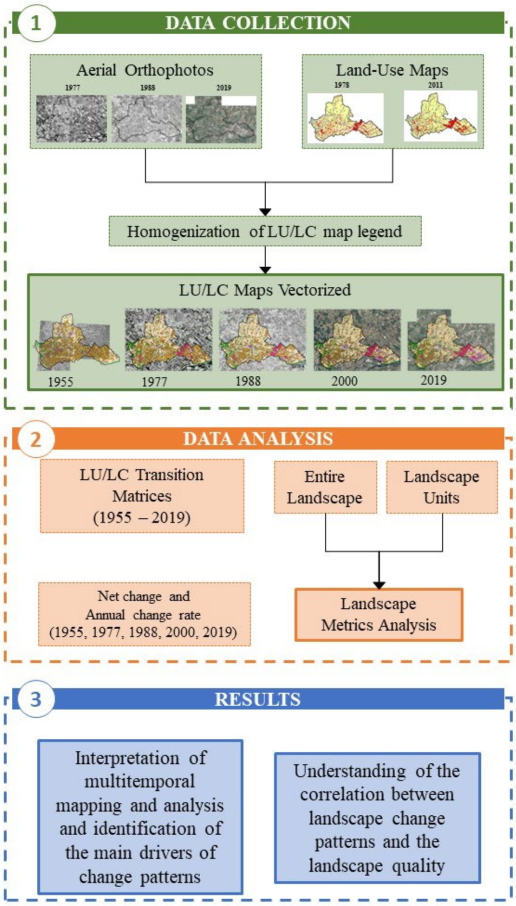


Fig. 3. The three-step conceptual framework.

2.3. Dataset

The sources of the data used in this study are shown in Table 1. Along with regional and national LUMs from 1984 and 2011, aerial photographs of Italy from 1955, 1977, 1988, 2000 and 2019 were gathered. The orthophotos and aerial pictures came from a variety of sources. The Italian military geographic institute (in Italian, Istituto Geografico Militare Italiano, IGMI) provided three partially overlapping aerial images taken in September 1955 (Italian survey mission Volo Base Gruppo Areonautico Italiano, GAI 55); the web-formatted aerial orthophotos taken in 1977 and 1988 were acquired from the local cartographic service (Marche Region, n.d.). These orthophotos are georeferenced digital grayscale images in Italy's Zone 2 of the Monte Mario Projection System (EPSG: 3004). The Italian Ministry of Environment purchased a set of 2,000 colour orthophotos in WMS format (EPSG: 32633-WGS 84 UTM Zone 33N) from the National Geoportal (Ministero Ambiente, n.d.). Nine digital orthophotos taken between April and September 2019 by the Italian agricultural payments agency (in Italia, Agenzia per le Erogazioni in Agricoltura, AGEA) comprise the most recent dataset (AGEA, n.d.). Each digital orthophoto is provided in a georeferenced format (EPSG: 32633-WGS 84 UTM Zone 33N) with four bands (RGB and NIR).

Two datasets were obtained for the studied area's LUMs. The local cartographic service provided the LUM for 1984 in vector (.shp) format. It is divided into 42 classes, arranged according to the LU/LC hierarchy. Built-up areas, arable land, woody/agricultural and specialist crops, arboriculture, forest/meadow grazing and unclassifiable regions are some of the categories at the first level. Each item from the first level is further broken down at the second and the third levels. The AGEA provided the LUM for 2011, which consists of 37 classes arranged into three levels of landscape classification.

These data sources, which include LUMs and aerial photographs, serve as the cornerstone for the analysis carried out in this study.

Table 1. Collected datasets.

N.	Title	Year	Source	Detail
1	Aerial photos	1955	Italian military geographical institute (IGM)	Hard copy scanned at 2500 dpi Scale 1:33,000 Altitude: 5000 m Average image resolution: 0,50 m
2	Aerial ortho-photos	1977	Cartographic Office of Marche Region	B/W band, digital GeoTIFF Scale 1:10,000 Altitude: 5700 m Image resolution:1,50 m
3	Aerial ortho-photos	1988	Cartographic Office of Marche Region	B/W band, digital GeoTIFF Scale 1:10,000 Altitude: 11500 m Image resolution:1,50 m
4	Land use map	1984	Cartographic Office of Marche Region	Vector format Scale 1:10,000 42 land cover classes Three hierarchical levels of LC/LU classification Minimum Mapping Unit 0,04 ha
5	Aerial ortho-photos	2000	National Geoportal	RGB digital, GeoTIFF Scale 1:10,000 Altitude: - Image resolution:1,50 m
6	Pedo-Soils Landscapes Map	2006	ASSAM	Vector format Scale 1:250000 Three hierarchical levels of Landscape Units (Region, Province, Systems) Minimum mapping unit of 0,5 ha
7	Land use map	2011	A.G.E.A.	Vector format 37 land cover classes Scale – Altitude: - Third hierarchical level of LU/LC classification; Minimum Mapping Unit 0,16 ha
8	Aerial ortho-photos	2019	A.G.E.A.	RGB + NIR digital GeoTIFF scale 1:5'000

	Altitude: -
	Image resolution:0,20 m

Defining the sub-units or landscape units characterising the studied area is essential in our research. In landscape ecology, a Landscape Unit refers to a homogeneous sub-land with similar characteristics and functions that is part of a larger landscape (Forman & Godron, 1981). These units exhibit specific features and functions contributing to the landscape (Ingegnoli, 2015).

To identify the Landscape Units in our case study, we referred to a coverage previously developed by the regional Agency for Food and Agriculture of the Marche region (Agenzia Servizi Settore Agroalimentare delle Marche [ASSAM]) (Marche, 2023), in collaboration with the Joint Research Centre – Institute of the European Commission, in 2007 (Gay et al., 2009). Table 2 provides an overview of the main features of the four landscape units identified in the studied area, and Fig. 4 illustrates their spatial distribution. These landscape units play a crucial role in understanding the dynamics and characteristics of the studied area, enabling us to analyse their specific attributes and functions in the broader landscape context.

Table 2. Landscape units' classification and taxonomy (Source: ASSAM).

Landscape Unit	**Type of landform**	**Type of environment**	**Code**
Valley bottoms and riverbeds	Flat floodplains of Pleistocene-formed terraces 0–300 m above sea level	Predominantly urbanised, with arable land and woods. A peak of riparian formations can be found along water courses.	**VBR**
Terraced surfaces		Urbanised with some non-irrigated farmland, riparian formations and woods (oak and black locust)	**TES**
Rolling hills	Hills with slopes ranging from slightly undulating to moderate, up to 550 m high. Geological foundations are calcareous or pyelitic formations running from southeast to northwest.	Predominantly agricultural lands (arable lands and crops)	**ROH**
Hills and reliefs		Historical villages are surrounded by predominantly agricultural land with crops, vineyards and olive groves. Oak woods are widespread, followed by black locust, elm and riparian formations.	**HAR**

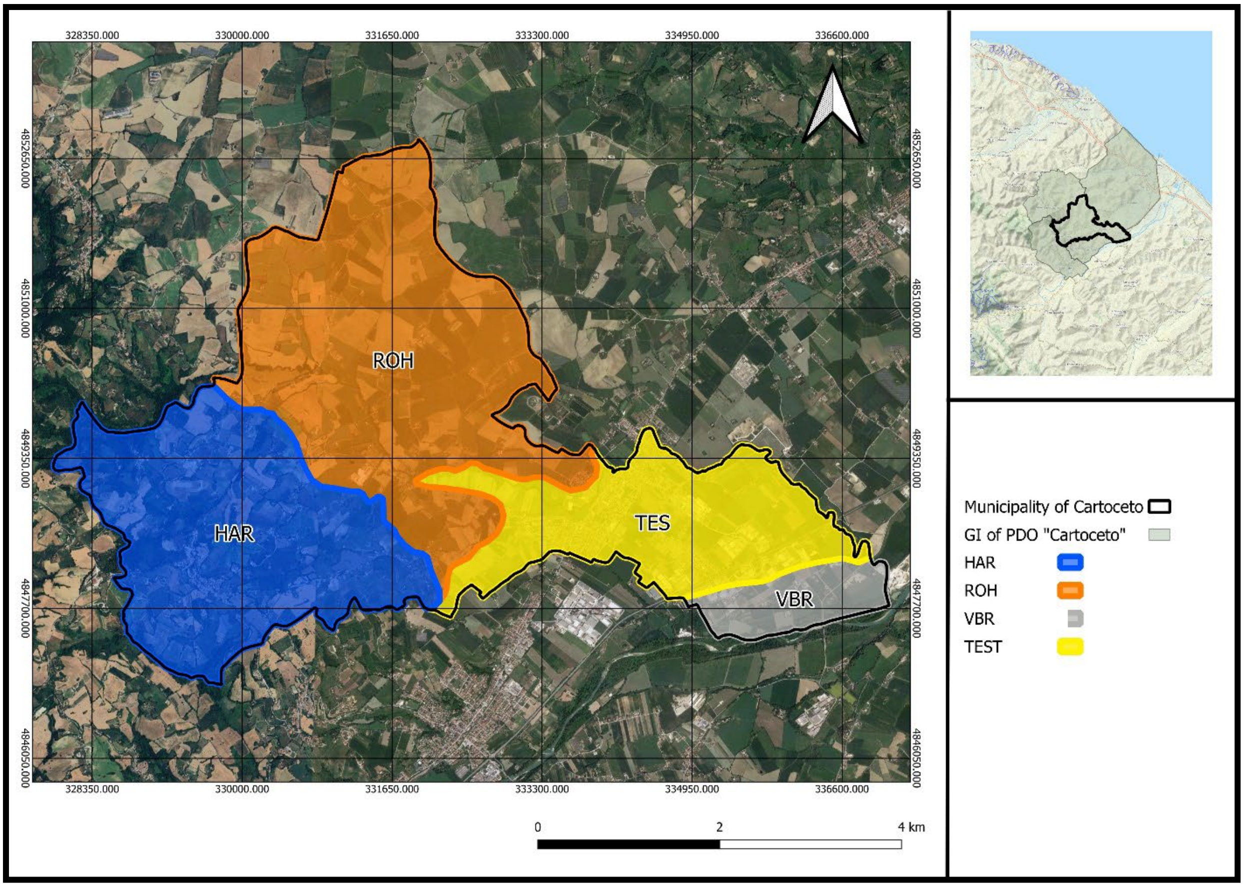


Fig. 4. Landscape units.

2.4. LU/LC classification and mapping

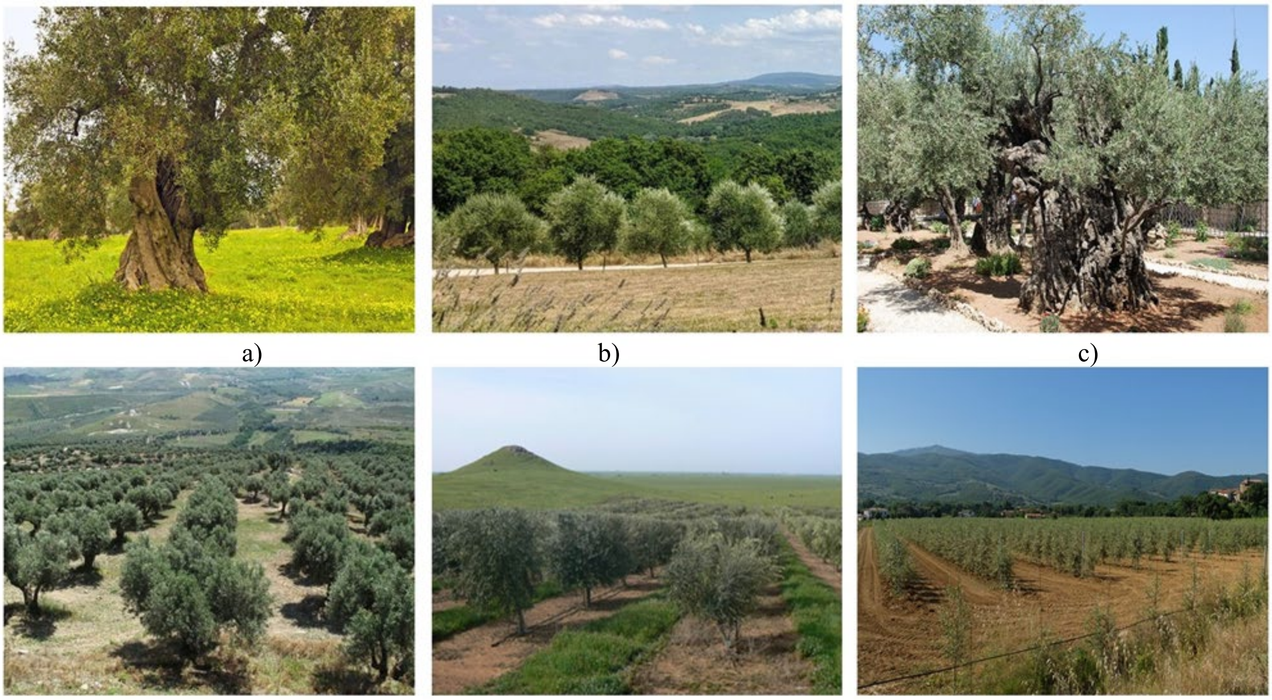
The LU/LC classification of the municipality of Cartoceto exhibits differences in terminology and numbering between the LUMs provided by the Marche Region for 1984 and the AGEA for 2011, resulting in divergent LU/LC schemes. Our objective was to standardise the utilisation categories of each entity according to the guidelines established by the Corine Land Cover (CLC) reference. The CLC initiative aimed to provide uniform and comparable quantitative LC information for European environmental policymakers and stakeholders (Feranec, 2016).

As shown in Table 3, we incorporated an additional hierarchical level (4° level) beyond the three primary levels that delineate major LU/LC transformations and land consumption in the studied area. This design was consistent with the specific characteristics of olive plantations, considering factors such as the number of trees per hectare and the arrangement of tree planting, as depicted in Fig. 5. Notably, our classification scheme represents a semantic innovation compared to the commonly used international olive classification systems. This distinguishes our study from similar research on olive cultivation, which typically does not incorporate such innovations (Br & Kubacka, 2021), (Lu et al., 2004). Olive groves are often viewed primarily from a production perspective, overlooking their significance as components of the historical landscape.

The 4° level of utilisation classes include various categories, such as vine cultivation and non-cultivated areas within the agricultural area. Additionally, industrial or commercial units encompass a distinct homogeneous category that provides for photovoltaic plants, as observed in a study conducted by Maggiore et al., 2019. Through our scheme, a total of 21 LU/LC categories were successfully identified.

Table 3. Multitemporal LU/LC classification framework.

1° Level	2° Level	3° Level	4° Level
1 Artificial surfaces	1.1 Urban fabric		
	1.2 Industrial, commercial and transport units	1.2.1 Industrial or commercial units	1.2.1.1 Industrial or commercial units 1.2.1.2 Photovoltaic plant
		1.2.2 Road and rail networks and associated land	
	1.3 Mine, dump and construction sites	1.3.1 Mineral extraction sites	
2 Agricultural areas	2.1 Arable land	2.1.1 Non-irrigated arable land	
	2.2 Permanent crop	2.2.1 Vineyards	2.2.1.1 Specialised vineyard 2.2.1.2 Vineyard mixed with trees
		2.2.2 Fruit trees and berry plantations	2.2.2.1 Fruit orchard
		2.2.3 Olive groves	2.2.3.1 Isolated olive trees with crops 2.2.3.2 Olive rows mixed with crops 2.2.3.3 Specialised olive orchards 2.2.3.4 Intensive olive orchards 2.2.3.5 High-intensive olive orchards 2.2.3.6 Garden olive trees
	2.3 Pastures		
	2.4 Heterogeneous agricultural areas	2.4.1 Land principally occupied by agriculture	2.4.1.1 Wasteland
3 Forest and seminatural areas	3.1 Forest	3.1.1 Broad-leaved forest	3.1.1.1 Broad-leaved forest 3.1.1.2 Riparian vegetation
4 Wetlands	4.1 Inland waters	4.1.1 Watercourses 4.1.2 Water bodies	



a) b) c)

d) e) f)

Fig. 5. Examples of different olive orchards: a) isolated olive trees mixed with crops, b) olive tree rows mixed with crops, c) garden olive trees, d) specialised olive orchards, e) intensive olive orchards, f) high-density olive orchards

Along with the classes outlined in Table 3 about the geospatial data (see Table 1), we derived the LU/LC for each period (1955, 1977, 1988, 2000 and 2019) by photointerpretation in QGIS (Vien 3.28-Firenze) (QGIS Development Team., 2022). This resulted in the creation of a vector-based, multitemporal geospatial dataset, provided with a comparable and consistent class system across almost 70 years. To further refine the photointerpretation quality for 1955, 1977, and 1988, we relied on regional data, specifically the LUM in 1984 (plate number 4 in Table 1). Similarly, we used the AGEA's LUM in 2011 (plate number 7 in Table 1) as a vector basis to support the interpretation of the aerial orthophotos in 2000 and 2019. Our team diligently cross-checked the digitised polygons against the aerial images and the LUMs to identify any changes or permanent LU/LC classes.

2.5. Valuation of intensity and velocity of landscape transformation through landscape metrics

In landscape analysis, the dynamics of change can be classified using measures such as areal change (including the percentage of Net Change and Annual Change Rate) and flow direction and intensity. Tools such as transition matrices, general Sankey diagrams and olive-specific Sankey diagrams can be utilised to visualise these changes. Calculating landscape metrics is also crucial in understanding the patterns and structures of these changes.

This case study employed a transition area matrix to assess the magnitude of LU/LC change from 1955 to 2019 (Moser et al., 2002; Walz, 2015). Relative and absolute modifications for each of the 21 classes were calculated from a 21x21 square matrix, highlighting the temporal changes by quantifying the total area of change per class (Vizzari, 2011).

Two indices, namely Net Change and Annual Change Rate, were used to assess how quickly LU/LC change in a specific time interval. The Net Change in each class was calculated by subtracting the total of the class (expressed as a percentage) from the area in the previous and subsequent years throughout the entire reference period. Index analysis was conducted by considering pairs of successive years(Walz, 2015). The Annual Change Rate reveals the rates of increase or decrease in the absolute intensity of area changes and the speed at which these changes occur. It is important to note that the reference periods considered may vary in length, so a careful interpretation of the obtained indices is recommended for accurate results (Lu et al., 2004).

Following the approach of specific authors (Andrieu et al., 2011; Di Fazio et al., 2011), we adopted Equations (1) to calculate the Annual Change Rate and (2) to calculate the Net Change (Puyravaud, 2003).

$$r[\%] = \frac{1}{t_2 - t_1} \ln\left(\frac{A_{t2}}{A_{t1}}\right) 100 \quad (1)$$

$$q[\%] = A_{t2} - A_{t1} \quad (2)$$

These formulas are used as follows: A_{t2} and A_{t1} represent the surfaces of the same land class at the end and at the beginning of the evaluated period, respectively, while t_2 and t_1 respectively indicate the end year and the beginning year of the time (Modica et al., 2017).

Using these analytical methods, we can obtain valuable insights into the temporal dynamics of LU/LC changes while gaining a quantitative understanding of the transition processes in the landscape.

Additionally, we analysed the changes in the landscape structure by applying spatial metrics (Kohli et al., 2016). These metrics help understand and describe the patterns of change in the landscape mosaic of LU/LC classes. The landscape model used includes matrix concepts, patches and corridors (Walz, 2015). The patches in vector LU/LC maps are polygons, relatively homogeneous areas that differ from their surroundings (Lausch et al., 2015; Moser et al., 2002).

The scale and resolution of the LU/LC map have impacts on the quantitative, synthetic and aggregated spatial indicators that landscape metrics provide (Herold et al., 2003, 2005). They play a crucial role in landscape research (Uuemaa et al., 2009) and landscape planning (Orlandi et al., 2020). The selection of landscape metrics for this study was based on a literature review (Aguilera et al., 2011; Alphan et al., 2022; Hesselbarth et al., 2021; Usman & Nichol, 2022), focusing on landscape complexity and diversity. A limited number of spatial indices were chosen at both the class and landscape levels to ensure clarity. These include the number of patches (NP) (McGarigal & Marks, 1995), average of patch size (APS) (McGarigal & Marks, 1995), edge density (ED) (McGarigal & Marks, 1995) and Shannon's diversity index (SHDI) (Shannon & Weaver, 1949). An overview of the selected metrics and their significance is provided in Table 4. Each class's total area and perimeter were extracted using the "Statistics Categories" tool in QGIS (QGIS Development Team., 2022).

Table 4. Description of metrics.

Index	**Unit**	**Equation**	**Definition**
Number of classes (NC)	Number	Data	Total number of classes on Entire Landscape or a Landscape Unit
Number of patches (NP)	Number	Data	Total number of patches on the Entire Landscape or Landscape Unit
Average of patch size (APS)	hectare	$APS = \sum_{i}^{n} \frac{\sum_{i=1}^{n} a_i}{n} = \frac{A}{n}$	A class level is a function of the number of patches and the considered landscape area.
Edge density (ED)	metre/hectare	$ED = \frac{\sum_{k=1}^{m} e_{ik}}{A}(10000)$	The sum of all perimeter lengths of class patches divided by the considered landscape area.

Shannon's diversity index (SHDI)	Number	$HDI = -\sum_{i=1}^{m}(P_i \cdot ln\, P_1)$	SHDI is a formula for entropy. The value takes the number of classes and the abundance of each class into account in the considered landscape.

3. Results

This section presents the results of the multitemporal mapping and analysis. These results provide crucial insights into the change in utilisation rates for each category in each year studied and the Transition Matrix, Net Change, Annual Change Rate and landscape metrics. In the following sub-sections, we delve deeper into these findings, exploring their implications and contributions to the relevant field of study.

3.1. LU/LC change

Fig. 6 shows the LU/LC maps produced for 1955, 1977, 1988, 2000 and 2019. The percentages of the LU/LC for each of the five years considered (1955, 1977, 1988, 2000 and 2019) are reported in Fig. 7.

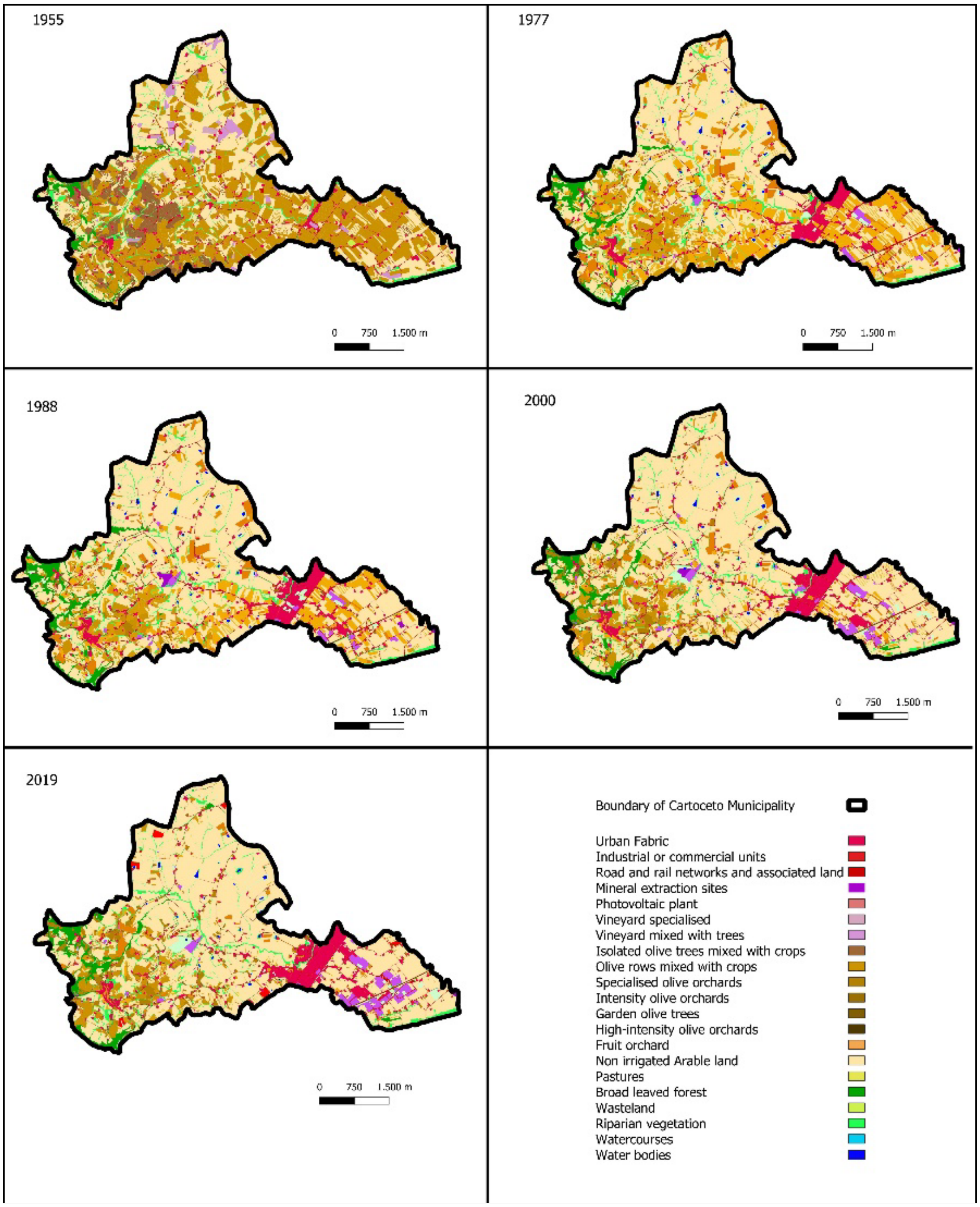


Fig. 6. The five land use maps (LUMs) produced for 1955, 1977, 1988, 2000 and 2019.

The dynamics of change on the different landscape units (see Fig. 4) exhibit distinct patterns, as depicted in Fig. 7. In aggregate terms, for the whole area the figures (Fig. 6 and Fig. 7) show a consistent reduction in the area covered by isolated olive trees mixed with crops (2.2.3.1 LU/LC). In 1955, this class covered 8.16% (188.97 ha) of the area, which decreased to 6.27% (145.27 ha) in 1977, 4.03% (93.36 ha) in 1988, 2.88% (66.91 ha) in 2000 and finally, 2.04%

(47.80 ha) in 2019. A more significant decline is observed in the olive rows mixed with crops (2.2.3.2 LU/LC) class. In 1955, it covered approximately 42% (935.054 ha) of the municipal territory, dropped to 19.39% (449.27 ha) in 1977 and further decreased to 10.71% (248.16 ha) in 1988. The negative trend continued with 3.58% (82.83 ha) in 2000, and the class almost disappeared in 2019, accounting for only 1.5% (35.41 ha).

In contrast, non-irrigated arable land (2.2.1 LU/LC) experienced a progressive increase. The area of arable land was 32% (762.16 ha) in 1955, expanded to 47.56% (1,101.81 ha) in 1977, 55.96% (1,296.73 ha) in 1988, 61.93% (1,434.76 ha) in 2000 and finally reached 61.10% (1,415.08 ha) in 2019.

To better understand the evolution of the olive-growing sector in the studied area, it is essential to consider the changes in olive groves based on more modern cultivation criteria. In 1955, specialised olive orchards (2.2.3.3 LU/LC) had a negligible extension of 0.21% (5.03 ha), which gradually increased to the current overall area of 4.21% (97.56 ha). Intensive olive orchards (2.2.3.4 LU/LC) also expanded slowly, starting from 1988 with an area of 0.43% and reaching a significant extension of 3.14% (72.83 ha) in 2019. In contrast, high-intensity olive orchards (2.2.3.5 LU/LC), the most modern and intensive cultivation model, struggled to establish itself in the studied area, appearing only from 2000 and covering an area of less than 1% (1.57 ha) in 2019.

The trend observed for garden olive trees (2.2.3.6 LU/LC) is noteworthy. This small-scale olive farming for personal consumption steadily expanded over the years, growing from 0.14% (3.35 ha) in 1955 to 1.71% (39.59 ha) in 2019, primarily driven by urban area growth. Additionally, the urban fabric (1.1 LU/LC) significantly increased in surface area, rising from 3.15% (73.06 ha) in 1955 to 7.44% (172.48 ha) in 2019. Moreover, the road and rail networks and associated land (1.2.1 LU/LC) have expanded significantly since the 1980s, reaching a total surface area of 2.57% (59.60 ha) in 2019.

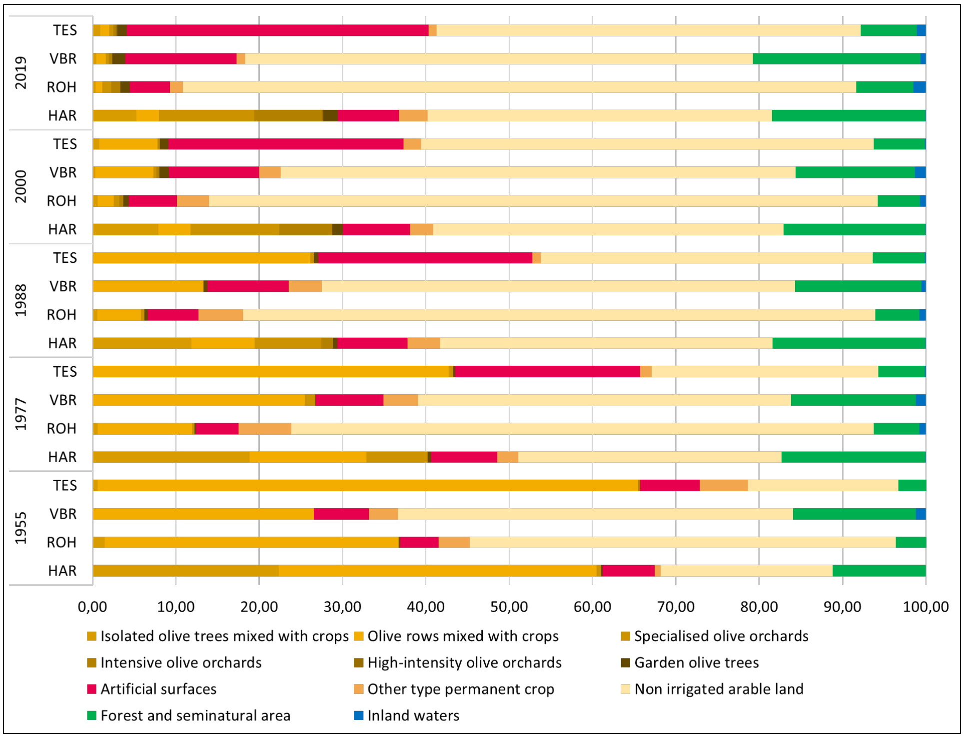


Fig. 7. Bar graph of LU/LC as a percentage of the Landscape Unit for 1955, 1977, 1988, 2000 and 2019.

Concerning the various typologies of olive cultivation in landscape sub-units, it is evident that olive rows mixed with crops (2.2.3.2 LU/LC) are heterogeneous across all investigated unitsThis typology (i.e., in 1955) covered 37.41% (274.77 ha) of the hills and reliefs (HAR) surrounding the historic settlement of Cartoceto. It occupied 32.34% (316.58 ha) of the rolling hills (ROH) located on the less steep eastern hillside of Cartoceto. Additionally, it was distributed across the valley bottoms and riverbeds (VBR), covering an area of 26.86% (33.01 ha), and the terraced surfaces (TES), with a surface area of 64.83% (310.67 ha). The TES represents flat areas connecting the alluvial deposits of the Metauro River, which proved favourable for urban expansion and intensified cultivation. From 1955 to 2019, there was a significant reduction in this type of mixed olive cultivation. A small amount remains in the HAR, covering 2.72% (28.21 ha), while it has nearly disappeared in adjacent areas, with only 0.77% (7.56 ha) remaining in the ROH, 1.13% (1.40 ha) in the VBR and 1.08% (5.15 ha) in the TES.

Nonetheless, the evolution of isolated olive trees mixed with crops (2.2.3.1 LU/LC) varies significantly, depending on the characteristics of the landscape unit. In the HAR, this traditional form of olive cultivation maintains a significant coverage share, accounting for 5.26% (38.66 ha) of the landscape unit surface and contributing to its traditional character. However, in the other units, the coverage was below 1% as of 2019.

The primary LU/LC class exhibiting a positive trend is non-irrigated arable land (2.2.1 LU/LC). The HAR increased from 18.26% (134.29 ha) in 1955 to 41.37% (299.93 ha) in 2019. Similarly, the ROH rose from 49.27% (483.19 ha) in 1955 to 80.82% (791.07 ha) in 2019. In the VBR, it increased from 47.36% (58.18 ha) in 1955 to 60.91% (75.67 ha) in 2019, and in the TES, it grew from 18.07% (86.43 ha) in 1955 to 50.91% (243.72 ha) in 2019.

Although generating derived LUMs through photo interpretation is time-consuming, it provides an accurate and consistent representation of LU/LC patterns for each period. The accuracy of the base maps is crucial for detecting landscape changes as it enables a better understanding of the distribution and arrangement of LU/LC types in the landscape and their impacts on ecological processes and biodiversity (Br & Kubacka, 2021). This information is critical for calculating landscape metrics and evaluating the effects of LU/LC changes, including composition, complexity level, fragmentation and other disturbances(Ingegnoli, 2015).

3.2. Annual rate of change and yearly net change

As mentioned in Section 2.5, the Annual Change rate (percentage) and the Net Change (percentage) have been calculated for both the scale of the Entire Landscape (refer to Fig. 8) and the single Landscape Units (refer to Fig. 9, Fig. 10, Fig. 11 and Fig. 12, respectively).

Fig. 8. Net Change (left) and Annual Change rate (right) in the study area.

As illustrated in Fig. 8, the category of isolated olive tree s mixed with crops (2.2.3.1 LU/LC) had the most significant decline from 1977 to 1988, with a Net Change of -2.24% and an Annual Change rate of -4.42%. However, in absolute terms, this decline is moderate, considering the small area of this category compared to the size of the Entire Landscape area.

On the one hand, Olive rows mixed with crops (2.2.3.2 LU/LC) experienced the most significant contraction between 1955 and 1977, with a Net Change of -20.96%, although the Annual Change rate was relatively slower at -3.18%. The decline rate increased in the subsequent periods, especially between 1988 and 2000. In contrast, the category of specialised olive orchards (2.2.3.3 LU/LC) showed a high rate of intensification during the period 1955–1977, with an Annual Change rate of 10.85% and a Net Change of +2.41%. The growth rate for the most intensive olive groves was relatively limited, with Net Change values below 1% and Annual Change rates below 2%. The exception was between 1988 and 2000 when intensive olive orchards (2.2.3.4 LU/LC) experienced a high growth rate of +13.54%. In contrast, the Net Change for garden olive trees (2.2.3.6 LU/LC) showed a consistent increase, albeit with small values, and the Annual Change rates were more pronounced between 1977 and 2000.

In analysing Fig. 9, Fig. 10, Fig. 11 and Fig. 12, it is noteworthy that the category of olive rows mixed with crops (2.2.3.2 LU/LC) exhibited a negative Net Change during the period 1955–1977, with values of -23.40% in the HAR, -21.40% in the ROH, -22.24% in the TES and a minor contraction of -1.09% in the VBR. The Annual Change Rates for olive rows mixed with crops (2.2.3.2 LU/LC) showed consistently negative values, primarily until 2000, in the HAR and the ROH. The Net Change and Annual Change rate for the category of isolated olive trees mixed with crops (2.2.3.1 LU/LC) exhibited a negative trend throughout the period, with more pronounced HAR changes than the ROH. In contrast, favourable variations in both the Net Change and the Annual Change rate were recorded for the categories of specialised olive orchards (2.2.3.3 LU/LC) and intensive olive orchards (2.2.3.4 LU/LC), particularly in the HAR during the periods 1955–1977 and 1988–2000.

Fig. 9. Net change (left) and Annual Change rate (right) on the HAR.

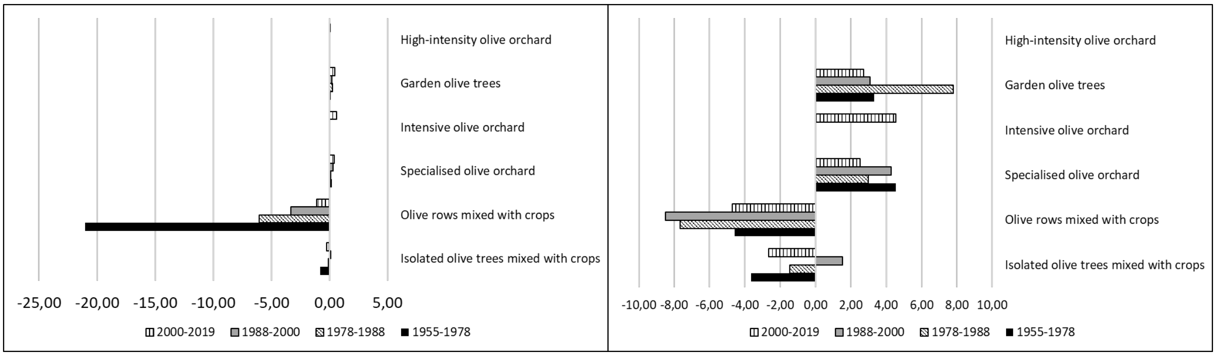


Fig. 10. Net change (left) and Annual Change rate (right) on the ROH.

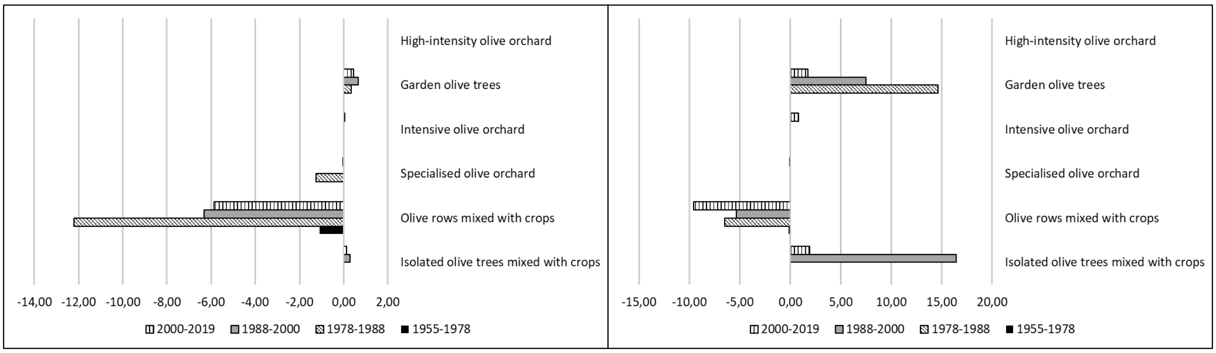


Fig. 11. Net Change (left) and Annual Change rate (right) on the VBR.

Fig. 12. Net Change (left) and Annual Change rate (right) on the TES.

3.3. Transition matrix and Sankey diagram

Regarding the diachronic LU/LC change, the comparison between 1955 and 2019 was particularly significant. This time interval allowed us to compute the change matrix (in hectares) based on the traditional Markovian chain (Weng, 2002). Markovian chains and transition matrices have long been used in modelling changes in LU/LC on various spatial scales (Ruiz-Benito et al., 2012; Weng, 2002). The results are presented in Fig. 13 using a Sankey diagram. Sankey diagrams illustrate the extent and final destination of LU/LC changes over different periods. The diagram in Fig. 13 clearly shows a significant decrease in the traditional olive cultivations composed of isolated olive trees with crops (2.2.3.1 LU/LC) and olive rows mixed with crops (2.2.3.2 LU/LC) from 48.5% of the total surface in 1955 to merely 3.5% in 2019, which were predominantly converted into non-irrigated arable land (2.1.1 LU/LC), urban fabric (1.1 LU/LC) and industrial or commercial units (1.2.1.1 LU/LC).

Despite this decline, a small portion of traditional mixed olive groves remained. This included 18.87 ha of isolated olive trees mixed with crops (2.2.3.1 LU/LC) and 19.22 ha of olive rows mixed with crops (2.2.3.2 LU/LC), showcasing the resilience of this traditional olive-growing method in the studied area. These remaining pockets of conventional olive groves contribute to preserving the landscape's cultural and historical significance.

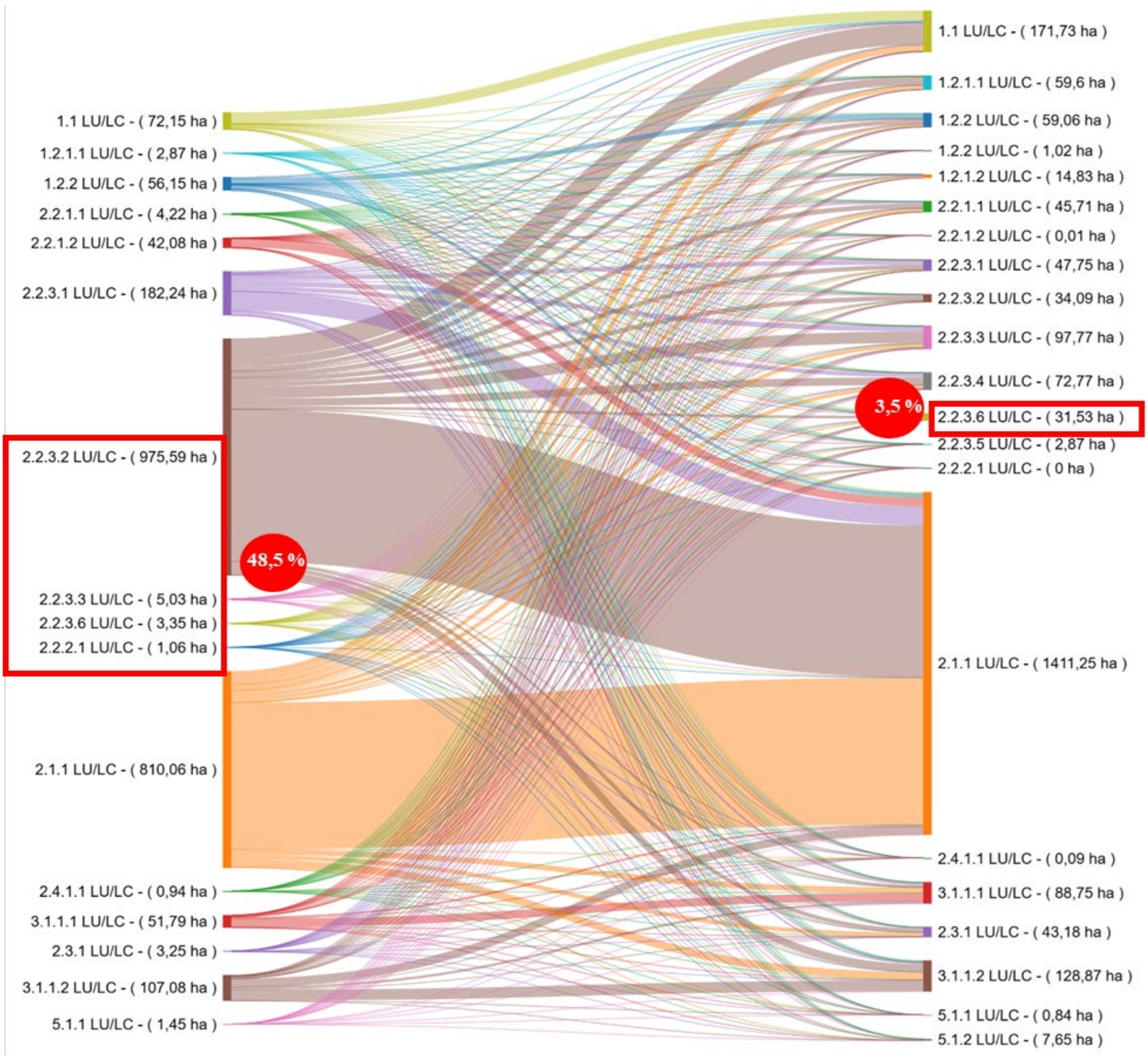


Fig. 13. LU change from 1955 (left) to 2019 (right). The loss of traditional olive groves (2.2.3.2 LU/LC) from 48.5% of the total surface in 1955 to merely 3.5% in 2019 is noteworthy. Note also that most areas of traditional olive growing forms have now turned into non-irrigated arable land (2.1.1 LU/LC).

The most significant transformation affecting the traditional olive groves was the intensification of LU/LC towards arable land. This led to the conversion of 78.21 ha of isolated olive trees mixed with crops (2.2.3.1 LU/LC) and a substantial acreage (626.26 ha) of olive rows mixed with crops (2.2.3.2 LU/LC) into non-irrigated arable land (2.2.1 LU/LC), as depicted in Fig. 13. In terms of the evolution of the traditional olive groves, the conversion of isolated olive trees mixed with crops (2.2.3.1 LU/LC) into more intensive olive groves resulted in the transition of 20.80 ha to specialised olive orchards (2.2.3.3 LU/LC), 17.65 ha to intensive olive orchards (2.2.3.4 LU/LC) and only 0.03 ha to high-intensity olive orchards (2.2.3.5 LU/LC). Additionally, 3.32 ha of the same class were converted into garden olive trees (2.2.3.6 LU/LC).

Similar changes were observed in the evolution of olive rows mixed with crops (2.2.3.2 LU/LC) towards a more intensive olive grove cultivation system. As shown in Fig. 13, this transformation resulted in the conversion of 47.47 ha into specialised olive orchards (2.2.3.3 LU/LC), 32.18 ha into intensive olive orchards (2.2.3.4 LU/LC) and 1.15 ha into high-intensity olive orchards (2.2.3.5 LU/LC). Furthermore, 11.37 ha were converted into garden olive trees (2.2.3.6 LU/LC).

The expansion of urban areas also affected traditional olive cultivation areas in various ways. New residential settlements (1.1 LU/LC) encroached on 82.75 ha of olive rows mixed with crops (2.2.3.2 LU/LC). Additionally, industrial or commercial units (1.2.1.1 LU/LC) and road and rail networks and associated land (1.2.2 LU/LC) respectively encroached on 34.17 ha and 18.76 ha of olive rows mixed with crops (2.2.3.2 LU/LC).

In 2019, a new LU/LC category emerged for renewable energy production from photovoltaic plants (1.2.1.2 LU/LC), occupying 5.57 ha. In contrast, the original surface of isolated olive trees mixed with crops (2.2.3.1 LU/LC) was minimally affected by urbanisation, with only 7.35 ha converted into urban fabric (1.1 LU/LC).

3.4. Results of landscape metrics

Landscape changes were assessed using landscape metrics for the Entire Landscape and the Landscape Unit. These metrics include NC, NP, APS, ED and SHDI. The maximum entropy value (S) was also computed as an ideal case when the maximum number of LU classes was evenly distributed [78]. The metrics were calculated for 1955, 1977, 1988, 2000 and 2019.

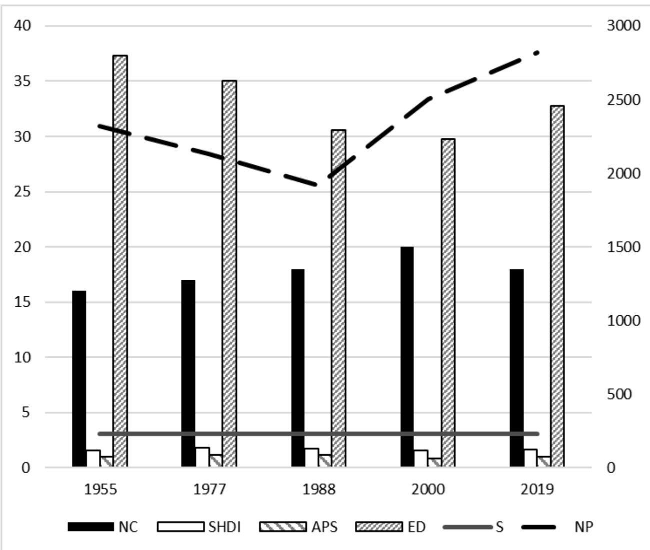


Fig. 14. The landscape metrics computed on the Entire Landscape.

Fig. 14 illustrates the main changes in landscape patterns in the studied area from 1955 to 2019. Notably, the NC varied yearly, with a peak occurring in 2000. This can be attributed to the emergence of new urbanised areas, industrial/commercial zones and small water bodies or ponds for irrigation, starting in the late 1970s. Introducing more intensive olive groves further contributed to this increase in class diversity. The rise in the NC signified an increase in landscape heterogeneity and fragmentation.

The NP metric confirmed this trend, particularly from 1988 onwards. In 1955, there were 2,319 patches across the studied area – a high number, considering the period before the extensive mechanisation of agriculture that began in the 1970s. Adopting mechanisation led to expanding agricultural parcels to enhance operational efficiency, decreasing the NP. However, since the late 1980s, the NP has steadily increased, peaking at 2,817 units in 2019 (Fig. 13) and indicating a significant increase in landscape fragmentation in the studied area.

The ED metric demonstrated a similar pattern. The ED reached its highest value of 37274 m/ha in 1955, reflecting the high degree of parcel fragmentation characteristic of the sharecropping system prevalent during that time. Subsequently, ED decreased until 1988 due to the regularisation of parcel shapes by mechanisation. However, it began to rise again in the subsequent period, reaching a value of 32 m/ha in 2019. This increase in ED is attributed to the overall rise in landscape heterogeneity resulting from the significant increase in the NP and their dispersed distribution across the studied area. This trend likely contributed to an overall increase in ecotones between patches.

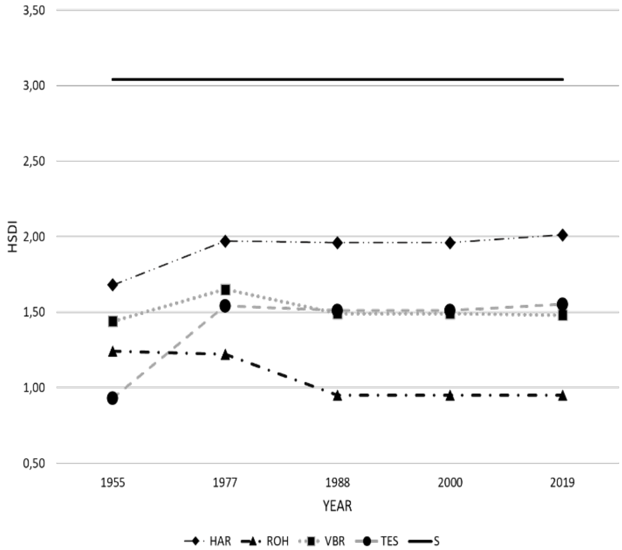


Fig. 15. Shannon's diversity index (SHDI) fluctuations over the investigated years at the Landscape Unit level.

Furthermore, the values of the SHDI, which serves as an indicator of landscape entropy, exhibited limited variations when applied to the Entire Landscape (Fig. 14). However, when examined on a more detailed spatial scale, such as the Landscape Unit, distinct trends and behaviours of this index became apparent, revealing the main driving forces of landscape transformation that would otherwise be masked. On the Entire Landscape, the SHDI score was 1.59 in 1955, peaked at 1.77 in 1977 and then settled at 1.64 in 2019, far from the maximum theoretical entropy value of 3.04. This indicates a simplification in the complexity of the landscape, attributed to the presence of LU/LC classes to a significant extent and with less fragmentation.

In contrast, analysing the trend of the SHDI on the Landscape Unit (Fig. 15) reveals disparate behaviours. In 1955, the HAR showed significant fragmentation and heterogeneity, attributed to the numerous patches and complex spatial arrangement typical of the sharecropping agricultural model. The SHDI value for this further increased over the years and stabilised at 2.01 in 2019. This fragmentation and diversity can be attributed to the high number of LU/LC classes (NC), which increased from 14 in 1955 to 16 in 2019. This heterogeneity also significantly limited the APS, which remained around 0.85 ha throughout the period. The ED value peaked in 1955 (54.72 m/ha), decreased in 1988 (42.46 m/ha) and then increased to 48.87 m/ha in 2019. The NP exhibited a heterogeneous trend, with 1,192 patches recorded in 1955 and 852 in 1988. Subsequently, there was a significant increase, reaching 1,334 patches in 2019.

In the ROH, the value of the SHDI decreased over time, from 1.24 in 1955 to 0.95 in 2019. This denotes progressive simplification and homogenisation of the landscape in this unit, resulting from the substantial intensification of cereal cultivation characterising its LU/LC evolution. The number of LU/LC classes (N) followed a trend similar to that of the HAR, with 13 LU/LC classes in 1955 and 16 in 2019. Conversely, the NP decreased from 1,112 in 1955 to 928 in 2019. The APS exhibited a heterogeneous trend, with 0.97 ha in 1955, increasing to 1.37 ha in 2000 and then stabilising at 0.89 ha in 2019. The ED values ranged from 47.63 m/ha in 1955 to 29.50 m/ha in 2019. These results indicated that the area underwent a process of homogenisation and an orderly trend of LU/LC conversion, primarily favouring low labour-intensity crops, which impeded ecological diversification.

The SHDI trends in the VBR and the TES during the study period were similar and distinct from the previous Landscape Unit examined. They exhibited intermediate values compared to the previously analysed Landscape Unit. In 2019, the SHDI values for the VBR and the TES were 1.48 and 1.55, respectively. Two primary drivers of transformation characterised these Landscape Units: expanding urbanised areas and spreading arable land. These factors increased heterogeneity, although to a lesser extent than observed in the HAR.

For more comprehensive insights into the effects of various factors that drive changes in the HAR and the ROH, it is beneficial to concentrate on the unique landscape metrics of each olive cultivation type. These metrics are illustrated in Fig. 16, Fig. 17 and Fig. 18.

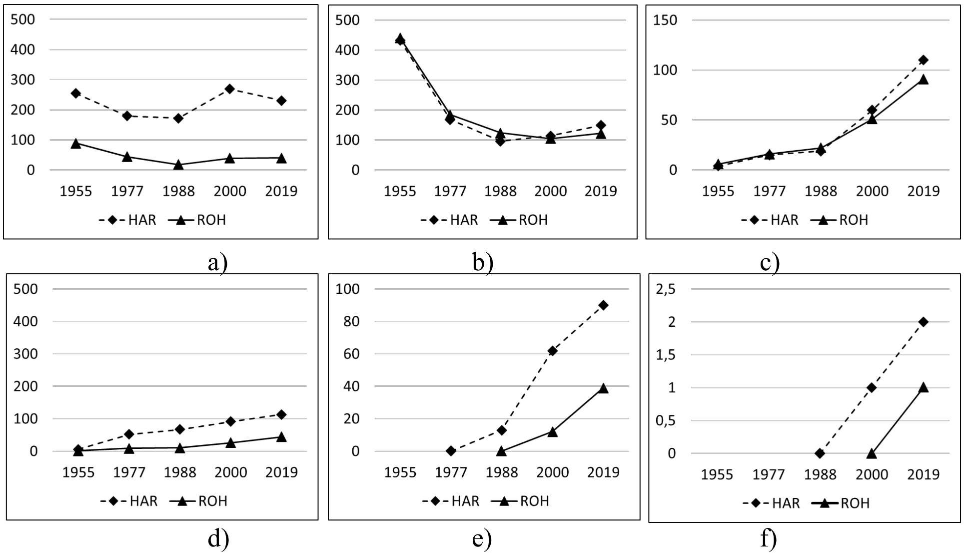


Fig.16. Number of patches (NP) for all olive orchard typologies on HAR and ROH. a) Isolated olive trees mixed with crops, b) olive tree rows mixed with crops, c) garden olive trees, d) specialised olive orchards, e) intensive olive orchards, f) high-density olive orchards.

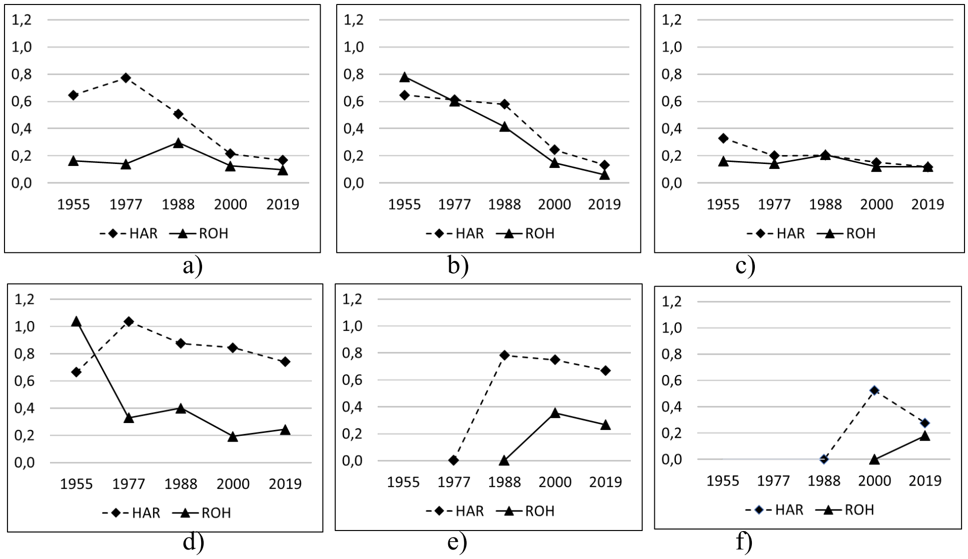


Fig. 17. Average patch size (APS) for all olive orchard typologies on the HAR and ROH. a) Isolated olive trees mixed with crops, b) olive tree rows mixed with crops, c) garden olive trees, d) specialised olive orchards, e) intensive olive orchards, f) high-density olive orchards.

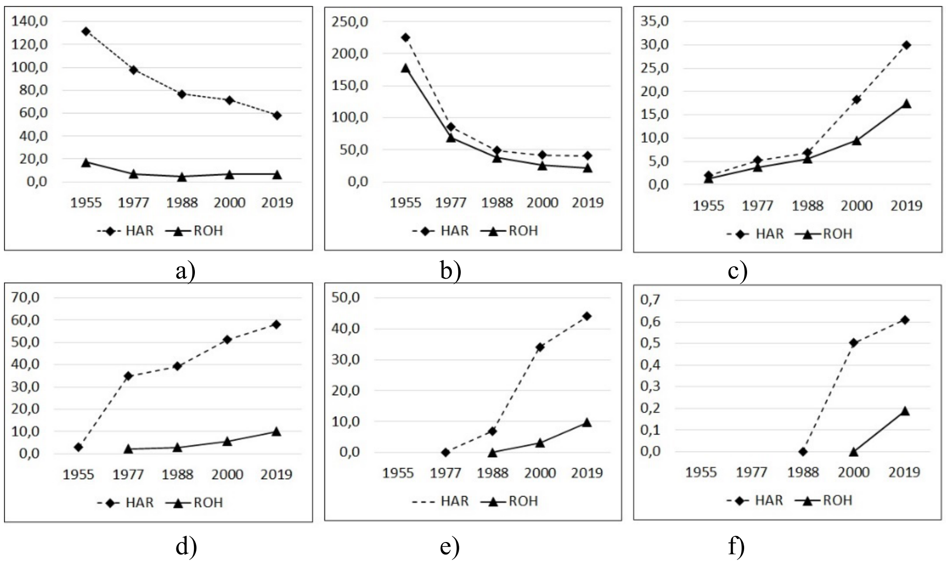


Fig. 18. Edge density (ED) for all olive orchard typologies on the HAR and ROH. a) Isolated olive trees mixed with crops, b) olive tree rows mixed with crops, c) garden olive trees, d) specialised olive orchards, e) intensive olive orchards, f) high-density olive orchards.

As shown in Fig. 16, the decrement of the NP metric for isolated olive trees mixed with crops (2.2.3.1 LU/LC) is more evident in the ROH than in the HAR. In 1955, 254 patches were identified in the HAR. Subsequently, the NP decreased to 172 in 1988 before increasing to 231 in 2019. The NP exhibited a wide range, from 89 in 1955 to 40 in 2019, in the context of the ROH. In contrast, the second classification of conventional olive cultivation, which involves intercropping, olive rows mixed with crops (2.2.3.2 LU/LC), experienced the most significant decline in the NP in both the HAR and the ROH. The number of occurrences varied from 433 in 1955 to 149 in 2019 for the HAR category and 441 to 122 for the ROH category.

In contrast, the garden olive trees (2.2.3.6 LU/LC) exhibited a consistent inclination to thrive in both Landscape

Units, ranging from 4 to 110 in the HAR and 6 to 91 in the ROH in 1955 and 2019, respectively. Modern and highly productive olive orchards have undergone distinct phases of growth. The specialised olive orchards (2.2.3.3 LU/LC) exhibited a consistent upward trend from 1955 to 2019. This trend was particularly pronounced in the HAR category, where the NP increased from 6 to 113. The cultivation of intensive olive orchards (2.2.3.4 LU/LC) experienced a notable expansion from 1977 onwards in areas classified as HAR and from 1988 onwards in areas classified as ROH. Additionally, the magnitude of the increase was more remarkable for the HAR than for the ROH. In 2000, the high-intensity olive orchards (2.2.3.5 LU/LC) were officially acknowledged in both units, with only a limited NP identified.

As illustrated in Fig. 17, the APS computed for cultivating isolated olive trees mixed with crops (2.2.3.1 LU/LC) showed a significant decrease. The olive orchard class notably decreased in land area in the HAR, from 0.65 ha in 1955 to 0.17 ha in 2019. Similarly, the APS metric in the ROH declined from 0.16 ha in 1955 to 0.10 ha in 2019. A consistent decrease in the olive rows mixed with crops (2.2.3.2 LU/LC) was also documented. In the ROH, the area of the APS decreased from 0.78 ha in 1955 to 0.13 ha in 2019. Hence, the conventional cultivation of olives persisted in both Landscape Units throughout the 64 years under study. However, it is noteworthy that the dimensions of the remaining land plots for these two olive orchard categories gradually decreased. The garden olive trees (2.2.3.6 LU/LC) exhibited a consistent transformation pattern, decreasing their area from 0.33 ha in 1955 to 0.12 ha in 2019 in the HAR and 0.16 ha to 0.12 ha in the ROH. As for the specialised olive orchards (2.2.3.3 LU/LC) in the HAR, the APS increased from 0.67 ha in 1955 to 0.74 ha in 2019.

Conversely, in the ROH, the APS for the specialised olive orchards (2.2.3.3 LU/LC) was recorded as 1.04 ha in 1955 and decreased to 0.24 ha in 2019. This indicates a distinct variation in the development of the modern olive cultivation industry across these two Landscape Units. In the HAR context, a reduction in the APS was observed in the intensive olive orchards (2.2.3.4 LU/LC), from 0.78 ha in 1988 to 0.67 ha in 2019. The observed trend in the ROH decreased from 0.38 ha in 2000 to 0.27 ha in 2019. The high-intensity olive orchards (2.2.3.5 LU/LC) exhibited a decreasing pattern in the HAR, ranging from 0.52 ha in 2000 to 0.28 ha in 2019. However, it is essential to note that the APS was calculated on small patches, indicating limited data availability.

Fig. 16 and Fig. 17 suggest a significant correlation between the olive landscape's fragmentation and the ED. As evident in Fig. 18, the ED values are sensitive to the level of fragmentation that has affected the evolution of the olive grove landscape. A noticeable downward trend is observed in the case of isolated olive trees with crops (2.2.3.1 LU/LC). The ED values for the HAR were determined to be 131.53 m/ha in 1955 and 58.22 m/ha in 2019.

Likewise, the ROH exhibited reduced values, from 17.24 m/ha in 1955 to 6.44 m/ha in 2019. A comparable pattern is observed in the case of olive rows mixed with crops (2.2.3.2 LU/LC). The HAR reduced its density from 225.97 m/ha in 1955 to 41.04 m/ha in 2019. The ROH had a density of 177.82 m/ha in 1955, decreasing to 22.11 m/ha in 2019. Based on these findings, it can be inferred that the ecological diversity of both landscapes in the Landscape Unit significantly decreased during the studied timeframe. This is because the ED indicates the potential health of the ecotones in the patches.

Conversely, the garden olive trees (2.2.3.6 LU/LC) exhibited an increasing trend in their ED values. The HAR notably increased its value from 1.99 m/ha in 1955 to 29.99 m/ha in 2019. In contrast, the ROH demonstrated a notable variation, ranging from 1.29 m/ha in 1955 to 17.42 m/ha in 2019, as observed in the studied area of the Landscape Unit. These findings reflect the potential ecological significance of this type of olive orchard, which is frequently associated with urban regions. The surge in ED values is evident upon examining the olive orchard typologies that are more intensive and productive. This can be attributed to the increased fragmentation of these olive orchards (as mentioned above), particularly regarding the HAR. The ED values of specialised olive orchards (2.2.3.3 LU/LC) increased from 2.94 m/ha in 1955 to 58.10 m/ha in 2019 in the HAR. Additionally, the ED values for the identical category rose from 0.44 m/ha in 1955 to 9.99 m/ha in 2019, per the ROH. In 2019, the intensive olive orchards (2.2.3.4 LU/LC) exhibited a significant range, with a high value of 44.06 m/ha in the HAR and a comparatively low value of 9.75 m/ha in the ROH. The high-intensive olive orchards (2.2.3.5 LU/LC) exhibited an upward trend in their ED, reaching 0.61 m/ha in the HAR and 0.18 m/ha in the ROH in 2019. However, this increase is deemed insignificant due to the limited NP.

As illustrated in Fig. 18, it is evident that the ED is strongly influenced by the fragmentation that has affected the evolution of the olive landscape. The isolated olive trees mixed with crops (2.2.3.1 LU/LC) showed a declining trend.

In the HAR, the ED was calculated as 131.53 m/ha in 1955, which decreased to 58.22 m/ha in 2019. Similarly, the values declined in the ROH, starting at 17.24 m/ha in 1955 and plummeting to 6.44 m/ha in 2019. The olive rows mixed with crops (2.2.3.2 LU/LC) showed a similar trend. In the HAR, the ED was 225.97 m/ha in 1955, dropping to 41.04 m/ha in 2019. The ROH started at 177.82 m/ha in 1955 and decreased to 22.11 m/ha in 2019.

These results indicate a significant decline in both landscapes' overall ecological richness over the investigated period since ED reflects the potential vitality of ecotones between patches. In contrast, the ED values for garden olive trees (2.2.3.6 LU/LC) revealed a growing trend. In the HAR, the ED amounted to 1.99 m/ha in 1955 and increased to 29.99 m/ha in 2019. The ROH ranged from 1.29 m/ha in 1955 to 17.42 m/ha in 2019. These findings prompt reflection on the potential ecological role of this particular type of olive orchard, which is often connected with urban areas.

When considering the more intensive and productive olive orchard typologies, ED values can be observed, likely due to the increased fragmentation of these olive orchards, particularly in the HAR. Finally, the ED values of specialised olive orchards (2.2.3.3 LU/LC) increased from 2.94 m/ha in 1955 to 58.10 m/ha in 2019 in the HAR. In the ROH, the ED values for the same class ranged from 0.44 m/ha in 1955 to 9.99 m/ha in 2019. The intensive olive orchards (2.2.3.4 LU/LC) exhibited a high value of 44.06 m/ha in the HAR and a low value of 9.75 m/ha in the ROH in 2019. The high-intensity olive orchards (2.2.3.5 LU/LC) also showed a trend of increasing ED values, reaching 0.61 m/ha in the HAR and 0.18 m/ha in the ROH in 2019, although these values are negligible due to the scarcity of the patches.

4. Discussion

This study's findings provide valuable insights into the landscape patterns and consequent changes for almost 70 years. The time references have been collected, considering the availability of reliable historical datasets from national and regional public authorities. Data availability from public entities is always critical, especially regarding landscape use and pattern analysis. For instance, the thematic map from 2019 was not enough to assess the various olive orchard cultivation types nor to analyse their transformations over time. So, spatial datasets from diversified sources have been thoroughly explored (see Table 1), along with the class details (see Table 3).

This study shows a significant outcome for 1955 and 2019 concerning the LU/LC change matrix based on the traditional Markovian chain approach representing the results in the form of a Sankey diagram (Fig. 13). The chart clearly shows the significant decrease in traditional olive cultivation types (isolated olive trees with crops and olive rows mixed with crops), from 48.5% (1955) to 3.5% (2019), of the total surface converted into arable land, impervious surfaces and others.

Moreover, the pace of changes over the time intervals has also been assessed(Fig. 9, Fig. 10, Fig. 11 and Fig. 12). For example, the significant surface losses of productive olive cultivation classes (2.2.3.1 LU/LC and 2.2.3.2 LU/LC) in the periods 1955–1977 and 1978–1988 were likely linked to heavy frosts in 1956 and 1985, which caused the death of millions of olive trees across Italy (see Fig. 10). To address this situation, the Italian government introduced subsidies (Official Journal of the Italian Republic 839 of 26 July 1956 (The President of the Council of Ministers, 1956), refinanced several times) to encourage farmers to adopt new and more productive olive orchards, leading to the birth of specialised olive farming. This is evident (Fig. 12, right side) in the rapid implementation of new intensive olive groves characterising the 1988–2000 period, which followed the frost of 1985. Subsidies from the CAP of the European Union in the 1980s also supported this evolution of the Italian olive sector to increase yields and mechanise operations in olive groves.

The transformation trends of LU/LC classes were analysed more thoroughly, dividing Cartoceto into Landscape Units. Different spatial patterns with distinct geomorphology and levels of anthropisation showed differentiated change patterns in LU/LC. For instance, currently, the HAR (middle hills with medium-high slopes on calcarenitic substrates and the presence of the historic village of Cartoceto) still shows a significant presence of the various types of olive groves, about 28% of its surface. On the contrary, the ROH (middle-low hills with medium-low slopes on pelitic substrates and the presence of scattered houses) is predominantly occupied by intensive arable land today, which covers about 70% of its surface. In comparison, the residual olive trees occupy a total area of less than 10%.

Examining specific olive grove typologies in the HAR and the ROH provides further insights into the impacts of landscape changes on these specific Landscape Units. The isolated olive trees mixed with crops (2.2.3.1 LU/LC) and olive rows mixed with crops (2.2.3.2 LU/LC) experienced a decline in ED values over time, indicating decreased ecological richness and the fragmentation of these olive landscapes. In contrast, the ED values for garden olive trees (2.2.3.6 LU/LC) showed an increasing trend, driven by the local community's desire to continue the local olive-growing tradition to meet family needs, which are referred to as "Sunday farmers" (Palazzo & Aristone, 2017). In fact, as reported by (Xi et al., 2018), urban expansion in agricultural areas leads to an increase in ED values, with a tendency towards fragmentation in the urbanization process. The more intensive olive orchard typologies, such as specialised olive orchards (2.2.3.3 LU/LC) and intensive olive orchards (2.2.3.4 LU/LC), exhibited varying ED values, reflecting the increased fragmentation in the HAR.

Landscape metrics have been exploited to understand the impacts of LU/LC change on landscape patterns, focusing on olive grove patches. The analysis has been conducted for the entire landscape and the landscape units, considering various LU/LC classes. Assessment of the landscape metrics, including NC, NP, APS, ED and SHDI, sheds light on the dynamics and implications of landscape changes over time. The metrics (see Table 4) were selected based on the research objectives.

eLIn the entire landscape, larger arable and urbanised patches influenced SHDI more than smaller and fragmented ones, such as the different olive groves. While SHDI did not show significant variations over the 70 years at the Entire Landscape level, other metrics, such as NC, ED and NP, showed diverse trends. The results indicated a significant increase in NC from 1955 to 2000, reflecting more heterogeneity and fragmentation in the landscape. This increase was mainly driven by the emergence of new urbanised areas and changes in agricultural practices, including the expansion of intensive olive orchards. The parallel rise in NP since 1988 further confirmed the trend of landscape fragmentation. The ED values declined from 1955 to 1988, indicating a decrease in landscape heterogeneity due to mechanisation and the regularisation of parcel shapes. However, from 1988 onwards, the ED values increased, indicating a higher degree of landscape fragmentation and ecotones between patches.

The metrics computed on the landscape units have shown more compelling results (i.e., Fig. 16, Fig. 17 and Fig.18). The analysis of the Landscape unit provides more detailed insights into the landscape dynamics and effects of different driving forces on LU/LC transformations. The SHDI values at the Landscape Unit level revealed diverse trends. On the one hand, in the HAR, the landscape exhibited high fragmentation and heterogeneity in 1955, which can be attributed to the sharecropping agricultural model. Over time, the SHDI values increased, indicating this unit's more complex and diverse landscape. On the other hand, the ROH experienced progressive simplification and homogenisation of the landscape, primarily due to cereal intensification. The different trends in the SHDI values among the Landscape Units highlighted the importance of considering the spatial scale in the landscape analysis.

Focusing on the two most significant landscape units (HAR and ROH), two distinct clusters have been formed. Plotting the computed values for SHDI and ED (two of the most significant metrics related to landscape diversity and functionality) against each other, the scatter plot has been obtained as shown in Fig. 19. The Figures illustrate that the drivers of landscape transformation in these two Landscape Units significantly differ over the entire period. In particular, the HAR exhibits higher values for both metrics, indicating a healthier landscape configuration. Furthermore, the red dashed lines denote the relative dispersion in 1955 and 2019. The shorter the line, the greater the similarity. Due to urbanisation and the replacement of traditional crops with predominantly arable lands, the degradation of the landscape matrix in the ROH results in the two Landscape Units moving apart in the plot. The visual analysis of the map presented in Fig. 19 confirms the simplification of the ROH compared to that of the HAR.

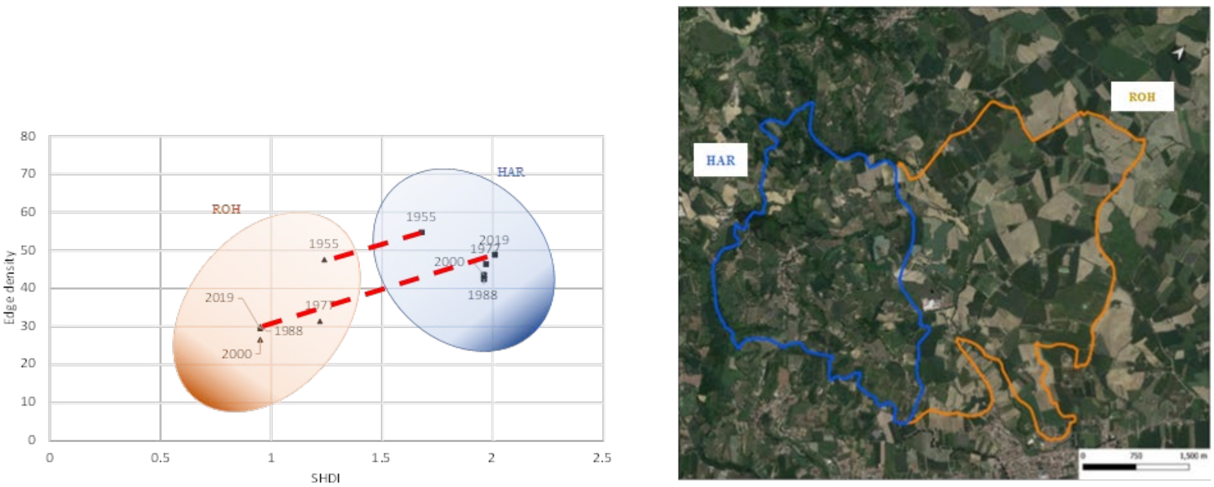


Fig. 19. The scatter plot displays the SHDI and ED values for the HAR(blue) and the ROH (orange) Landscape Units in each considered period. The red dashed lines indicate the relative dispersion in 1955 and 2019, with shorter lines suggesting more significant similarity. The map of the two Landscape Units is shown on the right-hand side.

The identified main drivers of change and their impacts on LU/LC and olive landscape changes in the studied area are summarised in Fig. 20 and Table 5., The landscape transformations have been modelled into five change patterns: persistence, intensification, substitution, abandonment and urbanisation(Table 5). The studied area could be divided into three parts (Fig.21), where the portions overlapping the ROH, TES and VBR are dominated mainly by the substituted arable land (yellow) or the urbanised land areas (red). In contrast, the HAR (blue) shows the persistence of traditional olive groves or their fragmentation into smaller parcels, with a shift to the intensification of high-yielding olive groves (orange). Finally, abandoned areas can be observed near the remaining woods (green).

Table 5. Persistence of traditional olive cultivation types and the five main patterns of change.

	Change pattern	**Cause**	**Colour**
1	Persistence	No changes	Blue
2	Intensification	Shift from traditional to intensive olive growing	Orange
3	Substitution	Shift from traditional olive growing to alternative crops (mainly arable lands)	Yellow
4	Abandonment	Abandonment and renaturation	Green
5	Urbanisation	Soil sealing by the expansion of built urban and commercial areas	Red
	Areas excluded from the analysis	LU/LC was different from traditional olive groves in 1955	Light grey

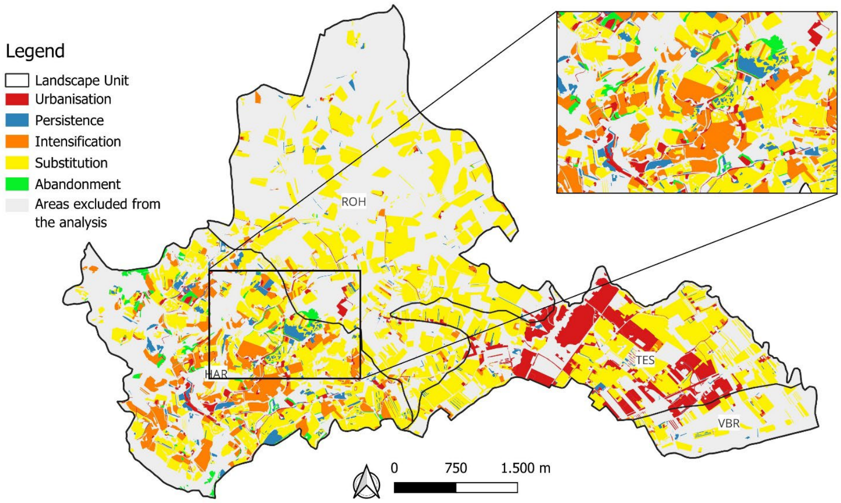


Fig. 20. Map of the five distinct dynamics observed between 1955 and 2019. The areas where traditional olive groves persist despite alterations (urbanisation, intensification, substitution and abandonment) in the surrounding landscape fabric are noteworthy.

(Gaston, 2010)Concerning the findings (As in Figure 20), the landscape simplification process has been illustrated by the values of the Shannon Diversity Index (SHDI) and the Edge Density (ED). The agricultural landscapes of the two UPs were almost identical, with 14 LU/LC for ROH and 13 LU/LC for HAR, covered by extensive crops in 1955.

Figure 6, referring to 1955, shows a strong presence of olive rows mixed with crops (2.2.3.2 LU/LC), corresponding to 38.14% in HAR and 35.19% in ROH. This indicates a tendency of the local community to maximise yield by using all available land, regardless of topographic characteristics, exposure, orientation or distance from roads. Many of these extensive areas have been replaced with higher-yielding crops due to the escalation of intensive farming in central Italy. In ROH, the creation of water catchments (32 NPs in 1977, constant until 2019) and several centre-pivot irrigation systems have further increased the removal of olive tree rows. This trend is evident in Fig. 19, where a significant shift has been observed from a heterogeneous landscape in 1955 to a simplified one. Figure 6 shows a shift towards the production of annual crops such as corn, wheat and sunflowers, defined as non-irrigated arable land (2.1.1 LU/LC), which occupied 80.82% of the area in 2019.

In contrast, the conversion of extensive olive growing areas has been noticed in the HAR either in the case of the isolated olive trees (2.2.3.1 LU/LC) mixed with crops or olive rows mixed with crops (2.2.3.2 LU/LC), within the high-density olive cultivation practices. This kind of cultivation practice represents a traditional approach driven by the benefits of the local communities in oil production, which has historical roots. In Figure 20, high heterogeneity in land use with a continuance of strong fragmentation has been observed along with the higher values of SHDI and ED. Non-irrigated arable land (2.1.1 LU/LC) has not had that much rise in HAR for various reasons. The topographical features, such as the historic centre of Cartoceto, have provided better possibilities for commercial oil farming for companies or city dwellers. Consequently, the extensive or abandoned olive growing areas have been converted into intensive olive growing areas, such as specialised olives orchards (2.2.3.3 LU/LC), intensive olive orchards (2.2.3.4 LU/LC), high-intensity olive orchards (2.2.3.5 LU/LC) and garden olive trees (2.2.3.6 LU/LC), as shown in Fig. 16, Fig. 17 and Fig. 18. Moreover, the high-yielding olive LULCs were introduced especially for the persistent areas (blue in Figure 20) in 2019. Thus, it has been observed that the heterogeneity of the past could be guaranteed. At the same time, the values of the NP, APS and ED indices (in Fig. 16, Fig. 17 and Fig. 18) did show a notable decrease, representing the deterioration of the existing ecological functions. Furthermore, severe abandonment of the more marginal olive-growing areas by the ditches has been noticed with lower yields due to the complicated cultivation possibilities. Therefore, the territory exhibits quite a mixed land use pattern, where it was difficult to identify the areas solely inclined towards the land-sparing model (Perfecto & Vandermeer, 2010).

Moreover, agricultural landscapes have been dwelling biodiversity with diversified cultivation practices for centuries (Gaston, 2010). Farming has shaped European landscapes for decades, creating a dynamic interaction between biodiversity and agricultural practices. However, the intensification of agriculture in the twentieth century led to the abandoning of traditional farming practices, causing a significant reduction in biodiversity. Many researchers are working to enhance environmental sustainability by conserving the existing biodiversity against higher land consumption for agricultural production. This recognises the necessity of implementing local strategies adapted to the characteristics of multifunctional landscapes (Grass et al., 2019).

Within this framework, traditional olive farming practices are eligible for contributions of up to 700 euros per hectare in Italy, in addition to the value of the production and other direct subsidies. In detail, Eco-scheme 3 (Italian Government, 2022b), which involves the preservation of the olive tree landscape, is valued at 220 euros per hectare. Meanwhile, Eco-scheme 2 (Italian Government, 2022a), which requires the maintenance of grass cover in fields, and Eco-scheme 5 (Italian Government, 2022c), which involves grass cover with specific species of interest for beekeeping, are valued at 120 euros and 250 euros per hectare, respectively. To these, contributions for conversion to or maintenance of organic farming practices may be added, potentially leading to a total contribution of approximately 1000 euros per hectare.

5. Conclusion

Our study extends current practices in multitemporal mapping and landscape analysis, providing a comprehensive overview of LU/LC change patterns and their impacts on olive landscapes in a GI area in central Italy. We reveal the complex dynamics and transformations over time by examining historical data, landscape metrics and various driving forces. The qualitative and quantitative methods integrated with the LU/LC analysis are part of a holistic approach that facilitates the definitions of anthropogenic and natural driving forces by applying different spatial models with the support of GIS techniques.

The LU/LC change matrix analysis between 1955 and 2019 highlights a significant decrease in traditional olive cultivation types converted into arable land, impervious surfaces, and other class types. This transformation is attributed to various drivers, including frost events, the introduction of new agricultural models, the expansion of intensive arable land, urbanisation and the ageing of farmers and citizens.

Landscape metrics, such as NC, NP, APS, ED and SHDI, provide valuable insights into landscape dynamics and fragmentation. The analysis of both the Entire Landscape and the Landscape Units reveals increased heterogeneity and fragmentation over time, driven by factors such as urbanisation, agricultural intensification and changes in LC patterns. In particular, the results of the landscape metrics show that applying the landscape units as a spatial model yields robust and positive outcomes related to ecological diversity, allowing the identification of three landscape spatial patterns and five change patterns (Fig. 20).

The ecological impacts of landscape changes have also been assessed on olive groves. The results show that specific olive grove typologies have experienced fragmentation and a decline in environmental richness. In contrast, others have manifested an increasing trend, potentially due to their connection with urban areas. These findings underscore the importance of ecological factors and biodiversity conservation in land management strategies.

The results also demonstrate the significance of considering the different spatial patterns in landscape analysis. Different landscape units, characterised by distinct geomorphology and levels of anthropisation, exhibit diverse trends in Landscape Unit evolution. For example, the HAR maintains a significant presence of traditional olive groves, while the ROH landscape unit is predominantly occupied by intensive arable land. These findings emphasise the influence of local factors on LU/LC patterns and highlight the need for tailored approaches to land management. This leads to the conclusion that the HAR shows remarkably higher diversity and richness (Fig. 19) than the simplified landscape pattern of the other units, underlying the pivotal role of traditional olive groves' tenacity in preserving a higher quality and more functional landscape. Such fortitude is due to the area's physiography and the local community's stronger historical attachment to traditional cultivation models of olive trees, both mixed with crops and arranged in rows.

The findings highlight the need for sustainable land management practices that balance agricultural productivity, ecological conservation and cultural heritage preservation. Future research should continue to monitor and analyse landscape dynamics, considering the ongoing changes in LU/LC patterns and the potential impacts of climate change. Such studies will give decision-makers and land managers valuable insights for promoting sustainable development and preserving landscapes.

In light of the ongoing debate among stakeholders within the PDO area, who are deliberating two alternative futures for the region between the expansion of intensive and highly intensive cultivation areas and the preservation of traditional structures tied to the local landscape and historical culture, the present study, alongside analyses of landscape transformations, has facilitated the trial of an innovative agroecological olive grove. The establishment of this grove was funded by the regional project Oliv-GET. In this context, the design of even a few new "ecological" olive groves in the area to be integrated within olive growing is of great significance, as it serves to break up the uniformity of the landscape.

Moreover, this approach aligns with the current trend of promoting tourism connected to olive landscapes. Specifically, we refer to regional regulations (Casciola, 2023) that, in response to the national law on olive oil tourism, are beginning to foster these types of activities in rural areas (Italian Republic, 2022). Future research can benefit from exploring approaches, such as moving windows landscape metrics tools, to capture landscape changes that consider finer spatial scales and innovative remote and proximal sensing to provide deeper insights into landscape change drivers, patterns and impacts. These insights can help inform decision-making processes, promote sustainable land management practices and ensure the preservation of olive landscapes for future generations.

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References

AGEA. (n.d.). *Italian Agricultural Payments Agency*. www.agea.gov.it

Aguilera, F., Valenzuela, L. M., & Botequilha-Leitão, A. (2011). Landscape metrics in the analysis of urban land use patterns: A case study in a Spanish metropolitan area. *Landscape and Urban Planning*, *99*(3), 226–238. https://doi.org/https://doi.org/10.1016/j.landurbplan.2010.10.004

Alberti, M., Marzluff, J. M., Shulenberger, E., Bradley, G., Ryan, C., & Zumbrunnen, C. (2008). Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. *Urban Ecology: An International Perspective on the Interaction Between Humans and Nature*, *53*(12), 143–158. https://doi.org/10.1007/978-0-387-73412-5_9

Alphan, H., Karamanli, E., Derse, M. A., & Uslu, C. (2022). Analyzing pattern features of urban/rural residential land use change: The case of the southern coast of Turkey. *Land Use Policy*, *122*, 106348. https://doi.org/https://doi.org/10.1016/j.landusepol.2022.106348

Andrieu, E., Ladet, S., Heintz, W., & Deconchat, M. (2011). History and spatial complexity of deforestation and logging in small private forests. *Landscape and Urban Planning*, *103*(2), 109–117. https://doi.org/https://doi.org/10.1016/j.landurbplan.2011.06.005

Angold, P. G., Sadler, J. P., Hill, M. O., Pullin, A., Rushton, S., Austin, K., Small, E., Wood, B., Wadsworth, R., Sanderson, R., & Thompson, K. (2006). Biodiversity in urban habitat patches. *Science of the Total Environment*, *360*(1–3), 196–204. https://doi.org/10.1016/j.scitotenv.2005.08.035

Bielecka, E. (2020). Gis spatial analysis modeling for land use change. A bibliometric analysis of the intellectual base and trends. *Geosciences (Switzerland)*, *10*(11), 1–21. https://doi.org/10.3390/geosciences10110421

Bogunovic, I., Telak, L. J., Pereira, P., Filipovic, V., Filipovic, L., Percin, A., Durdevic, B., Birkás, M., Dekemati, I., & Comino, J. R. (2020). Land management impacts on soil properties and initial soil erosion processes in olives and vegetable crops. *Journal of Hydrology and Hydromechanics*, *68*(4), 328–337.

Br, S., & Kubacka, M. (2021). *Landscape Diversity and the Directions of Its Protection in Poland Illustrated with an Example of Wielkopolskie Voivodeship*.

Casciola, D. (2023). Oleoturismo sempre più protagonista nelle Marche, la giunta regionale presenta la proposta di legge. *Il Sole 24 Ore*. https://www.ilsole24ore.com/art/oleoturismo-sempre-piu-protagonista-marche-giunta-regionale-presenta-proposta-legge-AE1jGxvC

Commission, E. (2023). *Common agricultural policy*. https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en

CONSORZIO OLIO DOP CARTOCETO. (2021). *Oliv get*. https://www.oliocartocetodop.it/progetto-oliv-get/

De Gennaro, B., Notarnicola, B., Roselli, L., & Tassielli, G. (2012). Innovative olive-growing models: an environmental and economic assessment.

Journal of Cleaner Production, *28*, 70–80.

De la Hera, I., Unanue, A., & Aguirre, I. (2009). Effects of area, age and vegetation cover on breeding avian species richness in urban parks from Victoria-Gasteiz. *Munibe*, *57*, 195–206.

Delogu, G., Caputi, E., Perretta, M., Ripa, M. N., & Boccia, L. (2023). Using PRISMA Hyperspectral Data for Land Cover Classification with Artificial Intelligence Support. In *Sustainability* (Vol. 15, Issue 18). https://doi.org/10.3390/su151813786

Di Fazio, S., Modica, G., & Zoccali, P. (2011). Evolution trends of land use/land cover in a Mediterranean forest landscape in Italy. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *6782 LNCS*(PART 1), 284–299. https://doi.org/10.1007/978-3-642-21928-3_20

Di Vita, G., D'Amico, M., La Via, G., & Caniglia, E. (2013). Quality Perception of PDO extra-virgin Olive Oil: Which attributes most influence Italian consumers? *Agricultural Economics Review*, *14*(389-2016–23498), 46–58.

Díez, C. M., Moral, J., Cabello, D., Morello, P., Rallo, L., & Barranco, D. (2016). Cultivar and tree density as key factors in the long-term performance of super high-density olive orchards. *Frontiers in Plant Science*, *7*, 1226.

Dimopoulos, T., & Kizos, T. (2020). Mapping change in the agricultural landscape of Lemnos. *Landscape and Urban Planning*, *203*, 103894. https://doi.org/https://doi.org/10.1016/j.landurbplan.2020.103894

Duarte, F., Jones, N., & Fleskens, L. (2008). Traditional olive orchards on sloping land: Sustainability or abandonment? *Journal of Environmental Management*, *89*(2), 86–98. https://doi.org/10.1016/j.jenvman.2007.05.024

Erraach, Y., Sayadi, S., Gomez, A. C., & Parra-Lopez, C. (2014). Consumer-stated preferences towards Protected Designation of Origin (PDO) labels in a traditional olive-oil-producing country: The case of Spain. *New Medit*, *13*(4), 11–19.

European. Commission. (1992). Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Union*, *206*(7), 50.

European Commission. (2021). *Geographical indications and quality schemes explained*. Agriculture and Rural Development. https://agriculture.ec.europa.eu/farming/geographical-indications-and-quality-schemes/geographical-indications-and-quality-schemes-explained_en

Fahrig, L., Baudry, J., Brotons, L., Burel, F. G., Crist, T. O., Fuller, R. J., Sirami, C., Siriwardena, G. M., & Martin, J. (2011). Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecology Letters*, *14*(2), 101–112.

Feranec, J. (2016). Project CORINE land cover. In *European Landscape Dynamics* (pp. 39–44). CRC Press.

Forman. (2014). *Foundations BT - The Ecological Design and Planning Reader* (F. O. Ndubisi (ed.); pp. 217–234). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-491-8_21

Forman, R. T. T., & Godron, M. (1981). Patches and structural components for a landscape ecology. *BioScience*, *31*(10), 733–740.

Garden, J. G., Mcalpine, C. A., Possingham, H. P., & Jones, D. N. (2007). Habitat structure is more important than vegetation composition for local-level management of native terrestrial reptile and small mammal species living in urban remnants: A case study from Brisbane, Australia. *Austral Ecology*, *32*(6), 669–685. https://doi.org/10.1111/j.1442-9993.2007.01750.x

Gaston, K. J. (2010). Valuing common species. *Science*, *327*(5962), 154–155.

Gay, S., Louwagie, G., Sammeth, F., Ratinger, T., Marechal, B., Prosperi, P., Rusco, E., Terres, J., van der Velde, M., & Baldock, D. (2009). *Final report on the project'Sustainable Agriculture and Soil Conservation (SoCo)'*. Joint Research Centre (Seville site).

Gómez, J. A., Infante-Amate, J., González de Molina, M., Vanwalleghem, T., Taguas, E. V, & Lorite, I. (2014). Olive cultivation, its impact on soil erosion and its progression into yield impacts in Southern Spain in the past as a key to a future of increasing climate uncertainty. *Agriculture*, *4*(2), 170–198.

Gómez, J. A., Sobrinho, T. A., Giráldez, J. V, & Fereres, E. (2009). Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. *Soil and Tillage Research*, *102*(1), 5–13.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., & Tiede, J. (2019). Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People and Nature*, *1*(2), 262–272.

Guerrero-casado, J., Carpio, A. J., Tortosa, F. S., & Villanueva, A. J. (2021). *Science of the Total Environment Environmental challenges of intensive woody crops : The case of super high-density olive groves*. *798*.

Guerrero-Casado, J., Carpio, A. J., Tortosa, F. S., & Villanueva, A. J. (2021). Environmental challenges of intensive woody crops: The case of super high-density olive groves. *Science of The Total Environment*, *798*, 149212.

Herold, M., Couclelis, H., & Clarke, K. C. (2005). The role of spatial metrics in the analysis and modeling of urban land use change. *Computers, Environment and Urban Systems*, *29*(4), 369–399.

Herold, M., Goldstein, N. C., & Clarke, K. C. (2003). The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote*

Sensing of Environment, *86*(3), 286–302.

Hesselbarth, M. H. K., Nowosad, J., Signer, J., & Graham, L. J. (2021). *Open-source Tools in R for Landscape Ecology*. 97–111.

Hürol, H. Y. and B. O. V. and Y. (2018). The conservation of traditional olive oil mills in Cyprus. *Journal of Architectural Conservation*, *24,2*(Routledge), 105–133. https://doi.org/10.1080/13556207.2018.1483551

Ingegnoli, V. (2015). *INGEGNOLI V (2015) LANDSCAPE BIONOMICS, BIOLOGICAL-INTEGRATED LANDSCAPE ECOLOGY, SPRINGER*. https://doi.org/10.1007/978-88-470-5226-0

ISTAT. (2023). *Adminstat ITALIA*. Italian Institute for Statistics. http://dati.istat.it/index.aspx?lang=en&SubSessionId=a8ce4981-cf62-4ae4-ada0-a526b72fb6e2#

Italian Government. (2022a). *Eco-schema 2 - Inerbimento delle colture arboree*. Ministry of Agriculture, Food Sovereignty and Forestry. https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/18875

Italian Government. (2022b). *Eco-schema 3 - Salvaguardia olivi di particolare valore paesaggistico*. Ministry of Agriculture, Food Sovereignty and Forestry.

Italian Government. (2022c). *Eco-schema 5 - Misure specifiche per gli impollinatori*. Ministry of Agriculture, Food Sovereignty and Forestry. https://www.politicheagricole.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/18879

Italian Republic. (2004). *Officila Journal of the Italian Republic directive 291 of 13 December 2004*. Official Journal of the Italian Republic. https://www.gazzettaufficiale.it/eli/id/2004/12/13/04A11617/sg

Italian Republic. (2022). *Official Journal of the Italian Republic directive 26 gennaio 2022 Linee guida e indirizzi in merito ai requisiti e agli standard minimi di qualita' per l'esercizio dell'attivita' oleoturistica. (22A01009) (GU Serie Generale n.37 del 14-02-2022)*. Official Gazette of the Italian Republic. https://www.gazzettaufficiale.it/eli/id/2022/02/14/22A01009/sg

Kohli, D., Sliuzas, R., & Stein, A. (2016). Urban slum detection using texture and spatial metrics derived from satellite imagery. *Journal of Spatial Science*, *61*(2), 405–426. https://doi.org/10.1080/14498596.2016.1138247

Lausch, A., Blaschke, T., Haase, D., Herzog, F., Syrbe, R.-U., Tischendorf, L., & Walz, U. (2015). Understanding and quantifying landscape structure – A review on relevant process characteristics, data models and landscape metrics. *Ecological Modelling*, *295*, 31–41. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2014.08.018

Lu, D., Mausel, P., Brondízio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, *25*(12), 2365–2401. https://doi.org/10.1080/0143116031000139863

Maggiore, G., Semeraro, T., Aretano, R., De Bellis, L., & Luvisi, A. (2019). GIS analysis of land-use change in threatened landscapes by Xylella fastidiosa. *Sustainability (Switzerland)*, *11*(1), 1–24. https://doi.org/10.3390/su11010253

Mairech, H., Lopez-Bernal, A., Moriondo, M., Dibari, C., Regni, L., Proietti, P., Villalobos, F. J., & Testi, L. (2020). Is new olive farming sustainable? A spatial comparison of productive and environmental performances between traditional and new olive orchards with the model OliveCan. *Agricultural Systems*, *181*, 102816.

Mao, Z., Centanni, J., Pommereau, F., Stokes, A., & Gaucherel, C. (2021). Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system. *Ecosystem Services*, *47*, 101220.

Marche, A. (2023). *Agenzia Servizi Settore Agroalimentare delle Marche*. http://www.assam.marche.it/en/ http://www.meteo.marche.it/blogmeteoassam.aspx?postid=5843b211-9043-4aaa-929e-ef0da7ec0b2b

Marche Region. (n.d.). *Land Department of Marche Region*. https://www.regione.marche.it/Regione-Utile/Paesaggio-Territorio-Urbanistica/Cartografia/Repertorio/Cartausosuolo10000_78-84

McGarigal, K., & Marks, B. J. (1995). FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. *General Technical Report - US Department of Agriculture, Forest Service*, *PNW-GTR-351*.

Millán, M. G., Pablo-Romero, M. del P., & Sánchez-Rivas, J. (2018). Oleotourism as a sustainable product: An analysis of its demand in the south of Spain (Andalusia). *Sustainability*, *10*(1), 101.

Ministero Ambiente. (n.d.). *Geoportale Nazionale*. Retrieved October 10, 2022, from http://www.pcn.minambiente.it/GN/

Modica, G., Praticò, S., & Di Fazio, S. (2017). Abandonment of traditional terraced landscape: A change detection approach (a case study in Costa Viola, Calabria, Italy). *Land Degradation and Development*, *28*(8), 2608–2622. https://doi.org/10.1002/ldr.2824

Moreno, V. M., Rubio, J. M. Q., & Guerra, I. R. (2011). Potencial del oleoturismo como diversificación económica del sector cooperativo agrario: el caso español. *Revista de Ciencias Sociales*, *17*(3), 533–541.

Moser, D., Zechmeister, H. G., Plutzar, C., Sauberer, N., Wrbka, T., & Grabherr, G. (2002). Landscape patch shape complexity as an effective measure for plant species richness in rural landscapes. *Landscape Ecology*, *17*(7), 657–669. https://doi.org/10.1023/A:1021513729205

Orciani, M., Frazzica, V., Colosi, L., & Galletti, F. (2007). *Gregoriano Cadastre : transformation of old maps into Geographical Information*

System and their contribution in terms of acquisition , processing and communication of historical data. *2*(2), 92–104.

Orlandi, F., Rojo, J., Picornell, A., Oteros, J., Pérez-Badia, R., & Fornaciari, M. (2020). Impact of climate change on olive crop production in Italy. *Atmosphere*, *11*(6), 595.

Ostermann, O. P. (1998). The need for management of nature conservation sites designated under Natura 2000. *Journal of Applied Ecology*, *35*(6), 968–973.

Palazzo, A. L., & Aristone, O. (2017). Peri-urban matters. Changing olive growing patterns in central Italy. *Sustainability*, *9*(4), 638.

Perfecto, I., & Vandermeer, J. (2010). The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proceedings of the National Academy of Sciences*, *107*(13), 5786–5791.

Pompeu, J., Soler, L., & Ometto, J. (2018). Modelling land sharing and land sparing relationship with rural population in the Cerrado. *Land*, *7*(3). https://doi.org/10.3390/land7030088

Pulido-Fernández, J. I., Casado-Montilla, J., & Carrillo-Hidalgo, I. (2019). Introducing olive-oil tourism as a special interest tourism. *Heliyon*, *5*(12), e02975. https://doi.org/https://doi.org/10.1016/j.heliyon.2019.e02975

Puyravaud, J.-P. (2003). Standardizing the calculation of the annual rate of deforestation. *Forest Ecology and Management*, *177*(1), 593–596. https://doi.org/https://doi.org/10.1016/S0378-1127(02)00335-3

QGIS Development Team. (2022). *QGIS Geographic Information System. Open Source Geospatial Foundation Project.* http://qgis.osgeo.org

Rallo, Barranco, D., Castro-García, S., Connor, D. J., Gómez del Campo, M., & Rallo, P. (2013). High-density olive plantations. *Horticultural Reviews Volume 41*, 303–384. https://doi.org/10.1002/9781118707418.ch07

Rao, P., Tassinari, P., & Torreggiani, D. (2023). Exploring the land-use urban heat island nexus under climate change conditions using machine learning approach: A spatio-temporal analysis of remotely sensed data. *Heliyon*, *9*(8), e18423. https://doi.org/https://doi.org/10.1016/j.heliyon.2023.e18423

Rescia, A. J., & Ortega, M. (2018). Quantitative evaluation of the spatial resilience to the B. oleae pest in olive grove socio-ecological landscapes at different scales. *Ecological Indicators*, *84*, 820–827. https://doi.org/https://doi.org/10.1016/j.ecolind.2017.09.050

Rodríguez Sousa, A., Barandica, J., Sanz-Cañada, J., & Rescia, A. (2019). Application of a dynamic model using agronomic and economic data to evaluate the sustainability of the olive grove landscape of Estepa (Andalusia, Spain). *Landscape Ecology*, *34*. https://doi.org/10.1007/s10980-019-00773-3

Ruiz-Benito, P., Gómez-Aparicio, L., & Zavala, M. A. (2012). Large-scale assessment of regeneration and diversity in Mediterranean planted pine forests along ecological gradients. *Diversity and Distributions*, *18*(11), 1092–1106.

Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication. Urbana, IL: University fo Illinois Press. cited in Magurran, AE, 2004, Measuring biological diversity*. Blackwell Publishing: Oxford, UK.

Taguas, E. V, Marín-Moreno, V., Díez, C. M., Mateos, L., Barranco, D., Mesas-Carrascosa, F.-J., Pérez, R., García-Ferrer, A., & Quero, J. L. (2021). Opportunities of super high-density olive orchard to improve soil quality: Management guidelines for application of pruning residues. *Journal of Environmental Management*, *293*, 112785. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.112785

The President of the Council of Ministers. (1956). *Official Journal of the Italian Republic 839 of 26 July 1956*. Official Journal of the Italian Republic. https://www.normattiva.it/atto/caricaDettaglioAtto?atto.dataPubblicazioneGazzetta=1956-08-08&atto.codiceRedazionale=056U0839&atto.articolo.numero=0&atto.articolo.sottoArticolo=1&atto.articolo.sottoArticolo1=0&qId=5cc8d9a4-21e5-4136-a4ae-24c4a6bb9ce7&tabID

Tous, Romero, A., & Hermoso, J. F. (2007). The hedgerow system for olive growing. *Olea (FAO Olive Network)*, *26*, 20–26.

Usman, M., & Nichol, J. E. (2022). Changes in agricultural and grazing land, and insights for mitigating farmer-herder conflict in West Africa. *Landscape and Urban Planning*, *222*, 104383. https://doi.org/https://doi.org/10.1016/j.landurbplan.2022.104383

Uuemaa, E., Antrop, M., Roosaare, J., Marja, R., & Mander, Ü. (2009). Landscape metrics and indices: an overview of their use in landscape research. *Living Reviews in Landscape Research*, *3*(1), 1–28.

Vizzari, M. (2011). Spatio-temporal analysis using urban-rural gradient modelling and landscape metrics. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *6782 LNCS*(PART 1), 103–118. https://doi.org/10.1007/978-3-642-21928-3_8

Walz, U. (2015). Indicators to monitor the structural diversity of landscapes. *Ecological Modelling*, *295*, 88–106.

Weng, Q. (2002). Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. *Journal of Environmental Management*, *64*(3), 273–284.

Wu, J., & Hobbs, R. (2002). Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. *Landscape Ecology*, *17*(4), 355–365.

Xi, Y., Thinh, N. X., & Li, C. (2018). *Spatio-Temporal Variation Analysis of Landscape Pattern Response to Land Use Change from 1985 to 2015 in Xuzhou City , China*. https://doi.org/10.3390/su10114287