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Effects of fire occurrence and recurrence on nitrogen and phosphorus losses by overland flow in maritime pine plantations in north-central Portugal

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ABSTRACT

Wildfires have increased in Portugal in the recent decades, raising concerns about the long-term negative effects of fire recurrence on the environment. We studied the impacts of recurrent fires on the nitrogen (N) and phosphorus (P) content of mineral soil in the first year after a fire. Total nitrogen (TN) and phosphorus (TP) losses by runoff were also evaluated within the two years after a fire. Nine sites in a maritime pine forest were selected following a large wildfire in September 2012 that affected roughly 3000 ha of the Viseu municipality. Three sites had been burnt four times in the past 40 years (4×), three sites had been burnt once in September 2012 (1×), and three control sites had not been burnt (0×). Runoff was collected in 9 micro-plots (0.25 m^2) at each site after rain events from September 2012 to September 2014. Soil N and P content were significantly higher in both burnt sites relatively to the control sites. Nitrogen as well as phosphorus losses via runoff were significantly higher at the 4× burnt sites than at both the 1× burnt and unburnt sites. Nutrient loss was particularly high after heavy rains. Vegetation and litter cover played an important role in reducing runoff and the associated N and P transport at the 4× burnt sites, since a decrease in both variables was observed with the increase in vegetation cover after fire.

1. Introduction

Fire is an important ecological factor that has affected the Mediterranean landscape in the past and continues to influence it in the present (Pausas et al., 2008). Fire affects soils in different ways depending on various factors such as intensity, severity, fire duration and residence time of temperatures above 100 °C (DeBano et al., 1979; Inbar et al., 1998; Caon et al., 2014; González-Pelayo et al., 2015). These effects cause changes in the soil physical properties, for example by decreasing soil porosity, increasing bulk density (Granged et al., 2011) and decreasing soil water retention and infiltration (González-Pelayo et al., 2010; Moody et al., 2013; Badía-Villas et al., 2014; Hosseini et al., 2016), but also on its chemical and biological properties, by changing soil pH and the nutrient cycles (Raison, 1979; Inbar et al., 1998; Inbar et al., 2014; Stoof et al., 2015; Hosseini et al., 2016). Mediterranean ecosystems are deeply affected by fire, so studying their impacts on the soil properties such as porosity, particle detachment from the surface, loss of organic matter and nutrients, water repellence and altered aggregate stability, are important (Shakesby and Doerr, 2006; Shakesby, 2011). Wettability, aggregate stability, infiltration and soil moisture are quite important physical parameters altered by fire (Giovannini et al., 1990; Jordán et al., 2011). Water repellency through depth can be affected (decrease or increase) by fire intensity (Aznar et al., 2016). Burnt vegetation and soil organic matter by fires, produce accumulations of hydrophobic substances on the soil surface that reduce wettability and infiltration while increasing runoff (Imeson et al., 1992; Wittenberg et al., 2014). Increased runoff, ash and soil erosion leads to the loss of nutrients transported as suspended sediment or solubilised in runoff (Badia and Marti, 2008; Badia et al., 2008; Badía et al., 2014). Type of soil and vegetation, slope, lithology, physiography, and other factor like human intervention can influence both the magnitude of fire impacts and the ecosystems' recovery (Certini, 2005; Shakesby, 2011).

Uncontrolled wildfires cause large environmental damages, especially in the Mediterranean region (San-Miguel-Ayanz et al., 2012) and Portugal has been one of the most affected countries in southern Europe (Ferreira et al., 2005b; Shakesby, 2011; Prats et al., 2014). With the increased frequency of fire, the cumulative loss of nutrients, particularly nitrogen (N) and phosphorus (P), has led to soil nutrient

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deficit in fire affected areas (Eugenio and Lloret, 2004; Eugenio and Lloret, 2007). The effects of fire frequency on nutrient availability and losses have not been widely studied (Malkisnon et al., 2011), whereas the impacts of individual fires on nutrient losses have been reasonably well described at least in Portugal (Thomas et al., 1999; Thomas et al., 2000a; Thomas et al., 2000b; Ferreira et al., 2005a; Ferreira et al., 2016a; Ferreira et al., 2016b). N and P are important elements in the growth of plants and are the two most important nutrients often limiting crop production (Jin-yan and Jing, 2003; Caon et al., 2014). Therefore, studying the effects of fire on N and P transport, is of great importance for assessing the effects of wildfires on soil nutrient losses and also on the quality status of downstream aquatic habitats (Ferreira et al., 2016b). In addition to above changes in the physical and chemical properties of soil, fires can dramatically affect nutrient cycling (DeBano et al., 1998). The soil O horizon and upper cm of the A horizon are typically affected by fire and suffer the largest changes in nutrient contents (Novara et al., 2011; Caon et al., 2014). Fire decreases nutrient contents, although the inorganic forms of some elements, which are produced by plants, can increase and temporarily increase soil fertility (Duguy et al., 2007). Some studies have demonstrated a connection between fire severity and recurrence and the availability of nutrients in the topsoil (Badía et al., 2014; Caon et al., 2014). Nutrients, water holding capacity, organic carbon, aggregate stability, and hydrophobicity are just a few soil properties that can be significantly altered with fire exposure, compromising the health of the entire ecosystem (Certini, 2005). The severity of a wildfire can play an important role in how severely soil properties can be altered. Severe fires can generally remove organic carbon and decrease nitrogen and phosphorus availability (Certini, 2005). Most studies have evaluated the impact of single fires on soil nutrients rather than the potentially more significant impact of long-term fire regimes (Badía et al., 2014; Machado et al., 2015; Ferreira et al., 2016a; Ferreira et al., 2016b). High fire frequencies can be a reason for coating of the soil surface, decrease of water infiltration and soil aggregation and increase of nutrient losses by runoff (Richards et al., 2012). Fires can also lead to large losses of nutrients from the combustion of timber, large debris, and organic matter on the soil surface, which leads to losses by volatilisation (Neary et al., 1999); Factors like the destruction of organic matter (Knoepp et al., 2005), consumption of vegetation and litter, reduced infiltration capacity and increased runoff (Ferreira et al., 2005b; Cerda, 2009) and erosion (Thomas et al., 1999; Knoepp et al., 2005) are principal causes of nutrient losses after fire. Soil erosion and nutrient losses have been reported to be considerably higher after the first rainfall events (Ferreira et al., 2015). The results for an individual fire, however, may not be the same for an area affected by recurrent fires (Hosseini et al., 2016), which may have long-term cumulative effects on some ecosystem properties, such as nutrient cycling and productivity (Carter and Darwin Foster, 2004; Eugenio and Lloret, 2007). Effect of fire recurrence on nutrient export by runoff has received little research attention, especially in fire prone regions. Studying the availability and losses of nutrients in areas with a high fire frequency is thus important for a realistic evaluation of the impacts of fires on soil fertility.

The aim of this study is to provide better understanding of the effects of fire occurrence and recurrence on post-fire N and P losses by overland flow in maritime pine plantations in north-central Portugal. In order to achieve this goal, total (i.e. dissolved plus particulate forms) nitrogen and phosphorus losses by overland flow were quantified for a recently burnt maritime pine plantation in Portugal. Specific objectives were to: i) measure total N and P losses from burnt and unburnt sites and, ii) compare N and P losses by runoff from burnt plots with contrasting fire histories: i.e. unburnt, 1 time (1×) burnt and 4 times (4×) burnt. These losses were furthermore related to the nitrogen and phosphorus stocks of the topsoil, for a better understanding of N and P cycles after fire. Our research hypothesis is that recurrent fires induce large changes on hydrological and erosive processes, as well as on nutrient exports.

2. Materials and methods

2.1. Study area and study sites

The study area is located in north-central Portugal and is part of the Vouga River Basin which drains into the Ria de Aveiro coastal lagoon (Fig. 1). The climate is classified in Köppen's system as a humid mesothermal temperate climate Csb, with a prolonged dry and warm summer. A national information source, Sistema Nacional de Informação de Recursos Hídricos (SNIRH, 2014), reported an annual rainfall ranging from 1200 to >2000 mm y^{-1} and mean monthly temperatures ranging from 9 °C in January to 23 °C in July. The terrain has steep slopes of 20° to 30°. The bedrock is schist, and the soils are mainly Humic Cambisols, Epileptic Umbrisols and, to a smaller extent, Umbric Leptosols. The soils are generally shallow, <30 cm deep, and are susceptible to degradation by soil erosion and land use.

2.2. Experimental set-up

The experiment was carried out immediately after fire and conducted in an area of *Pinus pinaster*, which was burnt by a wildfire in September 2012. Based on our observation in the field, a moderate severity fire had affected the area, since ashes were black, the litter layer and understory vegetation was almost consumed by fire, and tree crowns were only partially scorched (Shakesby and Doerr, 2006; Keeley, 2009; Maia et al., 2012). Within this area, a total of nine slopes (Fig.1) were selected for this study. Three slopes had burnt four times (4×) since 1975 (1978, 1985, 2005, and 2012) and three slopes had burnt once (1×) over the same period (2012) (Fig.1). Furthermore, three slopes with maritime pine stands that had remained unburnt (0×) since 1975 but were otherwise comparable to the six burnt sites were selected in the immediate vicinity (Fig. 1). Each slope was divided into two strips running from the base to the top of the slope section. One of these strips was used for repeated collection of ash and soil samples and another for monitoring overland flow at the micro-plot scale. Three micro-plots of approximately 0.25 m^2 were established on the bottom, middle and top section of each slope (Table 1; Fig. 2). The micro-plots were installed on spots where shrubs had been absent at the time of the 2012-fire, as indicated by the absence of remaining burnt-scorched twigs (Hosseini et al., 2016). Metal plates were inserted into the soil upslope of the micro-plots to divert run-on from upslope areas. The outlet of each micro-plot was connected to a 70-L tank with a garden hose to collect the overland flow (Hosseini et al., 2016).

3. Data collection

3.1. Soil sampling

Soil samples were collected in May as well as September 2013 at three randomly chosen locations immediately next to the micro-plots at each slope. A soil sampling core was used to collect the upper 5 cm of the mineral soil by removing any remaining ashes and litter. Samples were then stored in a cool box and transported to the lab for analysis.

3.2. Soil analysis

The content of available P and Kjeldahl N of the soil samples were analysed respectively, by the method of Bray and Kurtz (1945) and Kjeldahl method (Bremner, 1965).

Soil texture was analysed by sedimentation (Stokes' Law) with the Robinson pipet method (Guitián-Ojea and Carballas, 1976), and soil bulk density was determined by the cylindrical core method (Blake and Hartge, 1986). The bulk density of the soil was analysed for a same depth (0–5 cm) as considered for texture. Soil pH (H_2O) was determined in a soil: water solution (1:5) for three samples from each study horizon and analysed as described by Ross and Ketterings