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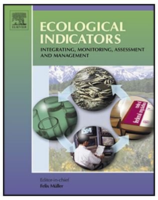

Soil physicochemical and microbiological indicators of short, medium and long term post-fire recovery in semi-arid ecosystems

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ABSTRACT

Natural disturbances such as wildfires cause significant alterations to the structure and functioning of semi-arid ecosystems. After such disturbances, the recovery of the soil ecosystem as a whole, and more specifically the belowground microbial communities, is poorly understood. In this study, we aimed to (a) assess the short, medium and long term changes in soil physicochemical and microbiological indicators and indices after a wildfire in a semi-arid environment, (b) analyse the key relationships of multiple soil parameters and indices, and (c) identify the most suitable indicators of post-fire recovery. The study was conducted across a wildfire chronosequence spanning sites recently burnt (three months) through to 14 years after fire in a semi-arid hummock grassland ecosystem of northern Western Australia. Immediate effects of the fire on the soil system were evident with increases in pH, electrical conductivity, and available nutrients. These chemical indicators showed a strong correlation with fire age and were consistent in the direction of change. Variations in the microbial composition were apparent one year after the fire, with a higher proportional abundance of bacterial communities. The fungi to bacteria ratio and the microbial quotient (proportion of microbial C to total organic C) proved to be significant indices to reflect the recovery of soils in these semi-arid environments. Overall, this study highlights the importance of understanding the post-fire response of belowground ecosystems, and particularly changes and recovery of soil microbial communities, at different time periods. The approach and methods followed in this research can be effectively extrapolated to other areas. This study can be used to inform better soil management of degraded systems in a rapidly changing climate.

1. Introduction

Arid and semi-arid ecosystems are increasingly being exposed to natural disturbances such as wildfires which can cause major alterations in their structure and functioning at regional or global scales (Cerdà and Robichaud, 2009; Guida et al., 2014). Dry environments can be vulnerable to land degradation following fire because of the loss of vegetation cover and the associated runoff and erosion, as well as a reduction in nutrients and organic matter (Vieira et al., 2015). The recovery of ecosystems after fire is determined by the traits of the vegetation communities, such as re-sprouting or recruitment from seed (Bradshaw et al., 2011; Diaz-Delgado et al., 2002; Nano et al., 2012; Rice and Westoby, 1999). But factors such as fire intensity, seasonality and history, can influence the post-fire responses of these environments (Knox and Clarke, 2006). In the next years, changes in climate are expected at a global level, with important impacts on patterns of temperature and rainfall across several fire prone regions, e.g. semi-arid grasslands and tropical savannas (Bradstock et al., 2012). These changes are likely to impact the response of ecosystems to fires (Enright et al., 2014; Guida et al., 2014).

The effects of fires on arid ecosystems, particularly on aboveground community diversity and composition, have been extensively studied (Boó et al., 1996; Engel and Abella, 2011; Hodgkinson, 1991; Smith et al., 2014; Snyman, 2015a; York et al., 2012). However, in recent years, there has been a growing interest in understanding the effects of fires on physical, chemical and biological properties of soils (Bento-Gonçalves et al., 2012; Guénon et al., 2011, 2013; Snyman, 2015b). Fire alters soil organic C, pH, nutrient cycles, soil texture and structure, infiltration capacity and

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microbial community structure and functions (Cerdà and Doerr, 2005; Certini, 2005; Gordillo-Rivero et al., 2014; Hart et al., 2005; Mataix-Solera et al., 2009). But ultimately, the impacts of fire on the soil system depend on several factors such as fire severity and intensity, climate conditions, topography or landscape heterogeneity (Cerdà and Robichaud, 2009; Wright and Clarke, 2008). Research has focussed on the immediate and short term changes to soils induced by fire during the last decades in *Eucalyptus* forest (Granged et al., 2011a), Mediterranean semi-arid grasslands (Novara et al., 2013), semi-arid rangelands (Snyman, 2015b), or boreal forest (Xiang et al., 2014), but there is limited knowledge of the recovery of soils in the long term, particularly in arid and semi-arid hummock grasslands.

A number of physical, chemical, and biological soil attributes have been used as suitable indicators of changes in soil processes after natural disturbances and to measure the recovery of soil functions (Schimann et al., 2012; Dinesh and Chaudhuri, 2013). Soil organic C (SOC) is one of the parameters most frequently used as an indicator of environmental change because of its numerous functions related to plant growth in natural conditions, e.g. water holding capacity or nutrient supply (González-Pérez et al., 2004). Fire-induced changes in the quantity and quality of SOC are key factors controlling the response of an ecosystem after a fire event (Abella and Engel, 2013; Certini, 2005). Nonetheless, a combination of physicochemical and microbiological indicators is necessary to better disentangle soil post-fire recovery (Goberna et al., 2012; Mataix-Solera et al., 2009; Mikita-Barbato et al., 2015). The response of microbial indicators (e.g. soil microbial biomass, soil microbial activity, and soil microbial structure and composition) to disturbance is relatively rapid compared to other living organisms, which makes them highly suitable to detect environmental changes (Dinesh and Chaudhuri, 2013).

Microbial indices or "quotients" are increasingly being used to assess ecosystem function and recovery following disturbance, e.g. the microbial quotient (microbial C: organic C), or the metabolic quotient (CO_2-C respired h^{-1}: microbial C) (Banning et al., 2011; Jangid et al., 2010). Recent studies show changes in abundance or shifts of particular microbial groups during primary (Bardgett et al., 2005) or secondary (Banning et al., 2011) succession. These changes have been also observed following land abandonment (Zeller et al., 2001), or after forest fire (Bárcenas-Moreno et al., 2011; Goberna et al., 2012; Hamman et al., 2007; Holden and Treseder, 2013; Holden et al., 2013). However, it is not thoroughly known how such changes in the microbial community are related to other soil parameters, particularly in semi-arid ecosystems. Furthermore, important challenges remain in selecting adequate soil indicators that are easy to measure and interpret and that are sensitive to variation after disturbance in the short, medium, and long term.

In this context, the aims of this study were (a) to assess the short, medium, and long term changes in soil physicochemical and microbiological indicators and indices (microbial quotient, metabolic quotient, and fungi to bacteria ratio) after a wildfire in a semi-arid environment, (b) to analyse the key linear relationships or correlations of multiple soil parameters and indices, (c) to identify the most suitable indicators of post-fire recovery. The study was conducted across a wildfire chronosequence in the semi-arid grasslands of Australia that included areas affected by fire in 2014, 2013, 2009, 2007, and 2000.

2. Materials and methods

2.1. Site description

The study sites were located in the Pilbara biogeographical region of north-western Australia (22°03′ S, 118°07′ E to 23°19′ S, 119°43′ E), which covers approximately 179,000 km^2 (McKenzie et al., 2009). The climate in this region is semi-arid with mean annual temperatures ranging between 19.4 and 33.2 °C. Maximum temperature values exceed 40 °C, and minimums are around 25 °C in summer and 12–29 °C during winter. Rainfall in the Pilbara is usually low (250–400 mm $year^{-1}$) with a high inter- and intra-annual variability and generally concentrated in the summer months as a result of sporadic thunderstorms and tropical cyclones (Bureau of Meteorology, 2015). The Pilbara is one of the most unique and ancient landscapes on Earth and is comprised of rather complex geological formations and deposits (e.g. Phanerozoic, Proterozoic, and Archaean sedimentary, granite, and volcanic rocks and Devonian limestone) (Pepper et al., 2013). Soils found in the Pilbara are red, shallow, stony soils on hills and ranges, and sands on the lower lying plains comprising Red Kandosols, Red Ferrosols and Leptic Rudosols (Isbell, 2002). Vegetation includes hummock grasslands, tussock grasslands, sclerophyll shrublands, and woodlands with a tussock grass understorey. The most common plant genera are *Acacia*, *Aristida*, *Ptilotus*, *Senna*, and *Triodia*. Pastoralism is one of the most extensive land uses in the area, followed by mining and a degree of traditional use (Van Vreeswyk et al., 2004).

2.2. Experimental design and soil sampling

Field measurements were taken in the winter season (June 2014) in 10 locations across the Pilbara (Table 1). These sites were selected to include similar ecosystems with the same soil type and analogous native vegetation comprising *Triodia* hummock grasslands ('spinifex') mixed with *Acacia* shrublands and woodlands, but to differ in the time since the last wildfire i.e. three months (zero years), one, five, seven and 14 years after the fire. During this 14-year period, each area was burned once (in 2014, 2013, 2009, 2007 and 2000) and the longest period without fire events in the region was 14 years. All the study sites where located in flat areas (same topographic conditions) and within the same climatic district with Newman (Western Australia) as the reference weather station (Bureau of Meteorology, 2015). Soil characteristics were similar at all study sites, with a predominance of loamy fine sand textures. To identify burnt areas by wildfire for each year we used the FireWatch application (Thornton and Wright, 2013) which uses Moderate Resolution Imaging Spectroradiometer (MODIS) data and a cell-based approach with an underlying irregular grid.

A plot of 10 m × 10 m was defined at each location, except for the recently burnt site (zero years since fire), in which two plots or quadrants were established. Each plot was divided into four subplots (5 m × 5 m), which were selected to encompass enough variability but within the minimum area possible to avoid changes in meteorology or landscape/topographic conditions within plots/sites. Three composited samples from the top 5 cm of the soil surface were randomly taken from each subplot, with a core of diameter 7.5 cm resulting in a sum of four samples per plot. In total, we had eight replicated soil samples ($n = 8$) for zero, one, five and seven years since fire, and 12 replicated soil samples ($n = 12$) for 14 years since fire (total $n = 44$). Samples were divided in two subsamples, one subsample was air-dried and sieved (2 mm mesh) and used for physical and chemical analysis, and other was stored at 4 °C for 15 d and used for microbial analysis.

2.3. Analysis of soil physical and chemical properties

Soil moisture or soil water content (SW) was determined gravimetrically after drying a known amount of soil to a constant weight at 105 °C over 24 h. For soil water repellence analysis, 20 g of soil from each sample were placed in a Petri dish after air drying at