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The role of forest fire severity on vegetation recovery after 18 years. Implications for forest management of *Quercus suber* L. in Iberian Peninsula

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ABSTRACT

Wildfires are a widespread phenomenon in Mediterranean environments. Wildfires result in different fire severities, and then in contrasting plant cover and floristic composition. This paper analyses the recovery of the vegetation eighteen years after a wildfire in Catalonia. The *Pinus pinaster* ssp. forest was affected by three different severities in July 1994, and studied the spring of 1995 and again in 2008. After eighteen years (2012), our research found that burnt sites constitute a dense forest with a broad variety of species, including many young pines, shrubs and herbaceous plants, but that the risk of fire remains very high, due to the large quantity of fuel and the flammability of the species. The management of the post-fire is critical when high severity fires take places, and it is recommended that high-severity fires must be avoided for a sustainable forest management. We recommend that once the timber (*Pinus* plantations) production is not profitable, *Quercus suber* L. and *Pinus pinaster* ssp. forest should be promoted, and pine plantations avoided.

1. Introduction

Long-term research studies are helpful in scientific research (Dixon-Coppage et al., 2005; Torn et al., 2015; Novara et al., 2016; Shi et al., 2016; van der Meij et al., 2016), to develop sustainable forest management strategies (Úbeda et al., 2006; Amores et al., 2008) and for vegetation (Beyene, 2015; Tarhouni et al., 2016) and soil (Brevik and Fenton, 2012; Brevik et al., 2015; Laudicina et al., 2015) recovery. These kinds of studies inform us of the post fire vegetation dynamics (Muños-Rojas et al., 2016) and their impact on ecosystem recovery after disturbances (Lasanta and Cerdà, 2005; Srinivasarao et al., 2014; Shaw et al., 2016). As a long-term strategy in burnt areas, some authors claim that the optimum solution is to not act and to let the vegetation regrow naturally (Vallejo et al., 1996). Others, including Igarashi and Kiyono (2008) and Zhang et al. (2010), argue that management increases species diversity and so it is necessary to thin the tree layer and to ensure that the accumulation of plant debris does not impede seed germination and plant growth. Various modes of action might therefore be taken after a forest fire. Vallejo et al. (1996) discusses the possible outcomes of replanting new species, replanting the same species, and not taking any action at all. Santana et al. (2011) reported that the frequency of treatment had a negative impact on forest structural diversity and uniformity and was associated with slower forest regeneration. However, it should be stressed that all forestry management practices implemented in the wake of a fire are highly dependent on the environmental conditions (Vieira et al., 2012), although it is widely recognized that in all cases there is a lack of long-term measurements that will help find the right management.

Therefore, the key point to discuss is whether or not to act, and if so, how to act and when to take action after a forest fire or during the post-fire vegetation recovery (Alfaro-Sánchez et al., 2014). In Catalonia, the dead trees used to be removed from the forest one year after the fire. Úbeda (1998) noted an increase in erosion as a consequence of the tree removal and there is a loss in soil quality due to the removal of the trunks (Mataix-Solera et al., 2015). Madrigal et al. (2011) recommend extracting the burnt wood two months after the fire, while ensuring dissemination and soil protection by needles, because, as discussed: "the urgency of the actions may cause more damage than good". They also consider that delaying the removal of burnt wood should only occur in areas where regeneration is likely to be successful. Under Mediterranean climatic conditions, there is a clear impact from any treatment done after the forest fire due to the bare soil, the crust development, the shallow and heterogeneous cover of ash and the lack of vegetation… that results in the highest erosion and runoff rates during the first year after the fire (Cerdà, 1998; Pereira et al., 2015). This is why there is a need to act soon after the fire with forestation, scarification, log barriers, aerial seeding and hydromulch (Fernández et al., 2011; Robichaud et al., 2013), although is widely accepted that

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soil damage will take place due to the bare soil when heavy machinery traffic or human trampling occurs (Cram et al., 2007; Whicker et al., 2008).

In Mediterranean woodlands, it is not only important how to act, is very important when to act due to the seasonally contrasting climatic conditions, the shallow and poor soils, and the millennia old human activities. There are several choices as to when to act when performing restoration actions in a burned forest. It is crucial not to perform any forestry action immediately after the fire to protect the seed bank (Madrigal et al., 2011). The rapid growth of vegetation in a burned forest a few years after the fire can make management to avoid fire risk due to the accumulation of fuel in the understory very expensive. This cost can be 500 € ha^{-1} in a young forest and 2000 € ha^{-1} a mature forest. This can occur rapidly in burnt Mediterranean forests, where the natural vegetation recovery happens very quickly after the fire. The failure to act in these situations is determined by various factors such as the high cost of performing forestry work in dense forests. These jobs may be similar to those undertaken during pre-fire management and some of them are: prescribed fire, mechanical clearing, or grazing. Some experts as Eugenio et al. (2006) and Alfaro-Sánchez et al. (2014) suggest delaying ten years to start with forest management after a wildfire.

The predominant species found in the Mediterranean forest, while highly combustible (Úbeda et al., 2006), are generally well adapted to fire because of the recurring nature of the fire hazard over time. Several authors, including Dell et al. (1986) and Terradas (1987) claim that Mediterranean vegetation employs different mechanisms to resist fire and that it is able to reestablish itself more quickly than other species in other environments. Indeed, the growth rate and longevity of species have been shown to be determinants of post-fire dynamics (Capitanio and Carcaillet, 2008). In the Mediterranean, this might be because soils contain seed banks that are resistant to fire and can sprout after the event, or because opportunistic species are able to grow as their seeds originate from unburnt sites (Arnan et al., 2013).

The colonization of the soil by resprouting species is a key determinant in avoiding soil erosion in the short- and medium-term (Cerdà and Lasanta, 2005; Úbeda et al., 2006; Bochet, 2015). The fact that there are Mediterranean species that need different amounts of insolation is an additional factor in ensuring a plant succession that can begin to protect the soil in the days immediately following a fire (Oliver and Larson, 1996). Prefire management as well as the characteristics of the vegetation and fire behavior affects the natural forest regeneration after a wildfire and appropriate preventive management strategies can improve the ability of the forest to regenerate, thereby increasing the resilience of such forests to future forest fires (Martín-Alcón and Coll, 2016).

The goal of this study was to assess the post-fire vegetation recovery after 18 years, and with this long-term experimental approach we can shed light into the discussion about whether or not to take action after forest fires. Our strategy was to survey the vegetation in four contiguous sites affected by the same fire but with different severities: low, medium and high severities, and a control site.

2. Material and methods

The study area is located in the Cadiretes Massif, in the northernmost area of the Catalan Coastal Ranges, Girona province, Northeast Spain (Úbeda et al., 2006), at an altitude between 190 and 250 m.a.s.l. The Cadiretes Massif is a predominantly granite structure, although soils on Paleozoic metamorphic rocks such as schist and slates can be found. Erosion processes have largely shaped the granitic section of the Cadiretes Massif, although in some areas metamorphic features underlie this relief. The massif is covered by dense Mediterranean vegetation, including species such as *Quercus suber* L., *Arbutus unedo* L. and *Erica arborea* L. *Pinus pinaster* ssp. plantations are also present. Mean annual rainfall ranges between 700 and 800 mm, with an autumn maximum (27%), followed by winter (25%), spring (25%) and summer (23%). Autumn is the season with the highest rainfall severity, with values frequently exceeding 15 mm h^{-1}. Summer temperatures often exceed 25 °C; while winter temperatures are generally mild, rarely below 0 °C. Evapotranspiration exceeds precipitation from June to August (Úbeda, 1998). According to US Soil Taxonomy (Soil Survey Staff, 2014), the soils of the control forest and low severity fire site are Typic Haploxerept and those of the medium and high severity fire sites areas are Lithic Haploxerept.

2.1. The fire of 5 July 1994

The fire, which started due to arson on 5 July 1994, burned 55 ha of the Cadiretes Massif on the property known as Can Noguera. The fire broke out in the lower part of the massif, next to the road, and reached the upper part of the massif over a period of some 30 h. The fire took place during a day with low atmospheric humidity and a strong northerly wind. As soon as the fire had been extinguished, three burnt forest areas and an unburnt control forest were selected to study the changes in vegetation according to the varying degrees of severity of forest fire. One year after the fire, the forest authorities applied established governmental policies: the dead trees were used to build log barriers with the trunks to reduce the high soil erosion rates usually found the year after a fire (Robichaud et al., 2008). The fire did not burn with the same severity throughout the study area and three sites can be identified according to the severity (Úbeda, 1998). This means that different maximum temperatures were reached and so the impact on both the vegetation and the soil varied (Úbeda, 2001). The study area comprises a plantation of *Pinus pinaster* ssp. with potential for *Quercus suber* L. The pine forest was almost completely devastated by the fire while the bark of the cork oak protected them from the flames. The recovery of the vegetation in each of the three severity sites is compared with the control forest site, where dry *Calicotome spinosa* L. was found because of the abandonment of forestry management practices in 2008 due to low income from the site and the economic crisis that made the maintenance of the pine plantations non profitable due to the low price of the timber.

2.2. Categorization of the fire severity sites in the burnt area

Fire severity categories were determined immediately after the fire in July 1994. Three fire severity sites were distinguished on the basis of leaf and branch condition and number, soil surface and quantity and ash color, where black indicates moderate combustion, grey indicates medium combustion, and white indicates strong combustion (Moreno and Oechel, 1989). The vegetation was contrasted with that in an unburnt **Control Forest (CF) site** (Fig. 1a). The maximum number of fire severity categories that can be distinguished using this method is three: i) **Low Severity Fire (LSF) site** (Fig. 1b). In this site the trees retained some leaves (although not all were green, and many would eventually fall) and a large number of branches, including smaller ones. A sizeable amount of litter was deposited immediately after the fire, below which a 2-cm thick burned, black layer of humus remained after the fire. All the *Quercus suber* L. survived as well as some *Pinus*. This site corresponds to the lower section of the burnt area; ii) **Medium Severity Fire (MSF) site** (Fig. 1c). In this site the trees had no leaves but retained a substantial number of their branches. A small quantity of plant litter remained. This area is located between the LSF site and the high severity fire (HSF) site; iii) **High Severity Fire (HSF) site** (Fig. 1d). In this site the trees lost all their leaves and branches and only the trunks remained. An extensive layer of grey and white ash covered the soil surface.

2.3. Vegetation inventories

Three 20-m transects were marked out on each of the four plots. Every 20 cm along each transect the name of the plant species was surveyed. The transects were inventoried five times: six months after the

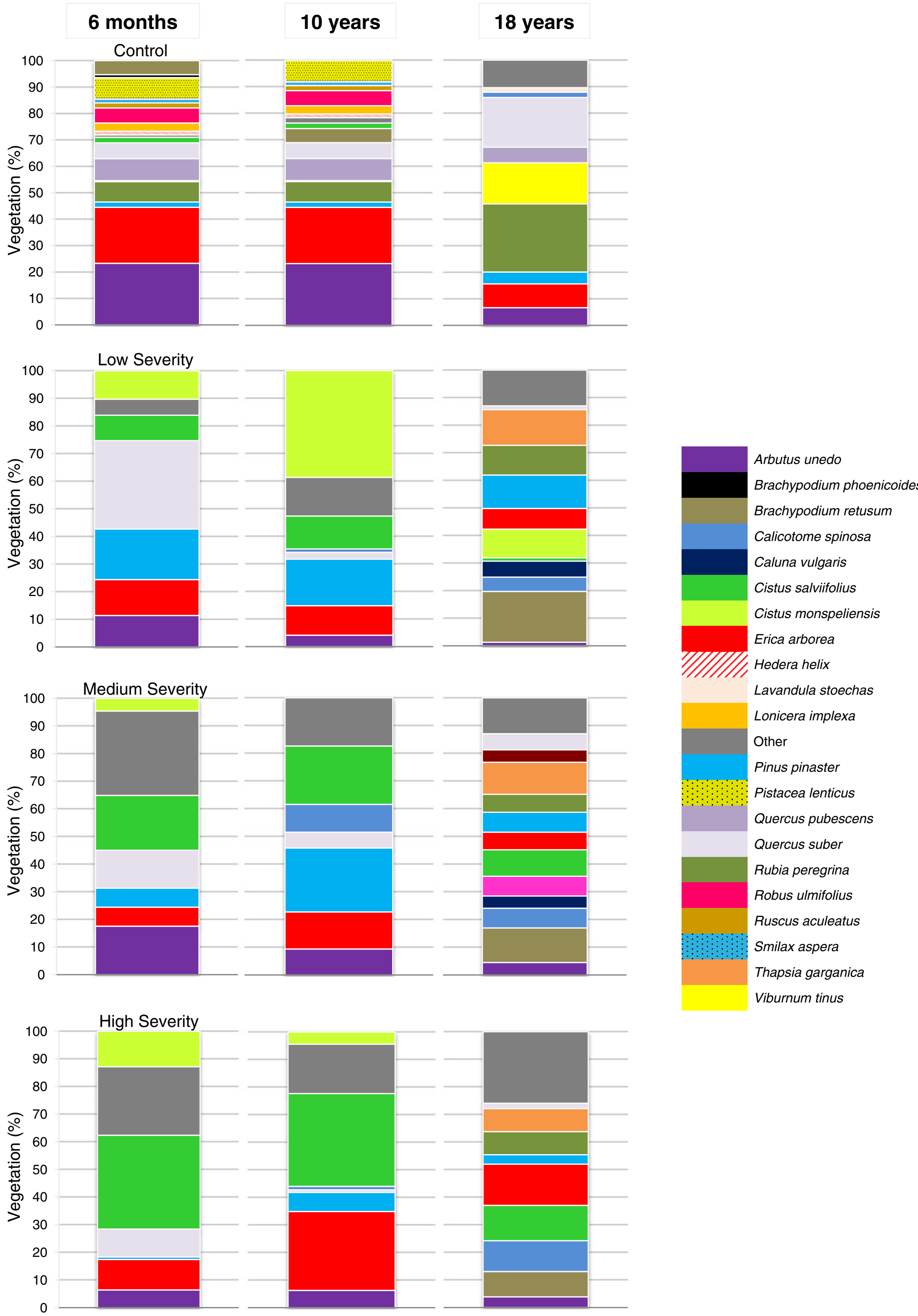

Fig. 1. Vegetation cover (%) changes on the control, low severity, medium and high severity sites after short - (Úbeda et al., 2006), medium - (Amores et al., 2008) and long-term (this study) measurements.

fire (before the first spring), ten months after the fire (after the first spring), two years after the fire (Úbeda et al., 2006), ten years after the fire (Amores et al., 2008) and eighteen years after the fire, which are the long-term measurements we are showing here.

3. Results

The plant survey is shown as percentages (Table 1) of the species in each of the burnt and in the control sites. Fig. 1a, b, c and d illustrates the

Table 1
Summary of the survey (inventory) of 2012 in each site.

Species inventory 2012/severity site	Control (%)	Low (%)	Medium (%)	High (%)
Quercus suber L.	18.7	1.4	5.8	1.9
Pinus pinaster ssp.	4.5	12.1	7.2	3.4
Erica arborea L.	9.0	7.5	6.4	15.0
Calicotome spinosa L.	2.0	5.2	7.1	11.2
Arbutus unedo L.	6.7	1.3	4.5	3.9
Cistus monspeliensis L.	0.0	10.4	0.0	0.0
Cistus salvifolius L.	0.0	1.2	9.6	12.8

percentage areas occupied by each species in the last sampling (December 2012) in the four study sites. Fig. 1a shows most of the species present in the control site in the last sampling. A total of 24 species were catalogued, the most predominant being *Rubia peregrina* L., occupying 26% of the total, followed by *Quercus suber* L. (19%) and *Viburnum tinus* L. (15%). A further 10% comprised other mainly herbaceous species. *Erica arborea* L. occupied 9% of the wooded area, followed by *Arbutus unedo* L. (7%) and *Quercus pubescens* Willd. (6%). *Pinus pinaster* ssp. occupied 4% and *Calicotome spinosa* L. and *Lavandula stoechas* L. each occupied 2%.

In the low severity site (Fig. 1b), 28 species were surveyed. The predominant species were *Brachypodium retusum* (19%), *Thapsia garganica* L. (13%) and "other" species, predominantly grasses, occupying less than 1%. Other dominant species were *Pinus pinaster* ssp. (12%), *Rubia peregrina* L. (11%) and *Cistus monspeliensis* L. (10%). Finally, among the other species we found *Erica arborea* L. (8%), *Caluna vulgaris* L. (6%) and *Calicotome spinosa* L. (5%). Around 1% of the forest today is occupied by such species as *Arbutus unedo* L., *Cistus salviifolius* L. and *Quercus suber* L. The Medium site (Fig. 1c) was occupied by 26 species and their presence was more balanced than in the other three sites. *Brachypodium retusum* and *Thapsia garganica* L. each occupied 12% of the forest. *Cistus salviifolius* L. occupied 10% of the wooded area, while 7% was occupied by each of *Calicotome spinosa* L., *Pinus pinaster* ssp. and *Centaura cephalariifolia* Willk. *Rubia peregrina* L., *Erica arborea* L. and *Quercus suber* L. each occupied 6% of the forest. Finally, *Arbutus unedo* L. and *Viburnum tinus* L. each occupied 5% and *Caluna vulgaris* L. occupied 4%. In the High severity (Fig. 1d) 26 species were found. The predominant species were *Erica arborea* L. (15%), *Cistus salviifolius* L. (13%) and *Calicotome spinosa* L. (11%). Noteworthy was the presence of *Brachypodium retusum* (9%), *Rubia peregrina* L., and *Thapsia garganica* L. with each occupying 8%. Finally, *Arbutus unedo* L. and *Pinus pinaster* ssp. each occupied 4% and *Quercus suber* L. occupied 2% of the forest.

4. Discussion

The data presented here from 18 years after a fire with different severities showed that in the Cadiretes Massif the severity of the fire did not determine the plant species composition or the vegetation cover. However, previous research (Úbeda et al., 2006) in the same study area demonstrated that the species composition and the vegetation cover were highly affected by the fire severity one year after the fire. The measurements carried out in an intermediate period (10 years after the fire by Amores et al., 2008) showed that the soil was totally covered (100%) by the plants but the species composition was different among the study sites. Those results show that the post-fire responses are highly affected by the time of recovery, and that the impact of fire is highly dependent of the fire severity (Úbeda and Sala, 2001).

The study area at the time of the fire in 1994 was a pine plantation. Thus, eighteen years later, what we have is a new forest developed after the fire and the post-fire recovery, and the land has been abandoned due to the low income from the timber. In the short-term, the recovery of the plant cover is critical to protect the soil from water or wind erosion, but in the long-term the forest runs the risk of being highly vulnerable to fire as the recovery took place with an abundance of highly flammable plant species. The goal of any management program therefore should be to minimize the fire hazard in this young new forest. But if fire breaks out, the goal of the management should be to minimize the fire's intensity due to the negative impact on the soil, vegetation, and the increase in soil erosion rates and runoff that result from high intensity fires; this will help achieve a sustainable forest management in which fire is present as an ecological factor (Pausas et al., 2008).

Quercus suber L. is predominant in the LSF site, because its bark is able to withstand the heat and so it avoids combustion (Pereira, 2011). The species also enjoys rapid regrowth thanks to an evolutionary strategy whereby the species typically sprouts from underground structures quickly regenerating aerial tissues (Zavala, 2001; Alanís-Rodríguez et al., 2011). Over time during natural succession the percentage of tree species tends to fall, while that of new species increases immediately after a fire. Madrigal et al. (2005) confirmed this in studies conducted in the Spanish Central Mountain Range where over time the forest understory became more profuse and began to dominate the shrubs leading to the disappearance of herbaceous plants. Santana et al. (2011) noted that the resurgence of these species is very rapid after a fire, as confirmed by our case study. The same tendency is seen in the MSF and HSF sites where *Quercus suber* L. forest were predominant in the first sampling but then gradually declined. These dynamics of the rapid post-fire regrowth of *Quercus suber* L. have also been studied and described in Arnan et al. (2013).

Pinus pinaster ssp. presents a dispersed distribution but is present in all the burnt areas. A number of factors affect the germination of pine after a fire, including sunlight (Pardo et al., 1999), predation, seed loss by erosion, rainfall (Francos et al., 2016), soil cover and protection, and finally, exposure and slope (Madrigal et al., 2005). The increasing presence of *Pinus pinaster* ssp. over time in all three areas affected by fire is determined by the excessive germination of the species, as discussed by Amores et al. (2008), and by the poor management practices carried out in the study area. The selective short- and medium-term clearing of Pinus should ensure the establishment of this species in areas of strong inter-specific competition (Madrigal et al., 2011). At the same time, fuel reduction programs result in the removal of understory and in damage to the forest structure. Santana et al. (2011) considered optimal programs to reduce fire risk while conserving biodiversity, and showed how forest thinning, undertaken at early ages, reduces the fire hazard by decreasing the horizontal continuity of the forest mass. In the case discussed here, we believe that if the owner decides to abandon the plantation of pines definitively, this should favor individuals due to the thinning of pine and shrub species, and favor species better adapted to fire, such as *Quercus suber* L. and *Quercus pubescens* Willd. (Hedo de Santiago et al., 2015).

Erica arborea L. was found here in almost all the inventories conducted in the burnt areas, presenting an above average percentage in the HSF site at each of the sampling times. According to Amores et al. (2008), ten years after the fire and during the 18-years survey the forest presented an *Erica arborea* L. understory of 85%, which is a high fire risk. This is the reason to undertake reduction treatments, including prescribed fires and the mechanical mastication of the soil seed bank (Fernández et al., 2013). Forest stands occupied by *Arbutus unedo* L. decreased constantly in size in the three sites over time, as they were restricted by competition with other species (Arnan et al., 2013). *Arbutus unedo* L. has failed to become the dominant forest species and continues to lose ground to the *Pinus pinaster* ssp. *Cistus monspeliensis* L. appears primarily in areas where the severity of the fire was low, and *Arbutus unedo* L. and *Cistus salviifolius* L. occupies areas where fire severity was medium or high. Thus, we see that fire allows species such as *Calicotome spinosa* L. to grow that do not appear in the control plot. The forest, after 18 years, presents a model of fuel "10" according to the Rothermel (1972) models, this is "The fires burn in the surface and ground fuels with greater fire intensity than the other timber litter models. Crowning out, spotting, and torching of individual trees is more frequent in this fuel situation, leading to potential fire control difficulties (30–35 Mg ha^{-1})".

The results of the eighteen-years inventory show that the fire severity did not result in different dominant species. In the control plot, with no management, *Rubia peregrina* L. and *Viburnum tinus* L. were dominant. In the Low and Medium severity fire sites there was a greater balance between the different species recovered after the fire. In the High Severity site, *Rubus ulmifolius* Schott, *Lonicera implexa* Aiton and *Hedera helix* L. were the dominant species. Most of these species are herbaceous, which increases the risk of wildfires. As shown, the risk of fire is high in both the High severity and the Control sites because of the increasing horizontal and vertical fuel continuity and their growing density (Fig. 1d and a).

In the unburnt Pine plantation (Control plot), *Arbutus unedo* L. and *Erica arborea* L. were the dominant species during the first decade after the forest fire; however, after eighteen years, *Rubia peregrina* L., *Quercus suber* L. and *Viburnum tinus* L. are more abundant. The herbaceous layer grew as a consequence of the lack of management, such as the widespread presence of *Erica arborea* L. Therefore, we were able to determine that over the last roughly seven years *Erica arborea* L. has grown freely. Before 2008 this plant was collected and the forest understory was almost nule. The species diversity increased due to the fact that prior to the fire this area was a pine plantation and now it is a post-fire forest with no treatments. The four plots were, before the fire, a *Pinus pinaster* ssp. plantation, the management of which involved the removal of herbaceous species and all the pine's potential competitors. When the forestry management of the area was curtailed in the control plot, the herbaceous species, such as *Rubia peregrina* L., recovered along with a number of flowering plants, such as *Viburnum tinus* L. There was also an increase in the presence of *Quercus suber* L., so much so that the percentage of forest occupied by *Pinus pinaster* ssp. decreased. Thus, between the samplings in 2004 and 2012, 10- and 18-years after the fire, the herbaceous and flowing species increased in abundance.

After eighteen years, the vertical and horizontal accumulation of fuel resulted in a high risk of wildfires. As such, forestry management programs are urgently required to reduce this risk. However, owing to the density of vegetation it is not possible to undertake prescribed fires without first clearing some of the understory. Owners do not incur any costs in employing prescribed fires as part of their management practices in Catalonia and the technique is still being tested in forests with different species and vegetation structures. Interestingly, it has been reported that prescribed fires have no negative effects on soil or forest biodiversity (Burrows, 2008; Pereira, 2011). In September 2014 the CPF (Center of Forest Ownership of Catalonia) revealed that a forest management plan had already been drafted for the property of Can Noguera, the one studied here. The plan identifies the risk of fire in the area given the excessive density of pines (over 2000 stems/ha) currently being managed (in an area that should not exceed 1600 stems/ha). According to the plan, it is necessary to proceed with the selective removal of trees to reduce the density and the risk of fire. The plan also seeks to promote *Quercus suber* L. in those plots where the trees are most viable for the future production of cork. The project has an estimated cost of 1200 € ha^{-1}and a maintenance cost of 400 € ha^{-1}. Although the plan has been drawn up, it has yet to be implanted for budgetary reasons. Indeed, the owners of forests in Catalonia are not required to implement forest management practices and actions of this kind are undertaken using public resources.

In Catalonia, as in many areas of the Mediterranean, forests are found in the same stage of evolution as the one described here as a consequence of the intense fires of the 90s, which were the result of the sudden rural abandonment that occurred during the 1960s. After the forest fires of 1994, there was not a post-fire management policy with the objective to design a forest structure with a low fuel load. Some management took place to remove the burned wood, which increased soil erosion and reduced soil quality (Úbeda and Sala, 1998). It is difficult to find a short-term forest management plan in burned areas with the aim of having a forest with low fuel load, unless the owner decides to take this opportunity to change the type of vegetation for economic reasons. Although it is still not a common practice, the introduction of livestock looks increasingly like a solution to be at low risk of high severity forest fires (Madrigal et al., 2005). Pausas (2011) states that the purpose of forest management should not be prevent fires, since that is virtually impossible, but to assume certain sustainable fire regimes. Here we propose the use of prescribed fires as it is found that the soil and vegetation damage is lower than with wildfires.

Studies of the kind reported herein are essential for understanding the evolution of Mediterranean forests after a wildfire. Moreover, they serve to determine the effects of forest fires and to ensure the implementation of good forest management practices and to understand the vegetation dynamics after forest fires (Lloret and Zedler, 2009). Additionally, long-term studies are able to shed more light on the actual sequence of plant succession (Abella and Fornwalt, 2015; Freestone et al., 2015) and to understand the impact of different severities of burning (Pereira et al., 2016). The results achieved in this research and the already known dynamics of Mediterranean forests (Capitanio and Carcaillet, 2008; Lloret and Zedler, 2009; Alfaro-Sánchez et al., 2014), allow us to conclude that after a wildfire it is necessary to manage the vegetation cover to reduce the risk of fire, and that a cover of *Quercus suber* L. and *Pinus pinaster* ssp. is the most suitable and sustainable. Many plantations are no longer viable from the economic point of view and have been abandoned.

5. Conclusions

Eighteen years after a forest fire in Catalonia, the forest is more diverse in terms of the kinds of species represented. The fact that no management programs have been implemented results in a high risk of high severity fires in the area given the fuel buildup. In the control, as in the three fire-affected sites, the lack of management has resulted in a forest with a horizontal and vertical fuel continuity that increases the risk of high severity fires. We recommend that once an owner decides to cease the production of timber, the Catalonia forest should be managed as a *Quercus suber* L. and *Pinus pinaster* ssp. forest and not as a pine plantation. In the Cadiretes Massif the severity of the fire does not determine the plant species composition or the vegetation cover after 18 years of a fire. However, fire severity was a factor that determined the vegetation cover 1-year and 10-years after the fire. Post-fire responses are highly affected by the time of recovery, and the impact of fire is highly dependent of the fire severity over shorter terms, but after 18-years the recovery of the vegetation was successful in all the three fire intensities study sites.

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References

Abella, S.R., Fornwalt, P.J., 2015. Ten years of vegetation assembly after a North American mega fire. Glob. Chang. Biol. 21, 789–802.

Alanís-Rodríguez, E., Jiménez-Pérez, J., Valdecantos-Dema, A., Pando-Moreno, M., Aguirre-Calderón, O., Treviño-Garza, E.J., 2011. Caracterización de regeneración leñosa post-incendio de un ecosistema templado del parque ecológico Chipinque, México. Revista Chapingo Serie Ciencias Forestales y del Ambiente 17 (1), 31–39.

Alfaro-Sánchez, R., Sánchez-Salguero, R., De las Heras, J., Hernández-Tecles, E., Moya, D., López-Serrano, F.R., 2014. Vegetation dynamics of managed Mediterranean forests 16 yr after large fires in southeastern Spain. Appl. Veg. Sci. 18, 272–282.
Amores, R., Outeiro, L., Asperó, F., Úbeda, X., 2008. Efectos a medio plazo en la vegetación mediterránea de una plantación de *Pinus pinaster* sometida a diferentes intensidades de fuego. AURORA Geogr. J. 2, 13–30.
Arnan, X., Quevedo, L., Rodrigo, A., 2013. Forest fire occurrence increases the distribution of a scare forest type in the Mediterranean Basin. Acta Ecol. 46, 39–47.
Beyene, S.T., 2015. Rangeland degradation in a semi-arid communal savannah of Swaziland: long-term DIP-tank use effects on woody plant structure, cover and their indigenous use in three soil types. Land Degrad. Dev. 26, 311–323. http://dx.doi.org/10.1002/ldr.2203.
Bochet, E., 2015. The fate of seeds in the soil: a review of the influence of overland flow on seed removal and its consequences for the vegetation of arid and semiarid patchy ecosystems. Soil 1, 131–146. http://dx.doi.org/10.5194/soil-1-131-2015.
Brevik, E.C., Fenton, T.E., 2012. Long-term effects of compaction on soil properties along the Mormon Trail, south-central Iowa, USA. Soil Horiz. 53 (5), 37–42.
Brevik, E.C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, J.N., Six, J., Van Oost, K., 2015. The interdisciplinary nature of soil. Soil 1, 117–129. http://dx.doi.org/10.5194/soil-1-117-2015.
Burrows, N., 2008. Linking fire ecology and fire management in south-west Australian forest landscapes. For. Ecol. Manag. 255, 2394–2406.
Capitanio, R., Carcaillet, C., 2008. Post-fire Mediterranean vegetation dynamics and diversity: a discussion of succession models. For. Ecol. Manag. 255, 431–439.
Cerdà, A., 1998. Changes in overland flow and infiltration after a rangeland fire in a Mediterranean scrubland. Hydrol. Process. 12, 1031–1042.
Cerdà, A., Lasanta, T., 2005. Long-term erosional responses after fire in the central Spanish Pyrenees: 1 water and sediment yield. Catena 60, 59–80.
Cram, D.S., Baker, T.T., Fernald, A.G., Madrid, A., Rummer, B., 2007. Mechanical thinning impacts on runoff, infiltration, and sediment yield following fuel reduction treatments in a southwestern dry mixed conifer forest. J. Soil Water Conserv. 62 (5), 359–366.
Dell, B., Hopkins, A., Lamont, B.B., 1986. Resilience in Mediterranean-Type Ecosystems. Dr. W. Junk Publishers, Dordretcht.
Dixon-Coppage, T.L., Davis, G.L., Couch, T., Brevik, E.C., Barineau, C.I., Vincent, P.C., 2005. A forty-year record of carbon sequestration in an abandoned borrow-pit, Lowndes Co., GA. Soil and Crop Science Society of Florida Proceedings. 64, pp. 8–15.
Eugenio, M., Verkaik, I., Lloret, F., Espelta, J.M., 2006. Recruitment and growth decline in *Pinus halepensis* populations after recurrent wildfires in Catalonia (NE Iberian Peninsula). For. Ecol. Manag. 231, 47–54.
Fernández, C., Vega, J.A., Jiménez, E., Fonturbel, T., 2011. Effectiveness of three post-fire treatments at reducing soil erosion in Galicia (NW Spain). Int. J. Wildland Fire 20 (1), 104–114.
Fernández, C., Vega, J.A., Fonturbel, T., 2013. Effects of fuel reduction treatments on a gorse shrubland soil seed bank in the north of Spain: comparing mastication and prescribed burning. Ecol. Eng. 57, 79–87.
Francos, M., Pereira, P., Alcañiz, M., Mataix-Solera, J., Úbeda, X., 2016. Impact of an intense rainfall event on soil properties following a wildfire in a Mediterranean environment (North-East Spain). Sci. Total Environ. http://dx.doi.org/10.1016/j.scitotenv.2016.01.145.
Freestone, M., Wills, T.J., Read, J., 2015. Post-fire succession during the long-term absence of fire in coastal heath land and a test of the chrono sequence survey method. Aust. J. Bot. 63, 572–580.
Hedo de Santiago, J., Lucas-Borja, M.E., Wic-Baena, C., Andrés-Abellán, M., de las Heras, J., 2015. Effects of thinning and induced drought on microbiological soil properties and plant species diversity at dry and semiarid locations. Land Degrad. Dev. http://dx.doi.org/10.1002/ldr.2361.
Igarashi, T., Kiyono, Y., 2008. The potential of hinoki (Chamaecyparis obtuse [Sieb.EtZucc.] Endlicher) plantation forest for the restoration of the original plant community in Japan. For. Ecol. Manag. 255, 183–192.
Lasanta, T., Cerdà, A., 2005. Long-term erosional responses after fire in the Central Spanish Pyrenees: 2. Soluterelease. Catena 60, 81–100. http://dx.doi.org/10.1016/j.catena.2004.09.005.
Laudicina, V.A., Novara, A., Barbera, V., Egli, M., Badalucco, L., 2015. Long-term tillage and cropping system effects on chemical and biochemical characteristics of soil organic matter in a Mediterranean semiarid environment. Land Degrad. Dev. 26, 45–53. http://dx.doi.org/10.1002/ldr.2293.
Lloret, F., Zedler, P.H., 2009. The effect of forest fire on vegetation. In: Cerdà, A., Robichaud, P.R. (Eds.), Fire Effect on Soils and Restoration Strategies. Science publisher, New Hampshire, USA, pp. 257–285.
Madrigal, J., Hernando, C., Martínez, E., Guijarro, M., Díez, C., 2005. Regeneración post-incendio de *Pinus pinaster* ssp. En la Sierra de Guadarrama (Sistema Central, España): modelos descriptivos de los factores influyentes en la densidad inicial y la supervivencia. Investig. Agrar. Sist. Recursos For. 14 (1), 36–51.
Madrigal, J., Hernando, C., Guijarro, M., 2011. El papel de la regeneración natural en la restauración tras grandes incendios forestales: el caso del pino negral. Boletín del CIDEU.10, pp. 5–22.
Martín-Alcón, S., Coll, L., 2016. Unraveling the relative importance of factor driving post-fire regeneration trajectories in non-serotinous *Pinus nigra* forest. For. Ecol. Manag. 361, 13–22.
Mataix-Solera, J., Molto, J., Arcenegui, V., García-Orenes, F., Chrenková, K., Torres, P., Jara-Navarro, A.B., Díaz, A., Izquierdo, E., 2015. Salvage logging effect on soil properties in fire-affected Mediterranean forest: a two years monitoring research. Geophysical Research Abstracts 17 (#2460-2).
Moreno, J.M., Oechel, W.C., 1989. A simple method for estimating fire severity after a burn in a California chaparral. Acta Oecol. 10, 57–68.
Muños-Rojas, M., Erickson, T.E., Martini, D., Dixon, K.W., Merritt, D.J., 2016. Soil physico-chemical and microbiological indicators of short, medium and long term post-fire recovery in semi-arid ecosystems. Ecol. Indic. 63, 14–22.
Novara, A., Poma, I., Sarno, M., Venezia, G., Gristina, L., 2016. Long-term durum wheat-based cropping systems result in the rapid saturation of soil carbon in the Mediterranean semi-arid environment. Land Degrad. Dev. http://dx.doi.org/10.1002/ldr.2468.
Oliver, C.D., Larson, B.C., 1996. Forest Stands Dynamics. John Wiley and Sons, Inc., New York. USA.
Pardo, J.E., Ruiz, L.A., Porres de la Haza, M.J., Fernández Sarria, A., Urbano, F., 1999. Caracterización de la relación entre la insolación y la regeneración vegetal tras incendios forestales en ámbitos mediterráneos. 1. XVI Congreso de Geógrafos Españoles, Málaga, España, pp. 221–232.
Pausas, G.P., 2011. Incendis necessaris. El foc en els ecosistemes terrestres: ara i sempre. Revista Mètode. 70. Universitat de València, pp. 59–67.
Pausas, J.G., Llovet, J., Rodrigo, A., Vallejo, R., 2008. Are wildfires a disaster in the Mediterranean basin? – a review. Int. J. Wildland Fire 17, 713–723.
Pereira, P., 2011. Efectes de les temperatures del foc en les cendres produïdes per algunes espècies vegetals mediterrànies. Treballs de la Societat Catalana de Geografia 71-72, 49–68.
Pereira, P., Jordán, A., Cerdà, A., Martin, D., 2015. The role of ash in fire-affected ecosystems. Catena 135, 337–339. http://dx.doi.org/10.1016/j.catena.2014.11.016.
Pereira, P., Cerdà, A., Jordán, A., Zavala, L.M., Mataix-Solera, J., Arcenegui, V., Misiune, I., Keesstra, S., Novara, A., 2016. Short-term vegetation recovery after a grassland fire in Lithuania. The effects of fire severity, slope position and aspect. Land Degrad. Dev. http://dx.doi.org/10.1002/ldr.2498.
Robichaud, P.R., Wagenbrenner, J.W., Brown, R.E., Wohlgemuth, P.M., Beyers, J.L., 2008. Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire runoff and erosion mitigation treatment in the western United States. Int. J. Wildland Fire 17 (2), 255–273.
Robichaud, P.R., Lewis, S.A., Wagenbrenner, J.W., Ashmun, L.E., Brown, R.E., 2013. Post-fire mulching for runoff and erosion mitigation: part I: effectiveness at reducing hill slope erosion rates. Catena 105, 75–92.
Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wildlands Fuels. INT-115. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT (40 pp).
Santana, J., Porto, M., Reino, L., Beja, P., 2011. Long-term understory recovery after mechanical fuel reduction in Mediterranean cork oak forests. For. Ecol. Manag. 261, 447–459.
Shaw, E.A., Denef, K., Milano de Tomasel, C., Cotrufo, M.F., Wall, D.H., 2016. Fire affects root decomposition, soil food web structure, and carbon flow in tallgrass prairie. Soil 2, 199–210. http://dx.doi.org/10.5194/soil-2-199-2016.
Shi, Y., Zhao, X., Gao, X., Zhang, S., Wu, P., 2016. The effects of long-term fertiliser applications on soil organic carbon and hydraulic properties of a loess soil in China. Land Degrad. Dev. 27, 60–67. http://dx.doi.org/10.1002/ldr.2391.
Soil Survey Staff, 2014. Keys to Soil Taxonomy. 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.
Srinivasarao, C., Venkateswarlu, B., Lal, R., Singh, A.K., Kundu, S., Vittal, K.P.R., Patel, J.J., Patel, M.M., 2014. Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet-cluster bean-castor rotation in Western India. Land Degrad. Dev. 25, 173–183. http://dx.doi.org/10.1002/ldr.1158.
Tarhouni, M., Ben Hmida, W., Neffati, M., 2016. Long-term changes in plant life forms as a consequence of grazing exclusion under arid climatic conditions. Land Degrad. Dev. http://dx.doi.org/10.1002/ldr.2407.
Terradas, J., 1987. La resposta dels ecosistemes a les pertorbacions en el context de la Teoria Ecològica. Quaderns d'ecologia Aplicada 10, 11–26.
Torn, M.S., Chabbi, A., Crill, P., Hanson, P.J., Janssens, I.A., Luo, Y., Pries, C.H., Rumpel, C., Schmidt, M.W.I., Six, J., Schrumpf, M., Zhu, B., 2015. A call for international soil experiment networks for studying, predicting, and managing global change impacts. Soil 1, 575–582. http://dx.doi.org/10.5194/soil-1-575-2015.
Úbeda, X., 2001. Influencia de la intensidad de quemado sobre el suelo. Edafología 8, 41–48.
Úbeda, X., Sala, M., 1998. Variations in runoff and erosion in three areas with different fire severities. Geoödynamik 19, 179–188.
Úbeda, X., Sala, M., 2001. Chemical concentrations in overland flow from different forested areas in a Mediterranean environment: burnt forest at different fire severity and unpaved road. Z. Geomorphol. 45, 225–238.
Úbeda, X., Outeiro, L.R., Sala, M., 2006. Vegetation regrowth after a differential severity forest fire in a Mediterranean environment, Northeast Spain. Land Degrad. Dev. 17, 429–440.
Vallejo, R., Escarré, A., Bellot, J., 1996. In: Terradas, J. (Ed.), La restructuració dels terrenys afectats pels incendis forestals. Ecologia del Foc, Editorial Proa, Barcelona, pp. 235–252.
van der Meij, W.M., Temme, A.J.A.M., de Kleijn, C.M.F.J.J., Reimann, T., Heuvelink, G.B.M., Zwoliński, Z., Rachlewicz, G., Rymer, K., Sommer, M., 2016. Arctic soil development on a series of marine terraces on central Spitsbergen, Svalbard: a combined geochronology, fieldwork and modelling approach. Soil 2, 221–240. http://dx.doi.org/10.5194/soil-2-221-2016.
Vieira, A., Bento-Gonçalves, A., Ferreira-Leite, F., Martins, C.O., Mendes, L., Loureiro Salgado, J., 2012. An integrated information system to support research on soil erosion mitigation techniques after forest fires. Geomorfologia 2010. Associação - Portuguesa de Geomorfólogos, pp. 51–57 (isbn:978-989-96462-3-0).
Whicker, J.J., Pinderlii, J.E., Breshears, D.D., 2008. Thinning semiarid forests amplifies wind erosion comparably to wildfire: implications forestoration and soil stability. J. Arid Environ. 72 (4), 494–508.
Zavala, F., 2001. Introducción a la ecología de la regeneración natural de encinos. Universidad Autónoma de Chapingo, México (94 pp).
Zhang, K., Dang, H., Tan, S., Wang, Z., Zhang, Q., 2010. Vegetation community and soil characteristics of abandoned agricultural land and pine plantation in the Qinlin Mountains, China. For. Ecol. Manag. 259, 2036–2047.