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Impacts of prescribed fire on soil loss and soil quality: An assessment based on an experimentally-burned catchment in central Portugal

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ABSTRACT

Prescribed (controlled) fire has recently been adopted as an important wildfire-fighting strategy in the Mediterranean. Relatively little research, however, has assessed its impacts on soil erosion and soil quality. This paper investigates hillslope-scale losses of soil, organic matter and selected nutrients before and after a 'worst-case scenario' prescribed fire in a steep, shrub-vegetated catchment with thin stony soil in central Portugal. Comparison is made with soil erosion measured: (1) on a nearby hillslope burned by wildfire and monitored at the hillslope scale; and (2) on long-unburned terrain at small-plot, hillslope- and catchment-scales. Hillslope-scale pre- and post-fire soil erosion was recorded over periods of 6 weeks to 5 months for (1) 9.5 months pre-fire and 27 months post-fire in the prescribed fire catchment, and (2) c. 3 years post-fire at the wildfire site. Organic matter content, pH, total N, K_2O, P_2O_5, Ca^{2+} and Mg^{2+} were measured in the eroded sediment and in pre- and post-prescribed fire surface soil. Results indicate that: (1) both the prescribed fire and the wildfire caused expected marked increases in erosion compared with unburned terrain; and (2) the hillslope-scale post-prescribed fire soil losses (up to 2.41 t ha^{-1} yr^{-1}) exceeded many reported plot-scale post-prescribed fire and post-wildfire erosion rates in the Mediterranean. As a comparison, post-fire erosion for both fire types was less than that caused by some other forms of common soil disturbance (e.g. types of tillage) and even that on undisturbed shrubland in low rainfall areas of the region. Total estimated post-prescribed fire particulate losses of organic matter and nutrients represent only 0.2–2.9% of the content in the upper 2 cm of soil, suggesting only a modest fire effect on soil quality, although this may reflect in part a lack of extreme rainfall events following the fire. The longer-term implications for soil conservation of repeated prescribed fire in the Mediterranean are explored and future research priorities identified.

1. Introduction

Fire suppression has been the generally accepted response to the steep rise in wildfire activity since the 1960s in Mediterranean Europe (Faerber, 2009; Leone, 2002; Pausas and Fernández-Muñoz, 2012). Wildfire has been mainly triggered by various socio-economic changes including rural outmigration and land abandonment, together with increases in the number of days with extreme fire hazard weather (Marques et al., 2011). Fire suppression has remained popular despite its failure to prevent some devastating wildfires (e.g. Silva et al., 2008) because of the widely-held conviction that, if possible, all fires should be suppressed (Lloret et al., 2009). Only recently has prescribed (or controlled) fire become an increasingly accepted, viable, alternative, wildfire-fighting tool (Fernandes and Botelho, 2003, 2004). In Portugal, contemporary interest in this role for prescribed fire began in the 1970s (Silva, 1997), but became particularly focused following high wildfire activity in 2003 and 2005, which led to a series of regulations (Silva et al., 2008). For wildfire-fighting purposes, prescribed fire in Portugal and elsewhere in the Mediterranean is applied for different reasons: in shrublands it is used primarily to reduce the severity and spatial continuity of wildfire and, in tree plantations, to reduce the ground fuel load in order to protect the trees from destruction by wildfire. Flame heights during prescribed fire are typically greater in shrublands than in tree plantations, where recently it has been shown that the effect on the soil is minimal (A. Meira Castro, pers. comm.). Despite a relatively large database on Mediterranean wildfire impacts on soil and soil erosion, there is relatively little information on prescribed fire effects. Differences between wildfire and prescribed fire regimes (including

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intensity, severity, timing and return interval) mean that the interchangeability of post-fire soil erosion results between the two can be limited (Fernández et al., 2008). For both fire regimes, less is known about soil quality effects.

Considering, first, knowledge of wildfire effects on soil and soil erosion, Mediterranean research began in the Iberian Peninsula in the 1980s (e.g. Díaz-Fierros et al., 1982, 1987; Vega and Díaz-Fierros, 1987; Vega et al., 1983), and emphasised much higher soil losses relative to unburned areas (for summaries, see Pausas et al., 2008; Shakesby, 2011). Reported losses, however, have often been modest compared with fire-prone terrain elsewhere in the world (for a summary, see Shakesby and Doerr, 2006) and with other types of land disturbance (e.g. tillage) in the region (Solé Benet, 2006). In the Iberian Peninsula, reported post-wildfire erosion losses tend to be larger in the wetter Atlantic coastal region (e.g. Menéndez-Duarte et al., 2009) than in drier eastern and southern parts, even for controlled fires, in part probably as a function of relatively thick soils on steep slopes. As an extreme example of low post-fire erosion in the dry south-east of Spain, Sánchez et al. (1994) found less erosion on an 80 m^2 plot in the first year after low-severity fire in south-east Spain than in the previous three pre-fire years. Many Mediterranean soils, however, are thin because of long-term degradation, so that even relatively small losses might conceivably have medium- to long-term degradational implications.

Post-wildfire soil quality impacts have received less attention than those on soil erosion and have focused mostly on nutrient losses in runoff (DeBano et al., 1998), although there are exceptions (e.g. Soto and Díaz-Fierros, 1993; Thomas et al., 1999, 2000a). Thomas et al. (1999, 2000a), for example, estimated that up to 50% of a very thin soil's store of phosphorus in a *Eucalyptus globulus* plantation in north-central Portugal had been removed in particulate form following wildfire, even though the quantity of soil lost was not high.

Most Mediterranean soil erosion research after prescribed and experimental fires has been plot-based and has focused predominantly on shrubs and grasses where effects on the soil are expected to be greater than in tree plantations as a result of much of the litter and living biomass being consumed (e.g. Campo et al., 2006; De Luis et al., 2003; Fernández et al., 2008; Marcos et al., 2000; Vega et al., 2005; Zavala et al., 2009). The plot results are not necessarily easily upscaled, however, despite the burning being carried out under controlled conditions and therefore expected to have a spatially uniform effect (Robichaud and Miller, 1999). Views vary about the significance of prescribed fire impacts on soil erosion and soil quality in the Mediterranean, as elsewhere in the world (Oliveras and Bell, 2008). As regards erosion, on an oak scrub plot in the Catalan Coastal Ranges of north-east Spain subject to low-severity fire, Soler et al. (1994) reported >16 times more sediment removed during 7 months of post-fire monitoring compared with an unburned control plot. On *Ulex europaeus* scrub subject to low- and moderate-severity controlled fires in north-west Spain, Soto et al. (1994) reported two-year post-fire plot-scale soil losses 1.6–4.5 times higher than on equivalent unburned scrub. Significantly, the annual erosion rates (c. 1–4 t ha^{-1}) during these two years were actually higher than some reported following Mediterranean wildfires (see Pausas et al., 2008).

Considering soil quality impacts, Rego et al. (1987) found that prescribed burning in northern Portugal caused reduced soil organic matter (SOM) and loss of some nutrients (e.g. K), although others (total N and available P) were little altered, and overall soil quality was not significantly affected. Úbeda et al. (2005) drew a similar conclusion for low-severity prescribed fire in Mediterranean grasslands, north-east Spain. Biodiversity and nutritional benefits of burning ground vegetation have been suggested (Silva, 1997), although on heathland the impact on soil quality is not well known (Mohamed et al., 2007). Andreu et al. (1996) found that SOM actually increased following low to moderate severity experimental fire in a pine forest in southern Spain. In contrast, important losses of nutrients following experimental fire have been reported (Soto and Díaz-Fierros, 1993), which might be exacerbated by frequent burning. On shrublands in Spain, Carreira et al. (1996) found a marked decrease in plant-available nutrients under a 'frequent fire' regime and González-Pelayo et al. (2010) argued that repeated short-interval experimental fires caused measurable soil quality deterioration.

Although linking climate to fire is difficult in the Mediterranean because of the complexity of fire–climate–vegetation–human interactions (Lloret et al., 2009), predicted hotter and drier summers (Harding et al., 2009) are thought likely by many researchers to increase wildfire activity in the future (Shakesby, 2011). In addition, torrential rainstorms are expected to become more frequent (Badía and Martí, 2008). If these predictions are correct, they reinforce the need for improved knowledge about the effects of prescribed fire on soil loss and soil quality in fire-prone terrain, where soils are often already thin and degraded (Grove and Rackham, 2001). In this paper such effects are reported at the hillslope-scale in a small fire-prone shrub-vegetated catchment in central Portugal burned experimentally during early 2009 with what is termed here a 'worst-case scenario' prescribed fire. Results are compared with nearby sites: (1) affected by a wildfire of moderate severity in summer 2008; and (2) unburned for a number of years. Specifically, the paper considers: (1) c. 3 years of hillslope-scale losses of soil, SOM and nutrients before and after the prescribed burn; (2) c. 3 years of hillslope-scale soil losses after a wildfire on comparable terrain; and (3) longer-term soil losses at plot- to catchment-scales on long-unburned terrain. The first aim of this paper is to assess the importance of soil erosion following the prescribed fire by comparing the soil losses with those: (1) recorded at the other burned and unburned sites and installations in this study; (2) following prescribed fire and wildfire elsewhere in the Mediterranean; and (3) associated with other land cover types and forms of soil disturbance. The second aim is to assess the significance of the prescribed fire with respect to estimated losses of SOM and nutrients in the upper soil. The third aim is to discuss the likely soil conservational implications of using repeated prescribed fire as a wildfire-fighting tool in the study area and elsewhere in the Mediterranean.

2. Study locations

2.1. Vale Torto prescribed fire site

This experimental burn was carried out in Vale Torto catchment (40°06′N, 8°07′W), located in Góis Municipality at c. 600–750 m a.s.l. on schist bedrock, central Portugal. Catchment characteristics are summarised in Table 1 and catchment form and relief are depicted in Fig. 1. The catchment covers a total area of 9.7 ha (Stoof et al., 2012). However, vehicle tracks are located very close to and mostly just inside the catchment perimeter. The fire was restricted to the area (9 ha) almost entirely demarcated by these tracks (Fig. 1).

Wildfires affected the catchment during the 1970s and early 1980s, and prescribed fire was used in 1996 to improve grazing. Vegetation is dominated by *Erica* spp., *Calluna vulgaris* (L.), *Ulex* sp. *Pterospartum tridentatum* (L.), *Genista triacanthos* (Brot.) together with various herbs. The soil is a very stony and shallow Lithosol ('gravelly loamy sand'; USDA, 1993). The catchment has steep slopes (mean slope, 20°). Soil rock fragment (or stone) content averages 16% by volume or >40% by weight (Table 1) and is highest on steep and lowest on gentle slopes. Surface rock fragment cover averages >50%. Although averaging 16 cm, soil thickness is generally less on upper and midslope sections, reaching >60 cm on the valley floor. The high organic matter content of the <2 mm fraction of the upper soil (c. 20%) explains its low dry bulk density (average, 0.82 g cm^{-3}) (Stoof et al., 2011). Both before and after fire, soil water repellency varied considerably temporally, from extremely high after long dry periods to wettable during wet, mostly winter conditions. At intermediate soil moisture levels, repellency became spatially highly heterogeneous (Stoof et al., 2011). Long-term records at Góis village (190 m