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Research paper

Land use change towards forests and wooded land correlates with large and frequent wildfires in Italy

Davide Ascoli[1], Jose V. Moris[1,2*], Marco Marchetti[3], Lorenzo Sallustio[3]

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ABSTRACT It is commonly believed that wildfires in southern Europe have been favored by the encroachment of flammable vegetation on cultivated and grazed areas no longer managed as a consequence of deep socio-economic changes in rural areas. Using the whole of Italy as study case, this paper explores the hypothesis that wildfires selectively burn areas with specific land use changes (LUC) characteristic of agricultural land abandonment, especially in large (> 500 ha) and recurrent burnt areas. Additionally, we examined LUC within 200 m buffer areas around perimeters of large fires to explore if active land management may hamper the growth of large fires. To investigate the study hypotheses, pre-fire LUC were compared within six different geographic domains defined according to the burnt areas from 2007 to 2017 across Italy. Estimates of LUC between 1990 and 2008 came from the Italian Land Use Inventory (IUTI), which is based on photointerpretation of 1,206,198 sample points on high-resolution aerial images. The analyses reveal that LUC in all geographical domains reflect typical trends of agricultural land abandonment in southern Europe during the last decades: expansion of forests, shrubland and new settlements at the expense of agricultural land, grasslands and pastures. However, results show higher rates of pre-fire LUC in burnt areas than in the rest of territory considered available for burning. We found that higher rates of forest expansion and shrub encroachment on abandoned grasslands and pastures are related to a higher incidence of large and recurrent fires, respectively. Furthermore, areas surrounding large fires were less affected by pre-fire land abandonment than burnt areas and show higher increases in vineyards and orchards. Our findings suggest that land abandonment have probably increased fire proneness at national scale by expanding shrub and tree encroachment, and thus increasing fuel connectivity and fuel build-up. Therefore, we urge for a greater integration between fire management and rural development policies.

KEYWORDS: land use change, global change, forest fire, extreme wildfire, agricultural land abandonment.

Introduction

Integrated fire management in Mediterranean environments requires the understanding of critical aspects of the fire regime causing negative impacts, in order to plan and implement adequate mitigation strategies (Corona et al. 2014, Moreira et al. 2020). In the Northern Mediterranean basin, a major critical feature of current fire regimes is the occurrence of large wildfires with increasing consequences for civil protection emergences and impacts on ecosystem services (Tedim et al. 2019, Augusto et al. 2020). Moreover, the recurrence of multiple fires in the same area with short fire return intervals have the potential to overcome ecosystem resilience to fire disturbance, trigger soil degradation processes and hamper rural development (Barbati et al. 2015, Ferreira-Leite et al. 2016, Elia et al. 2020a). Large and recurrent wildfires are a complex process involving multiple physical, biological, and anthropogenic drivers (Fernandes et al. 2020). In last decades, several studies and policy briefs point to land use and its changes as one of the major drivers of fire regimes modifications in southern Europe (Moreira et al. 2011, Mantero et al. 2020), although the role of anthropogenic climate change is increasingly apparent (Seidl et al. 2107). Nonetheless, land use dynamics are of key interest, since integrated fire management policies at the regional level rely on land use planning and management as the priority strategy to modify landscape flammability (Moreira et al. 2020), while addressing climate related issues requires global scale policies (Bowman et al. 2020).

In the second half of the 20th century, the Mediterranean region experienced deep socio-economic transformations with massive rural abandonment from depressed inland agro-pastoral zones and the migration of people toward urban-industrial areas (Moreira et al. 2011). The phenomenon of land abandonment, i.e., a process whereby human control over land (e.g., agriculture, livestock) is given up and the land is left to nature (FAO 2006), results in landscape changes that affect disturbance regimes (Mantero et al. 2020). In Italy, this process caused major land use changes (LUC) with the expansion of shrublands and forests in cultivated and grazed areas (e.g., Cimini et al. 2013, Orlandi et al. 2016, Sallustio et al. 2018a, Malandra et al. 2019). A common belief is that recent large fire seasons in Italy (e.g., 2007, 2017) have been favored by the encroachment of flammable vegetation, such as tall grass (Incerti et al. 2013) and maquis (Castagneri et al. 2013), on cultivated and grazed areas no longer managed (Bovio et al. 2017), or by build-up of understory fuels in unmanaged forests (Ascoli et al. 2020). At the same time, areas that maintained or increased agro-pastoral land uses are believed to limit fire growth and recurrence (Marchetti and Ascoli 2018). Although in Italy land managers and the scientific community largely supports these theses, few studies explicitly tested them under controlled experiments (Salis

1 DISAFA, University of Turin – Italy
2 Departement of Agricultural Science, University of Naples – Italy
3 Departement of Bioscience and Territory, University of Molise - Italy
*Corresponding author: moris.josev@gmail.com

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et al. 2014, Ursino and Romano 2014, Bajocco et al. 2019). Indeed, the majority of studies addressing key factors influencing Italian fire regimes assumed land use as a static driver over relatively long periods (e.g., Mancini et al. 2018a, Ferrara et al. 2019). Moreover, studies explicitly addressing the influence of LUC (Salis et al. 2014, Ursino and Romano 2014, Bajocco et al. 2019) reports contrasting results, probably because experiments were local in scope.

Using wildfire burnt perimeters and LUC estimates for the whole Italian territory (insular and peninsular), this paper aims at testing the following hypotheses: *(i)* current wildfires selectively burn areas that changed land cover from uses related to intense cultivation and grazing to successional stages characterized by shrub and tree encroachment. *(ii)* This process is particularly relevant for large wildfires (burnt area > 500 ha) and recurrent wildfires (multiple events during the study period). *(iii)* The maintenance of land uses characteristic of active land management hamper large fire growth.

Materials and Methods

Study area

The study area spans over the entire Italian territory (about 302,070 km^2), with a high environmental and socio-economic variability from north to south, including the two main islands (Sicily and Sardinia). These heterogeneous conditions from north to south are reflected in the variability of the wildfire regime (Elia et al. 2020b). In the Alpine region, most of the fires occur in winter due to the continental climate characterized by cold-dry winters, fully cured vegetation and frequent episodes of strong warm-dry winds (foehn) that dry out vegetation increasing fire proneness (Valese et al. 2014). On the contrary, in coastal and center-southern areas most fires occur in summer because of a minimum precipitation in July, dry winds from North Africa and high temperatures, typical of a Mediterranean fire regime (Elia et al. 2020b).

On average, 5,789 wildfires per year occurred in Italy in the period 2007-2017, with a mean fire size of 14.8 ha. In this period, 0.3% of the fire events exceeded 500 ha, although these large fires accounted for almost 25% of the total burnt area. Moreover, 16% of the total area affected by fires burnt at least twice. Approximately, 90% of the burnt area affected the southern Mediterranean provinces, where 93% of the fires occurred from May to October (Fig. S1). In contrast, wildfires in the northern Alpine provinces only accounted for 5% of the total burnt area, and 71% of these fires occurred from November to April. In the rest of north-central provinces, fire seasonality was more evenly distributed, and winter fires still accounted for 32% of the fires.

Land use is dominated by agriculture, mainly croplands (44% of the national territory), followed by forests (32%) and settlements (7%; Pagliarella et al. 2016). This configuration has changed during last decades with a progressive expansion of other wooded lands (e.g., shrubland) and forests at the expense of abandoned agricultural lots, especially in hilly and mountainous territories (Rivieccio et al. 2017, Camarretta et al. 2018, Malandra et al. 2019, Garbarino et al. 2020). Similarly, agricultural lands in lowlands and close to coastlines are experiencing an ongoing growth of impermeable surfaces (urban areas and related services; Romano and Zullo 2014). These changes lead to different environmental and socio-economic challenges that both national and EU policies are currently facing such as rapid urban expansion (Marchetti et al. 2019), and active land management for the promotion of ecosystem services and biodiversity conservation (Burrascano et al. 2016, Sitzia et al. 2016, Sallustio et al. 2017, Marchetti et al. 2018). The availability of information on such LUC impacts is now gaining particular emphasis in order to orient future policies and planning activities at different spatial scales, from national to municipal level, according to different sectorial EU directives.

Data Sources

The Italian Land Use inventory (IUTI)

The Italian Land Use Inventory (IUTI) has been promoted by the Italian Ministry of Environment and Protection of Land and Sea (MATTM), in order to support the national greenhouse gas assessment under the Kyoto Protocol framework (Corona et al. 2012). IUTI is a land use inventory based on 1,206,198 points nationwide selected according to a tessellation stratified sampling design (TSS). Each sample point represents an area of approximately 25 ha and it was randomly extracted using a 0.5 km square grid covering the whole national territory (Corona et al. 2012). Through a visual photointerpretation of sample points on high-resolution aerial images for the years 1990 and 2008, IUTI provides land use estimates at the two time steps as well as their changes over time. IUTI is based on a three level hierarchical classification system with nine land use classes consistent with the Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF; Sallustio et al. 2016; Tab. 1).

The national wildfire database

Wildfire data consisted in individual georeferenced fire perimeters provided by the “Comando unità forestali, ambientali e agroalimentari” (CUFA) Police Corp and by fire management agencies of auto-

Table 1 - The hierarchical three-level classification system adopted by IUTI

IPCC Category Level I	IUTI Category Level II	IUTI Subcategory Level III	Code
Forest land	Woodland		1
Cropland	Arable land and other herbaceous cultivations		2.1
	Permanent crops	Orchards, vineyards and nurseries	2.2.1
		Forest plantations	2.2.2
Grassland	Grassland, pastures and uncultivated herbaceous areas		3.1
	Other wooded land		3.2
Wetlands	Marshlands and open waters		4
Settlements	Urban development		5
Other land	Bare rock and sparsely vegetated areas		6

nomous regions. Fire perimeters from datasets of burnt areas, recorded by ground-based GPS surveys, were available for a period spanning from 2007 to 2017. This dataset includes all 20 regions of Italy.

Although the second time-step of IUTI officially refers to 2008, considering that photo interpretation was carried out on aerial photos from 2006, 2007 and 2008, and that points on areas recently burnt were classified according to the pre-fire land use class, we decided to include 2007 wildfire polygons in the analysis. Indeed, including burnt area in wildfires from 2007, the year with the largest burnt area in Italy in the period 1990-2019 (San-Miguel-Ayanz et al. 2020), allows a better representation of underlying LUC processes responsible for current fire regimes in Italy.

Data analysis

Experimental design

To test the study hypotheses, LUC occurred between 1990 and 2008 were compared within six different geographic domains. These geographic domains were defined according to different wildfire occurrences and extents (Fig. 1). The total estimated area of each domain is reported in Tab. 2. LUC was firstly analyzed within territories where at least one fire event was recorded from 2007 to 2017. IUTI sampling points falling within the area burnt at least once during the reference period were selected, and this subsample (hereafter "Total_fire") was used to obtain LUC estimates following the approach described by Corona et al. (2012). The "Total_fire" domain gathers all the IUTI sampling points (in total 31,185) located in the burnt areas of this study. The same approach was repeated for: *(i)* areas with multiple wildfires (minimum two events) occurred in the period 2007-2017 ("Fire_recurrence" subsample); *(ii)* areas where wildfires with a total extent lower than 500 ha occurred ("Non_large_fire"); *(iii)* areas where wildfires larger than 500 ha occurred ("Large_fire"); *(iv)* areas falling within 200-m buffer areas around perimeters of large fires ("Buffer_large_fire"); and *(v)* areas belonging to municipalities where at least one fire event occurred between 2007 and 2017, excluding the areas affected by fires ("Unburnt"). The threshold of 500 ha is used as the upper size class in European statistics (San-Miguel-Ayanz et al. 2020) and previous studies found that fires larger than 500 ha are increasingly controlled by fuel-related variables (e.g., Fernandes et al. 2016, Mancini et al. 2017). The 200-m distance corresponds to the recommended buffer size at the wildland-urban interface in several southern European regions, i.e., the maximum distance needed to mitigate fire behavior (Lampin-Maillet et al. 2010, Ascoli et al. 2018). The last geographical domain ("Unburnt") was used as reference to compare LUC among the geographical domains.

Figure 1 - Schematic representation of the experimental design. Left: distribution of the burned area in Italy in the period 2007-2017. Right: example using two municipalities. Municipalities not affected by wildfires in 2007-2017 were not included in the analyses (e.g., municipality 1). On the contrary, IUTI points within municipalities with wildfires (e.g., municipality 2) were allocated according to the geographical domains. Different symbols and colors highlight IUTI points within six geographical domains defined according to different wildfire occurrences (areas burnt at least once, burnt more than once, unburnt within the surroundings of fires above 500 ha, unburnt) and extents (fire events above and below 500 ha).

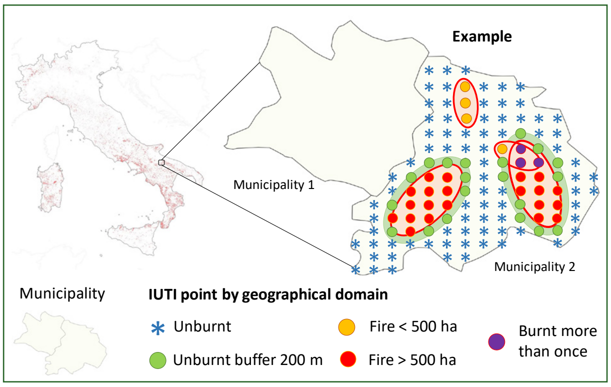

Table 2 - Geographical domains used in the analyses.

Geographical domain	Area (ha)
Total_fire	777,125
Fire_recurrence	126,250
Non_large_fire	597,725
Large_fire	201,175
Buffer_large_fire	81,025
Unburnt	22,549,075
Available	23,326,200

Analyses

Transition matrices were used to obtain LUC between 1990 and 2008 and to estimate flows among the different land use classes through time as well as their net changes (Pontius et al. 2004, Rivieccio et al. 2017). The methodology proposed by Fattorini et al. (2004) and applied by Sallustio et al. (2016) was implemented to estimate the proportion (p) of the nine land use classes in 1990 and 2008, their areas (â), and their relative standard errors (RSE) for each of the six geographic domains. Additionally, statistical tests were performed to assess the accuracy of the variation in size of the land use classes between 1990 and 2008 (Sallustio et al. 2016). Once surface estimates as well as their accuracies were obtained, we calculated the relative change (RC) of every land use class *j* of a given geographic domain *i* as follows:

$$RC_{ji} = \frac{\hat{a}_{ji2008} - \hat{a}_{ji1990}}{\hat{A}_i} \quad \text{(eq. 1)}$$

where $\hat{a}_{ji2008}$ is the estimated surface of land use class *j* in the geographic domain *i* in 2008, $\hat{a}_{ji1990}$ is the estimated surface of land use class *j* in the geographic domain *i* in 1990, and $\hat{A}_i$ is the total estimated surface of the geographic domain *i*. Positive RC values indicate a net expansion of the given land use class from 1990 to 2008, while negative RC values indicate a net reduction in area.

A comparative assessment of the LUC occurred in the different geographic domains was performed trough a selectivity analysis. We pooled the data from the "Total_fire" and "Unburnt" geographical domains to estimate LUC in all the municipalities affected by wildfires in the study period. This new geographical domain ("Available") was used to calculate the RC in areas considered as available for burning. A selectivity index (SI) for every land use class *j* of a given geographic domain *i* was calculated as follows:

$$SI_{ji} = \frac{|RC_{ji}|}{RC_{ja}} \quad \text{(eq. 2)}$$

where $|RC_{ji}|$ is the absolute value of the relative LUC occurred between 1990 and 2008 for land use class *j* within the geographic domain *i*, and RC_{ja} is the relative LUC occurred in the same period for land use class *j* within the "available" geographic domain (a).

SI is calculated analogously to the forage ratio (Manly et al. 2002), and similar indices are commonly used to study fire selectivity towards land use classes (Moreira et al. 2001, Oliveira et al. 2014). Absolute values of SI > 1 indicate that a particular LUC burns proportionally more than available (preference), while |SI| < 1 indicates avoidance (i.e., a particular LUC burns proportionally less than available).

The sign of SI depends on the RC occurred in the "available" domain, which consists mostly of unburnt areas (Tab. S13-S14). In our dataset, the sign of the RC for a given land use class (i.e., the net increase or decrease in area) was consistent in all the geographic domains, with the exception of two land use classes: "wetlands" and "other land". However, here we do not focus on these two land use classes since their estimated areas were small and their RC were negligible in all the geographic domains. As an example, SI = -0.5 means that the relative loss of a particular land use class within a fire-related geographic domain is half the relative loss occurred in the "available" domain, while SI = 2 means that the relative gain of a particular land use class is twice the relative increase experienced in the "available" domain.

Within the context of this paper, rural land abandonment (LA) could be understood as the reduc tion of agricultural and pastoral land (Arable land, Orchards and Vineyards, Grasslands and Pastures) with the following expansion of natural classes such as Forest and Other Wooded land (Elbersen et al. 2014). For a given geographic domain *i*, this is equivalent to:

$$LA_i = RC_{For} + RC_{OW} - RC_{Ara} - RC_{OV} - RC_{GP} \quad \text{(eq. 3)}$$

where RC_{For} is the relative change of the forest class in domain *i*, RC_{OW} is the relative change of other wooded land, RC_{Ara} is the relative change of arable land, RC_{OV} is the relative change of orchards and vineyards, and RC_{GP} is the relative change of grasslands and pastures. A rural land abandonment index (LAI) for a given geographic domain *i* was defined analogously to the selectivity index:

$$LAI_i = \frac{LA_i}{LA_a} \quad \text{(eq. 4)}$$

where LA_i is the measure of land abandonment in the domain *i*, and LA_a is the measure of land abandonment in the "available" domain. LAI is then an index describing the relative land abandonment within the various geographic domains with respect to the available domain. Values of LAI > 1 indicate that land abandonment is more evident within a fire-related geographic domain than in the available domain, and vice versa, and so the higher the LAI, the more emphasized is land abandonment in the fire-related geographic domain with respect to the available domain. Finally, we repeated the selectivity analyses after dividing the Italian territory into three zones characterized by different fire seasonality (see Figure S1) to explore differences in fire preference between fire regimes.

Results

Results show that LUC from 1990 to 2008 in all fire-related geographical domains considered in this study experienced the same general tendency, characterized by a conversion from agropastoral land use classes towards woodland classes such as shrublands and forests. However, the degree of these changes was not homogenously distributed among geographical domains, and burnt areas in the period 2007-2017 showed generally higher rates of LUC than unburnt areas. Table 3 shows the transition matrix within the burnt areas ("Total_fire"), while Table 4 summarizes LUC in these areas. The Appendices include a transition matrix (Tab. S1-S7) and a summary table (Tab. S8-S14) for each of the geographical domains.

In the study area (i.e., "Available" geographical domain), 11% of the territory experienced LUC from 1990 to 2008 (Tab. S7). The forest area increased by 455,000 ha (RC = 2.0%; Tab. S14). Other wooded land also increased, more moderately though (RC = 0.5%), as well as settlement (RC = 1.3%). Likewise, land occupied by orchards, vineyards and nurseries expanded (RC = 1.6%). On the contrary, arable land and other herbaceous cultivations decreased by 973,000 ha (RC = -4.2%), as well as grasslands, pastures and uncultivated herbaceous areas (RC = -1.3%). LUC followed similar trajectories in all the geographical domains. New forest area came mainly from previous other wooded land, grasslands and pastures, and arable land classes, while most of the new forest plantations came from arable land (Tab. S1-S7). Most of the new other wooded lands were previously classified as grassland and pastures. Similarly, most of the new orchards and vineyards were arable land before the conversion. On the other hand, most of the loss of arable land in unburnt areas was due to conversion towards orchards, vineyards and settlements.

Burnt areas (i.e., "Total_fire" geographical domain) were more dynamic than the whole study area (i.e., "Available") and around 13% experienced pre-fire LUC in the period 1990-2008. In fact, burnt areas are characterized by a higher relative increase in forest area, forest plantations, and other wooded land than unburnt areas (Fig. 2). Burnt areas are also characterized by a higher relative loss of grassland and pastures than unburnt areas. Consequently, SI highlights a fire preference (|SI| > 1) for areas with greater relative expansions of forest, forest plantations, and other wooded land, as well as areas with greater relative reductions of grassland and pastures (Tab. 5). In addition, the relative expansion of settlements, orchards and vineyards were less prominent in burnt areas, and surprisingly, the loss of arable land was less marked in burnt than unburnt areas (Fig. 2). Furthermore, SI values were of the same sign and order of magnitude across the territories of the three fire regimes explored (Tab. S15).

LUC in large burnt areas ("Large_fire") differed to some extent from those recorded in smaller burnt areas ("Non_large_fire"; Tab. 5). The increase in forest and forest plantations, and the reduction in grassland and pastures were higher in large burnt areas (Fig. 2). Moreover, smaller burnt areas showed a higher increase in other wooded land, as well as a higher reduction in arable land, and orchards and vineyards. On the other hand, areas affected by se-

Table 3 - Transition matrix of estimated size (ha) of land use changes (LUC) from 1990 to 2008 within all the areas burnt between 2007 and 2017 ("Total_fire").

		2008									
		Forest land	Arable land	Orchards and vineyards	Forest plantations	Grassland and pastures	Other wooded land	Wetlands	Settlements	Other Land	Total
1990	Forest land	229,900	425	250	0	1,425	5,475	0	125	0	237,600
	Arable land	4,075	157,875	7,100	1,175	6,850	8,525	175	675	0	186,450
	Orchards and vineyards	1,025	2,300	31,075	50	1,350	1,400	0	125	0	37,325
	Forest plantations	0	50	0	650	75	25	0	0	0	800
	Grassland and pastures	8,300	2,800	700	275	113,150	27,325	25	350	25	152,950
	Other wooded land	13,550	2,800	1,025	0	1,525	133,000	150	325	0	152,375
	Wetlands	175	25	0	0	50	250	2,025	0	0	2,525
	Settlements	50	0	0	0	275	175	0	3,150	0	3,650
	Other land	0	0	0	0	25	75	0	0	3,350	3,450
	Total	257,075	166,275	40,150	2,150	124,725	176,250	2,375	4,750	3,375	777,125

Table 4 - Estimated size of land use changes (LUC) from 1990 to 2008 within all the areas burnt between 2007 and 2017 ("Total_fire").

Land use class	p (%) 1990	â (ha) 1990	RSE (%) 1990	p (%) 2008	â (ha) 2008	RSE (%) 2008	Difference â (ha)	p-value	RC (%)
Forest land	30.6	237,600	0.9	33.1	257,075	0.8	19,475	< 0.001	2.5
Arable land	24.0	186,450	1.0	21.4	166,275	1.1	-20,175	< 0.001	-2.6
Orchards and vineyards	4.8	37,325	2.5	5.2	40,150	2.4	2,825	< 0.001	0.4
Forest plantations	0.1	800	17.7	0.3	2,150	10.8	1,350	< 0.001	0.2
Grassland and pastures	19.7	152,950	1.1	16.0	124,725	1.3	-28,225	< 0.001	-3.6
Other wooded land	19.6	152,375	1.1	22.7	176,250	1.0	23,875	< 0.001	3.1
Wetlands	0.3	2,525	9.9	0.3	2,375	10.2	-150	< 0.001	0.0
Settlements	0.5	3,650	8.3	0.6	4,750	7.2	1,100	< 0.001	0.1
Other land	0.4	3,450	8.5	0.4	3,375	8.6	-75	0.034	0.0

p = percentage; â = estimated area; RSE = relative standard error; Difference â = â 2008 – â 1990, and its statistical significance (p-value; see Sallustio et al. 2016); RC = relative land use change from 1990 to 2008 (Difference â / Total â).

Table 5 - Selectivity index (SI) for each land use class in each geographic domain.

Land use class	Geographic domain				
	Total_fire	Fire_recurrence	Non_large_fire	Large_fire	Buffer_large_fire
Forest land	1.28	1.17	1.23	1.49	1.15
Arable land	-0.62	-0.50	-0.64	-0.55	-0.94
Orchards and vineyards	0.22	0.01	0.21	0.28	1.18
Forest plantations	1.96	1.57	1.84	2.11	1.05
Grassland and pastures	-2.78	-3.27	-2.74	-3.08	-2.36
Other wooded land	6.64	8.65	7.05	5.70	4.00
Wetlands	0.60	1.23	0.13	1.93	2.87
Settlements	0.11	0.03	0.08	0.17	0.79
Other land	-0.74	-1.51	-0.96	0.00	-4.72
LA	11.4	12.6	11.6	11.4	9.2
LAI	1.83	2.02	1.85	1.83	1.47

LA: land abandonment ratio (%); LAI: land abandonment index.

veral fires ("Fire_recurrence") experienced a higher increase in the other wooded land class (SI = 8.75) and a higher reduction in grassland and pastures (SI = -3.27) than the rest of fire-related geographical domains (Fig. 2, Tab. 5).

The buffer areas of large fires ("Buffer_large_fire") are characterized by SI values closer to 1 than the rest of burnt geographical domains (Tab. 5). Buffer areas experienced lower relative increases in forest, forest plantations and other wooded land, and lower loss of grassland and pastures than burnt areas. Moreover, the levels of RC in the arable land, orchards and vineyards, and settlement classes were comparable to those of unburnt areas, indicating that LUC in buffer areas were generally more similar to unburnt than burnt areas (Fig. 2). As a whole, buffer areas of large fires show a lower degree of rural land abandonment (i.e., lower LA and LAI) than the rest of burnt areas (Tab. 5). Moreover, land abandonment between 1990 and 2008, measured by LA, is more evident is areas affected by fires between 2007 and 2017 (Tab. 5) than in the whole study area, where LA = 6.3%.

Figure 2 - Relative change (RC) from 1990 to 2008 in each of the nine land use classes and six geographic domains.

Discussion

We assessed, for the whole Italian territory, land use changes (LUC) associated to large and frequent wildfires, two features of current fire regimes in southern Europe responsible for major impacts on ecosystem services (Moreira et al. 2020). Most of previous research addressing LUC and wildfire dynamics in Italy had an anecdotal approach (e.g., Ascoli and Bovio 2010, Corona et al. 2012, Salvati et al. 2017, Vacchiano et al. 2017), which explains the limited number of studies found for the Italian territory in recent reviews on LUC and fire disturbance (Butsic et al. 2015, Mantero et al. 2020). The few experiments explicitly testing the influence of LUC took place in Sardinia through using Corine Land Cover maps (Salis et al. 2014, Bajocco et al. 2019). At the European level, Corine Land Cover products are commonly used to assess relationships between LUC and fire regime features (e.g., Salvati and Ferrara 2014, Oliveira et al. 2017). We applied, for the first time, the Italian Land Use Inventory (IUTI; Corona et al. 2012) to test fire-related LUC hypothesis.

Compared with Corine Land Cover maps when analyzing LUC, IUTI minimizes information loss due to the application of a Minimum Mapping Unit that causes an underestimation of the extension of fragmented or linear classes, as well as their changes over time (Munafò and Tombolini 2014). Moreover, compared with mapping approaches, land use inventories are convenient in terms of costs and efforts for updating, and allow objective estimates of accuracy (Pagliarella et al. 2016, Sallustio et al. 2016). In this context, IUTI has proved to be effective in offering a comprehensive set of information not limited to forests ecosystems but also adjacent landscapes (e.g., urban and agricultural), facilitating the operationalization of ecological principles into decision making contexts, even related to fire risk management (Marchetti and Sallustio 2019).

Our LUC estimates in unburnt areas display a general agreement with land use changes inventoried in Italy, and in the Mediterranean area in the last decades (Marchetti et al. 2019). Our results show that Italian landscapes were highly dynamic in the period 1990-2008. Indeed, the general LUC trends are characteristic of agricultural land abandonment in mountainous regions of southern Europe: expansion of forest area, shrubland and new settlements at the expense of loss of agricultural land, grasslands and pastures (Ustaoglu and Collier 2018, Mantero et al. 2020). Considering the spatial polarization of LUC within the country following an altitudinal and latitudinal gradient (Garbarino et al. 2020), increasing IUTI sampling efforts and including the effect of other possible drivers (e.g., socioeconomy; Carlucci et al. 2019) might be useful to better understand LUC-fire relations at regional and sub-regional scales, where funds and planning efforts are usually concentrated. Despite these gradients in LUC, interestingly fire preferences for LUC were consistent across Italy, and we did not detect remarkable differences between territories with a Mediterranean and an Alpine fire regime.

Notably, we observed that burnt areas are characterized by higher rates of pre-fire LUC, probably driven by land abandonment, than the rest of territory considered available for burning. The advance of new forests, and especially new wooded areas such as shrublands, as well the reduction of grassland and pastures, burned disproportionately to their availability, which can be interpreted as a fire preference for this particular LUC. On the contrary, areas with higher rates of new settlements, orchards and vineyards tended to be avoided by fire. Fire avoidance of areas with higher loss of arable land is surprising, but it may be due to the fact that a great proportion of this land use changed towards other agricultural classes such as orchards, vineyards, grasslands and pastures, which are generally less fire prone than Mediterranean shrublands and forests (Bajocco and Ricotta 2008, Barros and Pereira 2014). Given the positive relationship between built-up areas and fire frequency (Mancini et al. 2018b, Elia et al. 2019), the increase of urban areas may have risen fire ignition, although this aspect was not investigated here. In summary, the main LUC in the last decades, ascribable to land abandonment dynamics, have probably contributed to increase fire proneness in the landscape across the country by expanding areas that are more susceptible to burn due to shrub and tree encroachment.

Our analyses evidence that rates of LUC towards forest and forest plantations were higher in large fire events exceeding 500 ha. This result corroborates previous findings associating forest cover and continuity to wildfire size (Pausas and Fernández-Muñoz 2012, Fernandes et al. 2016, Viedma et al. 2017, Mantero et al. 2020), and support the thesis that landscape transformations towards higher forest cover and connectivity among forest patches affect land susceptibility to large fires (Moreira et al. 2020). Although there is a general negative trend in burnt area in Italy, partly due to increasing fire suppression efforts (Turco et al. 2016), the largest fire events in the most recent extreme fire season in 2017 (Bovio et al. 2017), occurred in forested landscapes such as the Vesuvio Fire (3,331 ha) and the Val Susa Fire (4,018 ha), with a forest burnt area equal to 69% and 66% of the total burnt area, respectively. Besides fire weather, fire size in Italy is strongly controlled by firefighting capacity (Bovio et al. 2017, Fernandes et al. 2020), whose effectiveness is reduced in continuous forested areas because of minor accessibility (Castelnou et al. 2019), higher potential fire intensity (Fernandes et al. 2016, García-Llamas et al. 2019, Ribeiro et al. 2020) and higher probability of long-distance spotting (Storey et al. 2020). In this context, for example, even landscape homogenization, related to successional stages that reduce forest gaps and increase forests connectivity among large forest patches (Sallustio et al. 2018b), can play a positive role in fire spread.

One of the most evident pre-fire LUC in burnt areas is the loss of pastures in favor of shrublands, and this LUC resulted particularly marked in areas where recurrent fires followed. This result might reflect particular dynamics of grazing management in southern Europe. Pastoral abandonment and subsequent restoration by intense grazing is a common process in many areas, from the Alps to southern regions (e.g., Pittarello et al 2016, Moris et al. 2017). Recurrent fires in the dry season (i.e., winter and summer in Alpine and Mediterranean regions, respectively) are a common practice in the Mediterranean areas to reverse shrub and tree encroachment that follow reduced grazing pressure (e.g., Ascoli et al. 2013, Coughlan 2014). In Italy, pastoral fires are among the major causes of fire ignition in several territories (Lovreglio et al. 2010). The association between loss of pastures and recurrent fires might reflect the need for a repeated use of pastoral fires to renew pastures and hamper shrub and tree encroachment (Ascoli and Bovio 2010, Bajocco et al. 2020).

Interestingly, buffer areas of 200 m along large fires perimeters, i.e., where large fires were extinguished or effectively controlled by fire-fighting, showed contrasting LUC in comparison to burnt areas. These buffer areas experienced lower relative increases in forest, forest plantations and shrubland, lower losses of grassland and pastures, and higher increases in orchards and vineyards. These results agree with the thesis that continuous management of agro-forestry territories limits the occurrence of large fires by both increasing fire-fighting accessibility and effectiveness (e.g., constraining fire flanks decreases overall fire potential and provide opportunities to tackle the head of the fire front), and decreasing fuel connectivity (Viedma et al. 2017, Damianidis et al. 2020).

Conclusions

Our results show a fire preference for areas with higher rates of pre-fire LUC driven by land abandonment, suggesting that land abandonment may be one of the driving factors increasing fire proneness at national scale. We found a higher incidence of large fires in areas affected by higher rates of forest expansion, as well as higher incidence of recurrent fires in areas with higher transition rates from abandoned pastures and grasslands towards shrublands.

Additionally, we observed that areas surrounding large fires were less affected by pre-fire land abandonment and experienced a higher increase of orchards and vineyards than burnt areas. All these findings are compatible with the general idea that land abandonment increases fire size and frequency because of higher landscape fuel connectivity and fuel build-up.

Therefore, the findings presented in this study suggest that LUC ascribable to land abandonment is a relevant driver of the current fire regime across Italy. Our results also agree with the key role of the maintenance of an agro-forestry mosaic as part of the solution to reduce large fire impacts (Moreira and Pe'er 2018), hinting at the need of a greater integration between fire management and rural development policies. With this regard, the development and use of indices such as the rural land abandonment index, even at regional and subregional scales, can offer a viable support within the ongoing debate regarding the new Common Agricultural Policy in the EU and its connection to issues such as biodiversity conservation, ecosystem services provisioning, and climate change mitigation and adaptation strategies, all directly and indirectly connected to the fire regime.

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