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Carbon loss during the early decomposition stages of tree stumps in a post-wildfire Spanish black pine forest

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A B S T R A C T

Post-fire carbon released by the decomposition process of tree stumps in a Spanish black pine (*Pinus nigra* Arn. ssp. *salzmannii*) forest of the Cuenca Mountain range (Spain) was assessed during the first three years after felling fire-killed trees. Carbon loss was estimated at high- and low-burn severity sites by two different ways: (1) via wood mass loss (indirect method); and (2) via *in situ* CO_2 efflux measurements (R_{stump}, direct method). By the indirect method, different aboveground wood decomposition parameters were estimated, i.e. decay rate (k_a) and half life period ($t_{0,5}$). By the direct method, multiple regression models related stump diameter and temperature to instantaneous R_{stump}. The results indicate that C loss depended on post-fire environmental conditions and woody substrate quality (i.e. stump size). Both methods showed similar C release patterns, with higher values obtained by the direct method for all study sites and tree stump sizes, likely because a portion of the CO_2 originating in the belowground part of stump was diffused through the decomposed aboveground part. Using the defined R_{stump} models for ecosystem upscaling, the annual C loss of the study sites ranged from 0.08 ± 0.01 to 1.33 ± 0.06 Mg C ha^{-1} $year^{-1}$. Thereby, stumps could be considered hot spots of CO_2 production during their early stages of decomposition, which particularly at post-fire managed areas, with large numbers are left to decompose, can represent a significant and poorly studied part of the total ecosystem respiration.

1. Introduction

Wildfire is a natural ecological factor and the most important disturbance in Mediterranean ecosystems (Fournier et al., 2012). Climate warming in the Mediterranean region has increased the intensity and frequency of large-scale wildfires, which have affected more than 4 million ha in the Mediterranean region of Spain in the last 20 years (Uribe et al., 2013). Wildfires directly control both vegetation dynamics and structure, and play a key role in the carbon cycle by reorganizing the post-fire carbon pools (Fournier et al., 2012). This disturbance produces a huge amount of coarse woody debris (CWD), including all the non-living woody biomass not contained in the litter pool (Olajuyigbe et al., 2011). However, while the recent concern has focused in downed and standing coarse wood (Harmon et al., 2011), the role of decaying tree stumps, referred to hereafter as stumps, have scarcely been studied before (Shorohova et al., 2008, 2012; Melin et al., 2009; Garrett et al., 2010; Palviainen et al., 2010; Olajuyigbe et al., 2011), being completely ignored in post-fire Mediterranean mountain ecosystems, despite becoming the main CWD pool left to decompose in managed areas.

Only few studies have investigated the amount, structure, decomposition rates and carbon losses of post-fire CWD, being most frequently studied in unburnt ecosystems (Jomura et al., 2008). Identifying the contribution of the CWD carbon loss to the total ecosystem respiration (R_{eco}) can significantly improve the understanding of C dynamics in post-fire ecosystems (Van Miegroet et al., 2007). Thus, a large pulse of C loss could be obtained from the partially buried stumps during their earlier stages of decomposition in post-fire areas as a consequence of

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the unusual decomposition conditions, directly influenced by the post-fire forest structure and environmental drivers of decay, principally temperature and moisture of dead wood (Bond-Lamberty et al., 2002; Liu et al., 2006; Zhou et al., 2007; Hagemann et al., 2010). This initial period is when the fastest decomposition and nutrient release are expected to occur (Palviainen et al., 2004; Olajuyigbe et al., 2011). Furthermore, differences in C loss at the stand-level can be influenced by differences in fire-related stump abundance (Hagemann et al., 2010; Harmon et al., 2011). So, considering them to be individual units of C emission to the atmosphere, we hypothesise that the stumps could act as hot spots of CO_2 production in recently burnt ecosystems, showing a great contribution to total C loss not proportional to the area they cover at the stand-level.

The accuracy in the stump C loss estimations can differ as a result of variable sampling strategies, ranging from diachronic studies based on chronosequences (wood mass loss method) to direct CO_2 flux measures (direct method) (Herrmann and Bauhus, 2008; Forrester et al., 2012). Nevertheless, in spite of being a more accurate method, the C loss estimation by the direct method has been rarely used on stumps, with only few works conducted in boreal forests (Bond-Lamberty et al., 2002; Wang et al., 2002; Hagemann et al., 2010), temperate coniferous forests (Mackensen and Bauhus, 2003; Gough et al., 2007; Jomura et al., 2008; Forrester et al., 2012; Olajuyigbe et al., 2012; Herrmann and Bauhus, 2013), and tropical forests (Chambers et al., 2001).

We measured the C loss from the early stages of stump decomposition at sites of different burn severities in a Spanish black pine forest. These measurements were carried out during the first three years after felling fire-killed trees by post-fire management practices. The objectives of this study were to: (1) analyse the environmental drivers of stump decomposition at sites of different burn severity; (2) estimate decay rates (k_a) and half life period ($t_{0.5}$) of the aboveground woody part of stumps; (3) compare C loss from stumps based on wood mass loss (indirect method) and *in situ* CO_2 efflux rates (direct method); and (4) estimate the stand-level total and annual C loss from the stumps.

2. Materials and methods

2.1. Study area, experimental design and field survey

The study area, located at 1400 m a.s.l. in the Cuenca Mountain Range Natural Park (Castilla-La Mancha Region, central-eastern Spain; 40° 15′ N; 1° 57′ W), was affected by a natural wildfire caused by a lightning storm which burnt approx. 1800 ha in July 2009 (Fig. 1). Typical of the region, the fire was of varied severity and produced a complex spatio-temporal mosaic of disturbance severities (unburnt, low-, moderate-, and high-burn severity patches) across the landscape. Different post-fire management practices depending on the proportion of stand-level tree mortality were carried out by the local Forest Service in December 2010 throughout the burnt area to restore the vegetation. Burnt snags were felled and removed, combined with the elimination of the remaining woody debris (branches, logs, and snags) by chipping by the roadside.

The sampling area is slightly hilly (slopes $\leqslant$ 10%) with a shallow soil over calcareous hard rock with frequent rock outcrops. The climate is Mediterranean-type with an average annual precipitation of 652 mm, which occurs mostly in spring and autumn, leaving dry summers. The mean annual temperature was 11.1 °C, with extreme values ranging between −9.8 °C and 34.4 °C. In this area, the Spanish black pine (*Pinus nigra* Arn. ssp. *salzmannii*) dominates the upper canopy composition, with scattered trees of *Pinus sylvestris* L., *Quercus faginea* Lam. and *Juniperus thurifera* L. The understory is dominated by shrubs (*Juniperus communis* L., *Juniperus oxycedrus* L., *Crataegus monogyna* Jacq., *Buxus sempervirens* L. and *Genista pumila* ssp. *rigidissima* (Vierh.)), and herbs (*Brachypodium retusum* (Pers.) and *Dactylis glomerata* L.). For more details of the study area, see Dadi et al. (2015).

Into the wildfire area, the three experimental sites (approx. two ha each), separated by about 500 m, were selected based on a burn severity map calculated using the differenced Normalized Burn Ratio index (*dNBR*, Key and Benson (2006), Fig. 1). We established (1) a low-burn severity site (LS, affected by surface fire); (2) a high-burn severity site of southern aspect (HSS, affected by active crown fire); and (3) a high-burn severity site of northern aspect (HSN, affected by active crown fire). At these sites, in order to compare satellite-derived values with ground-based measurements of burn severity, a field survey campaign to determine tree mortality and pre- and post-fire canopy cover was carried out after the wildfire (January 2011). Nine circular plots (15 m radius) within each site were randomly established in representative locations of the burnt and unburnt stand conditions at each experimental site. Stumps, defined as the standing cut tree boles left protruding from the ground after the fire-killed tree had been cut, and remaining live trees were geographically located (with both GPS and terrain measurements) in each plot. For each living tree, the diameter at breast height (DBH, cm), and total tree height (TH, m) were measured. Furthermore, the height (h, cm), bark thickness (Bt, cm), top and base diameters (DSt and DSb, cm) were measured for each stump. A conical shape was assumed for each stump and its aboveground wood volume outside bark (VS_o, m^3) was calculated (Eq. (1)).

$$VS_o = \frac{\pi h(R^2 + R \times r + r^2)}{3} \tag{1}$$

where h is the height of the stump in m; R and r are the maximum (lower part of the stump, close to the soil) and minimum (top part of the stump) radii in m, respectively. For the aboveground wood volume inside bark (VS_i, m^3), R and r were computed without considering the bark thickness, assuming the same thickness at the top and the base of the stump.

We selected both severities (low- and high-burn severities) due to different post-fire crown coverage (Table 1), and therefore different soil and dead wood environmental conditions. Further, we analysed more thoroughly the high-burn severity area (2 exposures) where major differences in post-fire C loss of decaying stumps were expected to occur in comparison to the LS site. All the sites were similar in elevation, soil type and total rainfall terms. At the beginning of the study, the vegetation structure and composition at the LS site were similar to the unburnt forest (described above), but at the HSS and HSN sites consisted principally of herbaceous vegetation (*Eryngium campestre* L., *Picnomon acarna* L., *Euphorbia nicaeensis* All. and *B. retusum* (Pers.)) and sparse shrubs (*J. communis* L. and *Berberis vulgaris* L.).

2.2. C loss and decay measurements based on wood mass loss (indirect method)

2.2.1. Undecomposed aboveground wood determinations

From a destructive sampling of 18 living trees carried out in June 2012, which were selected by stratified random sampling to obtain a well-distributed sample along the range of diameters within the stand (DBH ranged from 5 to 55 cm), a representative wood slice (3–4 cm thick) was taken from the basal part of each sampled tree (at 0.15 m aboveground level). Furthermore, 18 wood cores were extracted from other living trees (selected by stratified random sampling within the stand) at 0.15 m aboveground level with a 5-mm increment borer (Haglöf, Langsele, Sweden). The dimensions and fresh volume of each wood core and slice were calculated in the laboratory. Afterwards, they were oven-dried at