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Short-term response of soil microorganisms, nutrients and plant recovery in fire-affected *Araucaria araucana* forests

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A B S T R A C T

Soil contains a wide variety of microorganisms that are responsible for fundamental ecological processes. However, increased frequency and severity of fires reduce microbial diversity and alter soil nutrient availability, affecting vegetation recovery. By using a large-scale wildfire that burned endangered *Araucaria araucana* forests in south-central Chile (38°S), we assessed the short-term post-fire response of microorganisms, soil nutrients, and plant recovery. One year after fire, we sampled soils from burned and unburned areas, and measured the number of bacterial and fungal colony forming units, and the microbiological activity of the soil. We also measured soil nutrients (N, P, and K), organic matter content and species richness, abundance and plant diversity after fire. We found a significant increase in microbiological activity in burned soils (BS) compared to unburned soils (UBS), with bacteria and fungi being four and seven times greater in BS than in UBS, respectively. Concentrations of N, P and K were also greater in BS than in UBS. Plant species richness was two times higher in unburned than in burned areas, with a drastic reduction of the dominant tree species *Araucaria araucana* and *Nothofagus pumilio* after fire. The changes in soil properties after fire may be related to organic matter mineralization, the contribution of nutrients from ashes, or due to post-fire conditions (e.g., increased soil temperature after canopy removal by fire). Overall, our study shows a positive, short-term response in soil microorganisms abundance and nutrient content, but a rapid initial reduction of plant diversity of the main dominant tree species in these forest ecosystems after a severe fire. Further research is necessary as vegetation results are only preliminary and they can vary in the short-to-medium term. Our study provides insightful clues to delve into more applied research aimed at the post-fire restoration of the endemic, long-lived *Araucaria araucana* forests.

1. Introduction

Disturbances are important components of ecosystem dynamics, but increased variations in their regimens can greatly alter their structure and functioning (Hobbs and Huenneke, 1992, Mouillot et al., 2013). Some of the most striking examples of altered disturbance regimes involve changes in the frequency, severity, and seasonality of fires (Littell et al., 2009; Moritz et al., 2012). Fire can affect the composition of ecological communities through reductions in plant density and cover, as well as producing alterations in the chemical and biological properties of soil, such as pH, organic matter and nutrient contents, edaphic fauna and soil microorganisms (Certini, 2005; Hart et al., 2005; Neary et al., 1999). Among these, soil microbes are key for fundamental ecological processes that occur underground, including organic matter decomposition and nutrient cycling (Baldrian, 2017; Schulz et al., 2013). Fire can directly affect the abundance and diversity of microorganisms due to soil overheating, or indirectly by changing their physical and chemical environment (Banning and Murphy, 2008). Overheating of the soil can result in a significant reduction of microbial biomass, which in turn can affect the structure and diversity of the microbial community (Acea and Carballas, 1999; Guo et al., 2015). In this sense, forest fires can have an immediate and long-lasting impact on soil microorganisms, and therefore on the ecosystem services they provide (Whitman et al., 2014).

The effects of fire on soil are mostly related to frequency, severity, temperature peaks and duration of the wildfire (Gongalsky, 2006;

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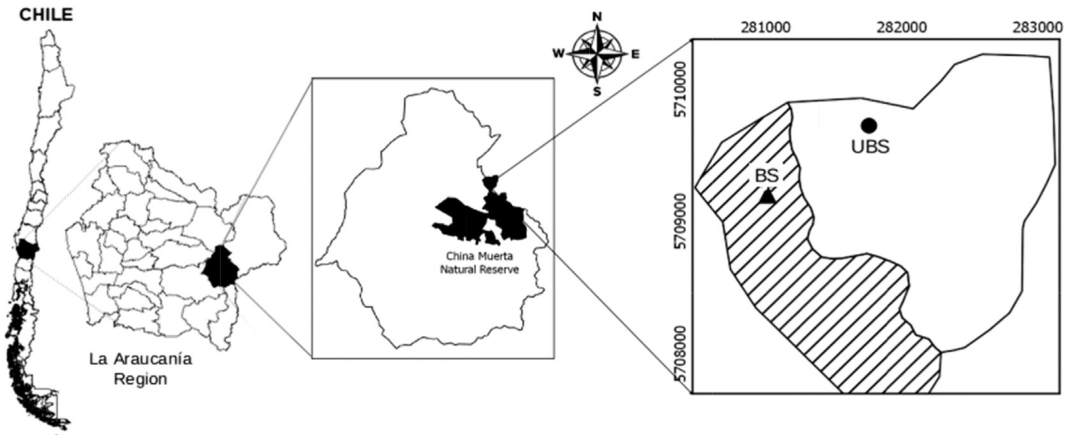

Fig. 1. Geographic location of the study area in the National Reserve China Muerta, La Araucanía region (38°S, 71°W), south-central Chile. The far right panel shows the burned (dashed) and the unburned areas. The burned sampling plots are located ca. 800 m apart from the unburned plots. Within each soil condition (i.e., BS and UBS) the sampling plots are located ca. 30 away from each other.

Williams et al., 2012). High-severity fires cause significant removal of organic matter, deterioration of structure and porosity of the soil, considerable nutrient losses (e.g., nitrogen) and a severe alteration of the amount and composition of microorganisms (Certini, 2005). On the other hand, low-severity fires can have positive impacts on ecosystems, such as increased mineralization of organic matter (Soong and Cotrufo, 2015), diversity maintenance in ecosystems (Velle et al., 2012) and prompting the early successional stages in forest ecosystems. Since wildfires are becoming increasingly frequent and severe worldwide (Krawchuk et al., 2009; Moritz et al., 2012; Stephens et al., 2014), it is crucial to understand their ecological impacts on soil microorganisms and the potential changes in ecosystem-related functions (e.g., biodiversity maintenance). Furthermore, understanding the effect of fire on the forest soil–plant system is critical for predicting potential feedbacks between climate change, wildfires, nutrient and soil microorganisms dynamics with the broader aim of ecosystem conservation and management (Singh et al., 2017).

The increased frequency and severity of fires worldwide has received a growing interest from the scientific community for assessing their impacts on soil microorganisms and biogeochemical cycles (Knelman et al., 2015; Velasco et al., 2009). However, rather few studies have examined the initial response of soil microorganisms and nutrients to fire in natural forests, particularly within old-growth forests of high ecological value. Such is the case of the patrimonial *Araucaria*-dominated forests in the Andes of southern South America. *Araucaria araucana* (Mol.) K. Koch is an endemic, long-lived native conifer from Chile and Argentina. Forests formed by *A. araucana* are particularly valuable because of their significant biodiversity and cultural values (Aagesen, 1998; dos Reis et al., 2014). By 1500, prior to the Spanish colonization, *A. araucana* forests covered ca. 500,000 ha in Chile, but during the 1920–1970s the area covered by the species was reduced by almost 50% due to logging and fires (Lara et al., 1999). In fact, *Araucaria araucana* populations outside national parks and reserves are still experiencing an increased risk of degradation, being subjected to logging (González and Veblen, 2007), cattle grazing (Fuentes-Ramirez et al., 2011), increasing and unsustainable harvesting of its edible seeds and fire-induced disturbances (Cóbar-Carranza et al., 2014; González et al., 2013). Currently, *A. Araucana* is classified as an endangered species in Chile; it was declared *Natural Monument* in 1990, with complete prohibition of logging, even of a single tree. Nowadays, *A. araucana* is considered an emblematic species because of its ecological and social importance (Aagesen, 1998; dos Reis et al., 2014).

Regarding the impacts of fire on soil properties in *A. araucana* forests, Rivas et al. (2016) studied the impact of fires on protein production by soil mycorrhizal fungi four years after fire. To this end, knowledge on the initial response (i.e., one year after fire) of soil microorganisms and nutrients in *A. araucana* forests is lacking. In the short term, studies have shown that soil microbial abundance can increase, decrease or remain unchanged after a fire (Bowker et al., 2004; Neary et al., 1999), whereas nutrients availability (i.e., N and K) generally tend to decrease after fire because of high combustion temperatures and volatilization (Esque et al., 2010). The ability of the soil microbial community to recover after a fire disturbance is crucial for plant recovery and for the functioning of the entire ecosystem. For instance, metabolic activity from microbial soil communities is responsible for most of carbon (C) mineralization and other soil nutrient cycling processes (Knelman et al., 2015; Mikola and Setala, 1998).

To date, most of studies dealing with fire in *A. araucana* forests in the southern Andes have focused on forest dynamics (e.g., using dendrochronological studies) or have assessed specific soil properties several years after fire (Rivas et al., 2012). However, an initial assessment and the interplay involving soil microorganisms, nutrients and vegetation after fire remains unclear. Therefore, we assessed the initial response (i.e., one year after fire) of soil microorganisms and nutrients within *Araucaria araucana* forests that were affected by a severe, large-scale fire in 2015 in the Andes of south-central Chile. Given the high severity of the fire, we hypothesize that the microbial activity and abundance of bacteria and fungi, as well as the availability of soil nutrients will decrease in burned soils, compared to adjacent unburned soils. Specifically, this research aimed at: (i) determining the abundance of soil bacteria, fungi and soil biological activity within burned and unburned soils; (ii) evaluating the impact of the fire on the availability of soil nutrients (i.e., N, P and K) and soil organic matter; and (iii) assessing the initial response of vegetation recovery and its relationship with microorganisms and nutrients in the first year after fire. Improving our understanding of the initial response of microorganisms, soil nutrients, and vegetation after fire is crucial for providing ecological insights to be taken into account when designing and implementing early conservation and restoration actions for the endangered *A. araucana* forests.

2. Materials and methods

2.1. Study area

The study area is located in the National Reserve China Muerta, in the Andes of south-central Chile (38°S, 71°W; Fig. 1). The Reserve encompasses 11,170 ha, mainly covered by the endemic, long-lived conifer *Araucaria araucana*. According to the vegetational classification of Gajardo (1995), the *A. Araucana*-dominated forests belong to the