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Fire increases the risk of higher soil N_2O emissions from Mediterranean Macchia ecosystems

K. Karhu [a, *], M. Dannenmann [b], B. Kitzler [c], E. Díaz-Pinés [d, 1], J. Tejedor [d, 1], D.A. Ramírez [e, 2], A. Parra [e], V. Resco de Dios [e, f, 3], J.M. Moreno [e, f], A. Rubio [d], L. Guimaraes-Povoas [c], S. Zechmeister-Boltenstern [g], K. Butterbach-Bahl [b], P. Ambus [a]

[a] Department of Chemical and Biochemical Engineering, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark
[b] Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Kreuzeckbahnstraße 19, 82467 Garmich-Partenkirchen, Germany
[c] Federal Research and Training Centre for Forests, Natural Hazards and Landscape, Seckendorff-Gudent-Weg 8, 1131 Vienna, Austria
[d] Departamento de Silvopascicultura, Universidad Politécnica de Madrid, C/ Ramiro de Maeztu s/n, 28040 Madrid, Spain
[e] Department of Environmental Sciences, University of Castilla-La Mancha, Avenida de Carlos III s/n, 45071 Toledo, Spain
[f] Centro de Investigaciones del Fuego, Fundación General del Medio Ambiente de Castilla-La Mancha, Avenida Carlos III s/n, 45071 Toledo, Spain
[g] BOKU – University of Natural Resources and Life Sciences Vienna, 1190 Wien, Austria

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ABSTRACT

Intensification of droughts under climate change is projected to increase fire frequency in the Mediterranean region. Fires cause direct emission of greenhouse gases (GHG) such as carbon dioxide (CO_2) and nitrous oxide (N_2O), due to the combustion of organic matter, creating a positive feedback on climate change. However, the potential importance of indirect GHG emissions due to changes in soil biological and chemical properties after fire is less well known. Increased soil mineral nitrogen (N) concentrations after fire pose a risk for increased emissions of gaseous N, but studies on the post-fire N_2O production and soil N turnover rates (mineralization, nitrification, microbial immobilization, denitrification) are still rare. We determined N_2O production, rates of N turnover and pathways for N_2O production from the soil of burned and unburned plots of a Macchia shrubland in central Spain using a ^{15}N labelling approach. Measurements were initiated before the controlled burning and continued for up to half a year after fire. Fire markedly increased the risk of N_2O emissions from soil through denitrification (N_2O production rate was 3 to ≈30 times higher in burned soils compared to control, with N_2O being produced solely from soil nitrate). In contrast, soil gross N cycling rates were not accelerated after fire. Thus, the increased N_2O production was not closely linked with N mineralization, but may be explained by increased mineral N availability from ash, increased pH in burned plots, and less competition for available N and C sources due to absence of plants.

1. Introduction

The Mediterranean area is considered to be especially vulnerable to climate change, because it lies at the transition between arid and humid regions of the world (Scarascia-Mugnozza et al., 2000). Climate change projections for the Mediterranean region include warmer temperatures and decreased precipitation, leading to intensification of water scarcity (droughts) (IPCC, 2013). Mediterranean Macchia shrubland ecosystems are naturally affected by fires, but models project increased occurrence of fires for the Mediterranean region with global warming (e.g. Carvalho et al., 2011). This is because reduced water availability in combination with higher temperatures increases fire risk and the length and

* Corresponding author. Present address: Department of Forest Sciences, P.O. Box 27 (Latokartanonkaari 7), FI-00014 University of Helsinki, Finland. Tel.: +358 50 448 6149.
E-mail address: kristiina.karhu@helsinki.fi (K. Karhu).
[1] Present address: Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Kreuzeckbahnstraße 19, 82467 Garmich-Partenkirchen, Germany.
[2] Present address: Crop Ecophysiology and Modeling Laboratory, Global Program of Integrated Crop and Systems Research, International Potato Center, Apartado 1558, Lima 12, Peru.
[3] Present address: Department of Crop and Forest Sciences-AGROTECNIO Center, Universitat de Lleida, Av Rovira Roure 191, 25198 Lleida, Spain.

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severity of the fire season (Moreno et al., 2010). Severe fire events during recent years in Spain, Italy and Greece have been linked to temperature anomalies (Amraoui et al., 2013), and heat waves like this are projected to increase with global warming (IPCC, 2013).

Direct CO_2 production during fires significantly contributes to GHG emissions in Mediterranean countries, and thus further accelerates climate change, if the area burned increases due to global warming (Miranda et al., 1994). Burning biomass is also a source of other GHGs such as N_2O and other air pollutants (Crutzen et al., 1979; Laursen et al., 1992). However, the post-fire effects on N_2O emissions due to mid-to long term changes in soil biological and chemical properties are less well known. Only a few studies from Mediterranean ecosystems have concentrated on changes in N_2O production and N cycling after fire (Dannenmann et al., 2011; Fierro and Castaldi, 2011; Inclán et al., 2012). Therefore, the risk for increased post-fire N_2O emissions (Skiba and Smith, 2000) from these ecosystems, and the magnitude of the potential feedback to climate change remains uncertain. Emissions of N_2O could increase as a consequence of changes in C and N cycling after fire (Brown et al., 2012). Fire disturbance combined with other climate change drivers (elevated CO_2, heat, altered precipitation and enhanced N deposition) has been suggested to cause strongly positive interactions between these factors, leading to higher N_2O fluxes than would be expected based on single-factor studies (Niboyet et al., 2011; Brown et al., 2012). This highlights the importance of studying the post-fire effects on soil N_2O fluxes under a global change context.

Our understanding of how fire may affect soil microbial N cycling in Mediterranean ecosystems is still limited. Fire consumes a large proportion of total aboveground N (up to 80% depending on fire severity, Boby et al., 2010), but it also enhances mineral N availability, as N uptake is drastically diminished, and N remains available in the ash mainly as ammonium (Levine et al., 1988; Marion et al., 1991; Prieto-Fernández et al., 2004). However, the extent to which the soil mineral N concentrations could be affected indirectly by altered inorganic N production (mineralization of organic N to ammonium (NH_4^+), and nitrification of NH_4^+ to nitrate (NO_3^-)) and uptake rates by soil micro-organisms (immobilization of NH_4^+ or NO_3^-) is largely unknown (Dannenmann et al., 2011). Fire directly produces NH_4^+, but NO_3^- is not formed in the fire, and requires nitrification to form (Knicker, 2007). Soil pH increases after fire, due to the high cation content of the ash (Jensen et al., 2001), and the increase in pH could stimulate nitrification (Ste-Marie and Paré, 1999) and denitrification (Skiba and Smith, 2000).

It is uncertain whether organic N and C availability to soil microbes increases or decreases after fire (Prieto-Fernández et al., 2004), as there are factors affecting into opposite directions. Microbial biomass in the surface soils decreases immediately after fire (Dumontet et al., 1996; Rutigliano et al., 2007:; Fontúrbel et al., 2012), and the released organic C and N from the microorganisms killed by the heat could increase substrate availability for the surviving microbes (Andersson et al., 2004), and thus increase mineralization. Organic N content has been found to increase, decrease or stay the same after fire, but in each case with decreased average lability (Prieto-Fernández et al., 2004). Therefore, it is also possible that N mineralization decreases after fire, as the remaining organic N is mainly stored in recalcitrant heteroaromatic N structures formed in the fire (Knicker, 2007). Soil microorganisms are important for determining the fate of the mineral N released in the fire: it could be either retained in the biomass (Bell and Binkley, 1989) or lost from the ecosystem through the microbial nitrification and denitrification (a process converting NO_3^- to N_2O and N_2), both of which are known to be stimulated by N additions (e.g. Levine et al., 1988; Barnard et al., 2005). The fate of the N has also consequences for the plant community, as losses of N through leaching and denitrification could potentially reduce the labile pool of N available for plant growth slowing recovery (Knicker, 2007).

The aim of this study was to measure N_2O emissions, pathways of N_2O production (nitrification and denitrification) and rates of soil N turnover after a fire in a Mediterranean Macchia ecosystem. We hypothesised that N_2O emissions would increase after the fire, due to increased mineral N availability in the soil. We also hypothesised that the effect would decline with time since fire, as recovery of vegetation would increase competition for available N.

2. Materials and methods

2.1. Site description and soil sampling

The site was established on a Macchia shrubland 160 km southwest from Madrid at the Coto Nacional de los Quintos de Mora (39°25′27″ N 4°04′17″ W), as part of the SECCIA (***S**imulation of **E**ffects of **C**limate **C**hange **i**n a Shrubland **A**ffected by Fire*) project. The field work was initiated in September 2009 and continued until April 2010 to follow the mid-to long-term changes in the N cycling rates. Yearly precipitation at the site is 622 mm and mean annual temperature (MAT) is 14.9 °C (1948–2006 "Los Cortijos" meteorological station; 39°19′ N, 4°04′ W; AEMET, Ministerio de Medio Ambiente, Medio Rural y Marino, Spain), but in 2009 the precipitation was 427 mm and thus lower than the long-term average (Parra et al., 2012). Warmest month of the campaign period (September 2009–April 2010), was September (19 °C), October and November were the driest months, while most rain (60% of the period) occurred between December and February (Fig. 1). Altitude of the site is 900–925 m and slope 15–25%. The soil is a Dystric Cambisol, formed on Quartzite bedrock. Average soil properties at 0–5 cm depth are given in Table 1. The dominating plant species are *Cistus ladanifer* L., *Erica arborea* L., *Phillyrea angustifolia* L., *Erica scoparia* L. and *Rosmarinus officinalis* L. A more detailed site description has been published by Parra et al. (2012). Other aspects of plant and ecosystem responses to drought and fire have already been investigated on the site (Hijonosa et al., 2012; Parra et al., 2012; Ramírez et al., 2012).

For the purpose of the present study, six plots of 25 m^2 were randomly assigned either into burned or control block ($n = 3$, see Fig. 2). The plots were burned on September 23rd 2009. The fire intensity was high (mean maximum temperature of 710.0 ± 25.4 °C), and similar among all burned plots (Parra et al., 2012). Soil samples (0–5 cm top-most soil, excluding litter layer) were collected from a regular (50 × 50 cm^2) grid (80-100 subsamples per plot) with a small soil corer, pooled and immediately sieved (5 mm). Soils were first sampled 1 day before the burning, and sampling was repeated 3, 13, 35 and 204 days after the controlled burning. Soils were transported to a nearby field-laboratory within the day of sampling on −1, 3 and 13 days after the fire, and gravimetric water contents were determined by oven drying at 105 °C to constant weight. Incubations started the following day. Soils collected 35 and 204 days after the fire were placed in insulated cool-boxes, and shipped to a laboratory in Denmark for processing within less than one week.

2.2. ^{15}N labelling and incubation experiment

Soil samples (20 g) were incubated in 2 l glass jars for 48 h, after labelling with ammonium nitrate (NH_4NO_3) (either double labelled $^{15}NH_4^{15}NO_3$, or single labelled $^{15}NH_4NO_3$, 5 atom% excess, 10 μg N/g moist soil). Soils were adjusted to the same water content as on the 1st incubation time before burning (35% gravimetric water content after adding the labelling solutions) to keep the incubations comparable. All incubations were conducted at a constant room