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Climate Aridity and the Geographical Shift of Olive Trees in a Mediterranean Northern Region

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Abstract: Climate change leverages landscape transformations and exerts variable pressure on natural environments and rural systems. Earlier studies outlined how Mediterranean Europe has become a global hotspot of climate warming and land use change. The present work assumes the olive tree, a typical Mediterranean crop, as a candidate bioclimatic indicator, delineating the latent impact of climate aridity on traditional cropping systems at the northern range of the biogeographical distribution of the olive tree. Since the olive tree follows a well-defined latitude gradient with a progressive decline in both frequency and density moving toward the north, we considered Italy as an appropriate case to investigate how climate change may (directly or indirectly) influence the spatial distribution of this crop. By adopting an exploratory approach grounded in the quali-quantitative analysis of official statistics, the present study investigates long-term changes over time in the spatial distribution of the olive tree surface area in Northern Italy, a region traditionally considered outside the ecological range of the species because of unsuitable climate conditions. Olive tree cultivated areas increased in Northern Italy, especially in flat districts and upland areas, while they decreased in Central and Southern Italy under optimal climate conditions, mostly because of land abandonment. The most intense expansion of the olive tree surface area in Italy was observed in the northern region between 1992 and 2000 and corresponded with the intensification of winter droughts during the late 1980s and the early 1990s and local warming since the mid-1980s. Assuming the intrinsic role of farmers in the expansion of the olive tree into the suboptimal land of Northern Italy, the empirical results of our study suggest how climate aridity and local warming may underlie the shift toward the north in the geographical range of the olive tree in the Mediterranean Basin. We finally discussed the implications of the olive range shift as a part of a possible landscape scenario for a more arid future.

Keywords: climate change; agricultural landscape; land use; official statistics; Southern Europe

1. Introduction

Climate change is a pivotal issue with well-known socioeconomic, cultural and political implications [1–4]. Earlier research foresees a potential impact on crop productivity, possibly altering the food and biomass available to animals and humans [5,6]. Several studies demonstrate that rising temperatures, declining rainfall and the concentration of precipitation over shorter periods lead to frequent and severe droughts, soil aridity, erosion and water shortages in both affluent countries and emerging economies, with negative consequences in the agricultural sector [7–10]. When combined with land mismanagement, climate change may drive land use transformations that impact vegetation cover and soil quality, fragmenting rural landscapes [11–15]. Given the continuous population increase characteristic of the Mediterranean region [16–19], sustainable land management strategies benefit from a more comprehensive assessment of long-term and short-term climate and land use dynamics, considering trends in natural and anthropogenic drivers together [20–22]. More specifically, a spatially explicit assessment of climate aridity trends may inform the development of efficient land management plans and apply useful nature-based solutions to achieve landscape, soil and environmental targets [23–26].

Climate changes have been documented worldwide [27,28] and are especially evident in the Mediterranean region, considered one of the global hotspots of climate variability in recent decades [29–32]. Earlier studies demonstrated significant variations in temperature and rainfall regimes (e.g., rising occurrence of seasonal events) and the increasing probability of extreme events as possible signals of climate change [33–35]. Although the relationship between climate change and land use change has been investigated extensively in some seminal works [36–39] and the most recent regional studies [40–42], relatively few studies analyzed the role of long-term climate variations in land use change at various spatiotemporal scales in the Mediterranean Basin [43–46]. A partial availability of (diachronic) regional and national land use maps [47,48] and incomplete data from long-term climate monitoring (e.g., weather stations) are some of the possible factors limiting research in this important field of study, especially in some world regions such as the Mediterranean Basin [49,50].

In this perspective, delineating other indicators aimed at evaluating the extent and spatial direction of climate change impacts and trends is imperative. Indicators based on documented (short-term) changes in the spatial distribution of plant or animal species contribute to answering this lack of basic information [51]. Considering the Mediterranean Basin as a climate change hotspot, the present study hypothesizes recent (human-driven) changes in the geographical distribution of likely the most typical Mediterranean crop—the olive tree—as an indirect response to climate change, confronting this assumption with empirical analysis of climate aridity and land use change at the northern (Alpine) range of the olive in Italy, a Southern European country representing the northern range for this crop species.

The olive tree is considered one of the most traditional elements of Mediterranean landscapes [52–54]. Braudel [55] evaluated the biogeographical distribution of the olive tree as the best criterion to delineate the biophysical (ecological) boundaries of the Mediterranean region. The olive tree has been cultivated since antiquity in the region, and olive groves form the most widespread land use across the whole basin [56]. At the same time, olive groves were (and are) also present in the geographical range as a wildwood type, either alone or, more frequently, in combination with natural vegetation (e.g., oak woods, maquis and garrigue, shrubland and extensive pastures under various management forms, including the traditional dehesa landscape in the Iberian Peninsula) and other mixed cultivated species of both tree and garden crops [57–59]. While olive tree production constitutes the economic base of almost all rural communities (from Portugal to Turkey and from Morocco to Israel [60]), relict environments grounded in the presence of wild olives are a key element of natural landscapes with biodiversity, aesthetic beauty and cultural amenities. Ecosystem services provided by olive groves contribute to soil protection from erosion and landslides, reducing wildfire risk and regulating water and nutrient cycling [61]. Especially in small islands and peripheral, inland districts, local communities devoted to agriculture largely depend on olive oil production [60,62,63].

Mediterranean rural landscapes with olive trees were demonstrated to experience intense climate variations, leading to changes in agronomic practices possibly adapted to warmer temperatures and altered rainfall patterns. In these areas, aridity and prolonged dry spells were signals of climate change [64,65], and short-haul crop migrations toward more suitable areas have been sometimes observed in connection with such changes [66–68]. As a result of rainfall decline with increased temperatures, especially during hot seasons, water scarcity has been increasingly affecting Mediterranean agriculture. In these contexts, the impact of global warming and non-efficient soil or water management on landscapes should be investigated more intensively.

The olive tree is one of the crops better adapted to summer droughts and hot climate regimes while being highly sensitive to snow and freezing during winter nights [57–59]. At the same time, extreme aridity can be harmful. Rossi et al. [69] stated that high olive production and low water input may indicate tightly interconnected food, energy and water resource systems. These findings suggest the importance of integrated solutions for more sustainable development of rural communities, from local to regional scales [70]. In such contexts, olive groves are experiencing deleterious impacts from drought [54,56,60,71], such as water-lacking diseases, photosynthetic performance impairment, oxidative stress and imbalances in plant nutrition [72]. In some cases, these issues were hypothesized to force farmers to adopt, in a sufficiently long time window, practical solutions to maintain as high of olive oil production as possible (e.g., rethinking the spatial localization of olive tree). In this sense, a specific measure could be installing olive trees in colder and wetter areas (e.g., in areas previously considered unsuitable or suboptimal for the species). However, to date, this assumption has been neither theoretically discussed nor empirically tested.

Benhadi-Marín et al. [73] and Martínez-Núñez et al. [74] combined olive trees with spiders and plant (pollen)-solitary bees to evaluate the (integrated) ecological (climate) and economic quality of agricultural management. Additionally, the indicators derived from the quantitative analysis of the crowns and rings of olive trees were quite extensively used for the estimation of soil erosion rates as a consequence of more intense rainfalls, an indirect signal of climate change [75,76]. These results also revealed high soil and water losses due to bare surfaces, intense tillage and intensive use of poor soils, which can be extended to a large part of the Mediterranean Basin [77–79]. However, the literature considering the olive tree as a proxy of climate change is relatively scarce and needs empirical confirmation with field studies and a more extensive bibliographic review.

Based on these premises, the present study explores the intrinsic relationship between climate change and the geographical shift of the olive tree toward the north in a Mediterranean country. First, a territorial analysis delineating at a sufficiently broad spatial scale, intensity, spatial distribution and temporal evolution of climate aridity (in turn connected with water scarcity in the surface soil layer) is provided. Second, the empirical results of this analysis are discussed for the possible impact on olive trees (i.e., assessing the human-driven expansion of this crop in areas previously considered suboptimal or unsuitable). With this perspective in mind, the geographical expansion of the olive tree is assumed to be a rational choice of territorial actors (e.g., farmers), maximizing income and optimizing land use in the context of climate change. Based on this assumption, olive tree expansion in unsuitable agricultural land may (at least indirectly) reflect changes in long-term climate regimes.

Italy seems to be a particularly appropriate area to test this assumption because of the largest latitudinal range in Southern Europe that corresponds with a broad heterogeneity in climate patterns, moving from arid to sub-humid wet regimes [80–82]. Prolonged dry spells became more and more recurrent in the country, involving previously non-affected areas such as Northern Italy. This region, including districts with intensive farming systems, has traditionally shown a wet, temperate alpine mixed climate, with mild and wet summers and temperate continental winters, having fog, snow and late freezing as basic characteristics of the cold season [83–86]. By hypothesizing the northern Mediterranean range of the olive tree moving progressively toward the north as a possible response to climate warming [87], our study provides empirical data contributing to delineating such a relationship in Northern Italy, a suboptimal region for olive cropping and one of the less suitable districts in Southern Europe because of the dominance of a temperate continental (non-Mediterranean) climate regime. Northern Italy—and more specifically, the area encompassing the Alps to the north and the Apennines to the south—includes seven administrative regions of the country (from west to east, Piedmont, Aosta Valley, Lombardy, Trentino Alto Adige, Veneto, Friuli Venezia Giulia and Emilia Romagna), displaying an evident (climatic) gap with the rest of Italy (Central and Southern regions), which are considered a traditional part of the geographical range of olive trees. Northern Italy experienced a mixed temperate continental regime less mitigated by the influence of the Adriatic Sea and more influenced by air masses originating from Alpine and Central European districts.

Combining official statistics from different data sources (Eurostat, the national statistical office of Italy (Istat) and other national sources of agricultural statistics) with land use databases, the continuous expansion of the olive tree in Northern Italy was investigated over a sufficiently long time horizon from official agricultural statistics (national censuses and sampling surveys) and land use maps. This analysis was carried out at multiple spatial levels (e.g., land use polygon, farm, district, elevation belt, province (NUTS-3 level—Nomenclature of Territorial Units for Statistics-) and administrative region (NUTS-2 level)) according to the sensitivity and precision of the adopted data source (from sampling surveys and national land use maps (less precise) to agricultural censuses and regional land use maps). The empirical analysis was integrated with a refined investigation of climate variations, focusing on the regionalized time series of a standard aridity index (the United Nations Environmental Program (UNEP) aridity index, considering rainfalls and reference evapotranspiration of soils and vegetation over a defined time frame) between 1951 and 2010. For the first time to our knowledge, the present study documents the shift toward the north of a traditional Mediterranean crop in Southern European countries. The results of this exploratory analysis delineate a temporal nexus between landscape change and climate variations, outlining the possible role of secondary data (official statistics) and diachronic land use mapping in connection with a narrative approach based on the literature review and field observations. A discussion on the relevance of climate aridity for the integrated analysis of land use changes in Mediterranean areas is finally presented, starting from the paradigmatic example of olive tree expansion in Northern Italy.

2. Materials and Methods

2.1. Study Area

Italy (301,330 km^2) is divided into three macroregions with different socioeconomic and ecological features (North, Centre and South), twenty administrative regions (NUTS-2 level), more than one-hundred provinces (NUTS-3 level) and almost 8100 municipalities (NUTS-5 level). Additionally, the Italian National Institute of Statistics (Istat) identified three elevation belts delineating different land morphologies, settlement patterns and agricultural systems in Italy (lowlands (up to 100 m at sea level), uplands (between 100 m and 600 m at sea level) and mountainous districts). Our research focused on a study area that included seven administrative regions of Northern Italy (Aosta Valley, Piedmont, Lombardy, Veneto, Trentino Alto Adige, Friuli Venezia Giulia and Emilia Romagna) with the exclusion of Liguria, a Mediterranean area highly suitable for the olive tree (Figure 1). These seven regions represent the part of Italy above the northern limit of the olive tree (traditionally corresponding with the Apennine mountain chain, running northwest to southeast across Central and Southern Italy). Comparisons with the rest of Italy were proposed in this study when necessary.

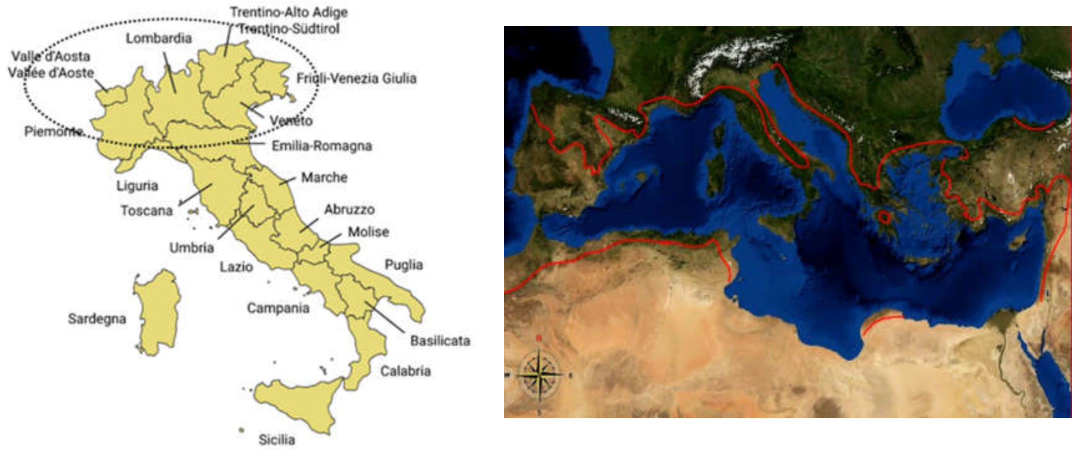

Figure 1. (left) A map of Italy with boundaries of the administrative regions. The dotted line indicates the study area in Northern Italy. (right) A general map of the Mediterranean Basin illustrating the geographical range of the olive tree.

The latitude, topography and proximity to the sea coast account for a considerable variation in climate, soils, vegetation, natural environments and rural landscapes. Average annual precipitation ranges between 350 mm in Sicily (Southern Italy) and 1500 mm in Friuli (Northeast Italy). Exceptionally diversified soil types and vegetation associations have been found across the country. After World War II, Italy underwent drastic land use changes due to urbanization, industrial concentration in flat areas, tourism growth and infrastructural development [88,89]. Crop intensification and land abandonment in marginal districts were (and still are) important symptoms of landscape transformation in Italy and likely in most regions of Mediterranean Europe [34,90]. Considering the proximity to the sea coast, our study further partitioned Italian land into five classes, overlapping elevation and distance from the sea layers (lowlands, coastal uplands, inland uplands, coastal mountains and inland mountains). We used this spatial partition as a reporting domain when computing elementary data from the national survey of agricultural land prices. Conversely, we used administrative regions (and provinces when possible) as a reporting domain when computing elementary data from national censuses of agriculture or annual agricultural surveys [91,92]. Finally, we used the native cartographic domain (i.e., spatial polygons corresponding with individual land use patches) when computing elementary data from land use maps [93].

2.2. Climate Data and Land Use Mapping

2.2.1. Climate Data Sources

The dataset used in this study included the month of precipitation and temperature time series from reference meteorological networks, including the Italian Air Force, the National Hydrological Service and the National Agrometeorological Service, for nearly 3000 gauging stations entirely covering the investigated area. The National Agrometeorological Data Base (BDAN) is a computerized archive, designed within the National Agricultural Information System (SIAN) of the Ministry of Agriculture, Food and Forestry Policies (MiPAAF). It collects basic observation data obtained from weather stations from different local and regional monitoring networks (Italian Council for Agricultural Research, Military Air Force, the former Hydrographic and Mareographic Service and the regional agrometeorological services). In addition to elementary data, BDAN includes several climate statistics and various agrometeorological indexes (www.politicheagricole.it, accessed on 6 April 2021).

2.2.2. Aridity Index

Increasingly considered as early warning indicators of climate change, aridity indexes, which are particularly appropriate to delineate the combined effect of rainfall reduction and local warming [64], were extensively used when evaluating land suitability to a given crop (including the olive tree) and the effectiveness of specific agronomic practices in various socioeconomic contexts [65,94]. The daily estimated evapotranspiration ET_0 (mm day^{-1}) was computed using the Penman–Monteith approach [30]. To describe long-term climate variations, we calculated the average rainfall and the aridity index (AI) by year [34]. This method is commonly used for estimating the gap between rainfall amounts and water demand. The formulation was adopted by United Nations Environment Program (UNEP; http://www.unep.org/, accessed on 6 April 2021), Food and Agriculture Organization (FAO; http://www.fao.org/, accessed on 6 April 2021) and United Nations Convention to Combat Desertification (UNCCD; http://www.unccd.int/main.php, accessed on 6 April 2021). Representing an accurate method of investigation and operational support to environmental assessment and land classification [95], the UNEP aridity index is defined as

$$AI = P/ET_0, \tag{1}$$

where ET_0 is the reference evapotranspiration and P is the total rainfalls, expressed with the same measurement unit (mm) and reported as annual averages [34]. The AI ranges between 0 and ∞, with higher values indicating wetter climate conditions. According to the standard AI classification [34], the investigated area was divided into four AI classes as follows: (1) AI < 0.50 for dry areas, (2) 0.50 < AI < 0.65 for dry, subhumid areas, (3) 0.65 < AI < 0.80 for subhumid areas and (4) AI > 0.80 for humid areas. The average annual rainfall and AI values were calculated separately for North, Central and Southern Italy along with four-time intervals (1951–1980, 1961–1990, 1971–2000 and 1981–2010).

To produce a homogeneous geographical coverage of the aridity index over a long period (1951–2010), kriging and co-kriging procedures were applied to the total annual precipitation and (minimum and maximum) temperature, respectively, producing raster maps at a 1 km spatial resolution using a data matrix of 32,640 values (60 years × 544 grid nodes). The resulting dataset was processed using ArcMap 10 (ESRI, Redwoods, USA) after synthesis of the temporal dimension obtained by calculating moving averages over a 30-year window. For each grid node, the mean AI values from 1951–1980, 1952–1981, 1953–1982, … and 1981–2010 were calculated. This allowed for compacting the data matrix for more efficient information management, filtering AI interannual variability at the same time.

2.3. Land Use Analysis

The latent shift toward the north in the spatial distribution of the olive tree was investigated in Italy, focusing on the seven administrative regions representative of a cold and wet area above the northern Italian limit (Figure 1, right). This area mostly coincided with the north and northeastern part of Italy, exposed to a continental or alpine climate regime with moderate (or negligible) Mediterranean influences. The area was located north of the historical biogeographical northern limit of the olive tree in Italy, which is the Apennine mountain chain moving from Liguria to Emilia Romagna. However, a restricted area close to Garda Lake (the biggest lake in Northern Italy, in between Veneto and Lombardy) specializes in local olive production because of the exceptionally mild climate observed in this district.

Three official data sources were adopted to assess the geographical expansion of the olive tree in Northern Italy at different spatiotemporal scales: (1) agricultural censuses (Istat) carried out in 1982, 1990, 2000 and 2010, as well as the sampling survey of farm structures (2016), producing data on cultivated land at the regional scale; (2) the annual survey of land prices (between 1992 and 2018) undertaken by the Italian National Institute of Agricultural Economics (INEA), now the Italian Council for Agricultural Research and Economics (CREA), providing data on crop surfaces at a subregional scale; (3) land use maps, including large-scale (1:100,000) CORINE Land Cover (1960 and 2018) databases; and (4) smaller scale (1:10,000) regional cartography focusing on Emilia Romagna (1976, 1994, 2003, 2008 and 2017). This region was more intensively studied because of the specific geographical location and intrinsic climate characteristics (at the interface between the Mediterranean and continental climate regimes). All these data sources include extensive (and comparable) information on the geographical extent of olive tree-cultivated areas. Olive tree-cultivated areas by administrative region (census data) and elevation belt (survey data) were quantified at different years based on secondary data availability.

3. Results

3.1. Trends in Climate Aridity in Italy (1951–2010)

In Italy, the Northern macroregion displayed the highest rainfall amounts on average (1019 mm between 1951 and 1980). Only 974 mm were recorded in Central Italy, and an even smaller amount was found in Southern Italy (735 mm). Thirty years later (1981–2010), rainfall amounts declined progressively in Northern Italy (865 mm) as well as in Central (833 mm) and Southern Italy (658 mm). However, a percent decline between the two-time intervals was more intense in Northern and Central Italy (−0.56% and −0.54%, respectively) than in Southern Italy (−0.39%). The largest decrease in total precipitation was recorded in the 2000s, with 2003, 2005, 2006 and 2007 being classified as very dry years all over the study period. The aridity index showed a similar pattern, decreasing by 0.68% per year in Northern Italy compared with −0.60% and −0.46% in Central and Southern Italy, respectively. Analysis of trends over time in the aridity index (Figure 2) revealed the continuous shift toward climate aridity in Northern Italy, a traditionally wet region (IA = 1.42 between 1951 and 1980) becoming progressively drier (IA = 1.16 between 1981 and 2010). A less intense shift toward aridity was observed in Central Italy, with even weaker signals of aridification from Southern Italy and the two major islands, although these contexts were already classified as dry subhumid (IA = 0.72 and 0.63 during 1951–1980 and 1981–2010, respectively).

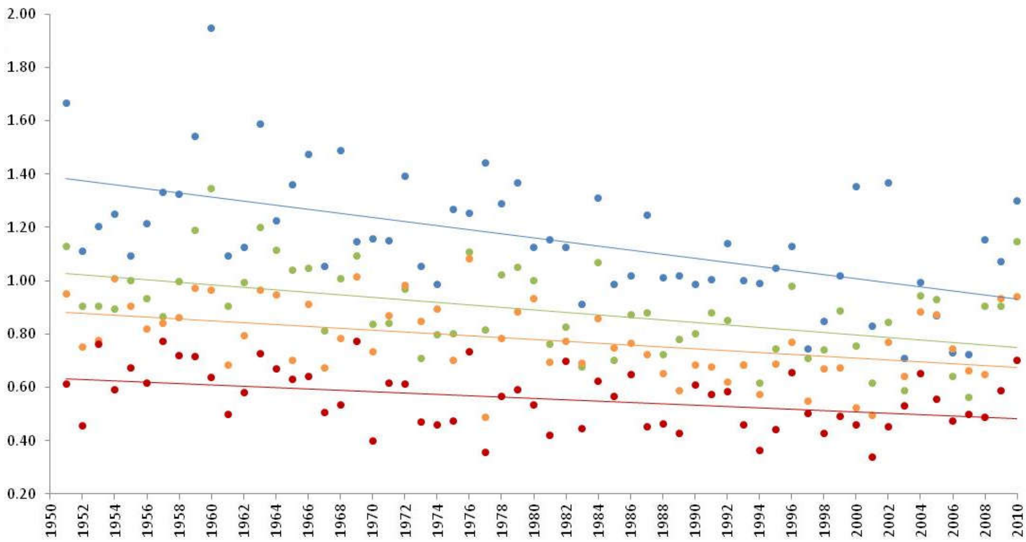

Figure 2. Long-term trends (1950–2010) in the climate aridity index (annual average, y-axis) by year and geographical division in Italy (blue = Northern Italy; green = Central Italy; orange = Southern Italy; red = Sicily and Sardinia). The colored lines indicate a linear trend fitting the aridity data in each division.

A regional analysis of climate aridity in Northern Italy (Table 1) revealed a particularly heterogeneous territorial context over time. All administrative regions in Northern Italy experienced a marked reduction in the average aridity index. Emilia Romagna was classified as the driest area in Northern Italy, showing an aridity index structurally below 1 and declining rapidly over time (0.96 and 0.81 in 1951–1980 and 1981–2010, respectively). Although being formally classified as non-arid, the average climate regime in Emilia Romagna has rapidly approached the 0.75 thresholds, and many parts of the region have already been classified as dry subhumid, experiencing a minimum IA value of 0.54. The Veneto region also showed relatively low values of the aridity index in both time intervals, decreasing from 1.18 (1951–1980) to 0.98 (1981–2010). Lombardy and Piedmont were the other two regions having aridity values close to one in the more recent time interval. Taken together, these results indicate how Northern Italy as a whole is slowly converging toward a drying climate regime similar to those observed in Central and Southern Italy, both regions included in the biogeographical range of the olive tree. Similar to Central and Southern Italy, relatively dry regimes were observed on a regional scale in Northern Italy, especially in flat districts and the gentle hilly areas of Emilia Romagna and Veneto, indicating local contexts with mild winters and sunny springs. These conditions appear to be potentially appropriate for olive tree growth all over the year.

Table 1. Descriptive statistics of the climate aridity index (sensu the United Nations Environmental Program (UNEP)) by selected region (Northern Italy) over 60 years (1951–2010) and the average values for two separate time intervals covering 30 years each (an aridity index < 0.75 indicates a dry subhumid climatic condition, typical of Mediterranean temperate regimes).

Region	1951–2010			1951–1980	1981–2010	% Change over Time
	Minimum	Average	Maximum			
Emilia Romagna	0.54	0.89	1.47	0.96	0.81	−15.3
Friuli Venezia Giulia	0.89	1.56	3.01	1.82	1.30	−28.6
Lombardy	0.56	1.16	2.21	1.32	1.00	−24.2
Piedmont	0.54	1.15	2.12	1.28	1.01	−21.3
Trentino Alto Adige	0.73	1.32	2.39	1.43	1.20	−16.5
Aosta Valley	0.52	1.43	3.08	1.51	1.34	−11.3
Veneto	0.65	1.08	1.73	1.18	0.98	−17.2
Italy	0.49	0.90	1.54	0.99	0.81	−18.4

3.2. Land Use Changes

The surface area of olive crops expanded in Northern Italy in respect with other Italian regions, where this crop was found to be stable or mostly regressing (Table 2). In 1992, olive trees extended about 6000 hectares in Northern Italy, doubling their surface area in both 2009 and 2018 (around 12,000 hectares). The olive tree surface area increased at all elevation belts, although the most rapid expansion was found in lowlands. Relatively large increases were also observed in both inland uplands and mountainous districts. The olive tree surface area in the uplands close to the seacoast was more stable over time. Although the expansion of olive trees involved relatively limited areas (59 km^2 in 1992 and 115 km^2 in 2018) in respect to the total surface of the study area, the increase of such comparatively small surfaces represents a non-negligible phenomenon for a study area originally classified as non-suitable to the olive tree. Moreover, olive tree expansion was observed not only in flat districts with a milder climate during winter, but also in mountainous areas. Such results may reflect a latent shift toward the north in the geographical range of this species, possibly mediated by economic agents (farmers) and supported by a milder climate regime.

Table 2. Olive tree cultivated areas in Northern Italy (hectares) by year and elevation belt.

Year	Inland Mountain	Inland Uplands	Littoral Uplands	Lowlands	Total
1992	1422	2829	605	1022	5878
2000	1392	4361	938	1643	8334
2009	1761	6185	957	3502	12,405
2018	1892	5432	734	3463	11,521

Considering the administrative regions in Northern Italy, the olive tree surface area increased systematically over time (Table 3), especially in Lombardy, Veneto, Emilia Romagna and Friuli Venezia Giulia. These regions constitute the eastern side of the Po Plain. More discontinuous data were found in Piedmont and Aosta Valley, both located on the western side of Northern Italy. The small extension of olive trees in Trentino Alto Adige mostly reflects a local expansion process along the Garda Lake, a small district with particularly suitable microclimate conditions for olive trees. Veneto and Emilia Romagna were the two regions with the largest surface of olive trees in Northern Italy.

Table 3. Surface area (hectares) of the olive tree in Northern Italy by administrative region and census year.

Region	1982	1990	2000	2010	2019
Piedmont	-	1	47	1020	132
Aosta Valley	-	-	-	45	-
Lombardy	1130	1325	1314	1963	2394
Trentino Alto Adige	243	261	362	394	392
Veneto	2591	2302	3730	5180	5160
Friuli Venezia Giulia	19	123	122	425	625
Emilia Romagna	1475	1306	2643	3814	4155

A disaggregated analysis at the province scale provided a refined evaluation of olive tree spreading in Northern Italy in recent decades (Table 4). The number of provinces with olive trees increased from 13 (1982) to 43 (2010). Olive trees expanded more in five provinces (Verona, Brescia and Vicenza, close to Garda Lake district, as well as Forlì-Cesena and Rimini, close to the Adriatic Sea). However, a less rapid expansion was also observed in other provinces far away from local contexts with supposedly more favorable microclimatic conditions, such as the Adriatic Sea coast or the Garda Lake. These cases included Alessandria, Treviso, Padua, Udine, Bologna and Ravenna. These territories have suboptimal (or completely unsuitable) climatic conditions for olive cropping.

Table 4. Surface area (hectares) of the olive tree in Northern Italy by province and census year.

Province Name	1982	1990	2000	2010	Annual Increase (%)
Turin	-	1	10	183	4.8
Vercelli	-	-	3	19	0.5
Novara	-	-	-	21	0.6
Cuneo	-	-	27	184	4.8
Asti	-	-	3	51	1.3
Alessandria	-	-	3	540	14.2
Biella	-	-	-	13	0.3
Verbano-Cusio-Ossola	-	-	-	9	0.2
Aosta	-	-	-	45	1.2

Varese	-	-	3	45	1.2
Como	-	14	33	60	1.6
Sondrio	-	-	-	92	2.4
Milan	-	-	2	23	0.6
Bergamo	60	60	128	194	3.5
Brescia	1069	1197	1027	1359	7.6
Pavia	-	-	64	21	0.5
Cremona	-	34	1	34	0.9
Mantova	-	-	29	75	2.0
Lecco	-	20	22	56	1.5
Lodi	-	-	-	3	0.1
Monza-Brianza	-	-	5	3	0.1
Bolzano	1	1	2	11	0.3
Trento	242	260	360	383	3.7
Verona	2253	1919	2695	3471	32.1
Vicenza	227	233	549	696	12.3
Belluno	-	-	-	23	0.6
Treviso	20	26	210	425	10.7
Venice	-	-	2	111	2.9
Padua	92	124	273	431	8.9
Rovigo	-	-	-	22	0.6
Udine	2	96	40	158	4.1
Gorizia	-	-	7	27	0.7
Trieste	17	27	51	88	1.9
Pordenone	-	-	25	152	4.0
Piacenza	-	-	7	35	0.9
Parma	-	-	2	33	0.9
Reggio Emilia	-	-	2	92	2.4
Modena	-	1	5	40	1.1
Bologna	-	12	45	257	6.8
Ferrara	-	-	-	12	0.3
Ravenna	349	250	388	540	5.0
Forlì-Cesena	322	336	789	1238	24.1
Rimini	805	707	1405	1566	20.0
Number of provinces with olive trees	13	19	34	43	0.8

Using high-resolution land use maps (1:10,000), a specific focus was carried out for Emilia Romagna, the closest region to the Appennine mountain chain (i.e., the northern limit of the olive tree in Italy) and the area experiencing the most intense climate variations toward aridity in Northern Italy. These maps delineated olive tree patches with homogenous criteria over time. A total of 766 hectares were observed in 1976, increasing to 1993 hectares in 1994, 2056 hectares in 2003, 2155 ha in 2008 and 4166 ha in 2017. In 1994, a total of 186 landscape patches classified as olive trees were found in Emilia Romagna, with a mean size of 10.7 ha and a maximum size of 107 ha. In 2017, a total of 3530 landscape patches classified as olive trees were identified with a mean size of 1.2 ha and a maximum size of 79.3 ha, indicating processes of crop expansion and fragmentation at the same time. The olive tree was cultivated under relatively small patches, likely more diffused across family (smaller) farms. These results indirectly confirmed that an increasing number of farmers evaluated the olive tree as a suitable crop for farming in Emilia Romagna, possibly as a response to drier microclimatic conditions.

4. Discussion

Global warming, together with economic development and demographic growth, have led to important landscape transformations over large areas of the Earth, including some Mediterranean regions in Europe [70,73,76,77]. After experiencing recurrent droughts with a generalized increase in climatic aridity, the Mediterranean Basin was considered one of the most important hotspots for desertification risk in Europe [96,97]. It has been widely demonstrated how the increasing level of ecological vulnerability in Southern Europe was associated with long-term ecological dynamics (e.g., soil and climate aridity), together with socioeconomic processes triggering important modifications in the rural landscape [98,99]. These negative conditions can be accentuated by unsustainable land management, especially in ecologically fragile areas [100,101]. Analysis of complex territorial dynamics involving socioeconomic and environmental issues suggests the adoption of multidisciplinary approaches aimed at delineating the intimate relationship between the "demo-economic" dimension and the "ecological" sphere, especially in rural areas with "high social density" and intense feedbacks between natural environments and human components [102–104].

In these regards, our approach provides some empirical evidence of the progressive shift toward the north of olive trees in Italy, possibly driven by farmers' rational choices. This latent process, more evident in recent decades, paralleled a generalized increase of climate aridity, reflecting drier soils and microclimatic conditions oriented toward summer droughts and milder winters (i.e., with no snow and air temperatures systematically above 0 °C overnight). These conditions, particularly frequent in the last two decades, make a large part of Northern Italy suitable to olive cropping, contrary to what was observed three or four decades ago [54]. Climate warming and aridification could be important reason supporting the recent, farmer-driven expansion of olive trees in the area. Earlier studies have identified Northern Italy as a (regional) climate hotspot in Europe, as far as water shortage, soil aridity and land degradation are concerned [105]. As a crop typically adapted to poor soils and a dry Mediterranean climate, olive trees have been increasingly cultivated in marginal districts of Northern Italy that were considered completely unsuitable (mainly because of the high probability of snow, ice and frost during winter) up to three decades ago. The choice of farmers to adopt an olive tree as a yield crop in marginal farms (especially in the Emilia Romagna and Veneto regions) can be assumed to be a rational strategy, adapting to drier climate conditions. In such contexts, a rustic crop like the olive tree, more likely to survive in the present climate conditions than a few years ago, may also give value to marginal soils, which are more exposed to prolonged droughts.

Olive tree surface areas increased in both the lowlands and uplands over the last two decades. Notably, despite intense competition for land with other crops (and other land use), olive trees also expanded in fertile (high-income) agricultural districts along the Po River, likely benefiting from the milder temperatures during winter and drier conditions during spring and summer. It cannot be excluded that a moderate increase in the economic demand for olive oil has driven the local expansion of the olive tree in Northern Italy. However, this hypothesis seems implausible, considering that a strong decline of the olive tree was documented for decades in Central and Southern Italy [106,107], where (1) optimal conditions for olive cropping were available, (2) high-quality oils were produced, (3) farming costs were generally lower, and (4) transportation costs to Northern Italy were relatively small. Olive oil from Central and Southern Italy was also extensively and traditionally used in Northern Italy because of the massive presence of internal migrants coming from the south [108]. Based on these considerations, a simple question may arise from the results of this study: did the climate make people change, or did people change vegetations in response to climate change? Although empirical findings indicate how the latter assumption seems to be more adherent to the olive tree case in Northern Italy, a theoretical discussion about environmental determinism against cultural baggage (e.g., [109]) can also contribute to shedding light on these intriguing issues.

Based primarily on farmers' rational choices, the olive tree spreading toward the north was temporally correlated with the progressive warming and aridification observed at the local scale in Northern Italy. These signals include lower amounts of precipitation (especially during winter) and higher temperatures over winter nights, a complete absence of winter fog in lowlands and less snow in the uplands, typical climatic characteristics of Northern Italian winters up to the late 1980s. Although the present study was not intended to delineate a causal relationship between climate and land use changes, olive tree expansion in Northern Italy was accompanied by early signs of climate aridity, long-term soil aridification and more frequent dry spells. In this perspective, olive tree expansion is assumed as a possible adaptation strategy of farmers (and especially small farmers) to climate change and more intense water shortages in Northern Italy [110]. Using the olive tree as a yield crop means significant savings in water requirements and irrigation costs, needing very elementary agronomic practices (small-cost fertilizers and chemicals) in the environmental contexts dominant in the flat and hilly districts of Northern Italy. As a matter of fact, increases in the surface area of the olive tree may indicate a progressive preference of Northern Italian farmers toward (originally unsuitable) low-income and rustic crops with very low costs, irrespective of elevation and microclimatic conditions. This phenomenon seems to be even more important, considering that land in Northern Italy, and especially along the Po Plain, is the most fertile in the country, supporting high-income crops (orchards, cereals and horticulture) in specialized districts with intensive farming systems.

The introduction (and ecological adaptation) of a particularly rustic and medium-low income crop such as the olive tree represents a landscape transformation that can be considered an early warning for progressive climate aridity. In this direction, further efforts are needed to clarify the cost–benefit relationship of introducing a rustic, low-income crop like the olive tree in the potentially fertile and high value-added land of Northern Italy. Assessing short-term trends in olive tree-cultivated areas is also appropriate in light of the sustainable use of water and soil in areas exposed to rising aridity [111,112]. The olive tree requirements in soil fertility and water amounts are rather modest and adapted to dry (local) conditions, instead of the large majority of crops in the area [113–115]. Olive trees thus represent an intrinsic, win-win adaptation to droughts because of the intimately low water requirements in comparison with traditional high-income crops in Northern Italy (e.g., horticulture, maize and orchards).

Taken together, the results of this study support the assumptions delineated in an earlier study based on climate modelling [116] and justify the importance of empirical studies testing together with the outcomes of general circulation models and landscape scenarios. Our study finally delineates landscape transformations in the flat and hilly lands of Northern Italy that have specific impacts on local socioeconomic systems and require continuous monitoring from both ecological and social perspectives [117]. Expansion of the olive tree in Northern Italy is definitely important, since tree crops, strongly contributing to a healthy rural landscape, may preserve key ecosystem functions at the core of social transition and political debate [118,119]. Short- and medium-term forecasts of regional climate trends in the Mediterranean Basin (e.g., aridity, prolonged dry spells and water scarcity) are in line with a further (farmer-mediated) expansion of the olive tree in Northern Italy [120,121].

Spreading toward the north of the olive tree in Italy reveals how dynamic the latent transformations in rural landscapes are, where farmers responding to a changing climate are the main economic agents of change. In such a context, regional planning should better cope with the feedback relationship between climate change and land use transformations at the local scale, assuming agriculture is more effectively governed by multilevel and multidisciplinary policies that incorporate short-term and long-term targets together

[122,123]. The results of the analysis of climate and land use trends in a representative case study, like Northern Italy, outlined a dynamic picture of the (evolving) environmental conditions that determine a new balance between regional climate regimes, landscape transformations and the local communities characterizing rural spaces.

5. Conclusions

The degradation of natural environments and physical depletion of the (forest tree crop) rural matrix is a major issue in any environmental policy. Conservation of extensive rural systems is a pillar that informs strategies of all the conventions of the United Nations (climate change, desertification and biodiversity). This issue also demonstrates the role of extensive farming systems in developing zero net land degradation goals in a range of socioeconomic contexts around the world, in advanced economies and emerging countries. In the Mediterranean region, the olive tree is one of the most widespread components of extensive rural systems. Here, the role of the olive tree as a powerful mediator of socioecological services is highlighted in all strategies of environmental interest (soil, water and air directives from the European Union, as well as the European Landscape Convention). With this perspective in mind, our study goes beyond traditional monitoring approaches, providing an integrated, exploratory climate and land use framework that may contribute to delineating a future way to achieve sustainable management of rural landscapes exposed to climate change. Rustic crops such as the olive tree are appropriate to preserve environmental quality, providing characteristic ecosystem services and economically viable productions and being more adapted to a changing climate (e.g., aridity) than other crops. In this perspective, specific landscape modifications can be seen as a (formal or informal) response to climate change, influencing the effectiveness of environmental policies, whose representativeness, in turn, depends on the quality of regional strategies for rural development and land resource conservation.

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