Impacts of Wildfire Frequency On Plant Recovery, Soil Properties And Water Storage In Pine Woodlands of North-Central Portugal

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Abstract

Purpose

Increasing wildfire frequency in Mediterranean-basin together with drought periods expansion could affect plant-soil-water dynamics processes. The goal is to assess the effects of wildfire frequency on plant recovery, soil properties, soil moisture content (SMC; %) and effective soil water content (ESWC; %) during the first hydrological year after a 2012 moderate-severity-wildfire.

Methods

This study was conducted in pine woodlands of North-central Portugal affected by 1-, 4-wildfires and unburnt (1975-2012). Soil samples were gathered from plant/bare microsites at top-mid-bottom hillslope positions to determine bulk density, soil texture, soil moisture, soil organic matter content-SOM, pF-curves (available water content-AWC, field capacity-FC, permanent wilting point-PWP) (n=54) during four dry/wet periods. Soil cover, plant recovery and soil water repellency were measured. On the burnt areas 72 sensors daily/seasonal monitored SMC and ESWC at two depths (2.5/7.5 cm) and two microsites (plant/bare).

Results

The 1 fire hillslopes showed higher plant recovery than the 4 fires hillslopes. SOM was higher in the burnt soils (17-20%) than in the unburnt ones (12-14%). Wildfire frequency: i) increased the water stress for plants and led to both maximum and minimum values of SMC/ESWC, respectively, for the wet-dry-seasons; ii) reduced the capacity of the soils to retain water (decreased FC/AWC, increased PWP), being more accentuated in bare microsites.

Conclusion

The increasing wildfire frequency and the predicted expansion of drought periods promotes lower water availability for plants in the more frequent bare soil patches. The water-stress window of the dry season happened sooner and extended for longer as increasing wildfire frequency.

Introduction

Landscape fires burn 3–5 million km² of the Earth's surface annually (Jones et al. 2019). In fire-prone ecosystems as Portugal continental, wildfire frequency is increasing and may challenge the resilience of these ecosystems (Vallejo and Alloza 2015). Warmer and drier scenarios may transform the high-biomass forestry systems into low-biomass shrublands (Acacio et al. 2009; Pausas and Bond 2019). However, although wildfire frequency has been highlighted as an important factor in the understanding of the effect of wildfires on vegetation and soil properties (Mayor et al. 2016), studies evaluating the cumulative effects of wildfire frequency on soil water balance are scarce (Shakesby 2011) and limited by the lack of long-term accurate records of the different wildfire events.

During the last decade, the average wildfire frequency in the Mediterranean basin has increased due to climatic (drought) and anthropogenic factors (land use changes) (Pausas and Fernandez-Muñoz 2012). Several authors have indicated how the increase in wildfire frequency in Southern Europe can lead to degradative long-term cumulative effects in soil hydrology (González-Pelayo et al. 2010; Shakesby 2011), soil fertility (Campos et al. 2016; Mayor et al. 2016; Hosseinni et al. 2017) and soil carbon balances (Santana et al. 2016). In turn, an increase in wildfire frequency induce significant delays in post-fire plant re-generation (Mayor et al. 2007; Gimeno-García et al. 2007), decline in plant productivity (Eugenio and Lloret 2004) as well as changes in plant composition and structure (Eugenio et al. 2006a; Santana et al. 2010, 2016).

Soil moisture content (SMC) has been found to be higher in burnt forests than in unburnt forests (Soto and Diaz-Fierros 1997; Cardenas and Kanarek 2014; Nolan et al. 2014), and this was attributed to a loss of vegetation capacity to intercept, retain and evaporate water from precipitation. Vegetation type and distribution affects SMC by the rate of evaporative drying (Katra et al. 2007), by root activity and organic matter addition, which in turns affects the soil hydraulic conductivity, and by the extraction of moisture for transpiration from the soil profile (Famiglietti et al. 1998). On the other hand, soil water availability for plants is not only determined by climate. The concept of effective soil water content (ESWC) is related to the climate (rainfall amount, evapotranspiration, etc.), but also to vegetation characteristics (i.e. rooting depth and plant physiological characteristics) and to soil properties (Porporato et al. 2002). Soil water retention differ depending on the soil type, and typically, the permanent wilting point (PWP) and field capacity (FC) should be measured to discern plant water stress and soil water availability (van Genuchten et al. 1991; Stolte 1997). Plant water stress is considered maxima if the soil water is below PWP, and minima at FC (Ebel 2012; Ankenbauer and Loheide 2017). Consequently, wildfires can have an effect in soil hydrological properties and the soil water availability for plants (González-Pelayo et al. 2006). Furthermore, the effects of wildfire frequency on SMC are not totally understood.

The mechanism of SMC redistribution during dry and wet periods depends on the different climatic regions. Grayson et al. (2006) defined the non-local (wet) and local (dry) states of SMC on temperate regions: "Non-local control occurs under wet conditions, with catchment terrain leading to organisation of wet areas along drainage lines. Local control occurs under dry conditions, where soil properties and local terrain (areas of high local convergence) influenced spatial patterns". The switching mechanisms are highly sensitive, and will probably be affected by the frequency of wildfire occurrence. Thus, during the dry periods the soil water balance dynamics depends in a set of soil properties such as texture (Grayson et al. 2006), soil organic matter content (SOM), bulk density, porosity and soil structure (Famiglietti et al. 1998), soil depth (Cardenas and Kanarek 2014; Nolan et al. 2014) and the dynamic state of the soil cover components (Fitzjohn et al. 1998; Cammeraat 2004), while during the wet periods it is dominated by lateral water movement through both surface and subsurface paths, with catchment terrain leading to organisation of wet areas along drainage lines (Grayson et al. 2006).

Topsoil SMC controls the hydrological processes, especially through different states of hydrophilic-hydrophobic topsoil layers (González-Pelayo et al. 2015; Malvar et al. 2016) related to biotic and abiotic soil cover components (Ruiz-Sinoga et al. 2010a). In humid Mediterranean environments, biotic cover factors determined the soil hydrological network (Lavee et al. 1998). The increase in wildfire frequency drastically reduce the biotic cover, such as vegetation and litter (Gimeno-García et al. 2007). Additionally, it depletes the topsoil organic layers (Eugenio et al. 2006b) and enhance the remaining abiotic components (bare soil, stones), which act as the key factors controlling SMC patterns (Ruiz-Sinoga et al. 2010a; Gabarrón-Galeote et al. 2013). Furthermore, the increase in wildfire frequency will increase soil nutrient losses and change the pattern of bare-vegetation microsites (Mayor et al. 2016; Santana et al. 2016) which will probably affect the SMC patterns (Sarah 2002). However, to the best of our knowledge, no studies have assessed the extent to which an increase in wildfire frequency will impact the soil water balance.

The main goal of this research is to assess the effects of wildfire frequency on plant recovery, soil properties, soil moisture content (SMC; %) and effective soil water content (ESWC; %) available for plants during the first post-fire year in fire-prone areas of North-Central Portugal with three different wildfire frequencies: unburnt mature pine forest (no wildfires in the period 1975 to 2012), burnt only once (affected by the 2012 wildfire) and burnt 4 times (affected by 1978, 1985, 2005 and 2012 wildfires). The specific objectives are:

1. To assess the effects of three wildfire frequencies (unburnt, 1 fire vs 4 fires) on vegetation recovery (plant height, stem diameter and stem length), soil cover and soil properties (texture, bulk density, pH, soil organic matter, pF-curves, soil water repellence, SMC and ESWC) at the end of the first year after the 2012 wildfire,
2. To assess the effects of two wildfire frequencies (1 fire vs. 4 fires) on the daily readings of SMC and on the effective soil water content (ESWC) for plants during the first year after the 2012 wildfire,
3. To compare the effects of wildfire frequency (1 fire vs. 4 fires), soil depth (2.5 and 7.5 cm) and microenvironment (soil below plant vs. bare soil) on SMC and ESWC.

Material And Methods

Study area and sites

This study was conducted near Várzea (40°46'059"N, 7°51'726"W), North-central Portugal, after a wildfire on 9th September 2012 that burnt through a *Pinus pinaster* Ait. forest area. Climate is humid Mediterranean, classified as Csb (FAO 2006), with a dry period from June to August and peak rainfalls between October and March. Mean annual rainfall and temperature are 1200 mm and 14°C, respectively (SNIRH 2015). The earliest available wildfire records of this fire-prone area are from 1975 to present, and no prescribed fires have been recorded from this time interval (ICNF 2013). Within this area, we selected three hillslopes for each of the following wildfire frequencies (Fig. 1): 1) unburnt from 1975 to 2012; 2) burnt 1 time by one wildfire on Sept 2012 (1 fire); and 3) burnt 4 times namely by four wildfires on 1978, 1985, 2005 and 2012 (4 fires). The average wildfire frequencies corresponded, respectively, to > 39 years, 37 years and 9 years. Soil burn severity for the 2012 wildfire was estimated as moderate at the two burnt areas (using soil visual indicators described in Vega et al. 2013) with all the litter being transformed to a uniform black layer of charcoal, although in the hillslopes burnt 4 times the ash colour was grey in some spots (Table 1). As a consequence of the wildfire frequency, pre-fire vegetation cover was different between sites. The unburnt and the areas burnt 1 time (1 fire) were covered by mature *Pinus pinaster* woodland, with *Pterospartum tridentatum* (L.) Willk., *Calluna vulgaris* (L.) Hull and *Agrostis* spp., as the dominant understory vegetation. The areas burnt 4 times (4 fires) were shrubland, characterized by sparse 7 years old young pines regenerated from the previous wildfire in 2005, and dominated by *Pterospartum tridentatum* shrubs and the co-occurring species *Agrostis* spp., *Calluna vulgaris*, *Cistus* spp., and *Halimium* spp. (Fig. 1).

Table 1

General site characteristics, soil type and properties in the Ah topsoil layer (0–5 cm depth) of each site (unburnt (0x), 1 or 4 times burnt areas). Mean (and standard deviation) for the granulometric composition (%), $n = 54$), bulk density (g cm^{-3} , $n = 54$), soil organic matter content (SOM in %, $n = 54$), pH ($n = 54$), pF-curves (pF1, pF2, pF2.5, pF3.5, and pF4.2, in %, $n = 54$), and available water content (AWC in %, $n = 54$) on each area followed by a different letter were statistically different at $p < 0.05$. Comparisons were analyzed per mean values as well as per plant and bare microenvironments

<i>Site</i>	Unburnt (0x)	Burnt 1 time (1x)	Burnt 4 times (4x)
<i>General characteristics</i>			
Slope aspect (°)	210	210	200
Slope angle (°)	7–14	7–15	7–17
Pre-fire vegetation	<i>Woodland</i>	<i>Woodland</i>	<i>Shrubland</i>
Fire severity	Unburnt	Moderate	Moderate
<i>Soil type and properties</i>			
Soil type (IUSS 2015)	Humic Cambisol	Umbric leptosol	Epileptic Umbrisol
Soil depth (cm)	30-35-40	15-20-25	30-35-40
Texture class	sandy loam	loam	loam
Sand/silt/clay (%)	55a/29b/15a	46b/38a/16a	48b/35a/16a
Bulk density (g cm^{-3})	1.0(0.2)a	0.9(0.2)b	1.0(0.1)ab
SOM (%)	13(3) b	17(1) a	19(3) a
pH	4.9(0.1)a	4.6(0.1)a	4.7(0.1)a
<i>Soil hydrological properties</i>			
pF0(%)	52(13)a	56(19)a	48(10)a
pF1(%)	52(13)a	55(18)a	46(10)a
pF2(FC; %)	38(10)a	40(14)a	34(7)a
pF2.5(%)	23(4)a	25(7)a	25(4)a
pF3.2(%)	12(1)c	16(3)b	18(3)a
pF4.2(PWP; %)	5(2)c	9(3)b	11(3)a
AWC (FC-PWP; %)	33(11)a	31(16)a	23(9)b

All selected sites had similar elevation (450–550 m.a.s.l.), slope aspect (200–210° azimuths) and steepness (7–8° on top to 14–17° on bottom slope positions), and the soils were developed from pre-Ordovician schist of the Hesperic Massif. According to IUSS (2015), the soils were classified at the unburnt areas as an association of Humic cambisol and Epileptic Umbrisol (dystric). In the 1 fire areas corresponded to Umbric leptosol and in the 4 fires areas to Epileptic Umbrisol. These soils were all acidic sandy loam in the unburnt areas and loam in the 1 and 4 fires areas. Soils were somewhat deeper in the unburnt and the 4 fires hillslopes (30–40 cm) as compared to 1 fire hillslopes (less than 25 cm). Topsoil Ah layers showed similar bulk density and pH, although the unburnt soils showed a somewhat coarser texture and lower SOM than the two burnt soils (Table 1).

Analytical methods

Rainfall

The rainfall data were recorded using 3 rainfall automatic gauges (ECRN-100 from Decagon devices) as well as 3 storage gauges in each of the three areas. In order to characterize rain volume and intensity for the whole area, median values were used.

Field measurements

During early November 2012, five resprouting *Pterospartum tridentatum* shrubs (target specie) and paired bare spots were randomly selected on each slope. In April 2013, three of these five shrubs (excluding the biggest and the smallest shrubs), together with their paired bare spots

(total of 54 spots), were selected as experimental microsites to monitor the direct effects of wildfire (plant recovery and soil cover) as well as the indirect effects of wildfire (soil physical and hydrological properties). On each shrub, the maximum plant height and the length and diameter of five stems were measured in May, July and September 2013. On each of the 54 spots, soil samples were taken on May 2013.

Topsoil cover was measured on six 0.5 x 0.5 m plots per hillslope (three on shrub and three on bare microsites (n = 54 plots). Ground cover was assessed twice; three months and one year after the 2012 wildfire. Five cover categories were considered and classified as biotic (litter and vegetation) or abiotic (ash, bare soil and stones) cover components (Ruiz-Sinoga and Romero-Díaz 2010). Ground cover was quantified by laying a square grid of 0.5 m x 0.5 m at a fixed position over the plot and recording the cover category at 100 grid intersection points as a percentage (Prats et al. 2019).

Soil water repellence (SWR) was measured in the field by the molarity of ethanol droplet (MED) method at 2–3 cm depth, after removal of the ash and/or litter layer (Doerr et al. 1998). The measurements were made on a monthly basis in one hillslope per area (unburnt, 1 and 4 fires) in five equidistant sampling points along the slope length in bare soil spots. A total of 15 SWR measurements were made at every sampling occasion. The nine MED classes, ranging from 0 to 9, corresponded to increases in ethanol concentrations of 0%, 1%, 3%, 5%, 8.5%, 13%, 18%, 24%, 36 and >36%. MED classes were grouped as follow: class 0, very wettable; classes 1, 2, 3, wettable/slightly water-repellent; classes 4, 5, moderate/strongly water-repellent; class 6, 7, very strongly water-repellent; and class 8, 9, extremely water-repellent.

Soil sampling

Main soil properties were characterized at each of the nine hillslopes by sampling the topsoil with 5 cm-height steel cores in April 2013. At each hillslope, topsoil samples were taken under the three shrubs and at three bare soil microsites (n = 54), after removing the above ash and/or litter layer. The samples were gathered with 100 cm³ steel cores for soil moisture content (SMC; % volume) after drying at 105°C 24 h and soil organic matter (SOM; % volume) determination after sieving at < 2mm and incineration by loss-on-ignition at 550°C 4 h (ISO 11465, 1993). Another set of 54 samples was gathered for pH (ISO 10390, 2005), granulometric determination (Guitian & Carballas 1976) and bulk density analyses with 250 cm³ steel cores (Malvar et al. 2016). A third set of 54 samples (100 cm³ steel cores) was used for the assessment of soil water retention curves using a sandbox apparatus (Van der Harst and Stakman 1961) and a pressure plate device (Stolte 1997). The amount of water retained in the soil was calculated at five suction pressures: -1, -10, -33, -124, and -1550kPa; corresponding respectively to: pF1 (saturation water), pF2 (field capacity, FC), pF2.5, pF3.2, and pF4.2 (permanent wilting point, PWP). Available water content (AWC; %) was calculated as FC - PWP, once water retained at PWP is not accessible for plant uptake (Chen et al. 2007; González-Pelayo et al. 2006). Additional soil samplings were carried out in June 2013 (n = 54) and September 2013 (n = 54), before the beginning of the dry period, to determine SOM and SMC.

Soil moisture probes

A total of 72 soil moisture sensors (Decagon Inc.) were installed in November 2012 in order to carry out a detailed assessment of the daily variations in SMC between the 1 time and 4 times burnt hillslopes. These burnt hillslopes were both affected by the 2012 wildfire and only differed in the wildfire frequency. Therefore, the sensors were installed at two soil depths (at 2.5 and 7.5 cm depth) under two microsites (shrub and bare) in each of the three shrubs selected in each of the six burnt hillslopes, totalizing 72 sensors (2x2x3x6). The EC5 and GS3 dielectric capacitance soil moisture sensors were connected to Em5b dataloggers, and determine volumetric soil moisture content (SMC; v/v) by measuring the dielectric constant of the media using capacitance/frequency domain differences. A capacitance sensor uses the soil as a capacitor element and use the soil charge storing capacity to calibrate to water content. They have a measuring range of 0.0–1.0 (m³ m⁻³) and an accuracy of ± 0.03 m³ m⁻³ typical in mineral soil solutions that have an EC < 8 dS/m. Besides volumetric water content, GS3 sensors can also measure bulk electrical conductivity in a range of 0–25 dS/m. To avoid influence of the hillslope aspect, all probes were oriented to 200–210° azimuths. SMC was measured at 5-min time intervals, which were averaged to obtain the daily SMC (n = 350, from 21 Nov. 2012 to 6 Nov. 2013). All the EC5 and GS3 sensors were calibrated before installation and the offset differences between sensors were minimized by making use of individual 4-point calibration in fluids with known apparent dielectric permittivity (following user's guide available at www.metergroup.com). In this way, the mutual differences between sensors, which is especially important in the dry range, could be minimized and a high relative measuring accuracy could be obtained (van den Elsen et al. 2014).

Data analyses

The daily average SMC (%) and results obtained from pF-curves (FC, PWP) were used to calculate the effective soil water content (ESWC; %). The ESWC approach is intended to assess the water volume that is effectively available for plant uptake. It was assumed that the availability of soil water to plants is at best at FC, and it declines with decreasing SMC (Chen et al. 2007). At PWP, it is generally accepted that the soil water is no longer available for plants. The effective soil water content (% of the total available water) was calculated using the following formula (Porporato et al. 2002):

$$ESWC = (SMC_{\text{actual}} - PWP) / (FC - PWP)$$

Where SMC_{actual} is the average daily SMC measured with the soil moisture sensors (% volume). FC (field capacity) and PWP (permanent wilting point) were calculated from the pF-curves assessed from the soil samples adjacent to each sensor location (Van Genuchten et al. 1991).

Linear mixed-effects statistical models (Littell et al. 2006) were used to assess the differences in mean plant height, stem diameter, stem length, SMC and SOM with wildfire frequency (unburnt, 1 fire, 4 fires) as the fixed factor, and the plant/ topsoil sample as the random factor. Similarly, linear mixed-models were constructed to assess the differences in the daily SMC and ESWC among four fixed factors: wildfire frequency (1, 4 fires), soil depth (2.5, 7.5 cm), microsite (plant and bare), and season (autumn 2012, winter 2012–2013, spring 2013, summer 2013, autumn 2013). The individual soil moisture sensors were included as the random factor. The covariance structure of the repeated measures was modelled using a compound symmetry function or autoregressive heterogeneous variance, as it gave the lowest – 2 Res Log likelihood model-fitting values (Littell et al. 2006). In order to assure a normal distribution of the model residuals, plant variables, SOM and SMC were fourth-root transformed, while daily SMC and ESWC were log-transformed. Explanatory continuous variables were tested as covariates in a forward selection procedure, including daily rainfall, maximum 30-min rainfall intensity (I_{30}), and accumulated rainfall amount from 1 (Ant_rain_1) and until 14 days (Ant_rain_14) before the daily SMC measurement. As the multiple rainfall characteristics are related, they were tested independently and only the variable with highest F-value was included in the model, following the principle of forward selection. Linear regressions and coefficient of determinations (R^2) between the explanatory variables and the daily SMC and ESWC were calculated.

Differences in ground cover, bulk density, pH, pF-values and on SWR, were tested using mixed-effects models with or without repeated measures similar to the models described earlier, except no covariates were used. If the assumptions for equal variance and normality were not met, as it was the case of SWR, relative frequencies of each class were calculated, and the non-parametric Wilcoxon test was used to assess the differences between wildfire frequency and soil depths.

Comparisons among the fixed effects, as well as differences between the levels of the factors were tested by least-squares means and adjusted by the Tukey-Kramer method (Kramer 1956). All statistical data analyses were carried out using the SAS 9.4 software package (SAS Institute, Inc. 2008), and all statistical tests used $\alpha = 0.05$.

Results

Rainfall

From the analysed 350 days, 138 were rainy days, with a total rainfall of 1473 mm. Maximum rainfall intensities in 30 minutes were measured in March and September 2013 (14 and 29 mm h⁻¹). Peak daily rainfall happened also in autumn 2013 (Fig. 2). Out of the summer drought (July, August and September 2013), the average and the median number of days between rain events were 4 and 3, respectively, while maximum days without rain amounted to 26.

Plant recovery, soil cover and topsoil properties

The plant response at the two burnt areas was very similar, although at the end of the last dry period of September 2013, before the rainfall season, the 4 fires hillslopes showed a slightly lower plant height, stem diameter and stem length, as compared to the 1 fire hillslopes, although without significant differences. Plant height (*Pterospartum tridentatum*) was very similar in the unburnt hillslopes through time, and significantly higher than the 1 and 4 fires hillslopes (Table 2).

Table 2

Plant recovery (mean plant height, stem diameter and length) and soil response (mean SMC, SOM) during the drying period of April 2013 to September 2013. Mean (standard deviation) values followed by different letters indicate significant differences between unburnt, 1 fire of 4 fires areas at $p < 0.05$.

Month	Unburnt	1 fire	4 fires
Plant response			
<i>Height (mm)</i>			
Apr 2013	664(271)b	68(25)e	90(38)e
June 2013	752(284)a	286(77)d	308(79)d
Sept 2013	695(230)ab	430(146)c	397(104)c
<i>Stem diameter (mm)</i>			
Apr 2013	4.4(1.9)b	1.6(0.3)f	1.8(0.4)ef
June 2013	4.8(2)a	2.0(0.5)de	2.4(0.6)cd
Sept 2013	5(2)a	3.0(0.9)c	2.7(0.8)c
<i>Stem length (mm)</i>			
Apr 2013	678(315)b	57(18)f	76(33)f
June 2013	722(324)a	267(88)e	315(89)de
Sept 2013	722(331)a	398(182)cd	385(105)c
Soil response			
<i>Soil organic matter (SOM; %)</i>			
Apr 2013	11(4)d	18(5)b	17(3)b
June 2013	13(3)cd	20(5)a	19(3)ab
July 2013	14(7)c	21(5)a	18(4)ab
Sept 2013	12(5)cd	21(6)a	17(3)b
Nov 2013	–	18(3)b	18(2)ab
<i>Soil moisture content (SMC; %)</i>			
June 2013	12(3)bc	11(3)bc	13(3)bc
July 2013	9(4)d	11(5)cd	5(3)e
Sept 2013	4(2)f	3(1)fg	2(1)g
Nov. 2013	–	13(4)b	17(4)a
<i>Effective soil water content (ESWC; %)</i>			
June 2013	41(30)ab	27(10)bc	38(13)ab
July 2013	34(36)bc	27(13)c	16(10)d
Sept 2013	16(24)d	7(3)e	7(3)e
Nov. 2013	–	26(8)c	43(11)a

Ground cover differed between unburnt and burnt areas (Fig. 3). Immediately after fire, abiotic soil surface components such as ashes, bare soil and stones amounted to 81% at the 1 fire and 99% at the 4 fires hillslopes. One year later, the unburnt hillslopes remained completely covered by (biotic) litter and vegetation, while in the 1 fire and 4 fires hillslopes amounted to only 49% and 16% of the biotic soil cover, respectively (Fig. 3).

Soil water repellence (SWR) did not display statistically significant differences between 1 and 4 fires area in the overall data pool (Fig. 4). However, in the unburnt area, moderately/strongly SWR levels were more frequent as compared to the burnt sites. Overall, annual SWR

frequency at 2–3 cm depth was non-repellent (MED class 0) in 44 and 43% of the measurements on the 1 and 4 fire areas respectively, and only 17% on the unburnt areas. The 4 fires areas showed very strong and extremely repellent categories in 21% of the measurements, while the 1 fire and the unburnt areas were close to 40%.

The pF-curves revealed no differences in the gravitational soil water content (SWC) ($< pF2$ and field capacity (FC, $pF2$), due to wildfire frequency (Table 1). However, the soil water retained at higher pressures ($pF3.2$ and $pF4.2$ or PWP) increased with wildfire frequency. Consequently, AWC (AWC = $pF2 - pF4.2$) was lower on the 4 fires hillslopes (Fig. 5) as compared to 1 fire site and unburnt site, although the differences were not significant.

The unburnt, 1 and 4 fires areas reflected differences in SOM, SMC and ESWC (Table 2). SOM did not vary between the five soil sampling campaigns, but the unburnt hillslopes showed significantly lower SOM contents than the burnt hillslopes. SMC decreased consistently during the dry periods, and markedly so in the 4 fires hillslopes in July 2013, which were statistically dryer than the 1 fire and the unburnt hillslope (Table 2). On the contrary, during the wet sampling of November 2013, the 4 fires hillslopes showed a significantly higher SMC (17% vs. 13%). ESWC varied in the wake of SMC. ESWC for the 4 fires hillslopes was significantly lower during July 2013 (16%), and significantly higher during November 2013 (43%), as compared to the 1 fire hillslopes.

Factors affecting soil moisture sensors readings

The overall mean SMC values for the soil moisture sensors at the 1 and 4 fires hillslopes during the first post-fire year were not statistically different (Table 3), and reached, respectively, 12.7% and 13.0% (S1). There was not a significant microsite effect (the overall mean SMC value for plant and bare microsites was the same, see S1) but there were strong depth and season effects, and both were statistically significant (Table 3). The presence of significant interactions indicated that the effect of wildfire frequency was not straightforward for all the levels of the factors. For example, wildfire frequency and microsite showed complex relations: the plant microsite was wetter than the bare soil microsite on the 1 fire hillslopes, but the opposite was found on the 4 fires hillslopes (Table 4). These patterns were consistent throughout all the seasons, but any of the within-season differences were significant.

Table 3

Summary of the F- and p-values obtained from the linear mixed-effects soil moisture content (SMC) and effective soil water content (ESWC) models for the 1 and 4 fires areas. F- and p-values highlighted in bold for the fixed effects, covariates or their interactions are statistically significant at $p < 0.05$.

	SMC		ESWC	
	F-value	p-value	F-value	p-value
<i>Fixed effects</i>				
fire	2.08	0.1505	3.11	0.0791
microsite	0.38	0.5381	0.4	0.53
depth	99.51	< .0001	63.55	< .0001
season	103.1	< .0001	60.93	< .0001
<i>Interactions</i>				
fire*season	1.5	0.2016	1.49	0.2045
fire*microsite	15.15	0.0001	2.57	0.1099
season*microsite	0.7	0.5954	0.43	0.7879
fire*season*microsite	1.16	0.3304	0.82	0.5117
fire*depth	3.8	0.0523	1.88	0.1718
season*depth	2.08	0.0844	1.81	0.1273
fire*season*depth	0.58	0.6764	0.6	0.6636
microsite*depth	0.07	0.7974	0.36	0.5499
fire*microsite*depth	2.67	0.1037	1.61	0.2055
season*microsite*depth	0.09	0.9841	0.1	0.9815
fire*season*microsite*depth	0.46	0.7659	0.33	0.8594
<i>Covariates</i>				
Ant_rain7_	2173.37	< .0001	1955.26	< .0001
Ant_rain7_*depth	285.47	< .0001	19.15	< .0001
Ant_rain7_*season	360.02	< .0001	287.93	< .0001

Table 4

Seasonal mean values of soil moisture content (SMC, %) and effective soil water content (ESWC, %) based on fire recurrence (1 vs. 4 fires), microsite (plant vs. bare soil) and season. SMC or ESWC values followed by different letters indicate significant differences at $p < 0.05$.

Fire	Microsite	SMC (%)				ESWC (%)					
		Autumn	Winter	Spring	Summer	Autumn	Autumn	Winter	Spring	Summer	Autumn
		2012	2013	2013	2013	2013	2012	2013	2013	2013	2013
1 Fire	plant	12.6bcdef	17.4ab	16.9abc	10.2def	12.6bcdef	0.6abcd	18.6ab	19.1ab	-5.5bcd	2.4abcd
	bare	10.7def	17.3ab	15.3bcde	9f	9.3ef	-9.9bcd	20.5ab	13.4abc	-12.2cd	-7.9bcd
4 Fires	plant	11.8cdef	17.8ab	14.6bcde	9.7ef	9.8def	-1.4bcd	34a	17.4ab	-9.5bcd	-1.7abcd
	bare	16.4abcd	19.8a	16.1abcd	9.6ef	12.9bcdef	15.8abc	35.2a	16.7ab	-18.6d	4.2abcd
Overall	1 Fire	11.7ed	17.4ab	16.1abc	9.6e	11ed	-4.6ed	19.6ab	16.3abc	-8.8e	-2.8ed
	4 Fires	14.1cd	18.8a	15.3bc	9.7e	11.3ed	7.2cd	34.6a	17bc	-14.1e	1.3ed

On the other hand, the ESWC values showed a tendency for keeping more effective water into the 1 fire area, under plant microsites and deeper soil layer (7.5 cm depth, S1), although differences were not significant (Table 4). There was also a significant effect of wildfire frequency on ESWC, with the 1 fire hillslopes (9.0%) exhibiting significantly higher values than the 4 fire areas (7.3%; S1). Plant microsites registered higher

overall ESWC values than bare soil microsites (9.9% vs. 6.4%), but only for the 1 fire hillslopes, and the differences were not significant. The effect of soil depth was significant and the surface soil layers exhibited much lower ESWC than the deeper soil layers (-4.1% vs. 20.4%; S1).

The mean seasonal SMC were significantly lower for summer 2013, due to the drought period, and highest for winter 2013 (Table 4). ESWC was significantly lower for the same dry season, when the effective soil water was below 0%; or in other words, below PWP and thus, plants were under water stress. The daily variations of SMC and ESWC showed that the hillslopes burned 1 time were more stable than the hillslopes burned 4 times (Fig. 6). Threshold ESWC of 0% (no water available for plants) was reached 17 days sooner in the 4 fires hillslopes than on the 1 fire hillslopes, and also 10 days sooner on the bare than plant microsites (respectively 15 and 3 days, for the 1 fire and 4 fires hillslopes). Although the differences were small, both SMC and ESWC were significantly higher during some of the driest days of summer 2013, and significantly lower during some of the wettest days of winter 2013 on the 1 fire hillslopes as compared to the 4 fires hillslopes. The plant microsites were slightly wetter than the bare soil microsites, although the daily differences were marginal (Fig. 6). The seasonal variations were highly correlated with rainfall amount. However, the most important covariate for both SMC and ESWC was the cumulated 7-days rainfall amount (Fig. 7). The worst coefficient of correlations happened during the dry seasons of autumn 2012 and summer 2013 ($r^2 = 0.53$ and 0.32), when the soils were much dryer and hydrophobic.

Discussion

Effects of wildfire frequency on plant recovery and soil properties

The increase in wildfire frequency had important effects on vegetation composition and structure. Vegetation physiognomy changed from pine woodland on the unburnt and 1 fire hillslopes to open shrubland on the 4 fires hillslopes. The occurrence of repeated wildfires killed the pine trees before they reach the reproductive age, which left a footprint that constrains vegetation recovery and compromise forest productivity (Kowaljow et al. 2018). Plant recovery (*Pterospartum tridentatum*) was slightly faster on the 1 fire than the 4 fires hillslopes, which can be attributed to the higher litter and vegetation cover on the 1 fire than the 4 fires hillslopes. These cover categories protect the topsoil water from high soil temperatures and evaporation, while ashes and bare soil increase the albedo and water evaporation (Sankey et al. 2012). However, exceptions were found between the higher water demand of plants during water stress periods as compared to bare agriculture lands (Bellot et al. 1999) or the lower SMC measured on the vegetated areas as compared with burnt gorse shrubland (Soto and Díaz-Fierros 1997).

The higher plant recovery on the 1 fire hillslopes can be also a consequence of the higher soil water availability for plants, which in turn is a function of soil texture, bulk density and SOM (Vereecken et al. 1989; Ankenbauer and Loheide 2016). Wildfires can have an effect on these parameters and decrease the clay fraction, via soil erosion, increase the bulk density, via loss of soil structure and loss of SOM (Boix-Fayos 1997; Certini 2005). However, none of these changes were observed in our study (Table 1). We observed that wildfire frequency increased the silt fraction and the SOM. The fining of the particle size distribution after burning can possibly be explained by physical weathering of the sand-sized particles into silt and clay-sized particles (Stoof et al. 2010; Rhoades et al. 2004). On the other hand, SOM can increase after moderate wildfires (Boix-Fayos 1997; De la Rosa et al. 2012), as it happened in our study, but typically SOM decrease by combustion after intense wildfires (González-Pérez et al. 2004). Furthermore, the increase in SOM in our burnt hillslopes did not lead to higher water retention (Table 2). SWR appeared to decrease at increasing wildfire frequency (Fig. 4), and was higher in the unburnt than the 1 or the 4 fires hillslopes. These patterns can be partially attributed to a destruction of repellent substances by fire (Jimenez-Morillo et al. 2017). SWR can be also more persistent on coarse-textured soils and under certain vegetation types (González-Pelayo et al. 2015), as it was the case of the sandy-loam and vegetated unburnt hillslopes as compared to the loam and bare burnt 1 and 4 fires hillslopes.

Effects of wildfire frequency on soil water retention

Instead of wildfire severity, most of the studies have focused in the effects of wildfire temperature in soil water retention. Researchers found difficulties in stating the subtle differences in soil water retention due to soil heating, in laboratory (Badia and Marti 2003; Stoof et al. 2010) as well as field prescribed burning (Silva et al. 2006), experimental fires (González-Pelayo et al. 2006; 2010; Soto and Diaz-Fierros 1997) and wildfires (Boix-Fayos 1997; Ebel 2012; Sankey et al. 2012). In general, soil water retention decrease with fire temperature, although this relation is not straight forward (Stoof et al. 2010): a) heating below 200 °C induces mild decreases in the amount of soil gravitational water at low pF tensions, b) heating at 300 °C strongly decreased both gravitational water and soil capillary water held at high pF tensions, c) heating at 500 °C attained an intermediate position, as the strong reduction of SOM is offset by the increase of the finer silt and clay fractions. The previous researchers have stated that the results were very sensitive to the details of the experimental set up.

We reduced at maximum the sources of variation on our hillslopes (same aspect, steepness, hillslope length, parent material) and maximized the amount of measurements (plant and bare microsites in each of 3 positions along each of the 3 hillslopes per wildfire frequency treatment sampled 4 times) and the differences were small. The 1 fire hillslopes showed the highest soil water retention (more gravitational, field capacity and wilting point water), followed by the unburnt and by the 4 fires hillslopes (Fig. 5; $n = 54$ soil samples). We hypothesize that the increased silt fraction can explain the higher water contents at high pF tensions observed on both the 1 and 4 fires soils as compared to the

unburnt soils. On the one hand, the higher gravitational water on the 1 fire soils can be attributed to the incorporation of ash to the soil, which enhanced the water retention at low pF tensions more effectively than the soil itself (Ebel 2012). On the other hand, the 4 fire soils had comparatively less fuel loads and lower fire temperatures, and fuels were likely transformed into charcoal, due to incomplete combustion. Consequently, the char incorporation to the soil can explain the lower gravitational water on the 4 fires soils, as charcoal retained less water as compared to the soil itself (Stoof et al. 2010). In fact, the fate of the organic matter can play an important role in water storage capacity (Minasny and McBratney 2017; De la Rosa et al. 2012; Gonzalez-Perez et al. 2004).

Effects of topsoil depth, microsite and season on post-fire SMC and ESWC

Our results showed that both SMC and ESWC significantly increased with soil depth, which agreed with literature about post-fire soil moisture patterns (Soto and Díaz-Fierros 1997; Silva et al. 2006; Nolan et al. 2014; Cardenas and Kanarek 2014) and on other unburnt Mediterranean forest/shrubland soils (Sarah 2002). The lower SMC and ESWC in the upper soil layer are attributed to the higher evaporation in post-fire soil surfaces, due to the different albedo as a result of the lack of a litter and the presence of black ashes (Bellot et al. 1999; Soto and Díaz-Fierros 1997).

Microsites exerted an effect on SMC and ESWC, but this effect differed between areas. Plant retained more soil water than bare microsites in the 1 fire hillslopes, but the opposite was true for the 4 fires hillslopes (Table 4). In his review, Sankey et al. (2012) found that plant microsites accumulated more SOM, nutrients and soil water than bare microsites, the effect being stronger on the wildfire-affected steppes than in the unburnt areas, as it happened in our 1 fire hillslopes. The existence of soil moisture radial gradients between plant to bare microsites have been well described for Mediterranean arid (Sarah 2002; Katra et al. 2007) and semi-arid conditions (Gimeno-García et al. 2011), and less pronounced for humid Mediterranean environments, with rainfall volumes of more than 700 mm of rain per year (Lavee et al. 1998; Ruiz-Sinoga et al. 2010b; Gabarrón-Galeote et al. 2012; Martínez-Murillo et al. 2013). The humid Mediterranean climate, with rainy winters and dry summers result in rapid fuel built-up, and a higher wildfire frequency (Badía and Martí 2003). The more frequent wildfires destroy the microtopographic shrub mounds and lower elevation bare interspaces. During the window of disturbance, the plants lose their capacity to buffer extreme temperatures and accommodate surface water relative to bare microsites (Sankey et al. 2012), which was likely the case of the 4 fires hillslopes. Both microsites are subject to erosion, but plants can be deflated at a greater rate than interspaces owing to wind erosion (Sankey et al. 2011).

The SMC and ESWC results of the seasonal soil sampling campaigns fitted in well with the soil moisture sensor data series. The wet season soil sampling campaigns (Table 2) showed that increasing wildfire frequency led to a loss of the soil buffer capacity to store extreme SWC and to accommodate greater quantities of water during autumn. On the other hand, the dry soil sampling of July showed that the more frequently-burnt soils had difficulties to retain soil water during the drying summer. Sankey et al. (2012) described that the increase in fire frequency implied that plants afforded less time to recover between fires, and soils were subjected to decreases in their water accommodation capacity. The same conclusions arose from the soil moisture sensor data series, both at seasonal (Table 4) and daily (Fig. 6) periods: an increase in wildfire frequency led to maxima SWC during winter periods, and minima SWC during dry periods, with longer periods of soil water stress for plant growing. During the first post-fire year our study shows that increasing wildfire frequency increases the water stress period of summer in 17 days. The microsite effect was also important, having the plant microsites 10 days less of water stress than the bare microsites. Sankey et al. (2012) hypothesized that this contrasting effect will depend on plant recovery to pre-fire levels, which depends on both wildfire frequency, and plant physiology to recover after disturbances. Plant water uptake play a major role in the complex post-fire seasonal behaviour of SMC during wet/dry seasons, but the few studies assessing this reached different results. Silva et al. (2006) did not find any significant effect, but others (Soto and Diaz-Fierros 1997; Nolan et al. 2014; Prats et al. (2016b) found an effect of plant water uptake during the dry seasons. The two first studies measured higher SWCs in burnt than unburnt/vegetated soils, while the third study attributed the higher SWC in burnt than hydromulched soil to the higher plant cover during the dry end of the 1st post-fire year.

In a nutshell, the effects of increasing wildfire frequency in pine forests can lead to a transition in vegetation structure (Eugenio et al. 2006a; Santana et al. 2014; Mayor et al. 2016). As a result, the post-fire spatial pattern of coarse vegetation regulates soil erosion, nutrient and fertility losses (Santana et al. 2010; Mayor et al. 2016) and seed establishment (Bochet 2015). Additionally, the more frequent bare space between shrubs, have a lower capacity to capture and hold resources (water, sediments, nutrients, seeds, etc.), thereby being unable to function as sink areas for a longer time after fire (Mayor et al. 2016). Finally, the temporal patterns of the hillslopes burnt at high wildfire frequency are these of longer water stress periods during the dry seasons. Vegetation recovery can take decades or hundreds of years to reach pre-fire levels (Cammeraat and Imeson 1999). Post-fire managers should follow strategies to preserve and restore pre-fire vegetation structures, due to their important role in water conservation and redistribution and prevent catastrophic tipping points towards desertification (Lavee et al. 1998; Ludwig et al. 2005) even in humid Mediterranean forestlands.

Conclusions

The conclusions about the effect of wildfire frequency on plant recovery, soil properties and soil water dynamics throughout the first year after the 2012 wildfire in unburnt hillslopes, hillslopes affected by 1 fire and 4 fires, are as follow:

- i) The increase in wildfire frequency switched the vegetation community, from pine woodland to shrubland, and delayed the plant recovery response of the shrub community,
 - ii) The increase in wildfire frequency significantly decreased the biotic ground cover, significantly increased the SOM content and the silt soil fraction, and slightly decreased SWR,
 - iii) Increasing wildfire frequency did not affect the overall annual/seasonal soil moisture content (SMC), although soil water retention was significantly lower at field capacity (FC) and significantly higher at the permanent wilting point (PWP) on the 4 fires as compared to the 1 fire soils, resulting in a lower available water content (AWC) as increasing wildfire frequency.
 - iv) However, the threshold for some effective soil water available for plants (ESWC > 0%) extended for longer (17 days more) in the 4 fires hillslopes than on the 1 fire hillslopes, and also in the bare than plant microsites (10 days). As a consequence, the effective soil water content (ESWC) was lower on the 4 fires than in the 1 fire area.
 - v) Both SMC and ESWC were significantly higher at deeper soil layers than on the superficial ones and were also significantly affected by seasonal influences. The microsite was not a significant factor, although overall mean values revealed higher ESWC under plant, as compared to bare microsites. Antecedent rainfall in 7 days was a significant covariate for both SMC and ESWC.
- Increasing wildfire frequency led to both maximum and minimum values of SMC, respectively for the wet and dry seasons. Sites burned more frequently had higher SMC during the wet seasons, when water was not a constraining factor for plant growing, and on the other hand, experienced a more pronounced drop of SMC and ESWC during the dry season. The opening of the water-stress window of the dry season happened sooner and extended for longer in these hillslopes. These findings showed that present and future global warming scenarios, are triggering catastrophic tipping points towards desertification even in humid Mediterranean forestlands.

Abbreviations

Soil moisture content (SMC)

Soil water content (SWC)

Effective soil water content (ESWC)

Field capacity (FC)

Permanent wilting point (PWP)

Available water content (AWC)

Kilopascals (KPa)

Soil water repellency (SWR)

Molarity of ethanol droplet (MED)

Antecedent rain (Ant_rain)

Soil organic matter (SOM)

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Not applicable.

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Conflicts of interest

Not applicable.

Availability of data and material

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Figures

Figure 1

Experimental set-up showing the unburnt (green circles), 1 fire (yellow circles) and 4 fires hillslopes (red circles) as well as a scheme of the microsites (plant and bare) and soil depths (2.5 and 7.5 cm) monitored in this study. Bottom pictures (from left to right) corresponds to a 4 fires (4x), a 1 fire (1x) and an unburnt (0x) hillslope. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Rainfall amount (mm) and maximum intensity in 30 minutes (I30, mm h⁻¹) for the study period and seasons: Autumn 2012 (21/11/2012-21/12/2012), Winter 2013 (22/12/2012-21/03/2013), Spring 2013 (22/03/2013-21-06-2013), Summer 2013 (22-06-2013-21-09-2013) and Autumn 2013 (28-09-2013-07-11-2013).

Figure 3

Ground cover (%). Biotic (litter and vegetation) and abiotic (ash, bare soil, stones) soil surface components on the unburnt, 1 fire and 4 fires areas after the 2012 wildfire (December 2012) and one year later (November 2013).

Figure 4

Soil water repellence (SWR) determined by the molarity ethanol drop test (MED) for the unburnt, 1 fire and 4 fires areas. SWR classes were grouped as follows: Class 0, very wettable; 1, 2 and 3, wettable; 4 and 5, moderately and strongly; 6 and 7 very strongly; 8 and 9, extremely repellent.

Figure 5

Soil water retention curves (% volume) for the unburnt, 1 fire and 4 fires hillslopes at a range of selected tensions (pF-values from 0 to 4.2; n=54). The curves were fitted to all data points following Van Genuchten et al. (1991).

Figure 6

Daily rainfall amount (mm), soil moisture content (SMC, % volume) and effective soil water content (ESWC, %) measured with the soil moisture sensors at the 1 fire ($n=36$) and 4 fires hillslopes ($n=36$) as well as for plant and bare soil microsites. Black asterisks indicate significant daily differences between 1 fire and 4 fires. Blue symbols indicate significant differences between plant and bare microsite for the 1 fire hillslopes (blue crosses) or the 4 fires hillslopes (blue asterisks) at the significance level of $p < 0.05$.

Figure 7

Linear regression and R2 between records of seasonal soil moisture content (up, SMC, %) and seasonal effective soil water content (down, ESWC, %) vs Antecedent rain in 7 days.

Supplementary Files

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