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Early vegetation recovery of a burned Mediterranean forest in relation to post-fire management strategies

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The risk of wildfires in the Mediterranean region is expected to increase with climate change. Fire is one of the main drivers of plant diversity and composition, triggering succession processes that vary according to the fire regime and species' regeneration traits. Human management can modulate these processes to promote the recovery of the burned soil-vegetation system, through the application of practices such as salvage logging. Effects of these managements have been studied mostly for coniferous forests, with contrasting results, while little is known about the responses of evergreen broadleaved woodlands. Here, we analysed the 34-month recovery processes of a *Quercus ilex* forest and an adjacent *Pinus pinaster* stand in central Italy with respect to their diversity, composition and plant fire-related traits, in relation to three different management strategies applied after fire. These were: (1) no intervention (NT), (2) salvage logging and mulching (SM and SMP for the pine stand), (3) salvage logging, mulching and erosion control measures (e.g. fascines for hill slope stabilization; EC). Overall, the increase of post-fire vegetation cover was negatively affected by SM and EC treatments, while their effects on γ- and α-diversity were positive. Species diversity was significantly lower in pine than in broadleaved plots and compositional differences associated with forest type were significant. Abundance of woody species was higher in the unsalvaged sites, except for a few species (e.g. *Q. ilex*), while herbaceous plants were not affected. Species composition in managed plots was different from control plots after 10 and 22 months, while differences decreased after 34 months. Effects of management strategies on the frequency of resprouters as well as on the proportion of species with persistent *vs* transient soil seed bank were minor; these traits were mainly driven by forest type. Our findings suggest that non-treatment is the best post-fire management strategy for a fast recovery of woody species in typical Mediterranean broadleaved forests. However, the EC strategy promoted a high diversity level, while not apparently altering species composition compared with the natural post-fire succession process.

Introduction

One of the consequences of global climate change is the increasing frequency and intensity of human induced wildfires in terrestrial ecosystems across the world (Di Virgilio *et al.*, 2019; Xu *et al.*, 2020). Recent projections indicate that the vegetation fire risk will continue to increase around the globe as climate proceeds towards warmer and dryer conditions (Bowman *et al.*, 2020). In Mediterranean Europe, models based on global warming scenario reaching from 1.5°C to 3°C have recently predicted a corresponding increase of the burned area from 40 per cent to 100 per cent (Turco *et al.*, 2018). In the Mediterranean, ca. 500 000 fire events destroy an average of about 4500 km^2 of vegetation annually, causing severe environmental and economic damage, including loss of lives, infrastructure and ecosystem services such as carbon sequestration and the provisioning of raw materials (San-Miguel-Ayanz *et al.*, 2013; Turco *et al.*, 2016, 2017).

Fire represents a perturbation that shapes vegetation structure, patterns and plant community composition in seasonally dry landscapes worldwide (Bond *et al.*, 2005). Its impact has been especially pervasive in the Mediterranean vegetation, also due to its use as a land management tool for millennia (Pausas and Ramón-Vallejo, 1999; Keeley *et al.*, 2011). Fire represents an evolutionary driving force that has shaped plant diversity, traits and adaptive strategies in the Mediterranean-type ecosystems across the world (Kelly and Brotons, 2017; Di Virgilio *et al.*, 2019). Vegetation response to fire is driven by dynamic processes of autogenic secondary succession that usually lead to the pre-fire condition recovery (Capitanio and Carcaillet, 2008; Marzano *et al.*, 2012). Resprouting from the stump or below-ground parts such as lignotubers or rhizomes and recolonization by seed are the main mechanisms adopted by woody and herbaceous plants to persist and recover after fire. The speed and outcome of succession processes mainly depend on fire regime, as well on the local soil, microclimate conditions and on the species' adaptive traits and strategies (Paula *et al.*, 2009). According to Buhk *et al.* (2007), the interrelation between local ecological factors and the different regeneration mechanisms can result in a high spatio-temporal variability in post-fire vegetation species' performance.

In Mediterranean ecosystems, many studies examined the short-term structural recovery and tree regeneration after a fire event, in relation to the type of vegetation, fire regime, fire severity and other variables (Marzano *et al.*, 2012; Viana-Soto *et al.*, 2017; Gonçalves and Sousa, 2017). Several studies also focused on the post-fire dynamic changes of community species diversity, species composition and functional groups composition (e.g. Capitanio and Carcaillet, 2008; Gosper *et al.*, 2012). Resulting evidence supported that: (1) all or the majority of plant species during the succession are in place at the beginning of the recovery phase, (2) richness is highest immediately following disturbance and (3) the initial plant community re-establishment is a rapid process, fitting the 'initial floristic composition' model by Egler (1954).

However, the vegetation responses to active post-fire management of the burned biomass still remain unclear, despite that practices such as salvage logging, mulching and others are often carried out to facilitate plant resprouting and establishment of tree seedlings (Castro *et al.*, 2011). In the Mediterranean region, many studies focused on the effects on soil conditions and tree regeneration in pine-dominated forests (Spanos *et al.*, 2005; Castro *et al.*, 2011; Francos *et al.*, 2019; Moya *et al.*, 2020), whereas relatively fewer investigations were conducted on plant community properties such as species composition and diversity (Leverkus *et al.*, 2014; Fernández and Vega, 2016). Overall, it is still poorly understood how these variables are affected by the application of post-fire management in evergreen broadleaved forests of the Mediterranean. Since post-fire recovery processes largely depend on pre-fire vegetation (Egler 1954; Espirito-Santo and Capelo, 1998), responses in pine forests may substantially differ from those in broadleaved forests, which deserve more investigation.

Taking advantage of a severe wildfire event in southern Tuscany (Italy) in 2017, we analysed the 3-year recovery processes in an evergreen forest by means of a diachronic approach (permanent plots). Before the fire, the forest was dominated by *Quercus ilex*, except for a minor part dominated by *Pinus pinaster*. The implementation of different post-fire management strategies by the local administration authority allowed us to test the effects of these measures on vegetation diversity, composition and structure, as well as on the growth of the main woody resprouting species, under comparable environmental conditions.

Accordingly, our aims were: (1) to advance our knowledge about early post-fire vegetation recovery in a broadleaved evergreen forest and a pine stand located in a poorly studied region, with a focus on community diversity, species composition, vegetative growth and regeneration traits, (2) to compare the effects of three commonly applied post-fire management strategies to favour vegetation recovery in the two forest types.

Materials and methods

The fire event occurred along the Tyrrhenian coast in southern Tuscany (central Italy: 42°47′ Lat. N, 10°50′ Long. E) close to the village of Castiglione della Pescaia (Grosseto province). The topography of this area is characterized by a system of low hills reaching 140 m a.s.l. with slightly to moderately steep slopes (5–25° inclination) and variable aspect. Bioclimate of this area is meso-mediterranean, with a mean annual temperature of 15.7°C and total annual rainfall of 655 mm, mainly distributed between November and April (Barazzuoli *et al.*, 1993). Summer drought is intense, with precipitation of ca. 80 mm (https://www.sir.toscana.it/, accessed on 29 June 2021) between June and September. The geological formation is dominated by quartzitic sandstones (Lazzarotto, 1993), determining the formation of shallow, subacidic and nutrient-poor soils (pH ca. 6.2) of the 'Ranker' type.

The burned vegetation was a typical Mediterranean evergreen maquis-forest dominated by the holm oak (*Q. ilex* L.) and other sclerophyllous species, such as *Arbutus unedo* L., *Erica arborea* L., *Myrtus communis* L., *Phillyrea angustifolia* L. and others (*Quercion ilicis* Br.-Bl. ex Molinier 1934 alliance). The mature forest stages could be referred to the *Cyclamino repandi-Quercetum ilicis* Biondi *et al.* 2003, association, whereas the regressive stages corresponded to the acidophilous 'maquis' community of the *Erico arboreae-Arbutetum unedonis* Allier et Lacoste 1980. The *P. pinaster* stand was developed along an adjacent retrodunal coastal strip and was characterized by a dense shrub layer with *Phillyrea angustifolia*, *Erica multiflora* L., *Rosmarinus officinalis* L. and other evergreens of the association *Phillyreo angustifoliae-Ericetum multiflorae* Arrigoni *et al.*, Nardi et Raffaelli 1985.

The year 2017 was characterized by strong droughts associated with decline in precipitation and soil moisture in Italy, as documented by the European Space Agency (https://phys.org/news/2017–09-italy-drought-space.html, accessed on 8 March 2021). Soil water deficit started in autumn–winter 2016 and increased in the following spring and summer, also due to unusually high temperatures (Magno *et al.*, 2018). Total annual rainfall in study area according to the closest weather station was exceptionally low (420 mm), whereas maximum daily temperatures reached 39.8°C in early August (https://www.sir.toscana.it/, accessed on 28 June 2021).

The fire started at 1.30 p.m. of 4 July 2017, lasted ca. 16 h and burned 85 and 15 hectares of the broadleaved and pine forest, respectively. It was a ground and canopy fire of high severity, with the above-ground vegetation completely charred; many trees, shrubs and all herbaceous plants were killed (Hayes and Robeson, 2009).

In early autumn 2017, the local administration authorities applied different management strategies in the fire area, with the intent of favouring vegetation regeneration, reducing soil erosion and also the visual impact of the burned forest caused by the standing charred trees. The following three management strategies, hereafter 'management types', were applied:

- 'Not Treated: NT' (Figure 1 NT): the burned hill areas, less accessible and not visible from the main roads, the village and the seashore were not treated. Here the soil-vegetation system was left to its natural development. The NT area was about 20 per cent of total burned area, all located in the broadleaved forest.
- 'Salvage logging and mulching treatment: SM' (Figure 1 SM): salvage logging was applied to remove the standing burned

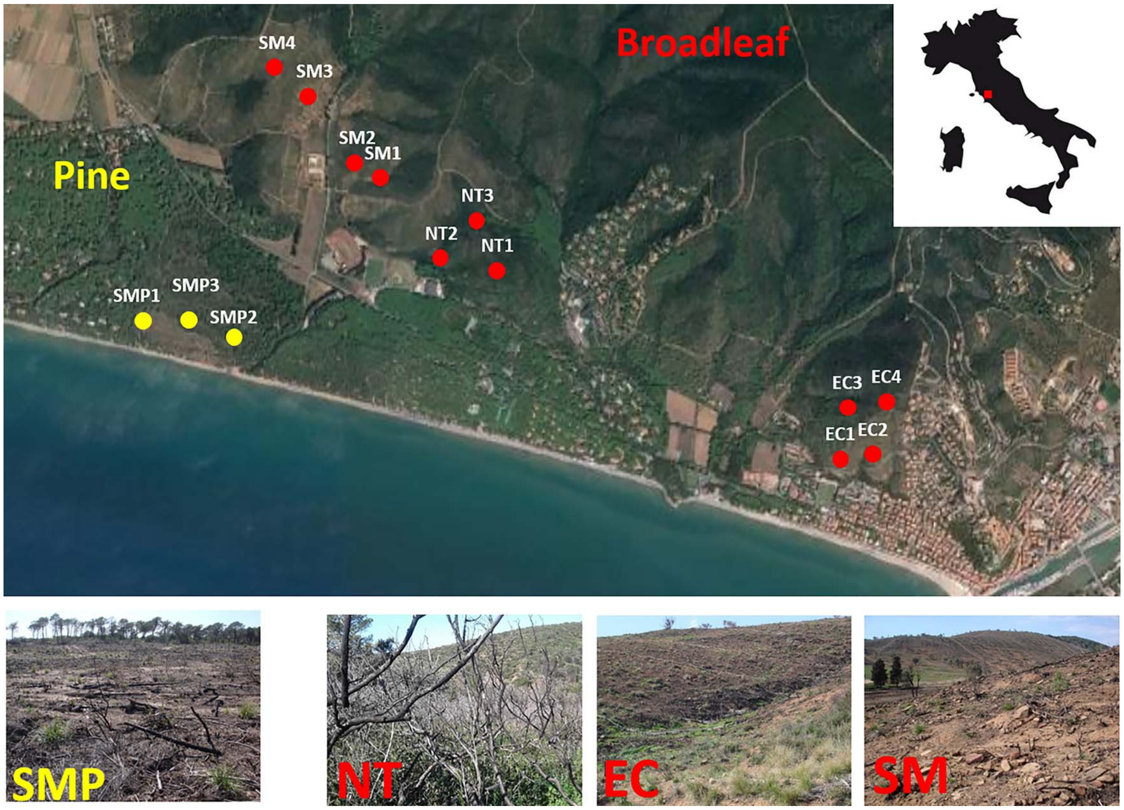

Figure 1 Overview-map of the study area with locations of plots and field photos of the areas soon after (winter 2018) the salvage logging: EC (salvage logging+mulching+erosion control), SM (salvage logging+mulching), SMP (salvage logging+mulching in pine plots), NT (not treated).

trees, both in the broadleaved and pine forest. The burned standing trees and snags, including larger shrubs, were felled, bunched and chipped. Part of the resulting biomass was used for mulching to protect and enrich the soil with organic matter; SM area was about 55 per cent of the total burned area, of which ca. 10 per cent was located in the pine forest (Figure 1 SMP).

- 'Salvage logging, mulching and erosion control treatment: EC' (Figure 1 EC): salvage logging was combined with the installation of a system of fascines to reduce soil erosion on the hill slopes close to Castiglione della Pescaia. Fascines were created along the contour lines using partially burned wood material (stems and branches) resulting from the salvage logging operations. This treatment was applied in about 25 per cent of the total fire area, all located in the broadleaved forest.

Since it is known that the harvesting method may affect the composition of the post-fire succession (Fraser *et al*., 2004; Macdonald, 2007), we note that the same harvesting techniques and logging machines were used in plots under SM and EC treatments, in the order: a feller-buncher and a forwarder, a chipper powered by a farm tractor (stopped at the landing site) and an excavator equipped with a forestry mulcher.

Field sampling design and data collection

After preliminary field surveys in December 2017–February 2018, we established 14 permanent plots of 25 m^2 (5 × 5 m), delimited by steel poles at the corners. Plot selection was designed as to cover the fire area and the parts subject to different management types, accounting as much as possible for the local variability of site conditions in terms of altitude, slope aspect and slope inclination (Figure 1). To this purpose, four plots (EC1–4) were randomly placed in areas subject to the EC treatment. These plots were established on the hill slope with the lower side along the line of the terraces created for the installation of the fascines. Four plots (SM1–4) were established in the part of the fire area subject to the SM treatment. Three control plots (NT1–3), were located in the area left to natural development; the low accessibility of this area did not allow to establish a larger number of plots.

Finally, three plots were placed in the pine forest (SMP1–3) in the coastal strip; no control plots could be established in this part of the fire area, as the vegetation was subject to the same treatment SM over its entire surface (Table 1). This group of plots is indicated hereafter as SMP.

Starting from early May 2018, we realized two types of vegetation surveys, one aiming at determining the changes in community cover, species diversity and composition, and one at determining the growth rate of the main woody resprouting species. The first type of survey was carried out in the period of maximum growth and reproductive activity at the following four time points after the fire: May 2018 (10 months), July 2018 (12 months), May 2019 (22 months) and May 2020 (34 months). The July 2018 survey was carried out to evaluate the changes from the spring to the summer in the first year after the fire. At each survey, total ground cover of the vegetation was carefully estimated and all

Table 1 List of the sampling plots with geographical details and type of post-fire management strategy: no intervention (NT), salvage logging and mulching (SM), salvage logging, mulching and erosion control (EC).

Plot	Lat N, Long E	Altitude *m*	Slope incl. °	Slope aspect	Forest type	Management type
EC1	42°46.063′, 10°52.440′	65	12	SW	Broadleaved	EC
EC2	42°46.074′, 10°52.429′	76	15	SW	Broadleaved	EC
EC3	42°46.096′, 10°52.415′	84	10	SW	Broadleaved	EC
EC4	42°46.124′, 10°52.401′	103	12	W	Broadleaved	EC
SM1	42°46.711′, 10°50.692′	25	7	NW	Broadleaved	SM
SM2	42°46.640′, 10°50.821′	58	10	NW	Broadleaved	SM
SM3	42°46.856′, 10°50.502′	47	9	SW	Broadleaved	SM
SM4	42°46.924′, 10°50.471′	68	10	S	Broadleaved	SM
SMP1	42°46.340′, 10°50.049′	4	-	-	Pine	SM
SMP2	42°46.313′, 10°50.163′	4	-	-	Pine	SM
SMP3	42°46.367′, 10°50.150′	4	-	-	Pine	SM
NT1	42°46.564′, 10°51.119′	73	4	NE	Broadleaved	NT
NT2	42°46.547′, 10°51.122′	81	3	NW	Broadleaved	NT
NT3	42°46.546′, 10°51.091′	74	8	W	Broadleaved	NT

vascular plant species were identified and scored for percentage of ground cover; species identification was mainly performed in the field based on the checklist of the flora of southern Tuscany (Selvi, 2010) and Flora d'Italia (Pignatti, 2017).

In the second analysis (vegetative growth), we determined the height increase of sprouts and suckers from the stumps of mainly *A. unedo*, *Daphne gnidium* L., *E. arborea*, *Erica multiflora*, *Lonicera implexa* Aiton, *M. communis, Pistacia lentiscus* L., *Olea europaea* L. *Phillyrea sp., Quercus pubescens* Willd., *Q. ilex*, *Rhamnus alaternus* L. and *Spartium junceum* L.

For each individual plant we measured the maximum height reached at six time points after the fire: May 2018 (10 months), July 2018 (12 months), February 2019 (19 months), May 2019 (22 months), November 2019 (28 months), May 2020 (34 months) and November 2020 (40 months); the measurements in the months of November and February were done in consideration of the growth activity of most Mediterranean sclerophyllous species in the autumn and towards the end of the winter (Grossoni *et al*., 2020).

Data analysis

We analysed the effects of the three post-fire managements and the two forest types on the following variables: vegetation cover, height and proportion of resprouters, species diversity and composition, abundance of main functional groups, proportion of species forming a persistent or transient seed bank in the soil. Statistical approaches used for each analysis are described below, and a graphical summary of the variables and methods is presented in Supplementary Material. All analyses were performed in R version 4.0.3 (R core team, 2018).

Effect of post-fire management and forest type on vegetation cover and height

Firstly, we compared the four groups of plots (NT, EC, SM, SMP) to test the differences in vegetation cover related to post-fire management type (NT *vs* EC *vs* SM), as well the effects of the SM treatment on the same variable in the pine and broadleaved plots to detect effects caused by the forest type (SM *vs* SMP). Differences were tested separately at three time points after the fire (10, 22, 34 months) with the Kruskall–Wallis test, followed by Dunn's *post hoc* tests in consideration of the non-parametric nature of the dataset. Next, we also considered the effect of time and site variables on vegetation cover during the three years. We applied linear models including management type and site characteristics, e.g. slope aspect (as categorical), slope inclination and altitude (as continuous variables), including all interactions. This analysis was performed only for the 11 broadleaved forest plots (four replicates for SM and EC and three for NT), using the *lm* function. Selection of the optimal model, among those generated by all possible combinations, was based on the Akaike Information Criterion (AIC) values; the AIC estimates the relative amount of information lost by a given model: the less information is lost, the higher the quality of the model (Bartón, 2012). For the best model selected we also calculated R^2 and parameter-specific *P*-values for each level (e.g. value) of the predictors.

Next, the mean height of woody resprouters (e.g. *A. unedo*, *Daphne gnidium*, *E. arborea*, *Erica multiflora*, *Lonicera implexa*, *M. communis*, *P. lentiscus, O. europaea*, *Phillyrea sp., Q. pubescens*, *Q. ilex*, *R. alaternus* and *S. junceum*) was compared at each time points after the fire (e.g. 10, 12, 22, 19, 28, 34, 40 months). Significance of differences between the three managements (NT *vs* EC *vs* SM) and the two forest types (SM *vs* SMP) was determined with the Kruskall–Wallis and Dunn's *post hoc* tests.

Effect of post-fire management and forest type on species diversity

Next, we determined the α-diversity of each plot as total species richness (SR), Shannon index (H′) and Evenness (J). Gamma diversity (γ) was also determined for each group of plots (NT, EC, SM, SMP) as the total number of vascular plant species. To investigate the effect of post-fire management and forest type on species diversity, significance of the differences in the α-diversity metrics among NT, EC, SM and SMP were tested separately for each year with the Kruskall–Wallis and Dunn's *post hoc* tests. The same model approach used for vegetation cover was repeated for SR, H′ and J to consider the effect of time and site variables during the three years in broadleaved plots. Since SR values were count data, the starting model was fitted with the *glm* function with a Poisson error distribution (Guisan and Zimmermann, 2000), whereas for the other continuous variables (H′, J) we used the *lm* function. The optimal model was selected based on the AIC, also calculating R^2 and *P*-values for each predictor.

Effect of post-fire management and forest type on species composition

Differences in the post-fire species composition of the communities related to management and forest type were analysed using a multivariate approach. To this purpose we calculated the Bray–Curtis distance between plots based on species cover at four time points after the fire (10, 12, 22, 34 months), using the *vegdist* function in Vegan R package (Oksanen *et al.*, 2019). Non-metric multidimensional scaling using the *metaMDS* function in Vegan was then applied to summarize and display distances among plots grouped by management (NT, EC, SM) and forest type (SM, SMP), separately for each of the four time points above; significance of the compositional differences between plot groups was determined using PERMANOVA with 999 permutations (*adonis* function). We also tested for multivariate homogeneity of dispersion using *betadisper* to distinguish between the compositional differences determined by management or forest type and the dispersion effects within each group of plots (Anderson *et al.*, 2006; Warton *et al.*, 2012). Next, we used the function *multipatt* in *indicspecies* to perform an indicator species analysis following Dufrêne and Legendre (1997); this analysis allowed us to identify the species that are significantly associated with the post-fire management and forest types, based on their abundance and frequency in the respective groups of plots (see also Carrari *et al.*, 2016).

Effect of post-fire management and forest type on plant functional groups and traits

Vegetation structural changes were investigated by the analysis of abundance (cover) variations of the main functional groups based on Raunkiaer life-forms; e.g. trees and large shrubs (phanerophytes), small shrubs (chamaephytes+nanophanerophytes), geophytes, hemicryptophytes (excluding graminoids), therophytes (excluding graminoids) and graminoids (both annual and perennial); source of data was *Flora d'Italia* (Pignatti, 2017). To evaluate the effects of management and vegetation type, differences in structural changes among NT, EC, SM and SMP were tested with non-parametric Kruskall–Wallis and Dunn's *post hoc* tests.

Finally, a similar analysis was performed at 10 months after the fire to examine, at the first spring, the differences in the proportion of species with resprouting ability and species that form a persistent (>1 year) or transient (<1 year) seedbank in the soil. Data about resprouting ability and seed persistence in the soil were retrieved from the most comprehensive database of plant functional traits of the Mediterranean flora, BROT 2.0 (Tavşanoğlu and Pausas, 2018). Data coverage for the species in our dataset was 97 per cent for resprouting ability (when excluding all annual species with no perennial underground organs) and 60 per cent for seed persistence in the soil. By these analyses we could evaluate the short-term effects of management and forest type on the relative contribution of species with different traits and post-fire recovery strategies to vegetation recovery.

Results

Vegetation cover and height growth

When pooling all surveys together, mean ground cover was highest in NT plots, whereas no differences occurred between SM and EC plots (Table 2). Model results showed a significant effect of management type on cover values in broadleaved plots, as well as a significant effect of the survey year (Table 3). Regarding the site variables, the best model showed a positive effect of the Northeast aspect compared with others (NW, W, SE, S); slope inclination was apparently also related to vegetation cover, though without statistical significance (Table 3). The positive effect of NT on vegetation cover was confirmed by the separate analysis of each temporal dataset (Figure 2A). However, differences decreased from the first to the third year: 10 months after the fire, NT plot cover was more than double of EC plots and 81 per cent higher than SM plots, whereas 34 months after the fire NT plot cover was 24 per cent higher than in EC plots and 52 per cent than in SM plots. In fact, NT plot cover increased by 23 per cent between 10 and 22 months and 33 per cent between 22 and 34 months after the fire, whereas such increment was 90 per cent and 54 per cent in EC plots, 62 per cent and 20 per cent in SM plots (Figure 2A). Average vegetation cover was lowest in the pine plots (SMP; Table 2), but the SM management in this forest type did not result in a difference with respect to the plots in the broadleaved forest (SM plots; Figure 2A).

Concerning the growth responses of woody resprouters, *Phillyrea* sp. (Figure 3C) showed a faster recovery in NT and EC than in SM plots (both pine and broadleaved). Differences in the growth rate of other species were smaller, though *E. arborea*, *O. europaea* and *Q. ilex*, showed significant differences 34 and/or 40 months after the fire. Regarding management, growth of *E. arborea* was faster in NT and SM compared with EC plots (Figure 3A), whereas that of *O. europaea* was faster in NT and EC than in SM plots (Figure 3B). On the contrary, *Q. ilex* grew faster in the treated than in the NT plots, though differences were not significant (Figure 3D).

Regarding forest type, the recovery of *E. arborea* and *Q. ilex* was faster in broadleaved plots, while no differences occurred for *O. europaea* and *Phillyrea sp.* (Figure 3). Growth rates of the other woody species (e.g. *A. unedo*, *Daphne gnidium*, *Erica multiflora*, *Lonicera implexa*, *Q. pubescens, R. alaternus* and *S. junceum*) were similar (data not shown).

Species diversity

In total, we recorded 153 species, of which 54 per cent in EC and SM plots, and 35 per cent and 32 per cent in NT and SMP plots,

Table 2 Ground cover and diversity of post-fire communities in the four plot types.

Variable	NT	EC	SM	SMP
Cover	154.6 ± 15	106.4 ± 12.6	106.1 ± 8.2	85.9 ± 11
γ-diversity	53	83	83	49
SR	18.5 ± 5.0	25.9 ± 6.1	23.6 ± 1.3	19.5 ± 1.4
H′	2.14 ± 0.18	2.36 ± 0.38	2.30 ± 0.32	2.15 ± 0.35
J	0.74 ± 0.07	0.73 ± 0.08	0.73 ± 0.07	0.75 ± 0.08

Values of vegetation cover (%), γ-diversity and α-diversity (SR: species Richness, H′: Shannon Index; J: evenness) are means ± standard error of the four time points (10, 12, 22, 34 months after the fire); plot types and management type abbreviations follow Table 1.

Table 3 Management and site variables effects on cover and diversity.

	Cover	SR	H′	J
Management type (EC)	−53.393**	7.361***	0.187*	
	(19.715)	(1.786)	(0.104)	
Management type (SM)	−59.074***	4.528**	0.391***	
	(15.614)	(1.786)	(0.132)	
Time (22 months)	44.955***	−0.364	−0.310***	−0.092***
	(8.688)	(1.727)	(0.099)	(0.029)
Time (34 months)	91.336***	−6.273***	−0.550***	−0.105***
	(8.688)	(1.727)	(0.099)	(0.029)
Slope inclination	2.189			
	(2.508)			
Altitude			0.008**	
			(0.003)	
Slope aspect (NW)	−38.711**			
	(15.752)			
Slope aspect (S)	−33.863			
	(21.097)			
Slope aspect (SW)	−47.474**			
	(18.181)			
Slope aspect (W)	−50.390***			
	(17.457)			
Constant	146.645***	22.768***	1.866***	0.798***
	(16.254)	(1.678)	(0.258)	(0.020)
Observations	33	33	33	33
R^2	0.883	0.546	0.613	0.347
Adjusted R^2	0.837	0.481	0.542	0.303
Residual Std. Error	20.375 (df = 23)	4.050 (df = 28)	0.233 (df = 27)	0.067 (df = 30)
F Statistic	19.323*** (df = 9; 23)	8.417*** (df = 4; 28)	8.560*** (df = 5; 27)	7.968*** (df = 2; 30)

Optimal linear model structures relating the response variables (cover, Species Richness-SR and Shannon Index-H′) to management, forest type, year, slope and aspect [R syntax of the starting model: y ~ management type * time *slope aspect *slope inclination*altitude]. Values for the predictor variables, management type (levels: EC, SM compared with NT), time (levels: 22 and 34 months compared with 10 months after the fire), slope aspect (level N, NW, W, SW, S compared with: NE), slope inclination and altitude are parameter estimates. R^2 refers to the fraction of the variation explained by the model structure and R^2 adjusted takes into account the number of independent variables used for predicting the target variable. Significance level: *$P < 0.05$, ** $< P < 0.01$, ***$P < 0.001$.

respectively. Pooling all surveys together, mean SR in broadleaved plots ranged from 18.5 in NT to 26 in EC (Table 2). The corresponding model, applied to the broadleaved plots, supported positive effects of both management (EC and SM) and time; in this case site variables were not included in the optimal model (Table 3). Looking at each single survey (Figure 2B), the management type significantly affected SR only 22 months after the fire (P-value = 0.018), when this variable was higher in EC than in NT plots; differences almost disappeared in the following years. SR strongly decreased with time in all broadleaved plots and reached the lowest value in the NT plots 34 months after the fire; at this time differences with EC were no longer significant. On average, SR was higher in SM than in SMP plots (+17 per cent; Table 2). However, no significant differences occurred between

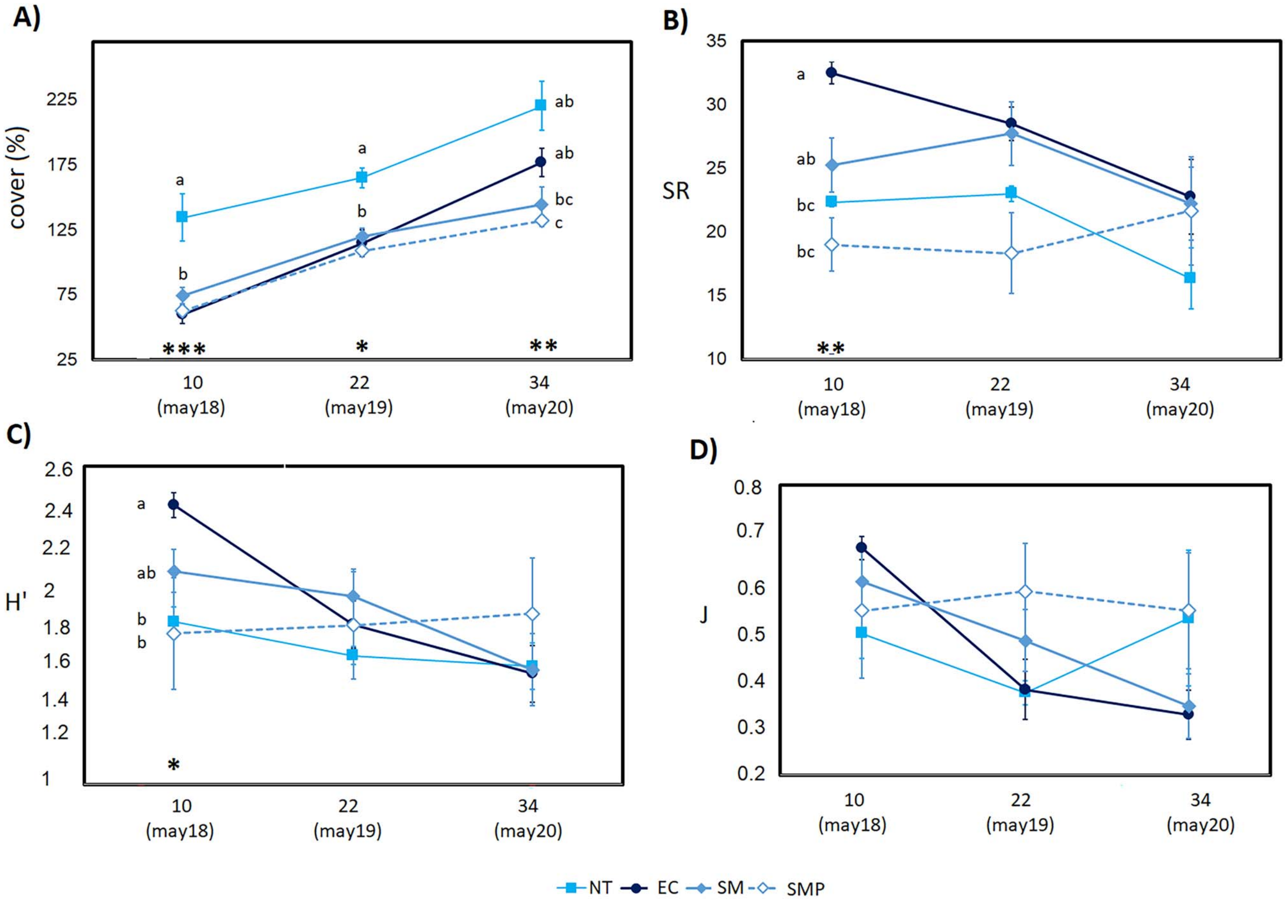

Figure 2 Variations in: (A) cover, (B) species richness (SR), (C) Shannon index (H′), (D) evenness (J) at three time points after fire (10, 22 and 34 months), in NT (not treated), EC (salvage logging+mulching+erosion control), SM (salvage logging+mulching in broadleaved forest) and SMP plots (salvage logging+mulching in pine stand). Differences among plot groups were tested with Kruskal–Wallis test at each time point (*** < 0.001, ** $0.001 < P < 0.01$, *$0.01 < p < 0.05$). Letters at each time point indicate significant differences among groups ($P \leq 0.05$; Dunn's test). Error bars represent the standard error of the mean.

the two forest types at 34 months after the fire due to the increase of this variable in the SMP plots.

Shannon diversity in broadleaved plots followed the same trend of SR, ranging from 2.14 in NT to 2.36 in EC plots (pooling all surveys). The optimal model selection showed a positive effect of the management types EC and SM, together with a significant increment with time (22 and 34 months compared with 10 months after the fire; Table 3). Looking at each single survey, Shannon diversity was affected by management type only at 10 months after the fire, when it was significantly higher in EC than in NT plots (Figure 2C). No effects were detected for the forest type under the SM treatment, despite the lower values for SMP (Figure 2C; Table 2). Evenness values showed minor differences (Table 2) and no effect of management was detected, neither when considering all plots (Figure 2D) nor the broadleaved plots only (Table 3). According to the best model selected, evenness decreased with the time after fire.

Species composition

PERMANOVA results indicated significant compositional differences caused by the management type among the three groups of broadleaved plots (NT, EC and SM). However, differences decreased with time (Figure 4). The first year NMDS scattergram had the lowest stress (0.107) and the best fit (R^2 linear fit = 0.933; non-metric fit R^2 = 0.989). Combined with the significant PERMANOVA test (p perm = 0.001) and the lack of a dispersion effect (p disp = n.s.), this showed that the largest differences in species composition were in the first spring (10 months after fire), when treated plots (SM and EC) were clearly separated from the NT plots (Figure 4A). Differences among the groups of plots persisted in the following surveys, though at 12 months after the fire, NT and SM plots were partially overlapping (Figure 4B). In the following years, SM plots became gradually more dispersed, indicating a reduction in the compositional differences with respect to both NT and EC plots. At 34 months after the fire, the EC and NT plots were floristically less different (p perm = 0.017; Figure 4D).

Regarding forest type, compositional differences between SM and SMP were significant at each time point (10 months after the fire: $p = 0.035$, 12 months: $p = 0.034$, 22 months: $p = 0.031$; 34 months: $p = 0.027$; data not shown).

The significant effects of management and forest type on composition were confirmed by the indicator species analysis,

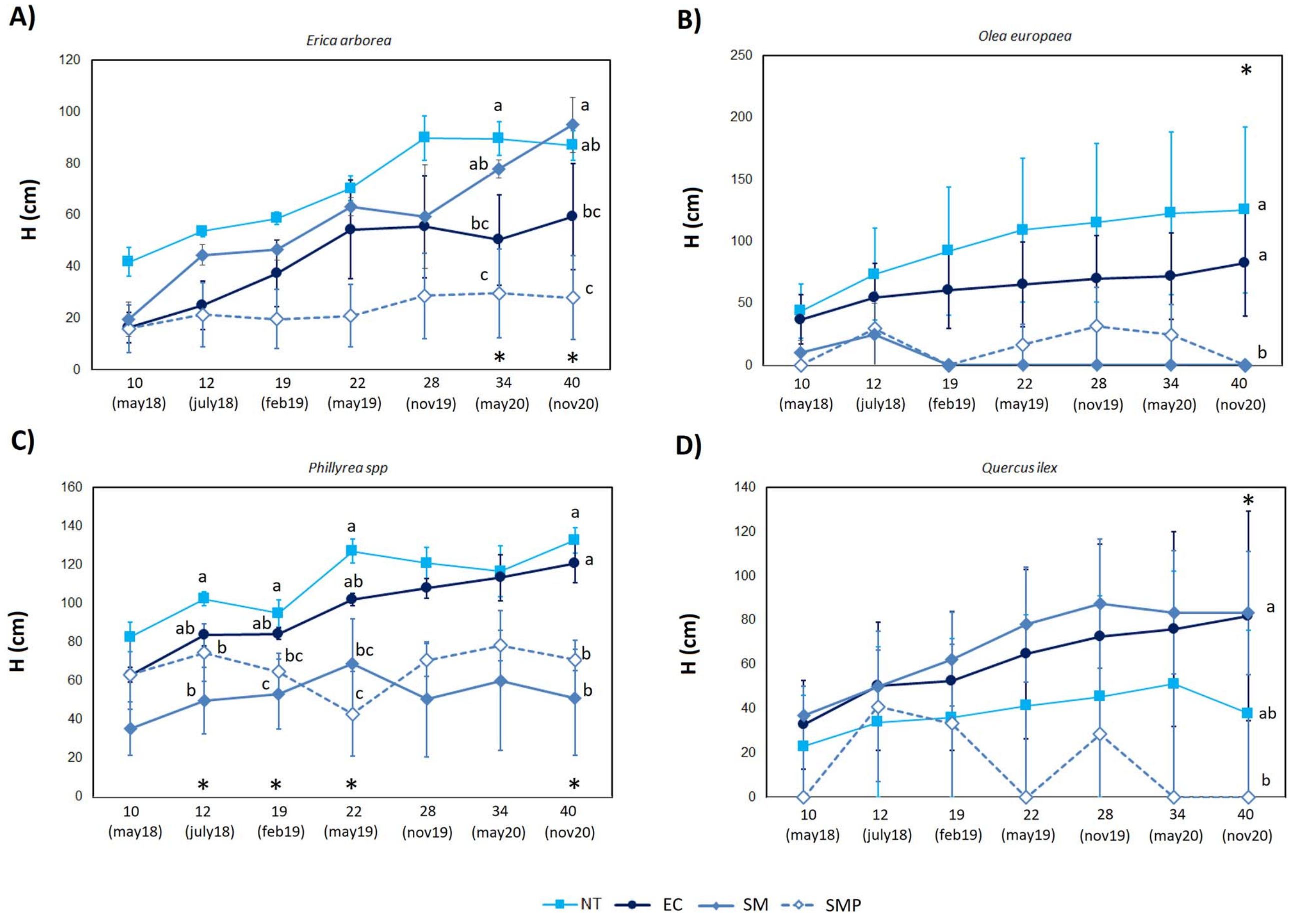

Figure 3 Height growth (H) of the four most frequent resprouting taxa in NT (not treated), EC (salvage logging+mulching+erosion control), SM (salvage logging+mulching), SMP (salvage logging+mulching in pine stand) plots; differences between groups at each time point (10, 12, 19, 22, 28, 34, 40 months after the fire) are shown (from Kruskal–Wallis test); (A) *Erica arborea,* (B) *Olea europaea*, (C) *Phillyrea sp.,* (D) *Quercus ilex*. Letters indicate significant differences among groups at each time point ($P \leq 0.05$; Dunn's test). Error bars represent the standard error of the mean.

which showed a variable number of different species favoured by management and forest type in terms of frequency and cover (Table 4). Except for the first survey in the SM and SMP plots, the number of indicator species decreased with time (from 4–5 at 10 to 1–2 at 34 months after the fire). Furthermore, the 10 months' species were always different from the 34 months' species. At 34 months after the fire, the only indicator species in the NT plots was a nano-phanerophyte (*Cistus creticus* L.), whereas in the SM and SMP plots we found two herbs (*Trifolium arvense* L. and *Foeniculum vulgare* Mill. respectively); the EC plots were characterized by one graminoid (*Briza maxima* L.) and one shrub (*P. lentiscus*).

Plant functional groups and traits

In terms of functional groups and life forms, the ground cover of phanerophytes, chamaephytes+nano-phanerophytes and hemicryptophytes increased with time (Figure 5A–C), whereas that of therophytic herbs sharply decreased after the first spring (Figure 5D). Management type affected the abundance of phanerophytes (Figure 5A) and chamaephytes+nano-phanerophytes (Figure 5B) in a different way. In the last spring (34 months after the fire), the cover of phanerophytes in the NT and EC was significantly higher than in SM plots (Figure 5A); similarly, differences were strongest after three years also for chamaephytes+nano-phanerophytes (Figure 5B). However, the highest cover of small woody species was recorded in the NT plots, whereas treated plots had a similarly lower cover. Regarding forest type, the cover of phanerophytes, chamephytes/nano-phanerophytes and therophytes (except for the last survey, 34 months after fire) was lower in the pine plots, though differences were not significant (Figure 5).

As expected, management type did not influence the proportion of resprouters in the broadleaved plots (Figure 6, left). Instead, this was affected by forest type, since frequency of resprouters in the SMP plots was highest than in the SM broadleaved plots.

Data about seed persistence in the soil was available for 78 species in our dataset; of these 39 (50 per cent) were reported to form a persistent (>1 year) or 37 transient (<1 year) seedbank; two species apparently formed no seed bank. The ratio persistent:transient was highest in the NT plots and lowest in the SMP plots, while intermediate values resulted for the EC and SM plots (Figure 6, right).

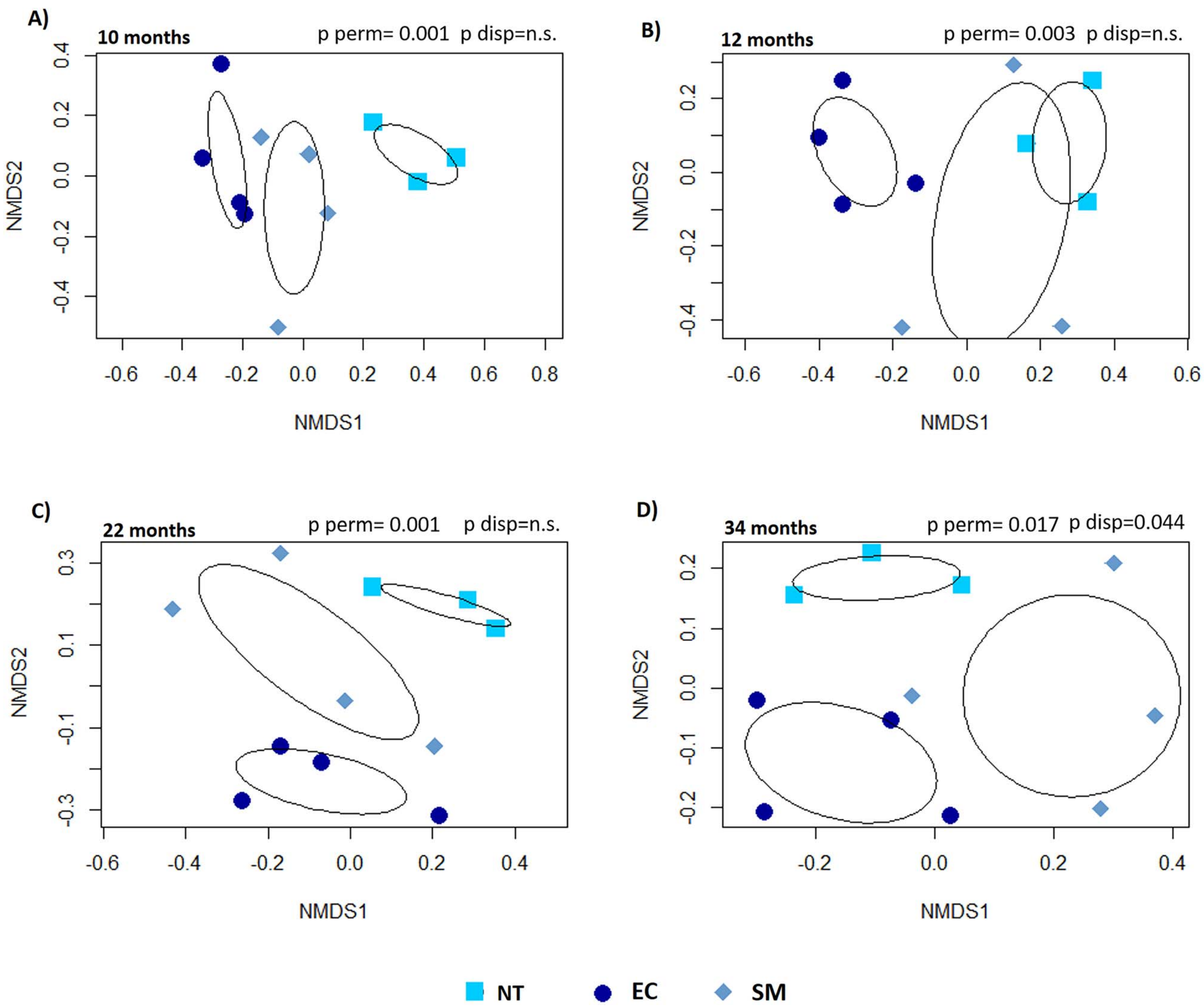

Figure 4 Non-Metric Multidimensional Scaling showing species composition differences between groups of plots by management (NT-not treated, EC-salvage logging+mulching+erosion control, SM-salvage logging+mulching) at the following time points (months after fire): (A) 10; (B) 12; (C) 22; (D) 34. p_{perm} indicates the significance of the compositional shift among groups, based on PERMANOVA; p_{disp} indicates the significance of the dispersion effect within each group of plots (e.g. year).

Discussion

Despite the limited sample size, determined by the low accessibility of the burned area, our findings provide evidence on early recovery processes in a Mediterranean forest dominated by *Q. ilex* and to a lesser extent *P. pinaster*, in relation to the management strategy adopted after fire. We found different responses of the vegetation subject to an active post-fire management with respect to that left to its natural dynamics. As expected, overall community response to fire was also dependent on forest type, though our results are here limited by the lack of control plots in the pine forest stands. Vegetation cover was always significantly higher in the non-treated plots, in line with Leverkus *et al.*, (2014) who found a negative effect of salvage logging on total cover two years after a wildfire. Other studies, however, detected no or little effects on vegetation cover after post-fire treatments such as salvage logging and mulching (Fernández and Vega, 2016; Moya *et al.*, 2020). Similarly, Francos *et al.*, (2019), observed similar regrowth in non-treated stands and stands in which burned trees were either cut and manually removed or cut and left to the ground. Divergent vegetation responses are likely associated with the different forest types and species assemblages analysed in the studies above, most of which were performed in stands with *P. pinaster* or *Pinus halepensis* Mill. under different climatic and soil conditions in the Iberian peninsula. Our findings also supported that vegetation cover was affected by slope aspect, similarly to findings by other authors who focused on the speed of the vegetation regrowth by means of a remote sensing approach (Schroeder *et al.*, 2007; Wittenberg *et al.*, 2007; Kinoshita and Hogue, 2011; Vo and Kinoshita, 2020).

Higher rates of vegetative regrowth in the NT plots were supported by the height increase of the woody species, most of which resprouted more vigorously and became taller when left

Table 4 Indicator species of the post-fire communities in the four groups of plots.

	NT		EC		SM		SMP	
	Indicator species	*P*-value	Indicator species	*P*-value	Indicator species	*P*-value	Indicator species	*P*-value
10 months	*Ornithopus compressus*	0.014	*Daucus carota*	0.033			*Erica multiflora*	0.006
	Phillyrea latifolia	0.031	*Rhamnus alaternus*	0.023			*Pinus pinaster*	0.006
	Fumaria capreolata	0.017	*Silene gallica*	0.029				
	Cistus monspeliensis	0.002	*Sonchus asper*	0.029				
	Calycotome villosa	0.031						
12 months	*Dorycnium hirsutum*	0.011	*Inula viscosa*	0.005	*Gastridium ventricosum*	0.028	*Cistus salvifolius*	0.008
	Phillyrea latifolia	0.037	*Phillyrea angustifolia*	0.003	*Trifolium arvense*	0.028	*Erica multiflora*	0.008
			Daucus carota	0.043	*Myrtus communis*	0.011	*Pinus pinaster*	0.005
			Verbascum pulverulentum	0.043				
22 months	*Phillyrea latifolia*	0.016	*Galactites tomentosa*	0.008	*Andryala integrifolia*	0.001	*Pinus pinaster*	0.005
			Daucus carota	0.049	*Convolvulus cantabrica*	0.027	*Cistus salvifolius*	0.003
			Misopates orontium	0.049	*Myrtus communis*	0.032	*Ononis reclinata*	0.039
34 months	*Cistus creticus ssp. eriocephalus*	0.013	*Briza maxima*	0.016	*Trifolium arvense*	0.02	*Foeniculum vulgare*	0.004
			Pistacia lentiscus	0.045				

Plant species significantly associated to each management and forest type at each time point (10, 12, 22, 34 months after the fire), as resulting from the indicator species analysis.

untouched after the event. However, not all of the species examined were negatively affected by active management, as in the case of the holm oak which grew faster in the EC and SM plots. Woody species may therefore have species-specific responses to the management strategies associated with variable resource-use strategies, functional traits, and possibly phylogenetic constraints, as corroborated by similar results of a study in a burned *P. halepensis* forest in Greece (Spanos *et al.*, 2005).

As expected, community α-diversity was higher in the first spring after the fire due to the massive emergence of mostly fugacious annual species, as typical of the fire-prone Mediterranean ecosystems (Trabaud and Lepart, 1981; Espirito-Santo and Capelo, 1998; Capitanio and Carcaillet, 2008). A notable exception, however, was observed in the pine forest plots, where diversity was initially low and tended to increase with time, unlike in the broadleaved plots. Overall, effects of management on community diversity were less marked than those on vegetation cover and growth, and not in the same direction. In fact, both SR and Shannon diversity were higher in the sites where erosion control measures (EC) and, to a lesser extent, snag removal (salvage logging) and biomass mulching (SM) were applied. Plant diversity was higher especially the first spring after fire. These findings support that such strategies may reduce the negative effects of the passage of tractors necessary for the logging (Castro *et al.*, 2011; Leverkus *et al.*, 2014), and appear in line with other studies reporting a positive influence of post-fire treatments on SR 10 months after the fire (Francos *et al.*, 2019). However, Moya *et al.*, (2020) did not find any effect of salvage logging on α-diversity, and other studies documented a reduction of SR in salvaged sites compared with non-treated sites (Leverkus *et al.*, 2014; Morgan *et al.*, 2020). Besides the interactive effects of different vegetation types, species assemblage, site conditions, fire severity and regime, application of mulching can also account for contrasting responses found in the studies above. Mulching can significantly reduce soil erosion and favour vegetation regeneration by seed (Kruse *et al.*, 2004; Dodson and Peterson, 2010; Castro *et al.*, 2011; Fernández and Vega, 2014, Fernández and Vega, 2016), although the effects of the interaction between salvage logging and mulching remain unclear (Fernández and Vega, 2016). Moreover, our data support the beneficial influence of the small terraces created with the EC treatment along the hill slope, where SR reached its maximum 10 months after the fire. Terraces could reduce soil erosion during autumn and winter rainfalls and favour the formation of soil pockets with high concentration of seeds of annual herbs, that could rapidly germinate and establish on a more stable substrate, compared with the other sites. Effects, however, occurred only in the first spring after the fire, since the decline in species diversity in the EC plots after 22 and 34 months was stronger than in the other plots, and finally led to a substantial cancellation of differences.

Effects of post-fire management on vegetation species composition are still poorly known. Despite our limited sampling

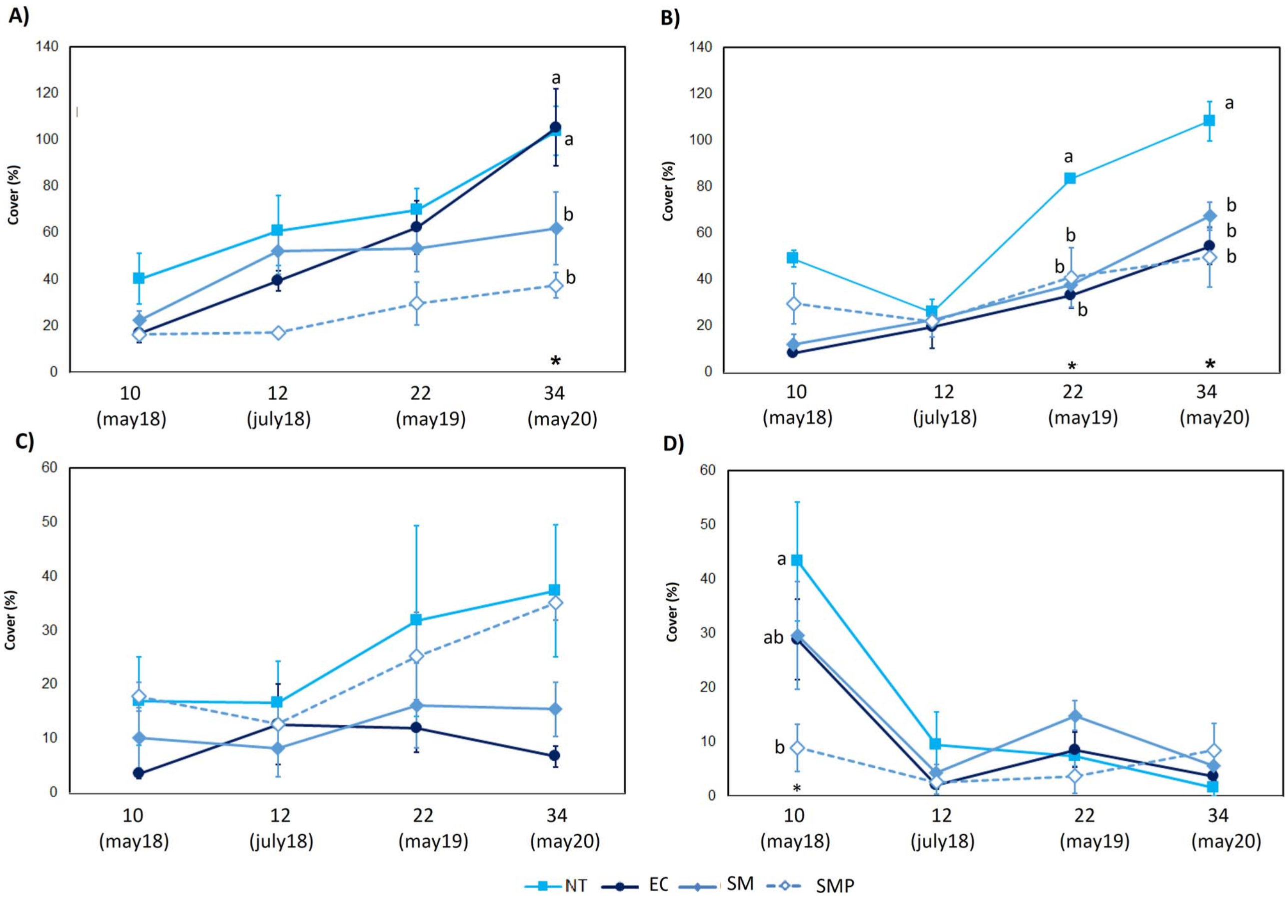

Figure 5 Ground cover variation of plant functional groups: (A) phanerophytes (B) chamaephytes and nano-phanerophytes (C) hemicryptophytes without graminoids (D) therophytes without graminoids, in NT (not treated), EC (salvage logging+mulching+erosion control), SM (salvage logging+mulching), SMP (salvage logging+mulching in pine stand). Differences between management and forest types are given for each time point (10, 12, 22 and 34 months after the fire; *** < 0.001, ** $0.001 < P < 0.01$, *$0.01 < P < 0.05$; based on Kruskal–Wallis); letters indicate significant differences ($P < 0.05$) based on Dunn's test. Error bars represent the standard error of the mean.

in the pine stand, the post-fire vegetation composition of this forest type appeared well distinct from that in the broadleaved sites under SM treatment over the three years. This fits existing evidence that influence of the vegetation types remains after burning, each tending to re-establish its pre-fire species composition (Espirito-Santo and Capelo, 1998). This is also in line with the 'initial floristic composition' model by Egler (1954; see also Marzano *et al.*, 2012), who stressed the importance of the pre-fire floristic assemblage of the community.

As for diversity, management effects on floristic composition of the broadleaved plots were strongest 10 months after fire, then differences tended to decrease, in parallel with the general reduction of SR. Twenty-two months after fire, however, species composition in SM and EC was still significantly different from that in NT plots, in line with findings in salvaged sites and sites subject to non-intervention or partial cut, after two years (Leverkus *et al.*, 2014).

Also in line with Leverkus *et al.*, (2014), we found a higher proportion of phanerophytes in unsalvaged areas, as well as indicator woody species for the non-treated stands. In our study, shrub indicator species such as *C. creticus* and *P. lentiscus* in NT and EC plots, respectively, suggested a more advanced recovery stage of NT and EC plots when compared with SM plots 34 months after fire. The greater regeneration capacity of woody species in non-treated areas compared with salvaged areas is largely supported by previous studies (McIver and Ottmar, 2007; Beghin *et al.*, 2010; Marzano *et al.*, 2012). On the contrary the relative abundance of herbs (annual and perennial) and graminoids was not affected by management strategies, in line with a study conducted in a coniferous forest six years after fire (Peterson and Dodson 2016).

Further aspects emerged from the analysis of the species forming a soil seed bank. The higher proportion of species with a persistent seed bank in the NT plots suggested that management can have a negative influence on these species, possibly via changed micro-habitat conditions. Salvage logging can reduce significantly the total number of seeders (Leverkus *et al.*, 2014), though the separate effects of management strategies on species with persistent and transient seed bank remain poorly known. Our findings suggested that forest type can significantly affect the relative proportion of these species after fire. The lower persistents:transients ratio found in the pine forest compared with the broadleaved forest is likely associated with the physical

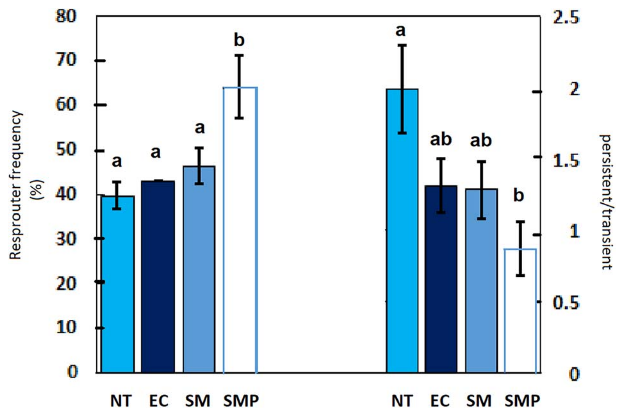

Figure 6 Frequency histogram showing the proportion of species with resprouting ability (left half of the figure) and the ratio between species forming a persistent *vs* transient seedbank in the soil (right half), in the four groups of plots by management and forest type (NT-not treated, EC-salvage logging+mulching+erosion control, SM-salvage logging+mulching, SMP-salvage logging+mulching in pine stand), in the first spring, e.g. 10 months after fire. Letters indicate significant differences at 5 per cent probability level, according to Dunn's test.

and chemical characteristics of the litter and soil under the pine canopy, which do not favour the conservation of viable seeds over the years and generally supports a poorer seedbank than deciduous forests (Bossuyt and Hermy, 2001).

Conclusions

This study brings new evidence on the post-fire early recovery processes of an evergreen forest in a poorly investigated Mediterranean area, in terms of vegetative regrowth, community diversity, composition, plant functional groups and traits. Despite the limited sample size for each management and forest type, our findings may help to better understand the effects of post-fire management strategies on the regeneration of a broadleaved community dominated by *Q. ilex*, also offering a comparison with a maritime pine stand in the same area.

Although active post-fire management had a clear negative effect on the reconstitution of vegetation cover and the speed of the secondary succession in terms of woody species recovery, it did not affect negatively community species diversity, which was even enhanced 10 months after fire. The adoption of soil erosion control measures and mulching, combined with salvage logging, promoted the recolonization by woody species and contributed to keep the highest plant diversity level. Despite the limit given by the lack of control plots in the pine stand, we finally suggest that different forest types and functionally diverging species assemblages may show contrasting responses to the same post-fire management strategy. Decisions about the most appropriate managements to be adopted in burned forest areas should therefore be supported by further studies focusing on this aspect.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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Conflict of interest

All authors declare that they have no conflicts of interest.

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Supplementary material

The following supplementary material is available at *Forestry* online: overview graph about the statistical approach used in the study.

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