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Medium-term dynamics of soil respiration in a Mediterranean mountain ecosystem: The effects of burn severity, post-fire burnt-wood management, and slope-aspect

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ABSTRACT

The interaction between burn severity and subsequent post-fire logging practices may exert a direct effect on soil respiration (SR) in recently burnt stands. This effect is associated with the modification of microclimatic conditions, soil carbon inputs, and the decay rates of woody detritus. In addition, slope aspect may determine SR rates by modifying the microclimatic conditions in post-fire environments. In this study, we assessed the changes in SR rates during the early (1.5–4 years) post-fire stages in a burnt and logged Spanish Black pine forest along a burn-severity gradient: (1) an unburnt site (UB), (2) a low burn-severity site (LS), (3) a south-facing high burn-severity site (HSS), and (4) a north-facing high burn-severity site (HSN). Monthly or fortnightly manual SR measurements (SR_M) were taken at midday between 2011 and 2013. In addition, we also quantified the litter layer and fine-root biomass at each site. Multiple regression models combining abiotic (both soil temperature and water content, Ts and SWC, respectively) and biotic (tree diameter at breast height, 1.30 m) were used for midday SR_M modelling. For temporal and spatial scaling of SR at the stand-level, we performed 8 seasonal campaigns of automated SR measurements (SR_A) along 4 linear gradients from trees or stumps to inter-tree/stump gaps with the aim of: (1) determining the main soil-surface areas (soil close to trees or stumps and/or soil away from them; SC and SA soil, respectively) and (2) correcting the modelled daily daytime and night-time SR_M rates.

Our results showed a significant reduction in fine-root biomass at the burnt sites, although over the 3-year study period this figure did tend to increase. The amount of litter was similar between sites suggesting that logging practices may influence the amount of post-fire detritus. We also found that the spatial variability in soil microclimate was high and was primarily influenced by post-fire canopy cover as well as the slope aspect. SR rates significantly varied between years and were higher in SA soil compared to SC soil at all the sites we studied. Higher SR rates were observed close to stumps compared to those close to trees, highlighting the large relative contribution of this decaying debris to post-fire SR rates. In the medium-term, the combined effect of fire and logging practices may lead to an increase in the annual stand-level SR at high burn-severity sites after fire. In contrast, the interaction between fire and logging practices did not alter the post-fire SR rates at the LS site during the same time period. Our results also underscored the dependence of post-fire SR rates on the slope aspects within the high-severity fire area. Finally, this study showed that our integrated spatio-temporal approach could be a useful tool for obtaining more accurate SR estimates for short-, medium- and long-term stand-scale carbon cycling studies in burnt areas.

1. Introduction

Wildfires are the predominant natural disturbance in the forest ecosystems bordering the Mediterranean basin (Certini et al., 2011). These disturbances can have a significant effect on the car-

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bon balance of these Mediterranean ecosystems, both by directly releasing C into the atmosphere via vegetation and litter combustion and by altering carbon-flux components such as soil respiration (SR, see Appendix A Table A1 for a list of abbreviations) (Marañón-Jiménez et al., 2011; Muñoz-Rojas et al., 2016). Most studies in different ecosystems report that SR is decreased in burnt areas compared to unburnt areas (Czimczik et al., 2006; Litton et al., 2003; López-Serrano et al., 2016; Marañón-Jiménez et al., 2011; Sullivan et al., 2011; Uribe et al., 2013), although others report no change (Irvine et al., 2007; Meigs et al., 2009) or even an increase (Gathany and Burke, 2011; Muñoz-Rojas et al., 2016). Moreover, several studies indicate that the period of post-fire changes in SR can fluctuate from a few years to decades following the wildfire (Köster et al., 2015; Sullivan et al., 2011). These soil respiratory responses to fire depend largely on the burn severity (also referred to as fire severity) and the subsequent post-fire wood management practices (i.e., salvage logging) which can determine the recovery pathways followed by the forest ecosystem (Castro et al., 2011; Marañón-Jiménez et al., 2011; Muñoz-Rojas et al., 2016; Uribe et al., 2013). Salvage logging is widely used worldwide and simplifies the fuel mass and post-fire stand structure (Castro et al., 2011; Leverkus et al., 2014; Marañón-Jiménez et al., 2011). Thus, the combined effect of burn severity and logging practices directly influence post-fire SR rates by reducing the overstory tree canopy cover and the understory herbaceous and shrub layer (Muñoz-Rojas et al., 2016), altering nutrient availability and soil microbial communities (Pourreza et al., 2014), affecting soil environmental conditions (Marañón-Jiménez et al., 2011), and modifying the amount of woody debris scattered on the ground (Castro et al., 2011). Together, these alterations may shift the relative contribution of both heterotrophic (SR_{het}) and autotrophic (SR_{aut}) soil respiration after fire. Although tree mortality may restrain post-fire SR_{aut} rates, this effect can be shrouded by the stimulation of SR_{het} rates both by environmental ameloration of the soil as well as the progressive nutrient and organic substrate input from decaying burnt wood improving soil fertility in burnt and logged areas (Castro et al., 2011; Gathany and Burke, 2011; Harmon et al., 2011; Irvine et al., 2007; Marañón-Jiménez et al., 2011; Smith et al., 2010). Notwithstanding, the interaction between burn severity and logging practices and its effects on SR have only been sparsely documented in Mediterranean ecosystems (Marañón-Jiménez et al., 2011). In addition, while the SR in burnt areas have been assessed in long-term synchronic studies using chronosequences (Bond-Lamberty et al., 2004; Czimczik et al., 2006; Köster et al., 2015; Smith et al., 2010), how post-fire SR dynamics are affected during the early post-fire stages of ecosystem recovery is less studied (Marañón-Jiménez et al., 2011; Muñoz-Rojas et al., 2016). Therefore, early comprehensive diachronic studies of short- (<1 year post-fire) and/or medium-term (1–5 years post-fire) SR are needed in post-fire areas which comprise complex mosaics of unburnt and logged areas with different degrees of burn severity and in which a complex spatial pattern of SR is anticipated.

To scale-up SR rates (based on instantaneous chamber-based measurements) to the stand level, the mechanisms and quantification of the temporal and spatial SR variation must be better understood. Previous studies have examined the spatial variability of SR at different scales, from (1) the tree-level through linear transects from nearest single-tree to canopy gaps, analyzing the spatial contribution of tree root respiration (Millard et al., 2008; Scott-Denton et al., 2003; Tang and Baldocchi, 2005), and (2) the stand-level using systematic sampling designs with many SR measurement points linked to the spatial arrangement of trees and canopy structure (Knohl et al., 2008; Luan et al., 2012; Ngao et al., 2012; Søe and Buchmann, 2005). Thus, in view of the large spatial variability in post-fire SR sources in different burnt logged areas, we used a spatially-limited sampling design and integrated both methodologies as a practical tool for scaling up instantaneous post-fire SR measurements to stand-level SR estimates. In addition, the temporal variability of SR, from hourly to inter-annual variations, has been described using manual and automated chamber measurement sampling strategies (Almagro et al., 2009; Laganière et al., 2012; Li et al., 2008; Luan et al., 2012; Marañón-Jiménez et al., 2011; Savage and Davidson, 2003; Uribe et al., 2013). Soil temperature (Ts), soil water content (SWC), and their interactive effects are recognized as the main abiotic factors controlling the temporal variability of SR in Mediterranean post-fire ecosystems (López-Serrano et al., 2016; Marañón-Jiménez et al., 2011; Uribe et al., 2013), moreover, the influence of different slope aspects produces significant heterogeneity in both factors (Inclán et al., 2008; Kang et al., 2003; Wang et al., 2015). However, while these soil environmental factors can drive slope aspect-related SR variations in different forest ecosystems (Kang et al., 2003; Wang et al., 2015), this issue has not been specifically studied in post-fire Mediterranean ecosystems. In addition, both Ts and SWC are also directly influenced by the forest structure and canopy cover after fire and/or logging (Barba et al., 2013; Dore et al., 2014; Hagemann et al., 2010; López-Serrano et al., 2016; Ma et al., 2010; Martínez-García et al., 2015; Muñoz-Rojas et al., 2016). The temporal variability of SR is also linked to biotic factors, among which are coarse and fine-root biomass activity (Laganière et al., 2012; Luan et al., 2011; Saiz et al., 2006; Vargas and Allen, 2008), aboveground litter input (Saiz et al., 2006), and decaying woody debris (Martínez-García et al., 2015), which are differentially altered in post-fire logged areas (Harmon et al., 2011; Meigs et al., 2009). Thus, understanding how these abiotic and biotic factors regulate post-fire SR in logged areas with varying burn severities and slope-aspects will give insight into the mechanisms driving SR variation after fire.

In this study, we assess the combined effect of different burn severities (low and high) and post-fire logging on the magnitude of SR during the early post-fire stages (1.5–4 years post-burn) in a Mediterranean mountain ecosystem. We hypothesize that the combined effect of fire and logging contributes to SR alterations, in relation to modifications in soil environmental conditions, soil carbon inputs (litter), and the decay rates of woody detritus. Furthermore, different slope aspects also imply variations in environmental conditions, which may also determine the rates of vegetation recovery and detritus decomposition. Therefore, we also analyzed SR in opposing aspect-slopes at high burn-severity sites. Our objectives were: (1) to quantify and characterize the spatial and temporal variability of SR at both unburnt and burnt logged sites, (2) to analyze the effect that slope aspect exerts on SR at high burn-severity sites (north-facing slope vs. south-facing slope), and (3) to determine the annual SR rates at the stand-level across the sites from 2011 to 2013.

2. Material and methods

2.1. Study area and experimental sites

The study was conducted in a Spanish Black pine (*Pinus nigra* Arn. ssp. *salzmannii*) forest stand located at the Cuenca Mountain Range Natural Park (Castilla-La Mancha Region, central-eastern Spain; 1400 m a.s.l.), where a natural wildfire burnt around 1800 ha in July 2009 (Supplementary Fig. S1). The climate is Mediterranean, with warm, dry summers and cold, rainy winters; the mean annual precipitation is 652 mm and mean annual temperature is 11.1 °C, with values ranging between −9.8 °C and 34.4 °C (Martínez-García et al., 2015). The study area is slightly hilly (slopes ≤ 5%) and has a shallow soil over calcareous hard rock with frequent rock outcrops (Martínez-García et al., 2015). Spanish black pines dominate the upper canopy layer, with Scots pine (*Pinus sylvestris* L.), Lusitanian