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ORIGINAL RESEARCH

Assessment of ecotone changes over the last six decades in two cultural landscapes: The case of the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site and of the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site

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Abstract
Cultural landscapes are often characterized by a complex landscape structure providing different habitats, nesting place, food reservoirs and ecological networks, for different fauna and flora species. Edges between different land uses can be assimilated to ecotones, and land uses changes over the years also affect ecotones characteristics and associated biodiversity. This study intends to contribute to the understanding of the relation between land use changes and ecotone characteristics and changes in two Italian cultural landscapes inscribed in the UNESCO WHL and in the FAO GIAHS (Globally Important Agricultural Heritage Systems) Programme, applying a GIS-based methodology. In the last six decades, in both study sites, agricultural areas decreased with consequent increase of forests and shrublands. This trend affected ecotones presence and density, but in different ways depending on the characteristics of the study areas. In the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site the analyses recorded an overall reduction of ecotones total length (− 6.4%), in particular of the first level ecotones (the ones between forests and agricultural areas) due to the loss of high altitude pastures that have been recolonized by forests, and of the second level ecotones (the ones between different types of cultivated areas) due to the agricultural mosaic simplification caused by the reduction of mixed cultivations and the spread of monocultures. In the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site, similar land use trends caused an increase of the total length of first (+53.7%) and second level ecotones (+13.5%). This different behavior highlighted for the two sites, demonstrates that the relation between land use changes and ecotones changes is site-specific. The average density of first level ecotones decreased in both the study sites (− 20.2% in the UNESCO site and − 30.3% in the GIAHS site), while the maximum density remains high (424 m/ha in the UNESCO site and 794 m/ha in the GIAHS site). The applied methodology and the classification of ecotones according to a hierarchical system demonstrated to be effective in their identification and assessment. The study demonstrated

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that cultural landscapes are characterized by important ecotones networks and that preserving landscapes of recognized cultural value also means protecting ecotones, and associated habitats and biodiversity. Instead of only focusing on increasing protected areas number and surface, EU Biodiversity Strategy for 2030 should consider traditional cultural landscapes as a pillar for biodiversity conservation.

Keywords Cultural landscape · Ecotone · Biodiversity · Ecological network · UNESCO · GIAHS

Introduction

Cultural landscapes are recognized to provide a wide range of ecosystem services to rural communities around the world (Zerbe 2022). These landscapes, resulting from the coevolution and adaptation of human activities to surrounding environments, are capable of providing high quality food (Folgado-Fernández et al. 2019), they represent important touristic destinations (Torquati et al. 2017; Panzera et al. 2021), they are part of the local identity (Riechers et al. 2020) and contribute to the preservation of agrobiodiversity and biodiversity (Agnoletti and Santoro 2022a, b; Santoro et al. 2020). Cultural landscapes are in fact often characterized by a complex landscape structure, capable of creating different habitats, nesting place, food sources and ecological networks, for different fauna species, in particular for small mammals, birds and invertebrates (Yan et al. 2021; Estrada-Carmona et al. 2022). Therefore, the conservation of cultural landscapes does not only mean the preservation of a cultural heritage, but also an effective contribution to biodiversity conservancy, especially in parts of the world, as in Europe, where rural landscapes are facing a homogenization in terms of landscape structures in the last decades.

The importance of cultural landscapes for biodiversity conservation is also recognized by different entities and policies. In 1992, UNESCO added the category of "cultural landscape" to the World Heritage Convention, becoming the first international legal instrument to recognise and protect these landscapes. The Food and Agriculture Organization (FAO) recognizes the close relation between agricultural heritage systems (another term for cultural landscapes) and biodiversity, considering that the agrobiodiversity definition has been published in 1999 (FAO 1999); according to this definition, agrobiodiversity is "the variety and variability of animals, plants and micro-organisms that are used directly or indirectly for food and agriculture, including crops, livestock, forestry and fisheries. […]. It also includes the diversity of non-harvested species that support production (soil micro-organisms, predators, pollinators), and those in the wider environment that support agro-ecosystems (agricultural, pastoral, forest and aquatic) as well as the diversity of the agro-ecosystems." This definition clarifies that human activities can enhance and preserve biodiversity. In addition, agrobiodiversity is one of the five criteria of the GIAHS (Globally Important Agricultural Heritage Systems) Programme, the main world programme specifically dedicated to agricultural heritage systems, established by the FAO in 2002. More recently, in 2014, the Florence Declaration signed by UNESCO and CBD (UNESCO and SCBD 2014) states that "the current state of biological and cultural diversity in Europe results from the combination of historical and on-going environmental and land use processes and cultural heritage" and that "landscapes rich in biocultural diversity are often those managed by small-scale or peasant farmers".

Cultural landscapes are mainly described, assessed, and monitored based on the structure of the landscape mosaic, in terms of number of land uses, number and size of patches, juxtaposition and spatial relation among different land uses (Frazier and Kedron 2017; Gökyer 2013). From the biodiversity point of view, the different land uses can be assimilated to different habitats or (agro)ecosystems, while the transition areas among different ecosystems or agroecosystems (i.e. the space between forests and cultivated areas) can represent an ecotone (Gosz 1991). Ecotones, in fact, can be defined as boundaries between ecosystems (Hansen and di Castri 1992), or as areas of transition between ecological communities, ecosystems, and/or ecological regions, occurring at multiple spatial scales (Kark 2017; Odum 1971). Ecotones can be found between natural, seminatural and/or human-generated ecosystems. Moreover, an ecotone is a dynamic landscape feature with spatial and temporal properties, as its characteristics can vary with land use or environmental changes, on local or global scales (Wiens et al. 1985; Forman 1995). Different studies (Smith et al. 1997; Qingsuo et al. 1997; Kark 2013) demonstrated that ecotones are particularly important for species richness, diversity and abundances, though some exceptions may occur, and that populations in ecotones are potentially more resistant to environmental changes (including climate change, invasions of pathogens or of invasive species) as they are adapted to small habitats among different ecosystems and therefore to balancing among different conditions. Despite EU rural policies in their last programing have subsided non-productive ecological focus areas, in the last decades agricultural intensification and, on the other side, abandonment of agriculture in marginal areas, are threatening both the conservation of cultural landscape and the related biodiversity and ecotones (Flohre et al. 2011; Angelstam et al. 2021).

The Prosecco Hills of Conegliano and Valdobbiadene (inscribed in the UNESCO World Heritage List since 2019) and the Olive Groves of the Slopes between Assisi and Spoleto (a GIAHS site since 2018), represent two typical Italian cultural landscape. The Prosecco Hills of Conegliano and Valdobbiadene UNESCO site is characterized by a "mosaic landscape where the plots dedicated to vineyards […] coexist with forest patches […]. The patches of vineyards are often connected to one another by small woodlands, hedges, rows of trees that serve also as corridors connecting different habitats. […] The result is a harmonious landscape with outstanding scenic values that maintains a delicate environmental and functional balance" (UNESCO 2019). The landscape mosaic is therefore composed of few land uses, mainly forests and vineyards, but their peculiar spatial arrangement, together with the rugged morphology of the site, is of key importance for the local biodiversity as the ecotone areas among these two land uses can be crucial for local fauna species, creating a dense and wide ecological network. The slopes between Assisi and Spoleto are instead characterized by olive groves cultivated on dry-stone or earth terraces, surrounded by forests at the higher altitudes. The production of high-quality extravirgin olive oil, recognized by the Denomination of Protected Origin (DPO), together with the fact that the area represents an important destination for rural tourism, guarantees farmers good incomes (even if cultivating on terraces has higher costs) and the preservation of a cultural landscape of ancient origin. While both areas, as many European cultural landscapes, have been investigated for what concern the land use structures and their features, the characteristics and the transformations of their ecological networks represented by the ecotonal zones between different land uses, still need to be assessed.

Assessing the ecotones structure in these important cultural landscapes recognized by UNESCO and FAO, as well as measuring their changes in the last decades, can contribute to the understanding of the consequence of socio-economic changes and land use changes on the local ecological network and on biodiversity at the landscape scale. In addition,

there is the need to understand of how the protection of cultural landscapes can be effective in the preservation of ecotones and of biodiversity. Therefore, the main aims of this study are the following:

- Investigate and quantify the presence of ecotones between forests and cultivated areas in two Italian cultural landscape of global importance, recognized by UNESCO or FAO.
- Assess and measure the transformations that may have affected ecotones in the last decades within these two sites.
- Contributing to the understanding of the effectiveness of cultural landscapes protection on the preservation of ecotones.

Materials and methods

The study areas

The first study area is represented by the entire Core Area of the UNESCO site The Prosecco Hills of Conegliano and Valdobbiadene. The area has a total surface of 9,191 hectares and is located in Veneto Region in northeastern Italy (Fig. 1). The area has been inscribed in the UNESCO World Heritage List in 2019 among the cultural landscapes, and is mainly known for Prosecco wine production but, differently from the surrounding plains, it preserves a unique landscape of great aesthetic beauty and cultural significance. Local farmers adapted to the local morphology, made by a system of *hogbacks* (parallel cordons of steep hills) that stretch from the east to the west (Busoni and Bondesan 2019), by developing vine cultivation on very steep slopes through the realization of earth embankments, locally called *ciglioni*. The area, in fact, is characterized by steep slopes, with average slope equal to 38%. The local landscape is mainly composed of only two land uses, vineyards and forests, but the disposition and the relations of these two land uses create a peculiar landscape mosaic, as different types and levels of interpenetration can be found (UNESCO 2019). Forests are predominantly composed of deciduous species, including *Castanea sativa*, *Fraxinus ornus*, *Ostrya carpinifolia*, *Quercus pubescens*, *Quercus robur*, *Quercus petraea*, *Robinia pseudoacacia* (Del Favero et al. 2000). Altitude ranges from 106 to 611 m a.s.l., while the average yearly temperature is of 12.6 °C and the yearly average precipitation is equal to about 1099 mm. Two Natura 2000 Network sites partly fall within the UNESCO site.

The second study area correspond to the GIAHS site of the Olive Groves of the Slopes between Assisi and Spoleto, which extends for about 9213 hectares in Umbria Region, in central Italy. The site is located along a mainly west-facing slope, between 200 and 600 m a.s.l., that has been remodeled through the realization of drystone terraces and earth terraces to obtain suitable areas for olive cultivation, but also representing a defense against hydrogeological risk and an efficient system for the preservation of water and soil. Forests are mainly represented by deciduous oaks (*Quercus pubescens*, *Q. cerris*) and by *Quercus ilex* (AAVV 2018). A Regional Park and six Natura 2000 Network sites are found along the border of the GIAHS site. The site is also one of the three study sites (the other ones are in Morocco and Algeria) of the MedAgriFood Resilience project, funded through the Joint Call of the Cofund ERA-NETs SUSFOOD2 and FOSC, whose aim is to identify the possible social and environmental shocks impacting agroforestry and agri-food heritage

Fig. 1 The two study areas are located in Italy, one in northeast (the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site) and one in the centre (the Olive Groves of the Slopes between Assisi and Spoleto)

systems in the Mediterranean area, applying a multidisciplinary approach linking together landscape, climatological studies, social role and biodiversity.

The climate of the two study areas falls under the temperate oceanic climate (Cfb) classification (Kottek et al. 2006) and both sites are included in the National Register of Historical Rural Landscapes, an institution established by the Italian Ministry of Agriculture, Food and Forestry Policies, to safeguard and promote traditional landscapes and practices (Agnoletti and Santoro 2022a, b), testifying the importance and the high integrity of their cultural landscapes.

Methodology

The first phase of the study focused on the realization of an updated and detailed mapping of the two study sites, distinguishing among the different land uses, in order to identify the ecotone zones between them. Since the landscape of the area is characterized by

a high complexity, in terms of landscape mosaic fragmentation, it was not possible to rely on land use maps at national or regional level, therefore a detailed manual photointerpretation has been done. The historical landscape has been assessed using black and white aerophotos of 1954 for the Olive Groves of the Slopes of Assisi Spoleto and of 1960 for the Prosecco UNESCO site, according to their availability and quality; the current landscape has been investigated through high-resolution orthophotos (20 cm of resolution) of the year 2021 for the Prosecco site and of 2022 for the Assisi-Spoleto GIAHS site, and through field surveys to validate the photointerpretation. The photointerpretation and all the following spatial analysis have been performed with QGIS 3.28 software, with the help of GRASS GIS and of SAGA and GRASS plugins (Fig. 2).

After this first phase, the patch edges have been extracted for the different study areas and years as linear vector layers, through the use of the SAGA tool Shared Polygon Edges. A subsequent visual check has been carried out by controlling the linear vector layers.

It has been decided to apply a hierarchical classification of the identified edges, classifying them in three different levels of ecotones, depending on the two land uses they divide (Fig. 3).

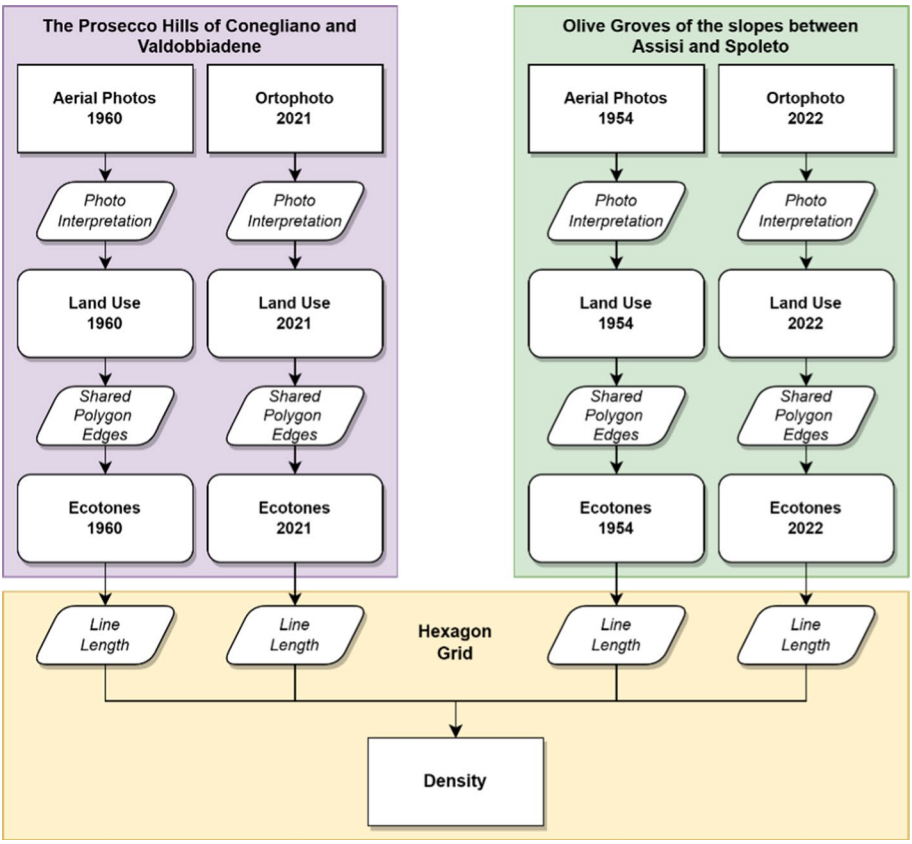

Fig. 2 Scheme of the methodology applied for the assessment of ecotones in the two Italian cultural landscapes

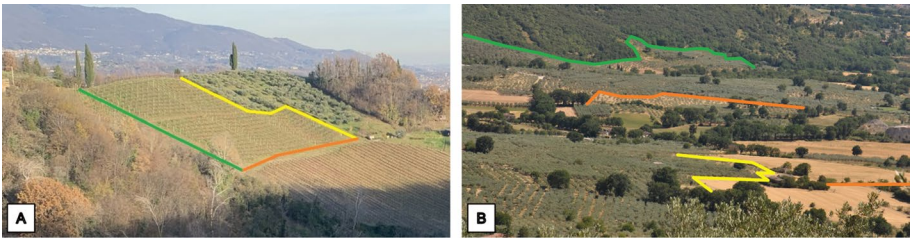

Fig. 3 Example of the three level of edges in the two sites, The Prosecco Hills of Conegliano Valdobbiadene (A) and the Olive Grooves of the Slopes between Assisi and Spoleto. First level edges in green, Second level in yellow, third level in orange

1. First level ecotones: the edges that divide two different land use macro-categories, i.e. dividing a forest patch from an agricultural one.
2. Second level ecotones: the edges dividing two different land uses, i.e. dividing a vineyard from a pasture.
3. Third level ecotones: the edges dividing two different patches with the same land use; in fact, even if the land use is the same, the patches have been divided if a physical feature was present (i.e. a ditch or a dry-stone wall).

Edges shared between forests or agricultural areas with anthropic areas (built-up areas, roads, urban parks, …) have not been considered as ecotones, as anthropic areas can't be considered ecological ecosystems or agro-ecosystems. Total length of each level of ecotone has been measured for each study areas and for each year, as well as their overall length increase or decrease.

After these first elaborations, a density variation analysis has been performed and density variation maps have been produced. This elaboration is based on a 10-hectares hexagon grid created through the MMQGIS plug-in. Hexagons grids are used for performing density analysis of ecological and/or landscape features as this kind of shape offers two main advantages: any given point inside a hexagon is closer to the center of that hexagon respect to the use of other shapes of the same size; hexagon is the only geometric shape for regular tessellations that shares a real border with every neighbor (Adamczyk and Tiede 2017). The choice of the hexagon size has been made after attempts with different sizes (5, 8, 10 ha), considering the overall extent of the two study areas and bearing in mind that different hexagons sizes can lead to different values of the measured landscape metrics (Venturi et al. 2021). The density variation analysis allowed to obtain data about the relevance of the ecotones at landscape level, both regarding the entire area and at a more local scale using the hexagons grids. For each year and for each study area, the density of the different levels of ecotones has been calculated as m/ha; the maximum density has been calculated for each hexagon, while the average density has been calculated as the total length of each ecotone level divided by the total area of the study site. In addition, every hexagon has been classified according to the variation of ecotones density to obtain density variation maps:

- Absence: no ecotones present in the past or to the present;
- Disapperead: ecotones were found in the past but not to the present;
- Reduced: ecotones reduced their density respect to the past of more than -10%;

- Unchanged: ecotones density of the past is similar (between -10% and + 10%) to the one of the present;
- Increased: ecotones increased their density respect to the past of more than + 10%;
- New: ecotones were not found in the past but are to the present;

Results

Land use changes in the last six decades

Both areas underwent similar transformation regarding land uses in the last six decades (Table 1). Agricultural areas decreased, especially in the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site (− 33%), where all the high altitude pastures were abandoned due to reduction of free-grazing livestock, while in the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site the reduction of agricultural surfaces was less widespread (− 13%), mainly corresponding to the abandonment of more marginal olive groves. The consequence of this trend has been the increase of forests and shrublands due to secondary successions on abandoned terrains, corresponding to + 42% in the UNESCO site and to + 33% in the GIAHS site. In both study sites urban areas increased, but their growing in terms of total hectares was not particularly significant.

The number of land uses of the most recent year is always higher than the one of the past, but this is largely influenced by the lower quality of the past black and white aerophotos that did not allow the proper identification of all the land use types, especially of the different typologies of mixed cultivations. For the same reason the number of patches of the past is lower, even if a certain degree of fragmentation of the landscape mosaic occurred over the decades.

The ecotones in the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site

In 1960 most of the ecotones identified for The Prosecco Hills of Conegliano and Valdobbiadene UNESCO site belonged to the first level (53.4%), followed by the second (25.8%) and the third (20.8%) level (Table 2). While first and second level ecotones were evenly widespread within the UNESCO site, third level ecotones were mainly found in the western part, where the morphology is less rugged and the gentle hills are all covered by vineyards, and along the southern border (Fig. 4). In 2021, the situation was slightly different, with the first level still as the most widespread typology (45.4%), followed by the third (36.9%) and the second level (17.7%). In 2021, the western part of the study area is almost entirely occupied by third level ecotones.

The analysis of the ecotones transformation showed an overall limited reduction, equal to -6.4%, but with significative differences among the different levels. First and second level ecotones underwent a decrease, equal to − 20.5% and to − 35.7%, respectively. The reduction of the first level ecotones is due to the loss of the pastures that were found at higher altitudes until the 1970s and that have been completely recolonized by the forest, causing a homogenization of the landscape mosaic and the loss of the ecotones between forests and pastures. The decrease of second level ecotones has been caused by the simplification of the landscape mosaic too, with the reduction of mixed cultivations and orchards and the spread of vineyards, that nowadays represent almost all the agricultural areas. Third level ecotones increased the overall length, but this value is affected by the reduced quality

Table 1 Changes of land use macro-categories in the two study areas

	Prosecco Hills of Conegliano and Valdobbiadene UNESCO site					Olive groves of the Slopes between Assisi and Spoleto GIAHS site				
	1960		2021		Variation	1954		2022		Variation
	ha	%	ha	%	%	ha	%	ha	%	%
Agricultural areas	5,319.20	57.9	3583.52	39.0	− 33	7410.62	81.3	6444.42	70.7	− 13
Forests and shrublands	3678.32	40.0	5205.98	56.6	+42	1252.23	13.7	1663.05	18.2	+33
Urban areas and roads	190.67	2.1	393.67	4.3	+106	407.68	4.5	978.34	10.7	+140
Unproductive areas	3.01	0.03	8.11	0.09	+169	42.39	0.47	25.22	0.28	− 41
Land use number	19		41		+115	30		40		+33
Patch number	12,384		17,133		+38	7561		13,129		+74

Table 2 Total length of the first, second and third level of ecotones and their variation in kilometers and percentage for The Prosecco hills of Conegliano and Valdobbiadene UNESCO site

	1960		2021		1960–2021	
	km	%	km	%	km	%
1st level	1093	53.4	869	45.4	− 224	− 20.5
2nd level	527	25.8	339	17.7	− 188	− 35.7
3rd level	425	20.8	706	36.9	+281	+66.1
Total	2045	100.0	1914	100.0	− 131	− 6.4

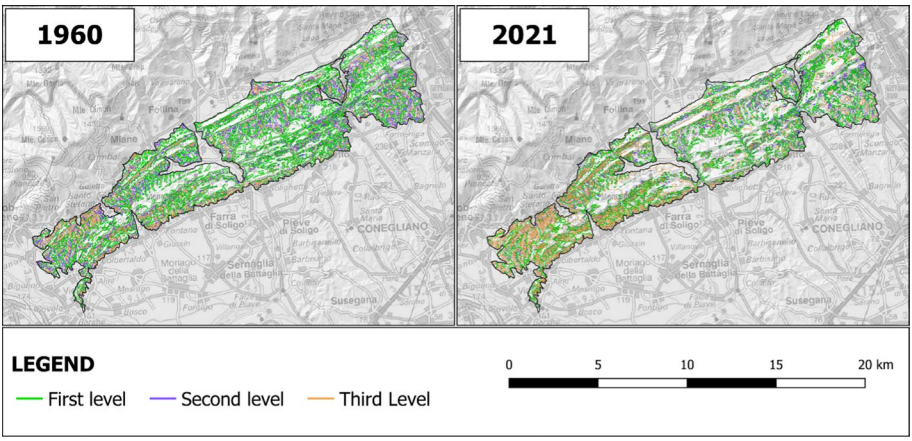

Fig. 4 Ecotones of first, second and third level identified and mapped for 1960 and 2021 for the Prosecco hills of Conegliano and Valdobbiadene UNESCO site

Table 3 Total length of the first, second and third level of ecotones and their variation in kilometers and percentage for the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site

	1954		2022		1954–2022	
	km	%	km	%	km	%
1st level	430	28.0	661	37.2	+231	+53.7
2nd level	370	24.1	420	23.6	+50	+13.5
3rd level	738	48.0	696	39.2	− 42	− 5.7
Total	1538	100.0	1777	100.0	+239	+15.5

of the 1960 black and white aerophotos that did not allow the precise identification of all the physical boundaries among adjacent vineyards.

The ecotones in the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site

In both 1954 and 2022 most of the ecotones identified for the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site have been classified as third levels, representing the 48% and 39.2% of all ecotones, respectively (Table 3). The first level represented 28% in 1954 and 37.2% in 2022, while the second level accounted for 24.1% in 1954 and for

23.6% in 2022. First level ecotones are mainly found around the city of Foligno, and in the southern part of the study site, especially in 2022 (Fig. 5). Second level ecotones, instead, are more concentrated along the western boundary of the site, corresponding to the areas at lower altitudes and with a greater concentration on different types of crops (olive groves, arable land, vineyards), while third level ecotones are almost evenly distributed within the study site.

The period 1954–2022 recorded an overall length increase equal to + 15.5%, but again with significative differences among the different levels. First and second level ecotones underwent an increase, equal to + 53.7% and to + 13.5%, respectively, while third level ecotones decreased in the period 1954–2022 (− 5.7%). The significant increase of the length of the first level ecotones is due to the abandonment of some olive groves with consequent secondary successions and colonization by shrublands and forests.

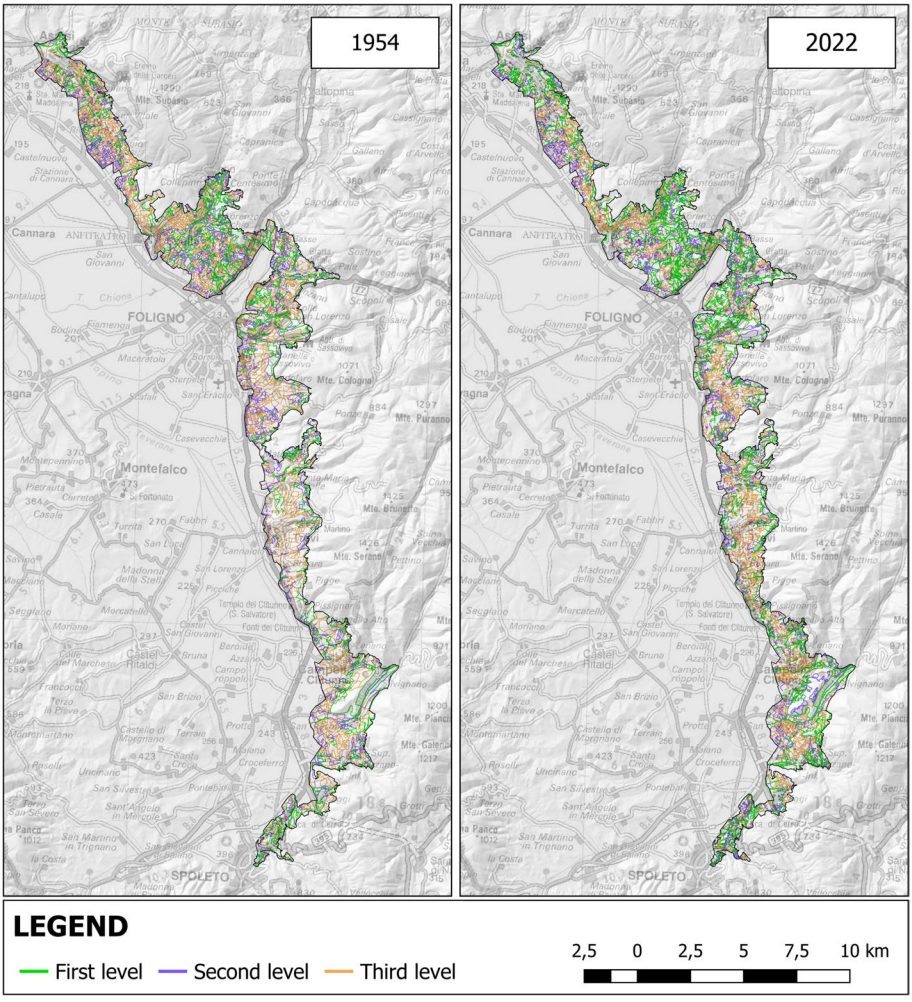

Fig. 5 Ecotones of first, second and third level identified and mapped for 1954 and 2022 for the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site

Density variation analysis

First level ecotones average density (calculated as an average value for the entire study areas) decreased in both the study sites, with a reduction of − 20.2% in the UNESCO site and of − 30.3% in the GIAHS site (Table 4). The density of the second level ecotones also decreased, but their average density was for both periods and both areas lower than the ones of the first level ecotones; the higher density of first level ecotones testifies their particular ecological and landscape relevance. The average density of the third level ecotones increased in both of the study sites in the considered time interval.

In the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site the maximum density of the first level ecotones decreased, passing from 502 to 424 m/ha (− 15.5%), while for the second and third levels it increased with the highest value (781 m/ha) recorded for the second level ecotones in 2021. The situation of the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site is a little bit different; the maximum density of first level ecotones significantly increased (from 442 to 794 m/ha, + 79.7%) even if the average density decreased, while the maximum density of second and third level ecotones slightly decreased in the last 68 years.

In the last decades, the land use changes that occurred in the two study areas have also affected the presence of ecotones. In The Prosecco Hills of Conegliano and Valdobbiadene UNESCO site many first level ecotones disappeared or decreased due to the disappearance of the mountain pastures, a phenomenon that occurred in almost every part of the area (Fig. 6). Second level ecotones too registered a significative decrease, but is partly balanced by the increase or appearance of new ecotones in some parts of the study area. The analysis of the density variation shows that the third level ecotones increased in most of the southern and central parts of the area, but this trend is partly affected, as already explained, by the quality of the 1960 black and white aerophotos.

In the GIAHS site of the Olive Groves of the Slopes between Assisi and Spoleto it is possible to identify two different situations (Fig. 7). In the southern part of the area, the density analysis registered an increase in the ecotones of all the three levels, while in the northern part ecotones mainly decreased, especially the ones of the third level. Concerning the ecotones of the first and second level it is also possible to observe a significative number of hexagons reporting new ecotones that were not present in 1954.

Table 4 Average and maximum density values for the different levels of ecotones for the two study areas in the two different periods

		Prosecco hills of Conegliano and Valdobbiadene UNESCO site		Olive Groves of the Slopes between Assisi and Spoleto GIAHS site	
		1960	2021	1954	2022
Average density (m/ha)	1st level	119	95	73	47
	2nd level	57	37	46	41
	3rd level	46	77	76	81
Maximum density (m/ha)	1st level	502	424	442	794
	2nd level	341	781	605	576
	3rd level	314	403	495	420

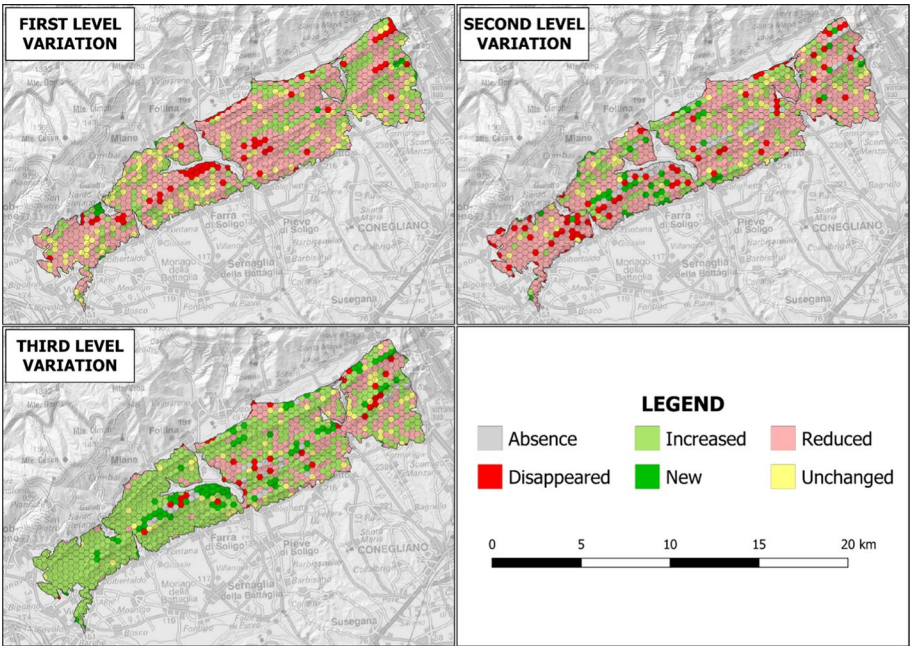

Fig. 6 Variation of the first, second and third level of ecotones in the period 1960–2021 for the Prosecco hills of Conegliano and Valdobbiadene UNESCO site

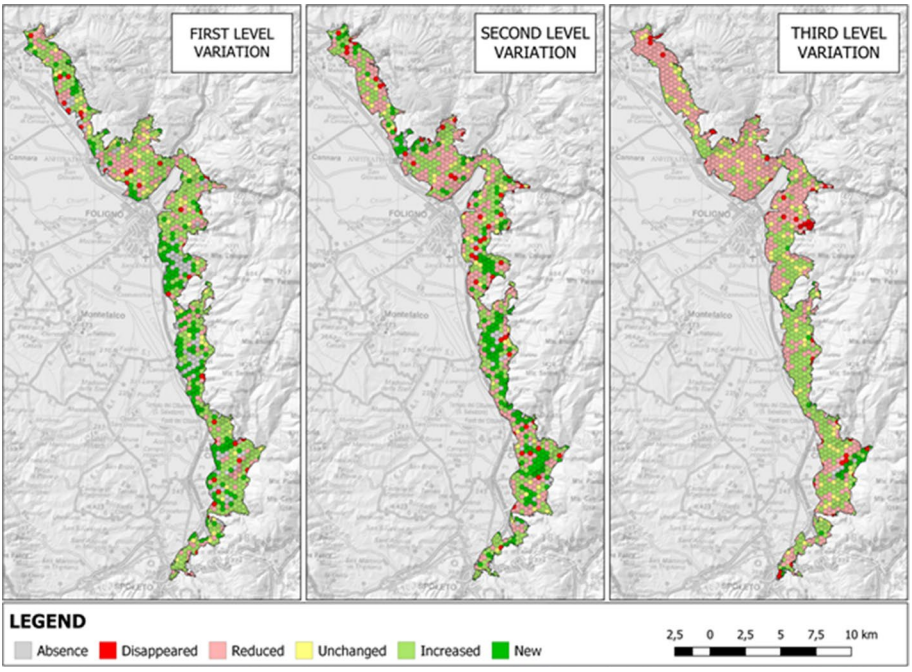

Fig. 7 Variation of the first, second and third level of ecotones in the period 1954–2022 for the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site

Table 5 presents an aggregation of results stemming from analyses conducted at both study sites. These consolidated data affirm the previously posited behaviors, evidencing distinct patterns in the two respective locations.

Within the Prosecco Hills of Conegliano Valdobbiadene, a noteworthy phenomenon emerges, where over 50% of the terrain exhibits a reduction in the density of first-level ecotones. Conversely, merely 23% of cases manifest an increase in ecotone density within this category. A parallel trend is observed for second-level ecotones, with an even more modest augmentation rate at 19%. However, a contrasting scenario unfolds at the third-level ecotones, where a majority portion (58%) exhibits an increase in ecotone density, while a mere 22% experiences a diminution.

In contrast, the olive groves situated between Assisi and Spoleto present a more intricate scenario. Notably, the density of first-level ecotones significantly skews towards augmentation, encompassing 42% of the total area, accompanied by the emergence of entirely new first-level ecotones in 17% of the studied surfaces. Second-level ecotone density, conversely, exhibits a more balanced distribution between increments (33%) and reductions (34%), with 19% of the areas reflecting the introduction of new second-level ecotones. The third-level ecotones predominantly showcase a density decrease at 47%, although areas witnessing an augmentation in density remain substantial at 35%.

Discussion

The applied methodology combined with the use of remote sensing demonstrated to be particularly effective in ecotone identification and in their spatial analyses, also considering that ecotones changes over time are recognized indicators of global and local changes (Churkina and Svirezhev 1995; Enserink 1997; Loehle 2000; Hufkens et al. 2009). The classification of ecotones according to a hierarchical system is based on their ecological importance and allows a deeper analysis of their transformation over the decades (Gosz 1993).

Coherently with what has also been demonstrated for other region of the world, differently from natural environments and landscapes, in cultural landscapes ecotones shifting and transformations are dependent on socio-economic drivers rather than on environmental and climatic ones (Smith and Goetz 2021; Cui et al. 2022, 2021). In the two study areas, changes in traditional agro-silvo-pastoral activities are responsible of changes in the

Table 5 Percentage of area covered by different types of variation for each level

Variation	Prosecco hills of Conegliano and Valdobbiadene UNESCO site			Olive Groves of the Slopes between Assisi and Spoleto GIAHS site		
	1st lvl (%)	2nd lvl (%)	3rd lvl (%)	1st lvl (%)	2nd lvl (%)	3rd lvl (%)
Absence	0.57	4.68	3.23	9.21	4.22	1.32
Disappearance	5.80	7.23	3.23	3.29	4.86	3.39
Increased	23.83	19.98	57.85	42.86	32.55	35.29
New	0.83	4.21	7.73	17.75	18.52	2.54
Reduced	56.14	56.44	21.80	19.79	34.06	46.70
Unchanged	12.82	7.47	6.16	7.11	5.78	10.76

land use structure and therefore in ecotones presence and density. In the Prosecco Hills of Conegliano and Valdobbiadene UNESCO site the loss of some land uses (pastures and wooded pastures) related to livestock grazing has caused the loss of first level ecotones, on their ecological connectivity and on landscape-scale biodiversity. On the other hand, in the Olive Groves of the Slopes between Assisi and Spoleto GIAHS site, the abandonment of some olive groves located in marginal areas led to the increase of forests and therefore of first level ecotones, while the simplification of the landscape mosaic due to the merging of adjacent olive groves caused the decrease of third level ecotones. In general, the decrease of the first level ecotones seems to be correlated to the simplification of the landscape mosaic for what concern its spatial complexity in terms of macro-categories of land use, while the loss of agricultural diversity corresponds to the decrease of second level ecotones, and the merging of adjacent patches to the decrease of third level ecotones. In addition, the study demonstrated that the relation between land use changes and ecotones changes is site-specific. Despite the changes measured in the two sites, the density variation analysis demonstrated that both of them still preserve a dense ecological network made by different types of well-connected and almost evenly distributed ecotones.

The land use changes reported for the two study sites highlighted a trend of agricultural abandonment in the marginal areas with consequent forest surface increase, and of agricultural simplification/intensification in more suitable areas, as the consequence of socio-economic changes occurred during the last six decades. These trends are common to many cultural landscape in Europe (Van der Zanden et al. 2017; Fayet et al. 2022; Debonne et al. 2022) with consequent landscape homogenization and simplification, but also leading to changes in the soil characteristics and in the floristic diversity, in particular along the forest-agriculture ecotone (first level) (Danso Marfo et al. 2019; Skrajna 2020).

The study demonstrated that cultural landscapes are characterized by important ecotones networks and that preserving landscapes of recognized cultural value, also means protecting ecotones, habitats and, therefore, related biodiversity. In particular, the preservation of a traditional landscape mosaic, with high complexity and different levels of interpenetration between different land uses, is crucial to maintain different microhabitats and ecotones. Therefore, supporting traditional agricultural practices and small-holder farmers, could represent the more effective strategy to preserve ecotones and associated biodiversity in cultural landscapes, avoiding the landscape simplification and homogenization.

Conclusions

Cultural landscapes provide different ecosystem services to local communities, including biodiversity and habitat protection. Thanks to their complex landscape structures, they are capable of representing different habitats in a relatively small surface. The study of the landscape structure and of the ecotones between different land uses is of crucial importance to predict transformations for the future as well as in understanding the role of traditional landscape structures in biodiversity conservation. Socio-economic changes deeply affected European rural areas in the last decades, causing a generalized landscape homogenization and simplification, caused by agricultural intensification in the flat areas and in the lower hills and by abandonment in marginal and mountainous areas, with negative consequences on biodiversity and on the ecological role of rural landscapes. Considering that most of the European rural landscape is a cultural landscape, shaped by human agro-silvo-pastoral activities through the centuries, the conservation of agricultural heritage systems

should be considered as a pillar for biodiversity conservation; Unfortunately, looking at the EU Biodiversity Strategy for 2030 it seems that little or no importance is given to cultural landscapes and to their role in preserving habitats and biodiversity. The EU Biodiversity Strategy for 2030 is, in fact, mainly focused on increasing the number and the surface of protected areas and do not consider that a large part of the European biodiversity is closely related to the variety and variability of habitats shaped and preserved by traditional agro-silvo-pastoral practices. The EU Biodiversity Strategy for 2030 neglects the multifunctional role of agricultural heritage systems, in particular the one related to biodiversity, that is instead well recognized and assessed at the scientific level. Further research is needed to assess the diversity at species level in ecotones within agricultural heritage systems, in particular in the ones considered of global importance and listed among the GIAHS sites or as cultural landscapes within the UNESCO WHL, while at policymaking level agricultural heritage systems should be considered and supported as biodiversity hotspots.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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