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Short-time phosphorus losses by overland flow in burnt pine and eucalypt plantations in north-central Portugal: A study at micro-plot scale

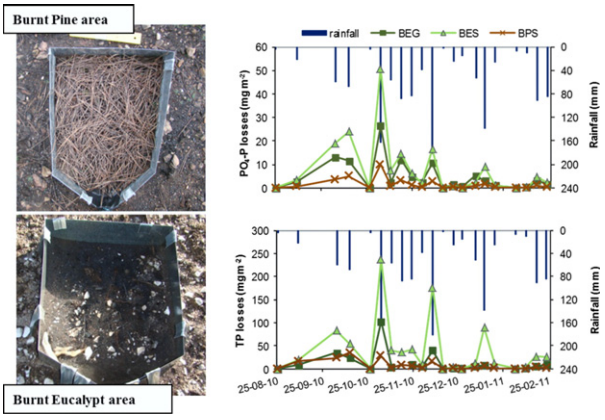
R.V. Ferreira, D. Serpa *, M.A. Cerqueira, J.J. Keizer

Centre for Environmental and Marine Studies (CESAM) & Department of Environment and Planning, University of Aveiro, Campus de Santiago, 3810-193, Aveiro, Portugal

HIGHLIGHTS

- Fires enhance runoff and erosion often leading to a loss of soil nutrients.
- Post-fire P exports by overland flow were evaluated in a Mediterranean forest.
- Peaks in P exports were mainly associated to the major rainfall events.
- Global P exports were significantly higher at the eucalypt than at the pine site.
- Global P exports were significantly higher at schist than granite soils.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the past decades, wildfires have affected vast areas of Mediterranean ecosystems leading to a variety of negative on- and off-site environmental impacts. Research on fire-affected areas has given more attention to sediment losses by fire-enhanced overland flow than to nutrient exports, especially in the Mediterranean region. To address this knowledge gap for post-fire losses of phosphorus (P) by overland flow, a recently burnt forest area in north-central Portugal was selected and instrumented immediately after a wildfire. Three slopes were selected for their contrasting forest types (eucalypt *vs.* pine) and parent materials (granite *vs.* schist). The selected study sites were a eucalypt site on granite (BEG), a eucalypt site on schist (BES) and a maritime pine site on schist (BPS). Micro-plots were monitored over a period of six months, *i.e.* till the construction of terraces for reforestation obliged to the removal of the plots. During this 6-month period, overland flow samples were collected at 1- to 2-weekly intervals, depending on rainfall. Total P and PO_4-P losses differed markedly between the two types of forests on schist, being lower at the pine site than at the eucalypt site, probably due to the presence of a protective layer of pine needle cast. Parent material did not play an important role in PO_4-P losses by overland flow but it did in TP losses, with significantly lower values at the eucalypt site on granite than that on schist. These differences in TP losses can be attributed to the coarser texture of granite soils, typically promoting infiltration and decreasing runoff. The present findings provided further insights into the spatial and temporal patterns of post-fire soil

* Corresponding author.
E-mail address: dalila.serpa@ua.pt (D. Serpa).

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nutrient losses in fire-prone forest types during the initial stages of the window-of-disturbance, which can be useful for defining post-fire emergency measures to reduce the risk of soil fertility losses.

1. Introduction

Fires are a widespread phenomenon, acting as a major driver of ecosystem change all over the world (Caon et al., 2014; Coombs and Melack, 2013; Doerr and Cerdà, 2005; Kugbe et al., 2015; Lane et al., 2008; Pereira et al., 2014a; Tsibart et al., 2014; Wang et al., 2015).

In the Mediterranean region, wildfires have affected increasingly large areas of land throughout the past decades (Pausas et al., 2008). This trend is expected to continue, especially since projections of future climate change foresee rising temperatures and increasing risks of drought spells in this fire-prone region (Anaya-Romero et al., 2015; Blake et al., 2010; Caon et al., 2014). While wildfires are a natural disturbance in many ecosystems, more frequent and more severe fires can offset the ecological balance of the ecosystem and have a significant negative impact on soil fertility, soil biological diversity as well as on the water cycle (Caon et al., 2014; Crouch et al., 2006; Malvar et al., 2015a).

Soil fertility is particularly affected by recurrent wildfires because the heating-induced changes in soil physical, chemical and biological properties deeply affect the biogeochemical cycles of carbon, nitrogen and phosphorus (Caon et al., 2014; Certini, 2005; Knoepp et al., 2005; Shakesby, 2011).

In the case of phosphorus, the combustion of vegetation as well as of litter by fire frequently produces a layer of P-enriched ash and charcoal that can be easily lost by leaching into the soil and/or lost by wind or water erosion (Bodí et al., 2011, 2014; Johnson et al., 2007; Pereira et al., 2014a, 2014b). Also the P pool of the topsoil itself can be markedly affected by fire since heating promotes the mineralization of topsoil organic matter and, thereby, the release of inorganic P (Badía et al., 2014; Certini, 2005; Kutiel and Shaviv, 1992). The fate of inorganic P following fire depends strongly on pre- and post-fire soil properties (Certini, 2005; Murphy et al., 2006). In acidic soils, inorganic P tends to adsorb to newly formed Al, Fe and Mn oxides and hydroxides (Certini, 2005; Murphy et al., 2006; Otero et al., 2015), whereas in neutral or alkaline soils it especially binds to Ca-minerals or precipitates as Ca phosphate (Badía et al., 2014; Certini, 2005; Murphy et al., 2006). Nonetheless, P sorption/desorption processes are highly dynamic (Otero et al., 2015), so even small changes in soil pH as often observed after fire can easily cause desorption of inorganic P from metal oxides or calcium compounds formed immediately after fire (Kutiel and Shaviv, 1992; Murphy et al., 2006). As the topsoil P reservoir is depleted by fire-enhanced overland flow and erosion (Caon et al., 2014; Certini, 2005; Ferreira et al., 2005; Pausas et al., 2008; Shakesby, 2011; Thomas et al., 1999, 2000a, 2000b), and P is exported in both its dissolved and particulate forms, there can be a loss of soil fertility (Caon et al., 2014; Johnson et al., 2007; Knoepp et al., 2005; Neary et al., 1999; Soto et al., 1997).

In the Mediterranean Basin, the effects of fire on soil P availability have been addressed by various studies (Badía et al., 2014; Caon et al., 2014; Johnson et al., 2007; Kutiel and Shaviv, 1992; Otero et al., 2015). Post-fire losses of P by overland flow, however, have been poorly investigated (Cancelo-González et al., 2013; DeBano et al., 1998; Díaz-Fierros et al., 1990; Lasanta and Cerdà, 2005). In Portugal, particularly few studies have measured post-fire P export by overland flow (Coelho et al., 2004; Ferreira et al., 1997, 2005; Thomas et al., 1999, 2000a, 2000b; Walsh et al., 1992), especially considering the more than 100.000 ha that are burnt each year. These prior studies investigated P losses for the two principal forest types in north-central Portugal, *i.e.* plantations of eucalypt (*Eucalyptus globulus* Labill.) and maritime pine (*Pinus pinaster* Ait.) but at larger spatial scales than in the present work, *i.e.* 16 m^2 plots (Ferreira et al., 1997, 2005; Thomas et al., 2000a, 2000b; Walsh et al., 1992), small (Ferreira et al., 1997, 2005) and large catchments (Santos et al., 2015a, 2015b). Perhaps more importantly, these prior studies only addressed soluble P losses and not total P losses (*i.e.* solute + particulate fraction). Hence, a better understanding of overall losses of nutrients after fire, in both dissolved and particulate forms, is required for a more accurate assessment of the risks of post-fire soil fertility losses and its possible impacts on forest recovery.

The present study aims to address this knowledge gap by determining the exports of total phosphorus (TP) and dissolved inorganic phosphorus (PO_4-P) by post-fire overland flow in a recently burnt forest area in the Mediterranean. The current work, however, does not quantify the effects of fire on P losses since a comparable and long unburnt pine plantation could not be found in the vicinity of the study sites. Instead it intends to compare these losses for different combinations of forest type and parent material. To this end, TP and PO_4-P losses by overland flow were quantified at the micro-plot scale for: i) two contrasting forest types, *i.e.* eucalypt and maritime pine plantations, which dominate the north-central Portuguese mountains and are both fire-prone; and ii) two contrasting bedrock types, *i.e.* schist and granite, which are the prevailing parent materials in north-central Portugal. Phosphorus losses by overland flow were further compared with their stock in the ash and upper soil layer, for a better appreciation of the relevance of these losses for the P cycle following fire.

As all three study sites were (partially) terraced with a bulldozer 6 months after the fire, completely changing the topography of the terrain (Martins et al., 2013), the present work was forcedly limited to the immediate post-fire period.

2. Materials and methods

2.1. Study area and sites

The study area was located within the Vouga River Basin, near the Ermida village in the Sever do Vouga municipality, north-central Portugal (Fig. 1). Between July 26 and July 28, 2010 a wildfire consumed a total of 295 ha of forest in this area (DUDF, 2011). Before the fire, the Ermida study area was covered predominantly by commercial eucalypt plantations (*Eucalyptus globulus* Labil.) but also included some maritime pine stands (*Pinus pinaster* Ait.). Fire severity was classified as moderate, because ashes were predominantly black, the litter layer and understory vegetation were almost completely consumed by the fire and tree crowns were only partially combusted (Table 1; Shakesby and Doerr, 2006). In addition, Maximum Temperatures Reached based on Near Infrared (NIR) spectroscopy measurements (see Guerrero et al., 2007; Maia et al., 2012) varied from 325 to 405 °C for the uppermost 2 cm (Pedrosa, 2012).

The climate of the study area can be classified as humid mesothermal with moderate but prolonged warm dry summers (Köppen; Csb, DRA-Centro, 2002). The mean annual temperature at the nearest climate station (Castelo-Burgães: 40°51′10″N, 8° 22′44″W at 306 m a.s.l.; 15 km north of the study area) was 14.9 °C (1991–2011; SNIRH, 2011), with average monthly temperatures ranging from