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SHORT COMMUNICATION

Changes in net N mineralization rates and soil N and P pools in a pine forest wildfire chronosequence

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Abstract The concern that climate change may increase fire frequency and intensity has recently heightened the interest in the effects of wildfires on ecosystem functioning. Although short-term fire effects on forest soils are well known, less information can be found on the long-term effects of wildfires on soil fertility. Our objective was to study the 17-year effect of wildfires on forest net mineralization rates and extractable inorganic nitrogen (N) and phosphorus (P) concentrations. We hypothesize that (1) burned forest stands should exhibit lower net mineralization rates than unburned ones; (2) these differences would be greatest during the growing season; (3) differences between soil variables might also be observed among plots from different years since the last fire; and (4) due to fire-resistant geochemical processes controlling P availability, this nutrient should recover faster than N. We used a wildfire chronosequence of natural and unmanaged *Pinus canariensis* forests in La Palma Island (Canary Islands). Soil samples were collected during winter and spring at 22 burned and unburned plots. We found significantly higher values for net N mineralization and extractable N pools in unburned plots. These differences were higher for the winter sampling date than for the spring sampling date. Unlike extractable N and N mineralization rates, extractable P levels of burned plots exhibited a gradual recovery over time after an initial decrease. These results demonstrate that *P. canariensis* forest soils showed low resilience after wildfires, especially for N, and that this disturbance might induce long-term changes in ecosystem functioning.

Keywords *Pinus canariensis* · Ammonification rate · Nitrification rate · Soil ammonium · Soil nitrate · Soil phosphate · Forest fire

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Introduction

Interest in the effects of fire on forest soil fertility has recently heightened due to the concern that climate change may increase fire frequency and intensity (Scholze et al. 2006; Westerling et al. 2006). The short-term effects of fires on forest soils are well known, particularly for prescribed fires (Palese et al. 2004); however, less information is available on the long-term effects of wildfires (Wan et al. 2001). Wildfires may lead to soil degradation, including deterioration of soil structure (Giovannini et al. 1988) and losses of soil organic matter (Gillon et al. 1995; Valette et al. 1994) and nutrients (Kutiel and Naveh 1987; Bormann et al. 2008). Although fire usually causes an immediate increase in available N pools (Boerner 1982; Hernández et al. 1997; Prieto-Fernández et al. 1998; Nardoto and Bustamante 2003; Knoepp et al. 2004), the opposite effect is often observed over the long term. Total N losses, including those caused by volatilization and erosion, together with insufficient N inputs through atmospheric N fixation and deposition, can lead to a significant decrease in soil N availability (Carreira et al. 1994; Durán et al. 2008). The above fire effects in combination with those on soil microbial populations can significantly alter soil N transformation rates and ultimately the global N cycle (Klopatek et al. 1990; Neary et al. 1999). Similarly, for P, wildfires often induce a short-term increase in the availability of P for plants and soil microbes (Alauzis et al. 2004; Nadel et al. 2007). This increase can be followed by a long-term decline due to decreases in organic P, phosphatase activity, and mycorrhizal infection (Klopatek et al. 1988; Romanya et al. 1994; Saa et al. 1998). Unlike N, P is controlled by geochemical mechanisms (weathering and sorption) and is less susceptible to ecosystem disturbances than N (Vitousek and Howarth 1991). Changes in biogeochemical P fractions may lead to increases or decreases in P availability after a wildfire (Garcia-Montiel et al. 2000). However, most studies of pine forests were done in managed forests where fire and forest management effects are usually entangled.

Our objective was to study the long-term (two decades) effect of wildfires on forest extractable inorganic N and P concentrations and on N transformation rates on unmanaged pine forests that do not suffer the increasing atmospheric deposition rate that anthropogenic activity causes in European continental forests (Klein et al. 2007) being wildfires the only significant disturbance in these forests. We used a 17-year wildfire chronosequence of *Pinus canariensis* natural forests in La Palma Island (Canary Islands). This chronosequence was previously used by Durán et al. (2008) to demonstrate the short-term effect of a summer wildfire on nutrient availability in the dry season by using ion exchange membranes. In this paper, net mineralization rates and extractable N and P pools were evaluated during the growing season (spring) and in winter, when pines growth is limited by low temperatures. Our hypotheses were as follows: (1) Burned pine forest stands should exhibit lower net N mineralization rates (both nitrification and ammonification rates) than unburned pine stands due to less carbon quality; (2) differences should be the highest during the growing season (spring), when more active microbial biomass is present, than in winter; (3) differences between soil variables should also be observed among plots of different ages since the last fire; and (4) P will be recovered faster than N because, unlike N, P availability is controlled by both geochemical and biological processes.

Methods

Study area

The field study was performed in *P. canariensis* stands placed in La Palma Island (Canary Island, latitude, 28°41′ N; longitude, 17°45′ W). Several characteristics render these forests attractive for this type of study. First, they are one of the last natural and unmanaged European pine forests. Secondly, these stands are far from the European continent and local N emissions are scarce, so that atmospheric N deposition is extremely low. Thus, N deficiencies in trees are frequently observed, which heightens the interest in such nutrient cycling studies. Thirdly, mature *P. canariensis* trees resist severe forest fires, as burned stands are very comparable in terms of tree structure and age. Fourthly, plots with similar soil and site characteristics but burned in different years are relatively easy to find in these forests.

The pine stands lie between 1,200 and 1,800 m above sea level, with a mean annual rainfall of 600 mm and a mean annual temperature of 16°C (Climent et al. 2004). The soils are of volcanic origin and are classified as leptosols, vertisols, and andosols, and the textures ranged from sand to loamy sand (IUSS Working Group WRB 2006). The organic matter content of the sampled areas ranged from 2% to 4%, with total N ranging from 0.3% to 0.4% and pH from 6.6 to 6.9. Vegetation was dominated by the presence of large individuals of *P. canariensis* Chr. Sm. ex DC. with an average canopy cover of 80%. The pine population is comprised of adult trees (20–30 m height) and occasionally very old trees (up to 700 years old). The understory vegetation is scarce, with few individuals of *Adenocarpus viscosus* (Wild.) Webb and Berthel, *Erica arborea* L., and *Cistus symphytifolius* Lam. Fire completely eliminates the undergrowth, and although fire reaches the pine canopies (crown fires), it rarely kills the trees, and individuals that exceed 100 cm dbh are commonly found.

Experimental design and chronosequence plot selection

A wide set of fire chronosequence sites can be found in La Palma island, ranging from unburned sites to recently burned sites (2005). However, only a few sites are comparable in terms of altitude, slope, aspect, and soil characteristics. Thus, the fire chronosequence was composed of unburned plots (control) and plots burned in 1987, 1990, 1994, 1998, and 2000. For each year and for the control plot, we selected four 25 m×25 m replicate plots, except for the 1987 forest stand, where only two replicates with homogeneous characteristics were found, which probably weakened the power of statistical analysis for this plot. Criteria for plot selection were that all plots were selected at 1,200- to 1,800-m altitude in mature *P. canariensis* forests, and half of the replicate plots were low-slope plots (4–8%), while half were high-slope plots (20–25%). Similarly, North and South aspect plots were selected in all sites. Soil characteristics were similar across the chronosequence, with a narrow range of organic matter and pH (see above). Fire intensity and severity was assessed by the amount and height of the charcoal black stains deposited on pine bark. Based on these signals and on the information given by a local environmental agency, all fires at the plots were classified as crown fires.

We performed two samplings, one in the spring (April, 2004), during the growing season, and a second one in the winter (February, 2005), when growth is usually limited by low temperature. Fifteen random soil samples were collected at each plot using a 15×5 cm metallic corer, which allowed the sampling of the first top 10 cm of the soil profile. The litter layer was removed before samplings, and samples were carried to the laboratory in coolers inside polyethylene bags.

Laboratory analysis

We sieved the collected samples to pass a 2-mm mesh. To calculate the soil properties on a dry weight basis, we measured the gravimetric water content by drying a subsample in a forced-air oven at 80° until constant weight. Carbon and organic matter content was estimated by a wet digestion method, and total N was estimated by Kjeldahl digestion with sulfuric acid and copper sulfate as a catalyst (Allen et al. 1986). We analyzed the NH_4^+–N and NO_3^-–N amounts by extracting 5 g of fresh soil sample with 50 ml of 2 M KCl and calculating the amount of N present in the extracts using the blue indophenol colorimetric method and a microplate reader (Sims et al. 1995; D'Angelo et al. 2001). We measured PO_4^{3-}–P using the method described by Nelson and Sommers (1996) for basic soils by extracting 2 g of fresh soil sample with 40 ml of 0.5 N Na_2CO_3 and calculating the amount of PO_4^{3-}–P present in the extracts using a Bran+Luebbe—AA3 colorimetric nutrient autoanalyzer. We measured net N mineralization rates using the procedure described by Eno (1960). For each soil sample, the top 10 cm of soil A horizon was removed and placed in a polyethylene plastic bag, then reburied in the forest floor for a 30-day incubation. Net N mineralization was defined as the net increase in NO_3^-–N and NH_4^+–N over the incubation interval, and the net increase in NO_3^-–N and NH_4^+–N was used to indicate net nitrification and ammonification rates, respectively.

Data analysis

We used a non-parametric ANOVA (Kruskal–Wallis test) to check the overall effect of wildfire and sampling date on the studied soil variables. Asymptotic permutation tests were performed to compare variable levels of the soils among different fire years and sampling dates. Significant levels were corrected by the Bonferroni procedure. To test for significant trends as time elapsed after fire, the average values of the variables were adjusted to either a linear or exponential regression line with the last-fire year as an independent variable. Statistical analysis was performed using the R 2.7.2 statistical package for Linux (R Development Core Team 2007).

Results

We found many significant differences between burned and unburned plots for all studied soil variables, with higher N and lower P values in unburned plots ($P<0.05$, Table 1). However, N differences were not detected on both sampling dates. Thus, net nitrification rate and both soil NH_4^+–N and NO_3^-–N concentration in burned vs. unburned plots demonstrated significant differences for the winter sampling, but not for the spring sampling date. For the other soil variables, differences were found in both winter and spring soil samples between burned and unburned plots, but these differences were higher in winter than in samples collected in the spring (Table 1). Furthermore, all soil variables exhibited higher values in winter than in spring (Figs. 1 and 2). Differences in soil variables among plots from different years since the last fire were highly variable. Thus, soil extractable PO_4^{3-}–P showed a significant linear trend ($P<0.05$) toward the increase in PO_4^{3-}–P with time after fire for the spring sampling dates and close to the significant level for the winter sampling dates ($P=0.088$, Fig. 2). Increasing PO_4^{3-}–P values reached those of unburned plots from both winter and spring sampling dates. Similarly, the mineral N to extractable P ratio showed a continuous exponential decrease, rapidly reaching the unburned levels ($P=0.036$ and $P=0.064$ for spring and winter sampling dates, respectively). No other significant repetitive pattern was observed for other soil variables.

Discussion

As stated in our first hypothesis, within a few years after a wildfire occurrence, burned pine forest stands had lower net mineralization rates (both nitrification and ammonification rates) than unburned pine stands. Wildfires dramatically reduce the amount and quality of soil organic carbon (Chandler et al. 1983; Gillon et al. 1995), leaving the most recalcitrant organic fraction in the soil (White 1986). This lower organic matter quality may explain the decrease in net mineralization rates in the burned plots. Other processes can also contribute to explain the low N mineralization rates observed after wildfire, such as the depletion of N stocks by large combustion and drainage losses, the reduction of microbial biomass after fire, and fluctuations in the ratio of fungal to bacterial biomass (Grogan et al. 2000; Turner et al. 2007; Bladon et al. 2008). Increases in N mineralization rates and microbial activity have been reported after initial post-fire stages as an effect of transient

Table 1 Mean and standard errors for net mineralization, ammonification, and nitrification rates (mg kg soil^{-1} day^{-1}) and extractable soil N and P pools (mg kg soil^{-1})

		Spring			Winter		
		Mean	SE	*P*	Mean	SE	*P*
Net ammonification rate	Unburned	0.016	0.006	*	0.543	0.038	*
	Burned	−0.004	0.001	*	0.129	0.031	*
Net nitrification rate	Unburned	−0.007	0.003	NS	0.204	0.001	**
	Burned	−0.005	0.001	NS	0.036	0.003	**
Net mineralization rate	Unburned	0.019	0.008	*	0.747	0.019	**
	Burned	−0.009	0.002	*	0.165	0.033	**
NH_4^+–N	Unburned	21.03	3.86	NS	49.25	9.77	*
	Burned	18,00	0.69	NS	25.76	1.22	*
NO_3^-–N	Unburned	6.92	0.84	NS	47.97	10.04	*
	Burned	8.28	0.24	NS	9.47	0.18	*
PO_4^{3-}–P	Unburned	39.4	2.84	*	60.83	4.78	*
	Burned	19.82	1.52	*	30.01	2.61	*
N/P	Unburned	0.68	0.08	*	1.81	0.42	NS
	Burned	2.55	0.32	*	2.5	0.36	NS

df=1, n=4 (unburned), 18 (burned)

NS non-significant

**P*<0.05; ***P*<0.01

increases in temperature, water content, pH, and labile sources of C and N for microbes (Attiwill and Adams 1993; Christensen and Muller 1975; Hobbs and Schimel 1984; Klopatek et al. 1990; Rutigliano et al. 2007). Our results supported the hypothesis that these increases are short-lived because the opposite trend was found for all burned plots by 4 years after a wildfire. Furthermore, 17 years after the last fire (the 1987 burned plots), a significant decrease in net mineralization rates was still observed in comparison to unburned plots, indicating slow recovery of N turnover for this pine forest. The NH_4^+–N and NO_3^-–N soil pools also demonstrated lower concentrations in burned plots in the winter sampling date; however, no significant differences were found for these soil nutrients during the spring soil samples. The lower values found in the spring sampling date for nutrient pools suggested more intense nutrient uptake by plants and soil microbes, which may decrease absolute differences in nutrient pools between burned and unburned plots. However, repeated sampling in different years should be necessary to confirm this hypotheses. Besides, soil NH_4^+–N and NO_3^-–N concentrations are based on a single-day sampling scheme, and temporal variability within plots is likely to account for a significant part of the variance.

We expected higher differences between burned and unburned plots in net mineralization rates from the spring sampling dates than in the winter sampling dates, based on the higher soil temperature, which would promote higher microbial activity (Gallardo and Schlesinger 1994). However, differences in the absolute values of net mineralization rates between burned and unburned plots were much higher in the winter than in the spring. In the spring soil samples, either low net mineralization rates or net immobilization rates were observed in comparison with the winter samples. Since there was no significant differences in soil water content between spring and winter soil samples (data not shown), a higher C to N availability in spring than in winter may likely explain the net immobilization rates observed during spring (Gallardo and Merino 1998). This relative high C availability may come from the production of root exudates frequently observed during the growing season (Grayston et al. 1996). Thus, when the primary C source for microbes is not only solely from soil stable organic matter but also from plant-derived soil C, a higher immobilization rate results in differences between burned and unburned plots (regarding absolute terms), which are lower in spring than in winter.

We expected to find variations in N mineralization rates and inorganic N pools among plots burned in different years, with values approaching the unburned plots in the oldest fires. However, no evidence of recovery with time was observed. Forest fires may produce long-lasting deep transformations in soil organic matter quality through several processes, such as combustion and restructuring of organic molecules in complex recalcitrant forms (Knicker et al. 2005; Smithwick et al. 2005), which directly affect N

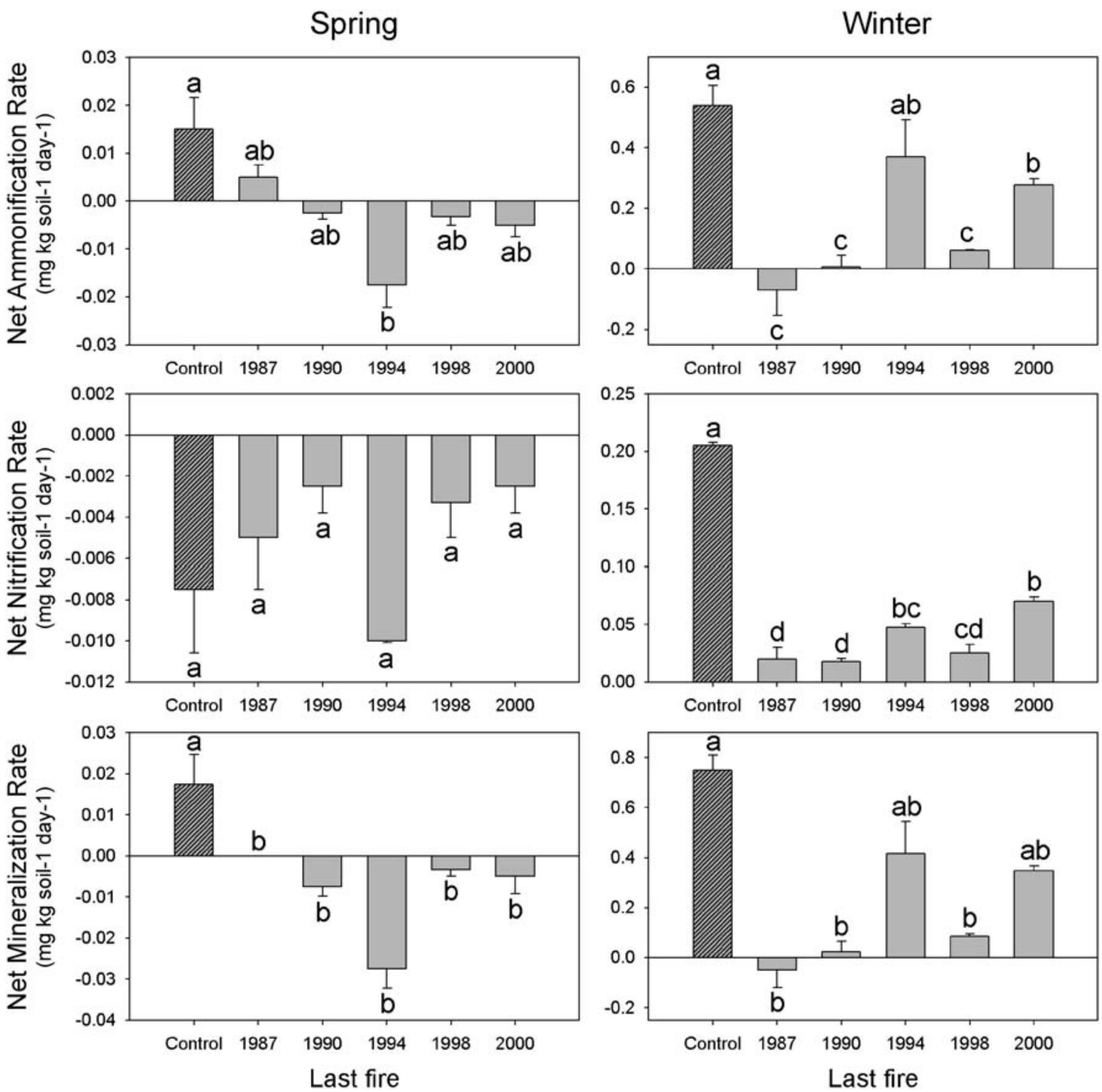

Fig. 1 Net mineralization, ammonification, and nitrification rates for the top 10 cm of the soil profile in burned and unburned plots of a *P. canariensis* forests. *Bars* represent mean values and standard error (n=4). A *common letter* indicates no significant difference between the compared years

mineralization rates and N pools. Additionally, fire affects the litter layer and underground vegetation, resulting in soil that can be particularly susceptible to erosion (Mabuhay et al. 2003). In the *P. canariensis* forest, the survival of old pines may limit the undergrowth plant cover leading to a slow recovery of these protective elements. This effect, together with the moderate slopes of these *P. canariensis* forests, may result in erosion that continues for many years (Owens and Collins 2006). The combined effect of these mechanisms may cause a long-term reduction in ecosystem productivity, preventing the ecosystem from recovering to pre-fire conditions (Ojima et al. 1994; Wirth et al. 2002). These results may be partially contradictory with those obtained by Durán et al. (2008), in which no reduction was observed in N availability (measured by using ion exchange membranes) after the wildfire. However, that study was carried out in summer, and the high dependence of membranes on soil water conditions probably made these results incomparable with those obtained in this study, conducted in spring and winter, and by using chemical extractions of N and P pools. Furthermore, Durán et al. (2008) studied mainly the short-term fire effects, whereas the present study is focused in the long-term effects.

As suggested by our third hypothesis, extractable P showed recovery symptoms as time elapsed since the last fire, unlike N. Our most recent burned plots exhibited minimum P availability, suggesting a lack of retention mechanisms that would lead to the loss of this nutrient through drainage (Sardans et al. 2006). However, P usually tends to be much less mobile than N in soils and much less prone to leaching

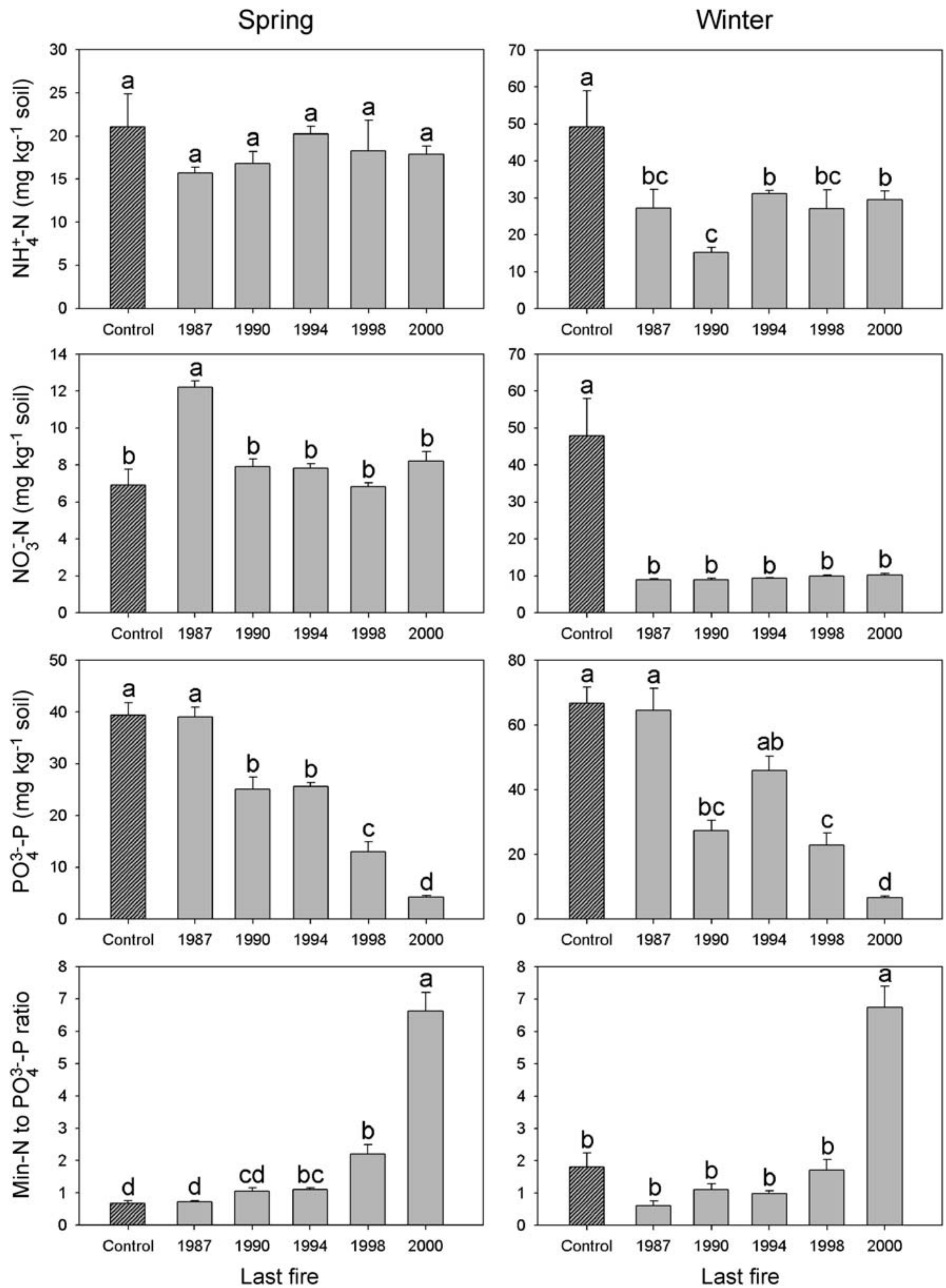

Fig. 2 Means and standard errors for extracted soil ammonium, nitrate, phosphate, and the mineral N (NH_4^+–N + NO_3^-–N) to P ratio. *Same letter* indicates no significant differences between forest plots

losses, especially in volcanic soils (Schlesinger 1997). Accordingly, an alternative hypothesis is that burning could have resulted in restructuring of biogeochemical P fractions, possibly leading to increased sorption (Garcia-Montiel et al. 2000; Ketterings et al. 2002; Serrasolses et al. 2008). Thus, the less dependence of P from on biological retention mechanisms could make this nutrient less susceptible to losses than N (Vitousek and Howarth 1991). Consequently, during forest development after wildfire, changes in the biogeochemistry of P may result in the release of non-occluded P from occluded forms, recovering the pre-disturbance P levels (Garcia-Montiel et al. 2000). However, the increase in extractable P concentrations with time may be also explained due to increasing external inputs of P-rich dust, which can be an agent that prevents P limitation in soils (Crews et al. 1995). The importance of this process is supported by the findings of Moreno et al. (2006), who observed large transfer of mineral particles with a high phosphate content from the African deserts to the Canary Islands. Both biogeochemical differences in the N and P cycle as well as P external inputs may explain the faster recovery of P compared to N after wildfires (Durán et al. 2008).

Our results suggest that the *P. canariensi*s forests exhibited a low resilience for N mineralization rates after wildfires and that differences between burned and unburned plots for net mineralization rates and N pools were minimized during the growing season. Furthermore, unlike N, extractable P demonstrated recovery to pre-fire levels along our fire chronosequence. These findings may have important consequences for forest management since wildfire may exacerbate N limitation and nutrient imbalance in the ecosystem. Thus, the nutritional status found in the burned plots revealed that fire effects are more important for ecosystem functioning than is expected from single observations of burned plots, where adult trees and the forest physical structure seem to be unaffected after wildfire for several years.

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