



## Changes in soil N and P availability in a *Pinus canariensis* fire chronosequence

Jorge Durán\*, Alexandra Rodríguez, José María Fernández-Palacios, Antonio Gallardo

Department of Physical, Chemical and Natural Systems, Pablo de Olavide University, 41013 Seville, Spain

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### ABSTRACT

Fire induces changes in ecosystem nutrient regimes and can cause major losses of N and P. Much has been written about the effect of fire on nutrient availability in soil; most studies have been concerned with the short-term effects of shock. The primary objective of our study was to discover the effect of forest fires on long-term N and P availability, for which we used the ion exchange membrane method in a chronosequence of forest fires (1987, 1990, 1994, 1998, 2000 and 2005). The study was conducted on the island of La Palma (Canary Islands, Spain) in October 2006. We hypothesized that a rapid increase in nutrient availability would occur after the fire, followed by a reduction due to erosion and leaching, and then gradual recovery and an eventual return to initial levels.  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$  and mineral-N availability peaked significantly 1 year after the fire. However, 5 years after the fire the N levels were similar to those found on unburned land. P availability decreased significantly a year after the fire, but gradually recovered over time. The N and P availability ratio increased significantly after the fire, falling during the chronosequence, with the lowest levels found on the unburned land. These results confirm that fire produces (a) a rapid and short-term increase in N availability, without a long-term decline, and (b) a long-term reduction in P availability, which tends to recover over time after the fire.

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### 1. Introduction

Fire affects ecosystem nutrient regimes, the composition of species, plant growth and soil biota (Wan et al., 2001). Soil degradation subsequent to fire is due to the damage to soil structure (Betremieux et al., 1960; Giovannini et al., 1998), loss of organic matter (Valette et al., 1994; Gillon et al., 1995) and loss of mineral nutrients (Debano and Conrad, 1987; Kutiel and Naveh, 1987). Fire usually increases short-term N availability (Boerner, 1982; Nardoto and Bustamante, 2003; Knoepp et al., 2004), but can have the opposite effect in the long term (Vitousek and Howarth, 1991). Total losses of N, including those due to volatilization and erosion, together with the lack of an effective replacement, could lead to a significant reduction in N availability in the soil (Carreira et al., 1994). A similar trend is observed for P. Its increased availability after fire (Alauzis et al., 2004) can be followed by a long-term decrease due to the decline in organic P, less phosphatase activity and less mycorrhizal infection (Klopatek et al., 1988; Romanya et al., 1994; Saa et al., 1998). Most studies, however, focus on the short-term effects of fire, and little is known about the long-term

consequences of forest fires on nutrient availability in ecosystems (Palese et al., 2004). There is a need for research that looks beyond the immediate effects of fire, in order to know the extent to which forest fires decrease the nutrient reserves of ecosystems, increase their transformation rates and alter their availability.

The forest systems of the island of La Palma are unique in Europe. The *Pinus canariensis* forests have not been intensively managed by man, and thanks to their distance from Europe, they are not affected by the growing atmospheric nutrient deposition caused by anthropogenic activity in continental Europe. The only significant disturbances affecting these forests are wildfires. Therefore, they are ideal for this project, which aimed to identify the effect of forest fires on N and P availability. Our initial hypothesis was that increased nutrient availability would occur after a fire, followed by a reduction due to erosion and drainage and a gradual return to initial levels.

### 2. Methods

#### 2.1. Study site

The study was conducted on the island of La Palma (latitude:  $28^{\circ}41'\text{N}$ ; longitude:  $17^{\circ}45'\text{W}$ ). All sites were at an altitude of 1200–1800 m above sea level, with mean annual rainfall of 600 mm and a mean annual temperature of  $16^{\circ}\text{C}$  (Climent et al., 2004). The soil is volcanic in origin and its evolution is closely

\* Corresponding author at: Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, 41013 Sevilla, Spain. Tel.: +34 954349535; fax: +34 954349814.

E-mail address: [humia20@gmail.com](mailto:humia20@gmail.com) (J. Durán).

related to weather conditions. Leptosols, Vertisols and Andosols predominate (IUSS Working Group WRB, 2006) and the content in organic matter of the sampled areas ranges from 2% to 4%, with a pH of 6.5–7 (unpublished data). The vegetation is dominated by the presence of *P. canariensis* C. Sm., with nearly 80% coverage, made up of very old (up to 700 years old) and tall trees (20–30 m). The understory is sparse, with just a few individuals of the *Adenocarpus viscosus* (Wild.) Webb and Berthel, *Erica arborea* L. and *Cistus symphytifolius* Lam species.

## 2.2. Experimental design and laboratory analysis

Twenty-six plots along a chronosequence of fires were selected in October 2006. They included plots burned in different years (1987, 1990, 1994, 1998, 2000 and 2005) as well as unburned plots. The fires affecting these forest systems completely destroy the undergrowth and although fire reaches the tops of the trees, the adult individuals are not killed. The number of replicates, chosen to take as much geographical, geological and biological variability into account as possible was four 25 m × 25 m plots for each year with a fire, except 1987, for which we were only able to obtain two replicates with homogeneous characteristics. Fifteen sampling points were selected at random on each plot.

Many studies have shown that the ion concentrations in resin extracts are strongly correlated to plant uptake of such ions (Abrams and Jarrel, 1992; Maclaughlin et al., 1993; Huang and Schoenau, 1996; Fernandes and Coutinho, 1997), and this technique has been effectively used in different studies concerning N (Quian and Schoenau, 1995; Ziadi et al., 1999) and P availability (Cooperband and Logan, 1994; McGrath et al., 2000; D'Angelo et al., 2001). Resin balls inside buried pouches were originally used, but the method has major disadvantages in view of its three-dimensional nature (soil disturbance and placement work). These disadvantages can be overcome with the use of two-dimensional ion exchange membranes (IEMs; Subler et al., 1995). It is now believed that nutrient extraction from soil using exchange membranes is one of the most reliable methods for measuring nutrient availability for plants (Ziadi et al., 2006). I-100 and I-200 (Electropure excellion-inc., Laguna Hills, California) ion exchange membranes were used to estimate N and P availability in the soil.

They were first subjected to expansion treatment by submerging them in distilled water at 82–90 °C for 48 h. They were then cut into 2.5 cm × 2.5 cm squares and attached to a plastic rod with acrylic glue to be positioned in the soil. The ion exchange capacity of the membranes remains intact with this design (Cain et al., 1999). The membranes were positioned at a depth of 10 cm with a metal spatula, and the soil around them was compacted to ensure good contact between the membranes and the soil. A cation exchange membrane and an anion exchange membrane were incubated for 15 days at each sampling point. After being removed, the membranes were taken individually to the lab and dried at ambient temperature. The attached soil was removed, the plastic rod was cut and an extraction was performed with 50 ml of 2 M KCl by orbital spinning for 1 h at 200 rpm in 125 ml flasks. These extracts were used to calculate the quantity of NH<sub>4</sub>-N, NO<sub>3</sub>-N, and total N-mineral (NH<sub>4</sub>-N + NO<sub>3</sub>-N) by the indophenol blue method (Sims et al., 1995) and PO<sub>4</sub>-P by the molybdenum blue method (Allen et al., 1986), with a microplate reader.

## 2.3. Statistical analysis

The Kruskal–Wallis non-parametric test was used to measure the effect of the fire on the studied variables and permutation tests were used to identify the differences between the fire years. Spearman tests were used to examine correlation between the variables. All analyses were performed using the R 2.4.0 statistical package for Linux (R Development Core Team, 2007).

## 3. Results

Fire had a significant effect on all the studied variables ( $p < 0.005$ ). NH<sub>4</sub>-N, NO<sub>3</sub>-N and mineral-N availability was significantly elevated in the plots sampled 1 year after fire (Fig. 1a–c). This increase was larger in the case of NO<sub>3</sub>-N (10 times more than in the control plots) than for NH<sub>4</sub>-N (2.5 times more than in the control plots).

The highest N availability levels were found on the plots burned 1 year before sampling: 0.11 μg of NH<sub>4</sub>-N cm<sup>-2</sup> d<sup>-1</sup>, 0.51 μg of NO<sub>3</sub>-N cm<sup>-2</sup> d<sup>-1</sup> and 0.62 μg of mineral-N cm<sup>-2</sup> d<sup>-1</sup> (Fig. 1a–c). On the plots burned 6 years prior to sampling, however, the levels of N

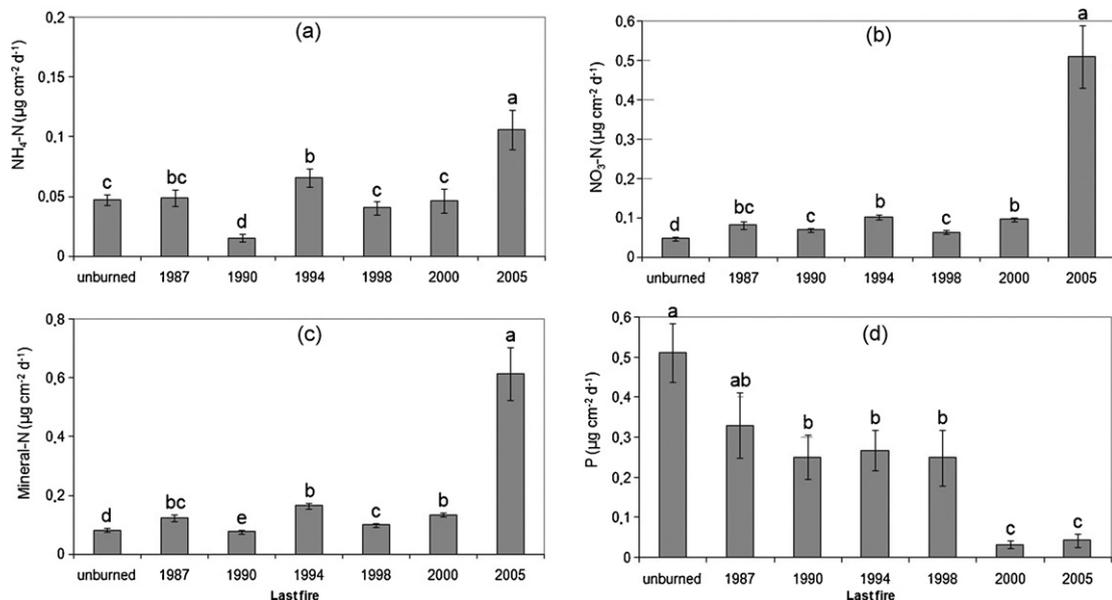


Fig. 1. NH<sub>4</sub>-N (a), NO<sub>3</sub>-N (b), mineral-N (c) and P (d) availability in plots burned in different years and in unburned plots. Different letters show significant differences (permutation test,  $p < 0.005$ ).

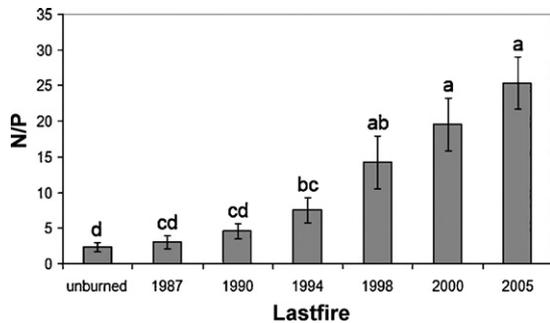


Fig. 2. N and P availability ratios for plots burned in different years and for unburned plots. Different letters show significant differences (permutation test,  $p < 0.005$ ).

were similar to those of the unburned plots. From this time on, levels remained similar on the rest of the plots, with an average of  $0.04 \mu\text{g}$  of  $\text{NH}_4\text{-N cm}^{-2} \text{d}^{-1}$ ,  $0.08 \mu\text{g}$  of  $\text{NO}_3\text{-N cm}^{-2} \text{d}^{-1}$  and  $0.12 \mu\text{g}$  of mineral-N  $\text{cm}^{-2} \text{d}^{-1}$  (Fig. 1a–c).

$\text{NO}_3\text{-N}$  availability was greater than that of  $\text{NH}_4\text{-N}$  on the burned plots. This difference was at its highest 1 year after the last fire ( $0.51 \mu\text{g}$  of  $\text{NO}_3\text{-N cm}^{-2} \text{d}^{-1}$  (Fig. 1b) vs.  $0.11 \mu\text{g}$  of  $\text{NH}_4\text{-N cm}^{-2} \text{d}^{-1}$  (Fig. 1a)), whereas on the rest of the burned plots,  $\text{NO}_3\text{-N}$  availability was approximately double that of  $\text{NH}_4\text{-N}$ .

A significantly positive correlation ( $r = 0.53$ ,  $p < 0.05$ ) was found between  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  availability 1 year after fire, whereas no correlation was found, neither at the other sites of the chronosequence nor in the unburned control plots.

P availability increased over time after fire (Fig. 1d). The most recently burned plots had the lowest P availability levels ( $0.03 \mu\text{g P cm}^{-2} \text{d}^{-1}$ ) and these values increased according to time since the most recent fire, with the highest P availability levels ( $0.51 \mu\text{g P cm}^{-2} \text{d}^{-1}$ ) found on the unburned plots.

The ratio between N and P availability increased significantly 1 year after fire and then progressively decreased along the chronosequence, with the lowest levels being found on the unburned plots (Fig. 2).

#### 4. Discussion

Similar to other studies conducted on different ecosystems (Smithwick et al., 2005), our results show that fire has a significant effect on N and P availability.  $\text{NH}_4\text{-N}$  availability was significantly greater on the plots sampled 1 year after fire, in spite of the possible losses through leaching and erosion during that time. This trend is common to many ecosystems (Debano and Conrad, 1987) and is caused by the deposition of ash rich in  $\text{NH}_4\text{-N}$  and the creation of conditions enabling mineralization (Raison, 1979). This increase in  $\text{NH}_4\text{-N}$  availability 1 year after fire was not found on the plots burned 5 years before sampling, where the quantity of  $\text{NH}_4\text{-N}$  did not significantly differ from that of the unburned plots. These results are similar to those obtained by other authors (Chorover et al., 1994), showing that nutrient uptake by plants, microbial immobilization and nitrification could be the causes of this reduction in  $\text{NH}_4\text{-N}$  availability in the medium term (Covington and Sackett, 1992). Moreover, leaching can also reduce the quantity of  $\text{NH}_4\text{-N}$  present in the soil, contributing to reduce N availability in terrestrial ecosystems (Debano and Conrad, 1987). On our plots, however, we did not find that fire had caused reduction in bioavailable N forms, as  $\text{NH}_4\text{-N}$  or  $\text{NO}_3\text{-N}$  levels on the burned plots were no lower than those of the unburned sites. This could suggest the existence of effective N retention mechanisms in these woods after fire; however, it would be necessary to compare these results with total N stocks to be able to draw such a conclusion.

$\text{NO}_3\text{-N}$  availability 1 year after fire was nearly five times greater than  $\text{NH}_4\text{-N}$  availability. Many post-fire studies of N pools in many types of ecosystems show a short-term increase in  $\text{NH}_4\text{-N}$  in the soil, followed by an increase in  $\text{NO}_3\text{-N}$  (Grogan et al., 2000). After fire, the  $\text{NH}_4\text{-N}$  added by ash deposits, together with increased temperature, pH and humidity, could improve nitrification (Raison, 1979). We found a significantly positive correlation between  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  availability 1 year after fire, supporting the existence of a coupling between ammonification and nitrification. However, such a coupling was not found in any of the other sampled sites, suggesting that the availability of these two nutrients is determined by independent processes in these cases.

Unlike other studies (Juo and Manu, 1996), we found a heavy reduction in P availability 1 year after fire. The literature however, reports contradictory findings of the effects of fire on P availability. While some found increased total P and available P in soil after fire (Brewer, 1995; Ross et al., 1997; Giardina and Rhoades, 2001), the opposite was found in other cases (Giardina et al., 2000). This reduced P availability could suggest that these forests retain P less efficiently than N after fire, indicating that they are limited by nitrogen availability. So, even if there was initially an increase in P availability, a lack of P retention mechanisms could lead this nutrient to be lost through drainage (Sardans et al., 2006). However, because P usually tends to be much less mobile than N in soils and much less prone to leaching losses, especially in volcanic soils (Schlesinger, 1997), an alternative hypothesis is possible. Burning could have resulted in restructuring of biogeochemical P fractions possibly leading to increased sorption/decreased bioavailability. For example, the fire could have burned some of the soil organic matter thus exposing new inorganic surfaces (allophanes or oxides) that strongly retain P and make it unavailable for plants and exchange resins (Garcia-Montiel et al., 2000). After this initial loss of availability, we found a gradual recovery of P availability levels over time after fire. This could suggest a continuous, external source of the nutrient. Crews et al. (1995) showed that inputs of atmospheric dust can be an agent that prevents P limitation in soils, and Moreno et al. (2006) found that wind processes transfer large quantities of mineral particles with a high phosphate content every year from the African deserts to the Canary Islands. These processes could be the cause of the gradual recovery of the P availability levels registered in our chronosequence. However, other processes can be responsible for the observed recovery. Changes in the biogeochemistry of P during forest succession after fire can result in the release of non-occluded P from occluded forms, increasing the bioavailability of this nutrient (Garcia-Montiel et al., 2000). The results obtained for the relationship between N and P availability confirm that the nutrient balance varies along the chronosequence. The high values obtained for the N/P availability ratio on the plots burned in 2005 indicate a potential P deficit just after the fire. Once again, more N than P retention capacity in the early stages of forest regeneration could lead to peak N availability and a potential deficit of P. Over time, however, the external sources of P suggested by Moreno et al. (2006) could lead to a reduction in the N/P availability ratio due to an increase in P availability. The lowest values obtained for the N/P ratio were found on the unburned plots, showing that in the absence of significant disturbance and in relative terms, the forests on the island of La Palma seem to be N-limited, whereas a significant disturbance such as fire could radically change the nutrient availability pattern, causing a temporary P deficit after the fire.

Our results confirmed our hypothesis that fire increases N availability and that the increase is only short-term. Although we hypothesized a long-term reduction in nitrogen availability

compared to unburned sites, this reduction was not found in our chronosequence. With regards to P, the results do not confirm increased availability after fire, but do show evidence of longer-term availability reduction with only gradual recovery.

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