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

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10 Abstract: This research examines the evolution of olive landscapes in Cartoceto, Italy, post-World War II. This study investi-11 gates the structural and functional attributes of two distinct olive cultivation models, mixed olive groves with a low tree density and 12 high-density olive groves. The research employs remote sensing aerial imagery and land use cartography to reconstruct the past 13 terrain and classify distinct categories of olive orchards. Landscape metrics are utilised to evaluate the impact of human and natural 14 factors on the temporal development of olive landscapes across multiple spatial configurations, defined as Landscape-scale and 15 sub-units or Landscape Units. The results indicate that olive landscapes have experienced noteworthy alterations, characterised by 16 a reduction in the conventional large-scale system and an increase in specialised planting models of smaller sizes, classified as 17 "high intensity". The region surrounding Cartoceto's historic centre has conserved a greater variety of mixed olive heritage and has 18 witnessed the emergence of novel high densities of trees compared to other areas. Obtaining these results has been facilitated solely 19 by utilising diverse spatial configurations of smaller sub-units than the entire landscape. The outcomes of this investigation provide 20 a foundation for forthcoming enquiries into olive terrains and the development of sustainable rural landscape strategies. 21

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

### 23 1. Introduction

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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,

\*Corresponding authors. *E-mail address*: s.chiappini@univpm.it, e.marcheggiani@univpm.it 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).

54 However, an integrated approach consisting of the level of intervention and the well-being of local populations 55 could ensure a sustainable agricultural production system aligning with biodiversity conservation. This will also entail 56 strategies tailored to the unique characteristics of local and regional contexts, transcending the dichotomy between 57 "land sharing" and "land sparing" concerning a diversified land management practice (Pompeu et al., 2018). At the 58 same time, particular areas have managed to preserve traditional olive cultivation practices, contributing to the vitality 59 of local communities and historic villages. Although it has been shown that intensive and highly intensive olive 60 orchards are better for the environment than traditional olive orchards in terms of water use efficiency, soil organic 61 carbon sequestration, and less evaporation and runoff, the ecosystem services that olive-growing landscapes provide 62 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<sup>-1</sup>), intensive (up to 350 - 700 trees ha<sup>-1</sup>) and super high-density olive orchards (up to 1200 - 2500 trees ha<sup>-1</sup>) (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

82 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 83 84 quantifying land use and land cover (LU/LC) changes (Alberti et al., 2008). Moreover, the accuracy and resolution of 85 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). 86

87 This study is part of a larger project, Olive-Get (CONSORZIO OLIO DOP CARTOCETO, 2021), funded by the 88 European Union's European Agricultural Fund for Rural Development (EAFRD), which aims to promote innovation 89 (remote and proximal sensing and data sharing) in traditional or monumental olive groves while preserving high-90 quality standards and skilled management. In this context, our research seeks to provide objective territorial evidence 91 to support farmers and decision-makers based on multitemporal analysis of historical data, landscape metrics and local 92 driving forces. We will extend current practices in landscape analysis and provide a comprehensive analysis of land 93 use/land cover (LU/LC) and their impacts on olive landscapes, revealing the complex dynamics and transformations 94 that have occurred over time in the GI's PDO of Cartoceto. Furthermore, the combined use of different spatial 95 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 96 97 land use. This approach will provide a more solid understanding of the trajectories of change in olive grove landscapes 98 and their broader socio-ecological implications, based on the different landscape patterns.

#### 99 2. Materials and Methods

#### 100 2.1. Studied area

101 Cartoceto is a picturesque town in central Italy, specifically in the Marche region. The municipality covers an area of 24 km<sup>2</sup> (43° 46' 4" north, 12° 52' 54" east) and has a population of 7,926 as of 2023. The population density of 102 103 Cartoceto is approximately 341.7 inhabitants per square kilometre, nearly double the regional average (ISTAT, 2023). 104 The town is near the Metauro River's hydrographic basin, which flows from west to east until reaching the Adriatic 105 Sea. The altitude in Cartoceto ranges from 27 to 377 m above sea level (Fig. 1).

106 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 107 108 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 109 110 cultivating mixed arable land with olive trees and vinevards and practising polyculture on small farms spanning a few 111 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 112 various LU dynamics, such as intensified arable lands, urban expansion, and protected areas of the Natura 2000 113 (Ostermann, 1998) is a network of protected areas. It provides essential habitat for many species (European. 114

115 Commission, 1992) and human settlements.



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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).



131 132 133

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

#### 134 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.

#### 144 2.3. Dataset

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145 The sources of the data used in this study are shown in Table 1. Along with regional and national LUMs from 1984 146 and 2011, aerial photographs of Italy from 1955, 1977, 1988, 2000 and 2019 were gathered. The orthophotos and 147 aerial pictures came from a variety of sources. The Italian military geographic institute (in Italian, Istituto Geografico 148 Militare Italiano, IGMI) provided three partially overlapping aerial images taken in September 1955 (Italian survey 149 mission Volo Base Gruppo Areonautico Italiano, GAI 55); the web-formatted aerial orthophotos taken in 1977 and 150 1988 were acquired from the local cartographic service (Marche Region, n.d.). These orthophotos are georeferenced 151 digital grayscale images in Italy's Zone 2 of the Monte Mario Projection System (EPSG: 3004). The Italian Ministry 152 of Environment purchased a set of 2,000 colour orthophotos in WMS format (EPSG: 32633-WGS 84 UTM Zone 33N) 153 from the National Geoportal (Ministero Ambiente, n.d.). Nine digital orthophotos taken between April and September 154 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: 32633-155 156 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

- 161 third levels. The AGEA provided the LUM for 2011, which consists of 37 classes arranged into three levels of 162 landscape classification.
- 163 These data sources, which include LUMs and aerial photographs, serve as the cornerstone for the analysis carried 164 out in this study.
- 165 **Table 1.** Collected datasets.
- 166

N.	Title	Year	Source	Detail
				Hard copy scanned at 2500 dpi
1	A	1955	Italian military geographical institute (IGM)	Scale 1:33,000
1	Aeriai photos			Altitude: 5000 m
				Average image resolution: 0,50 m
				B/W band, digital GeoTIFF
h	A anial antha mhataa	1077	Cartographic Office of Marche	Scale 1:10,000
Z	Aeriai ortito-pilotos	19//	Region	Altitude: 5700 m
				Image resolution: 1,50 m
				B/W band, digital GeoTIFF
2	Aprial orthombotos	1099	Cartographic Office of Marche	Scale 1:10,000
3	Aeriai ortito-pilotos	1900	Region	Altitude: 11500 m
				Image resolution:1,50 m
				Vector format
	Land use map     1984     Cartographic Office of Marche     Scale 1:10,000       42 land cover classes	Scale 1:10,000		
4	Land use map	use map 1984 Cartographic Office of Marche 42 land cover classes	42 land cover classes	
			1001	Three hierarchical levels of LC/LU classification
				Minimum Mapping Unit 0,04 ha
				RGB digital, GeoTIFF
5	Aerial artha photos	2000	National Geoportal	Scale 1:10,000
5	Achai onno-photos	2000	National Ocoportal	Altitude: -
				Image resolution:1,50 m
				Vector format
	Pado Soils Landscapes			Scale 1:250000
6	Map	2006	ASSAM	Three hierarchical levels of Landscape Units (Region, Province, Systems)
				Minimum mapping unit of 0,5 ha
				Vector format
				37 land cover classes
7	I and use man	2011		Scale –
/	Land use map	2011	A.G.E.A.	Altitude: -
				Third hierarchical level of LU/LC classification;
				Minimum Mapping Unit 0,16 ha
0	A amal anthe	2010		RGB + NIR digital GeoTIFF
ð	Aeriai orino-photos	2019	A.U.E.A.	scale 1:5'000

-	Altitude: -
	Image resolution:0,20 m

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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.

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

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



Fig. 4. Landscape units.

# 185 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).

191 As shown in Table 3, we incorporated an additional hierarchical level (4° level) beyond the three primary levels 192 that delineate major LU/LC transformations and land consumption in the studied area. This design was consistent with 193 the specific characteristics of olive plantations, considering factors such as the number of trees per hectare and the 194 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 195 196 research on olive cultivation, which typically does not incorporate such innovations (Br & Kubacka, 2021), (Lu et al., 197 2004). Olive groves are often viewed primarily from a production perspective, overlooking their significance as components of the historical landscape. 198

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

# 202 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	3.1 Forest	3.1.1 Broad-leaved forest	3.1.1.1 Broad-leaved forest
	areas			3.1.1.2 Riparian vegetation
4	Wetlands	4.1 Inland waters	4.1.1 Watercourses	
			4.1.2 Water bodies	



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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 211 212 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 213 comparable and consistent class system across almost 70 years. To further refine the photointerpretation quality for 214 1955, 1977, and 1988, we relied on regional data, specifically the LUM in 1984 (plate number 4 in Table 1). Similarly, 215 216 we used the AGEA's LUM in 2011 (plate number 7 in Table 1) as a vector basis to support the interpretation of the 217 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. 218

# 219 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).

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

$$\begin{array}{l} 240 \\ 241 \end{array} \qquad q[\%] = A_{t2} - A_{t1} \tag{2}$$

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 252 253 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 254 was based on a literature review (Aguilera et al., 2011; Alphan et al., 2022; Hesselbarth et al., 2021; Usman & Nichol, 255 256 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), 257 258 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 259 significance is provided in Table 4. Each class's total area and perimeter were extracted using the "Statistics 260 261 Categories" tool in QGIS (QGIS Development Team., 2022).

262 **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	$APS = \sum_{i=1}^{n} \frac{\sum_{i=1}^{n} a_{i}}{n} = \frac{A}{n}$	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.

		m
Shannon's diversity	Number	$HDI = -\sum (P_i \cdot \ln P_1)$
index (SHDI)	INUIIIDEI	$\sum_{i=1}^{n}$

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.

#### 263 **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.

#### 268 *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.
- 271



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

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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).

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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.



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

303 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 304 305 37.41% (274.77 ha) of the hills and reliefs (HAR) surrounding the historic settlement of Cartoceto. It occupied 32.34% 306 (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 307 surfaces (TES), with a surface area of 64.83% (310.67 ha). The TES represents flat areas connecting the alluvial 308 309 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, 310 311 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. 312

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, com plexity level, fragmentation and other disturbances(Ingegnoli, 2015).

# 327 *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).

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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.

341 On the one hand, Olive rows mixed with crops (2.2.3.2 LU/LC) experienced the most significant contraction 342 between 1955 and 1977, with a Net Change of -20.96%, although the Annual Change rate was relatively slower at -343 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 1955-344 1977, with an Annual Change rate of 10.85% and a Net Change of +2.41%. The growth rate for the most intensive 345 olive groves was relatively limited, with Net Change values below 1% and Annual Change rates below 2%. The 346 347 exception was between 1988 and 2000 when intensive olive orchards (2.2.3.4 LU/LC) experienced a high growth rate 348 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. 349

350 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, 351 352 -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 353 HAR and the ROH. The Net Change and Annual Change rate for the category of isolated olive trees mixed with crops 354 (2.2.3.1 LU/LC) exhibited a negative trend throughout the period, with more pronounced HAR changes than the ROH. 355 In contrast, favourable variations in both the Net Change and the Annual Change rate were recorded for the categories 356 357 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. 358



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.

### 373 *3.3. Transition matrix and Sankey diagram*

Regarding the diachronic LU/LC change, the comparison between 1955 and 2019 was particularly significant. This 374 time interval allowed us to compute the change matrix (in hectares) based on the traditional Markovian chain (Weng, 375 2002). Markovian chains and transition matrices have long been used in modelling changes in LU/LC on various 376 spatial scales (Ruiz-Benito et al., 2012; Weng, 2002). The results are presented in Fig. 13 using a Sankey diagram. 377 Sankey diagrams illustrate the extent and final destination of LU/LC changes over different periods. The diagram in 378 379 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 380 merely 3.5% in 2019, which were predominantly converted into non-irrigated arable land (2.1.1 LU/LC), urban fabric 381 (1.1 LU/LC) and industrial or commercial units (1.2.1.1 LU/LC). 382

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.



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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).

391 The most significant transformation affecting the traditional olive groves was the intensification of LU/LC towards 392 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 393 substantial acreage (626.26 ha) of olive rows mixed with crops (2.2.3.2 LU/LC) into non-irrigated arable land (2.2.1 394 LU/LC), as depicted in Fig. 13. In terms of the evolution of the traditional olive groves, the conversion of isolated 395 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 396 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 397 high-intensity olive orchards (2.2.3.5 LU/LC). Additionally, 3.32 ha of the same class were converted into garden 398 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).

### 411 *3.4. Results of landscape metrics*

412 Landscape changes were assessed using landscape metrics for the Entire Landscape and the Landscape Unit. These

413 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.
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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.

424 The NP metric confirmed this trend, particularly from 1988 onwards. In 1955, there were 2,319 patches across the 425 studied area – a high number, considering the period before the extensive mechanisation of agriculture that began in 426 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

434 across the studied area. This trend likely contributed to an overall increase in ecotones between patches.



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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, 444 the HAR showed significant fragmentation and heterogeneity, attributed to the numerous patches and complex spatial 445 arrangement typical of the sharecropping agricultural model. The SHDI value for this further increased over the years 446 and stabilised at 2.01 in 2019. This fragmentation and diversity can be attributed to the high number of LU/LC classes 447 (NC), which increased from 14 in 1955 to 16 in 2019. This heterogeneity also significantly limited the APS, which 448 remained around 0.85 ha throughout the period. The ED value peaked in 1955 (54.72 m/ha), decreased in 1988 (42.46 449 m/ha) and then increased to 48.87 m/ha in 2019. The NP exhibited a heterogeneous trend, with 1,192 patches recorded 450 451 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.





470 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
 471 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.

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

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486 Units, ranging from 4 to 110 in the HAR and 6 to 91 in the ROH in 1955 and 2019, respectively. Modern and highly 487 productive olive orchards have undergone distinct phases of growth. The specialised olive orchards (2.2.3.3 LU/LC) 488 exhibited a consistent upward trend from 1955 to 2019. This trend was particularly pronounced in the HAR category, 489 where the NP increased from 6 to 113. The cultivation of intensive olive orchards (2.2.3.4 LU/LC) experienced a 490 notable expansion from 1977 onwards in areas classified as HAR and from 1988 onwards in areas classified as ROH. 491 Additionally, the magnitude of the increase was more remarkable for the HAR than for the ROH. In 2000, the high-

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.

493 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 494 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 495 consistent decrease in the olive rows mixed with crops (2.2.3.2 LU/LC) was also documented. In the ROH, the area 496 of the APS decreased from 0.78 ha in 1955 to 0.13 ha in 2019. Hence, the conventional cultivation of olives persisted 497 498 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 (2.2.3.6 499 500 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 501 APS increased from 0.67 ha in 1955 to 0.74 ha in 2019. 502

503 Conversely, in the ROH, the APS for the specialised olive orchards (2.2.3.3 LU/LC) was recorded as 1.04 ha in 504 1955 and decreased to 0.24 ha in 2019. This indicates a distinct variation in the development of the modern olive 505 cultivation industry across these two Landscape Units. In the HAR context, a reduction in the APS was observed in 506 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 507 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 508 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 509 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 520 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 521 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 522 523 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 524 525 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) 526 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 527 528 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 529 530 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 531 532 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 544 545 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 546 547 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 548 in 2019. The high-intensity olive orchards (2.2.3.5 LU/LC) also showed a trend of increasing ED values, reaching 0.61 549 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 550 patches. 551

# 552 **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.

564 Moreover, the pace of changes over the time intervals has also been assessed(Fig. 9, Fig. 10, Fig. 11 and Fig. 12). 565 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 566 the death of millions of olive trees across Italy (see Fig. 10). To address this situation, the Italian government 567 introduced subsidies (Official Journal of the Italian Republic 839 of 26 July 1956 (The President of the Council of 568 569 Ministers, 1956), refinanced several times) to encourage farmers to adopt new and more productive olive orchards, 570 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 571 572 the CAP of the European Union in the 1980s also supported this evolution of the Italian olive sector to increase 573 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 581 landscape changes on these specific Landscape Units. The isolated olive trees mixed with crops (2.2.3.1 LU/LC) and 582 583 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 584 (2.2.3.6 LU/LC) showed an increasing trend, driven by the local community's desire to continue the local olive-585 growing tradition to meet family needs, which are referred to as "Sunday farmers" (Palazzo & Aristone, 2017). In fact, 586 as reported by (Xi et al., 2018), urban expansion in agricultural areas leads to an increase in ED values, with a tendency 587 588 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 589 the increased fragmentation in the HAR. 590

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 596 597 ones, such as the different olive groves. While SHDI did not show significant variations over the 70 years at the Entire 598 Landscape level, other metrics, such as NC, ED and NP, showed diverse trends. The results indicated a significant 599 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 600 expansion of intensive olive orchards. The parallel rise in NP since 1988 further confirmed the trend of landscape 601 fragmentation. The ED values declined from 1955 to 1988, indicating a decrease in landscape heterogeneity due to 602 603 mechanisation and the regularisation of parcel shapes. However, from 1988 onwards, the ED values increased, 604 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). 605 606 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 607 the one hand, in the HAR, the landscape exhibited high fragmentation and heterogeneity in 1955, which can be 608 attributed to the sharecropping agricultural model. Over time, the SHDI values increased, indicating this unit's more 609 complex and diverse landscape. On the other hand, the ROH experienced progressive simplification and 610 homogenisation of the landscape, primarily due to cereal intensification. The different trends in the SHDI values 611 612 among the Landscape Units highlighted the importance of considering the spatial scale in the landscape analysis.

613 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 614 functionality) against each other, the scatter plot has been obtained as shown in Fig. 19. The Figures illustrate that the 615 drivers of landscape transformation in these two Landscape Units significantly differ over the entire period. In 616 particular, the HAR exhibits higher values for both metrics, indicating a healthier landscape configuration. 617 618 Furthermore, the red dashed lines denote the relative dispersion in 1955 and 2019. The shorter the line, the greater the 619 similarity. Due to urbanisation and the replacement of traditional crops with predominantly arable lands, the 620 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. 621







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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.

642 (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 643 two UPs were almost identical, with 14 LU/LC for ROH and 13 LU/LC for HAR, covered by extensive crops in 1955. 644 645 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 646 all available land, regardless of topographic characteristics, exposure, orientation or distance from roads. Many of 647 648 these extensive areas have been replaced with higher-yielding crops due to the escalation of intensive farming in 649 central Italy. In ROH, the creation of water catchments (32 NPs in 1977, constant until 2019) and several centre-pivot 650 irrigation systems have further increased the removal of olive tree rows. This trend is evident in Fig. 19, where a 651 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 (2.1.1 652 653 LU/LC), which occupied 80.82% of the area in 2019.

654 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 655 high-density olive cultivation practices. This kind of cultivation practice represents a traditional approach driven by 656 the benefits of the local communities in oil production, which has historical roots. In Figure 20, high heterogeneity in 657 land use with a continuance of strong fragmentation has been observed along with the higher values of SHDI and ED. 658 Non-irrigated arable land (2.1.1 LU/LC) has not had that much rise in HAR for various reasons. The topographical 659 features, such as the historic centre of Cartoceto, have provided better possibilities for commercial oil farming for 660 companies or city dwellers. Consequently, the extensive or abandoned olive growing areas have been converted into 661 662 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, 663 Fig. 17 and Fig. 18. Moreover, the high-yielding olive LULCs were introduced especially for the persistent areas (blue 664 665 in Figure 20) in 2019. Thus, it has been observed that the heterogeneity of the past could be guaranteed. At the same 666 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 667 marginal olive-growing areas by the ditches has been noticed with lower yields due to the complicated cultivation 668 possibilities. Therefore, the territory exhibits quite a mixed land use pattern, where it was difficult to identify the areas 669 670 solely inclined towards the land-sparing model (Perfecto & Vandermeer, 2010).

671 Moreover, agricultural landscapes have been dwelling biodiversity with diversified cultivation practices for 672 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 678 679 hectare in Italy, in addition to the value of the production and other direct subsidies. In detail, Eco-scheme 3 (Italian 680 Government, 2022b), which involves the preservation of the olive tree landscape, is valued at 220 euros per hectare. 681 Meanwhile, Eco-scheme 2 (Italian Government, 2022a), which requires the maintenance of grass cover in fields, and 682 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 683 or maintenance of organic farming practices may be added, potentially leading to a total contribution of approximately 684 685 1000 euros per hectare.

### 686 5. Conclusion

687 Our study extends current practices in multitemporal mapping and landscape analysis, providing a comprehensive 688 overview of LU/LC change patterns and their impacts on olive landscapes in a GI area in central Italy. We reveal the 689 complex dynamics and transformations over time by examining historical data, landscape metrics and various driving 690 forces. The qualitative and quantitative methods integrated with the LU/LC analysis are part of a holistic approach 691 that facilitates the definitions of anthropogenic and natural driving forces by applying different spatial models with 692 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.

707 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 708 in Landscape Unit evolution. For example, the HAR maintains a significant presence of traditional olive groves, while 709 710 the ROH landscape unit is predominantly occupied by intensive arable land. These findings emphasise the influence 711 of local factors on LU/LC patterns and highlight the need for tailored approaches to land management. This leads to 712 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 713 and more functional landscape. Such fortitude is due to the area's physiography and the local community's stronger 714 715 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

720 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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