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Soil organic matter quality and microbial catabolic functions along a gradient of wildfire history in a Mediterranean ecosystem

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ABSTRACT

The principal aim of this research was to determine the influence of an increasing wildfire history on the recovery at short and long term of soil organic matter (SOM) composition and microbial properties. The contemporary wildfire events (since 1950) were recorded for 27 plots located on the siliceous part of the French Mediterranean region (Maures mountain ranges). A wildfire history index was built, tested and calculated in order to display numerical values representative of the different wildfire history parameters (i.e. number of fires, time since fire and mean fire interval). Microbial basal respiration and biomass were analysed as well as intensity of the use of 31 C-substrates, catabolic diversity and C-substrates utilisation profiles. Furthermore, a qualitative characterisation of the SOM was carried out by solid state ^{13}C NMR. Potential drivers of the microbial recovery were identified by studying the relationships between microbial activities and chemical functions of SOM. Our results showed that fire histories resulting in considerable losses or alterations of SOM, such as recent or close fires, decreased the microbial catabolic evenness. This could be attributed to a preferential utilisation of N-containing compounds and complex substrates such as aromatic and polymers reflecting a greater N microbial demand and a selection of specific catabolic functions. Moreover, a large number of fires (4 fires in 57 years compared to 1–2) resulted in lasting degradation of the relative intensity of methyl C function in polymethylene, *O*-Alkyl C, aromatic C and phenolic C functions inducing a slow-down in recovery of microbial properties. These results also confirm our hypothesis that some chemical functions of SOM can be in equilibrium with wildfire history. Finally, this research demonstrates that FT-NIR analysis can be used as a valuable tool to assess both the wildfire history and the vulnerability of soil quality to shifts in historical fire regimes.

1. Introduction

Shifts in historical fire regimes have been observed both in eastern coast of the Iberian Peninsula and the southern French Mediterranean area (Pausas et al., 2004; Curt et al., 2009). The abandonment of agricultural lands from the late 1960s, resulting in the closure of open areas, accentuated by a climate of drought, increased the size of fires, and thus locally the fire frequency. Repeated burnings progressively impoverish soils in organic matter and nutrients (Reich et al., 2001; Boerner and Brinkman, 2003) to such a point that soil microbial communities and their mineralising activities may be altered on a long-term. In spite of the fact that fires reduce competition in communities in the first regenerative phases (Vilà and Sardans, 1999), shorter periods to recover nutrients through microbial mineralisation, may lead in the long term to a reduction in site productivity and to a loss of ecosystem resilience.

Cumulative effects of fires are evidenced at plant community level (Curt et al., 2009). Soils studies have focused on the effects of a single wildfire on short-term nutrient and SOM dynamics (Carreira and Niell, 1992; Knicker et al., 2005; Knicker, 2007) and depletion of soil microbial biomass or changes in microbial catabolic diversity (Hernández et al., 1997; D'Ascoli et al., 2005; Zhou et al., 2009). The stability of soil microbial communities and the ability of their activities to recover may depend on nutrient availability (Moore

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et al., 1993) which is directly linked to both SOM content and quality remaining after disturbance or brought by the vegetation (De Angelis et al., 1989; Hart et al., 2005). The degree of change in SOM depends on (i) fire regime factors such as intensity, duration and recurrence (Flannigan et al., 2000; Cécillon et al., 2009), (ii) initial soil chemical and physical properties (Knicker, 2007), and (iii) local conditions such as vegetation composition and topography (Certini, 2005). If cumulative effects of repeated prescribed fires on microbial activities were evidenced (Reich et al., 2001; Boerner and Brinkman, 2003), to date little emphasis has been placed on quantifying the trends in long-term recovery of soil organic matter (SOM) quality and microbial properties with an increase in wildfire frequency. Moreover, a better understanding of relationships at the long term between wildfire history and soil quality can have direct implications in choice of land management options (Scheffer and Carpenter, 2003).

In this study, soil microbial properties were hypothesised to be in equilibrium with wildfire history, up to a limit which depends on number of fires, time since fire and also fire interval. A high fire frequency (4 fires in 57 years compared to 1–2), a short time since fire (4 years compared to 17 or 57 years) and/or a short mean fire interval (<12 years compared to >20 years) would cause lasting degradation of the soil organic matter resulting in a breakdown of microbial relationship to wildfire and a change in trends of recovery. Moreover, the quality of SOM is expected to be primary driving factors by which the vegetation influences soil microbial properties (Hart et al., 2005). Our objectives were (i) to assess the effect of various wildfire histories on the soil organic matter quality (i.e. chemical functions assessed by solid state ^{13}C NMR spectroscopy) and microbial properties (i.e. catabolic level physiological profiles, biomass and basal respiration), (ii) to identify the wildfire history threshold resulting in an abrupt change of soil properties and (iii) to identify the chemical functions of SOM better related to the microbial properties. Finally, we aimed to assess the potential of Fourier transform near infra-red (FT-NIR) spectroscopy for predicting soil microbial properties and wildfire history parameters. FT-NIR spectroscopy is a rapid and simple analytical technique involving diffuse reflectance measurement in the NIR region (4500–10000 cm^{-1}). NIR analysis is now widely used to predict soil chemical and biological properties (e.g. Brunet et al., 2007; Cécillon et al., 2008) and specific soil quality indices (Cécillon et al., 2009). So, FT-NIR spectroscopy could be a valuable tool for wildfire history and soil characterisation and management. A wildfire history index was built, tested and calculated in order to display numerical values representative of the different wildfire history parameters (i.e. number of fires, time since fire and mean fire interval) that affects the soils properties and their recovery.

2. Materials and methods

2.1. Study area

The study was conducted in part of the Maures mountain range (Var, southern France, 43°20′ N and 6°37′ E). The region is characterised by a Mediterranean climate with dry, hot summers and wet, temperate winters. The mean annual precipitation is 920 mm (1962–2003). The average monthly temperature varies from 7 °C in January to 22 °C in July, with mean annual temperatures close to 14 °C. The study area (90 km^2) presents a range of altitude from 100 to 400 m above sea level. The mother rock is a gneiss migmatitic (crystalline siliceous rock) composed of ferro-magnesian minerals (micas, amphibols). The loamy sand soils are classified as Dystric Leptosol and Dystric Cambisol (IUSS Working Group WRB, 2006). The study area is characterised by a heterogeneous mosaic of Mediterranean forest ecosystems generated by various wildfire frequencies. At the early stage of succession (i.e. following forest fires), plant communities are dominated by herbaceous and fast growing species such as *Cistus monspeliensis* L., *Calycotome spinosa* L., *Erica arborea* L. and *Quercus suber* L. At the later successional stage (i.e. with no fire for at least 57 years), closed forests are dominated by a tree stratum of *Quercus suber* L., *Quercus ilex* and *Pinus pinaster* Aiton subsp. *pinaster*.

2.2. Wildfire history mapping, soil sampling and wildfire history index

The burned surfaces were mapped using a series of aerial pictures spanning a 56-year period from 1950 to 2006 and public fire databases. This map was then used to choose twenty seven sampling plots. Each sampling plot (300–400 m^2 in size) is characterised by homogenous vegetation structure and cork oak as a common species to all. All sampling plots were similar in elevation (60–360 a.s.l.), position in the slope (mid-slope), orientation (SW-SE) and geological parent material. Geographic location of the plots, together with soil and vegetation characteristics, is presented in Table 1. The sampling plots were selected to obtain a large range of wildfire history defined as the number of fires, the interval between each fire and the interval between the last fire and a given sampling date. The wildfire history parameters of each sampling plot are presented in Table 2.

Firstly, seventeen plots were sampled in January 2007 to study relationships between soil microbial activities, soil organic matter quality and fire frequency. Then, in February 2008, in January 2009 and finally in June 2009, three other sets of respectively 24, 12 and 12 plots were sampled to assess the predictability of soil microbial properties by FT-NIR spectroscopy over a maximum range of wildfire history. For each plot, after removing the thin litter layer from the soil surface, five bulk soil subsamples of the surface layer (0–5 cm depth), each 20 cm × 20 cm in size, were randomly cored and pooled. The composite soil samples were sieved (2 mm mesh size), homogeneously mixed and kept at 4 °C until analysed for microbial properties or air-dried prior ^{13}C NMR and FT-NIR analyses.

A Wildfire History Index (WHI) was required to analyse properly the relationships between wildfire parameters (i.e. number of fires, interval between fires and sampling time) and the recovery of soil properties. WHI was designed to include the number of fires, the time between the last fire and soil measurements, and the time interval between fires. WHI was also parameterised (i) to increase with the number of fires, (ii) to decrease with the time since the last fire and, more generally (iii) to give more weight to recent fires than to old fires. WHI was calculated for all soils (Table 2) according to the following equation:

$$\mathrm{WHI} = \sqrt{\sum_{i=1}^{n}\left(\frac{1}{Y_\mathrm{m} - Y_i}\right)}$$

where n is the total number of fires, Y_m is the sampling year and Y_i the year of ith fire. The square root of this sum is applied to reduce the variability of the values for recent fires.

2.3. Soil organic matter content and quality by solid-state ^{13}C CP/MAS NMR

Organic matter content of soils collected in 2007 was obtained by loss on ignition (16 h, 550 °C). Prior to being analysed only for NMR, these soil samples were treated with a mixture of chlorhydric acid (1N) and fluorhydric acid (10%) (v:v) using the procedure of Gelinas et al. (2001). This pre-treatment was used to suppress paramagnetic elements which interfere with the NMR