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Short-term wildfire effects on the spatial pattern and scale of labile organic-N and inorganic-N and P pools

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ABSTRACT

The spatial heterogeneity of essential plant resources plays a crucial role in the structure, composition and productivity of many terrestrial ecosystems. Fires may affect both the availability and spatial pattern of soil nutrients. However, little is known about the effect of fire on the spatial pattern of soil resources. We hypothesized that shortly after a wildfire, the spatial patterns of soil mineral-N, organic labile-N (microbial biomass-N and dissolved organic-N) and extractable-P pools would become more clumped because of ash accumulation and post-fire deposition of litter around individual adult trees. To test this hypothesis, we used plots within a Pinus canariensis forest (with both Pinus canariensis and Adenocarpus viscosus present) and sampled them one month before and one month after a wildfire. Using geostatistical analyses, we examined the spatial patterns of soil mineral-N (NH₄-N and NO₃-N), dissolved organic-N (DON), microbial biomass-N (MB-N) and soil extractable-P (PO₄-P). Burned plots of P. canariensis and A. viscosus both had values that were significantly greater than the unburned plots for all variables, except for DON in both cases, and the N:P ratio in the case of A. viscosus, which showed significantly lower values. Except for DON, we observed an increased spatial dependence and range after a fire for all studied variables in the P. canariensis plots (large individuals). However, in plots with A. viscosus (smaller individuals), we only found differences before and after the fire for the PO₄-P and DON spatial patterns. Our results confirm the changes in the spatial structure of soil variables with fire, and suggest that, on a short-term basis, the physical structure of the plant community may determine the new spatial structure after fire, with a more clumped distribution around large surviving trees and shrubs. The spatial patch size of limiting resources has important consequences for the success of restoration of forest communities on burned areas.

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1. Introduction

The spatial patterns of soil resource availability for plants play a crucial role in the structure, composition and productivity of many terrestrial ecosystems because of the influence on processes at the individual, population and community levels (Tilman, 1988; Gross et al., 1995; Hutchings et al., 2003; Gallardo et al., 2006; Maestre and Reynolds, 2007). In recent decades, many researchers have focused on understanding how plants affect and respond to the spatial pattern of different soil resources (Jackson and Caldwell, 1993a,b; Schlesinger et al., 1996; Maestre and Cortina, 2002; Gallardo, 2003a,b). In almost all cases, the presence of trees and shrubs alters soil physical, chemical and biological properties through its impact on energy and nutrient flow (Gallardo et al.,

2000). Spatial heterogeneity of soil limiting resources may have important consequences for the restoration of altered habitats, since it may determine the probability of finding a favourable site and therefore differing performances of individuals within a population (Gallardo et al., 2006).

Fire is one of the most important disturbances with respect to its effect on nutrient cycling in temperate forest ecosystems (Grogan et al., 2000), significantly affecting the soil-plant system (Wienhold and Klemmedson, 1992). Many previous studies have studied changes in soil nutrient availability and microbial biomass after a fire (Carreira et al., 1994; Romanyà et al., 1994; Dumontet et al., 1996; Alauzis et al., 2004; Turner et al., 2007; Durán et al., 2008). Ash may provide an important nitrogen (N) and phosphorus (P) source on a short-term basis (Raison, 1979; Christensen, 1987; Wienhold and Klemmedson, 1992). This change in soil nutrient composition directly affects soil microorganisms (Hart et al., 2005; Mabuhay et al., 2006), which in turn play an important role in soil fertility (Wardle, 1998).

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Intense disturbances of plant-soil interactions may affect the magnitude and scale of soil heterogeneity (Hutchings et al., 2003). For example, Fraterrigo et al. (2005) found changes in variance and spatial structure in soil nutrients and N transformations in forest sites historically used for agriculture, and Lane and Bassirirad (2005) reported significant changes over time in the spatial structure of organic matter in response to successional changes initiated by restoration. However, little is known about the effect of fire on the spatial structure of soil resources. Hirobe et al. (2003) showed that wildfires may affect both the level and the spatial pattern of nutrient availability. Fuel type (vegetation) and location, together with wind force and direction, are factors that make a fire act very heterogeneously on soil properties (Certini, 2005; Hamman et al., 2007). This heterogeneity and post-fire ash redistribution on the soil may play an important role in the spatial pattern of nutrients, significantly affecting the recolonization of the site by plants and soil microorganisms (Grogan et al., 2000).

Nitrogen is the essential element that most frequently limits primary production in terrestrial ecosystems (Vitousek and Howarth, 1991). The two main sources of labile organic-N are the soil microbial biomass and dissolved organic matter. The soil microbial biomass may act both as source and sink of soil nutrients (Singh et al., 1989). Dissolved organic-N (DON) is emerging as a key element in the nitrogen cycle (Schimel and Bennett, 2004). Although its use by plants has become increasingly recognized (Chapin et al., 1993; Jones and Kielland, 2002), little is known about the factors that control and affect its concentration in the soil (Neff et al., 2003; Christou et al., 2005), and even less is known about the effect of ecosystem disturbance on its spatial distribution. Soil inorganic nitrogen and phosphorus represent immediate nutrient availability for plants and microbes, and they come directly from the mineralization of labile organic sources (Binkley and Vitousek, 1991).

The increasing occurrence of wildfires is a component of global change that affects terrestrial ecosystems (Flannigan and van Wagner, 1991; Piñol et al., 1998). Understanding the consequences of this global environmental change requires knowledge about how fire impacts different levels of ecological organization. The main objective of this study was to describe the effect of fire on the spatial pattern of soil organic labile-N (soil microbial biomass-N and DON), mineral-N, and soil extractable-P at a relevant scale for individual plants. We hypothesize that shortly after a wildfire, the spatial pattern of soil mineral-N, labile organic-N and extractable-P pools would become more clumped because of ash accumulation and post-fire deposition of litter around individual adult trees. The study was done in Pinus canariensis forests on La Palma Island (Canary Islands, Spain). We measured changes in spatial pattern by quantifying patch size and spatial variance, which we expected to be increased by fire.

2. Materials and methods

2.1. Study site

The study was carried out in a *Pinus canariensis* Chr. Sm. ex DC. forest on the western face of La Palma Island (Canary Islands, Spain, $28^{\circ}41'N$, $17^{\circ}45'W$). The altitude of the study area was between 1200 and 1500 m, with mean annual precipitation of 600 mm and a mean annual temperature of 16 °C (Climent et al., 2004). Soils are volcanic in origin, and are classified as leptic umbrisols (FAO, 1996). The soil organic matter content of the sampled plots was about 4% and the soil pH oscillated between 6.5 and 7 (unpublished data). These fires are intense and usually affect several hundred hectares. Although *P. canariensis* adult individuals may lose all

needles during a wildfire, most will regrow after the fire. These trees are fire resistant by having very thick bark (Climent et al., 2007). The current lack of management for commercial purposes and the fire resistance of adults of *P. canariensis* (Climent et al., 2007) make these forests composed mainly of mature individuals of this species, with pine canopies covering almost 80% of the soil surface. Under the pine tree canopy, the understory is sparse and composed of *Adenocarpus viscosus* (Wild.) Webb & Berthel, *Erica arborea* L. and *Cistus symphytifolius* Lam.

2.2. Experimental design

In late September 2005, a wildfire (crown fire) burned a large area where we had intensively sampled two randomly chosen plots one month earlier. One month after the wildfire, we sampled two plots adjacent to the previously sampled ones. On both dates, each plot contained one of the two most common species, P. canariensis and A. viscosus. Plot dimensions depended on the size of the individual plant inside the plot and were chosen to maximize the spatial detection of soil properties around individual plants. Thus, plots with a P. canariensis tree were larger $(8 \text{ m} \times 8 \text{ m} \text{ and } 6 \text{ m} \times 6 \text{ m}, \text{ before and after the wildfire,}$ respectively) than plots with an A. viscosus shrub ($3 \text{ m} \times 3 \text{ m}$ and $4 \text{ m} \times 4 \text{ m}$, before and after the wildfire, respectively). The sampled plots were very homogeneous in terms of rock cover, exposed soil, charred and unburned litter and ash cover. Soil samples were collected from the top 10 cm of the soil profile at 100-cm intervals in large plots and 50-cm intervals in small plots by using a metallic cylinder of 5 cm diameter \times 15 cm high. To increase the spatial resolution, we sampled on a smaller scale within each plot, by randomly selecting four 1 m \times 1 m squares within the large plots and four 50 cm \times 50 cm squares within the small plots. Soil samples were collected at 50 and 25 cm intervals or 25 and 12.5 cm intervals, respectively, (Fig. 1). The total number of soil samples was 121 in the 8 m \times 8 m and 4 m \times 4 m plots and 89 in the 6 m \times 6 m and 3 m \times 3 m plots. Samples were immediately placed in an ice-filled cooler and transported to the lab. Although we selected adjacent plots before and after fire (separated by a few meters), and apparently with identical physical characteristics, we are aware of the lack of replicates in this experimental design, and we only emphasized great differences that are unlikely to be explained by differences between nearby plots.



Fig. 1. Diagram of sampling design inside a plot. Each circle shows a sampling point.

2.3. Laboratory analysis

All soil samples were sieved (<2 mm mesh) in field-moist conditions and then analyzed for mineral-N (NH₄-N and NO₃-N), extractable-P (PO₄-P), microbial biomass-N (MB-N), and dissolved organic-N (DON). In order to extract mineral-N from soil, fresh soil subsamples (5 g) were shaken with 50 ml of 2 M KCl for 1 h at 200 rpm in an orbital shaker and the suspension was filtered through a 0.45 μ m Millipore filter. These extracts were used to determine the amount of NH₄-N and NO₃-N by colorimetry (indophenol blue method) using a microplate reader (Sims et al., 1995; D'Angelo et al., 2001). Extractable-P was estimated by the method for basic soils described by Nelson and Sommers (1996). Fresh soil subsamples (2 g) were shaken with 40 ml of 0.5 M NaHCO₃ in an orbital shaker for 1 h at 200 rpm, filtered through a 0.45 µm Millipore filter and analyzed for PO₄-P using an autoanalyzer for nutrients (Bran+Luebbe – AA3). Soil microbial biomass-N was analyzed using the fumigation-extraction method as outlined by Brookes et al. (1985). Fresh soil subsamples (5 g) were fumigated with chloroform for 5 days. Non-fumigated replicates served as controls. Samples were extracted with 100 ml of 0.5 M K₂SO₄, shaken for 1 h and filtered through 0.45 µm Millipore nitrocellulose filters. Total N in the extracts was converted to nitrate using the persulphate oxidation technique (D'Elia et al., 1977), and the concentration was estimated by the colorimetric method described above. This method has proven to be a rapid and efficient way to measure total N in K₂SO₄ extracts (Cabrera and Beare, 1993; Hossain et al., 1993). DON was estimated by subtracting total N of non-fumigated K₂SO₄ extracts minus mineral-N from the same extracts (Cabrera and Beare, 1993; Doyle et al., 2004). All results were expressed as mg kg^{-1} of soil, based on soil that was oven-dried (80 °C) for 48 h.

2.4. Statistical analysis

A two-sample Asymptotic Permutation Test was performed to compare all variables estimated before and after the wildfire (Röhmel, 1996). Although traditional statistical tests with spatially correlated data may have inflated rates of type I error (Legendre et al., 2002), we found significance levels below 0.001 in all cases (see results below), due to extreme changes in their concentrations after fire. Under these conditions, a type I error is very unlikely. Geostatistical analysis was used to describe the spatial variation of all variables measured in each plot (Robertson, 1987; Rossi et al., 1992). We used semivariograms to show the average variance found in comparisons of samples taken at increasing distance from one another, i.e., the lag interval. To facilitate comparisons, all semivariograms were fitted to a spherical model. The use of other models did not significantly improve the fit. To estimate the magnitude of spatial dependence, we calculated the percentage of total variance (sill; $C + C_0$) explained by the structural variance (C, variance explained by spatial autocorrelation). Range indicates the geographic scale of this dependence, i.e., the distance beyond which samples are spatially independent. Variance that occurs on a smaller scale than the field sampling is found at 0 lag distance, and is known as nugget variance (C_0) . A high nugget variance also may indicate sampling or analytical errors (Isaaks and Srivastava, 1989). A nugget model would indicate lack of spatial dependence for the scale being studied. By common convention, the semivariogram analysis is restricted to distances that are half the longer dimension of the study area. The model fitted to the semivariogram allows for interpolation ("kriging"), which provides optimal and unbiased estimates of non-sampled points. The interpolation of points using semivariograms (kriging) requires the stationarity assumption, a property that met all our variables (Legendre and Fortin, 1989). Prior to geostatistical analysis, all soil properties were transformed to a normal distribution following the formula proposed by Box and Cox (1964):

$$Y' = \frac{(Y^{\lambda} - 1)}{\lambda}, \quad \text{if } \lambda \neq 0, \quad Y' = \log Y, \quad \text{if } \lambda = 0$$

where λ is the transformation parameter.

All statistical analyses were performed with R 2.4.1 for Linux (R Development Core Team, 2007), using the coin and exactRankTests modules for the permutation test (Hothorn and Hornik, 2006), and the geoR and gstat modules for geostatistical analysis (Pebesma and Wesseling, 1998; Ribeiro and Diggle, 2001).

3. Results

Soil microbial biomass-N, mineral-N, NH₄-N, NO₃-N and extractable-P showed values that were significantly higher in burned *P. canariensis* and *A. viscosus* plots than in unburned plots (p < 0.001). However, soil DON concentration for both species and the mineral-N-to-extractable-P ratio in *A. viscosus* plots showed values that were significantly lower in burned than in unburned plots (p < 0.001, Fig. 2). Thus, the mean soil mineral-N concentrations were ten and three times higher in *P. canariensis* and *A. viscosus* burned plots, respectively. For extractable-P, mean values were four and six times higher in *P. canariensis* and *A. viscosus* burned plots, respectively, than in unburned plots. Finally, the mean MB-N had four and three times



Fig. 2. Mean values and standard error for labile organic-N (microbial biomass-N and DON), mineral-N (NH₄ and NO₃-N) and extractable-P for the *P. canariensis* (A) and *A. viscosus* (B) plots before and after the wildfire. Each mean represents a single plot. For *P. canariensis*, sample size (n) was 121 and 89 before and after fire, respectively. For *A. viscosus* plots, n was 89 before fire and 121 after fire.

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Table 1

Variogram model parameters for all soil properties measured before and after the wildfire.

	Sill $(C + C_0)$	Nugget (C_0)	Range (m)	$C/(C + C_0)$ (%)	r^2
Plots with P	. canariensis				
NH₄-N					
Before	Nugget mode	$e[(C/(C + C_0)] = 0$)		
After	15.22	7.13	3.54	53	0.87
NO ₃ -N					
Before	0.27	0.18	1.08	31	0.60
After	4.05	0.15	1.62	96	0.90
Mineral-N					
Before	Nugget mode	$el([C/(C+C_0)] = 0$)		
After	15.99	8.81	1.70	45	0.80
PO ₄ -P					
Before	Nugget mode	$el ([C/(C + C_0)] = 0$)		
After	3.84	1.38	3.15	64	0.78
MB-N					
Before	6.77	3.95	1.50	42	0.77
After	301.43	101.29	1.64	66	0.84
DON					
Before	0.13	0.05	0.71	62	0.72
After	Nugget mode	$el ([C/(C + C_0)] = 0$)		
Plots with A	viscosus				
11015 11111	. 150505				
NH₄-N					
Before	0.41	0.18	1.62	56	0.92
After	2.81	1 17	1.52	58	0.88
	2101		1100	50	0.00
NO2-N					
Before	0.85	0.23	1.87	73	0.83
After	3.86	1.53	1.20	60	0.87
Mineral-N					
Before	0.08	0.04	1.40	50	0.83
After	3 26	1.60	1 72	51	0.83
	5120	1100		01	0.00
PO₄-P					
Before	0.50	0.14	0.74	72	0.82
After	0.22	0.16	1.00	27	0.82
MB-N					
Before	1 52	0.85	13	44	0.78
After	33.22	20.26	2.00	39	0.88
	55.22	20.20	2.00	30	0.00
DON					
Before	3.55	1.30	1.82	63	0.83
After	3.55	0.00	0.35	100	0.78
	5.00	0.00			0.70

higher values in *P. canariensis* and *A. viscosus* burned plots, respectively, than in unburned plots.

Most of the empirical semivariograms fit significantly well to a spherical model, indicating the existence of spatial dependence (*p* < 0.05, Table 1). However, DON in the *P. canariensis* burned plot, and NH₄-N, mineral-N and extractable-P in the P. canariensis unburned plot did not show spatial structure (nugget model). The percentage of total variance explained by the structural variance (spatial dependence) in the P. canariensis unburned and burned plots ranged between 31-62% and 45-96%, respectively. For A. viscosus plots, variance that was explained by the structural variance ranged between 44-72% and 27-100% in burned and unburned plots, respectively. The distance (range) over which samples remained spatially correlated in P. canariensis plots increased from 0.71-1.5 m in unburned plots to 1.62-3.54 m in burned plots. All variables in the burned P. canariensis plot, except for DON, showed a greater range and spatial dependence than in the unburned plot (Table 1, Figs. 3 and 4). In plots with A. viscosus the spatial dependence before and after the wildfire was similar for most variables. However DON and PO₄-P showed higher and lower spatial dependence, respectively, in burned plots than in unburned plots (Table 1, Figs. 3 and 5). Spatial ranges increased after the fire for mineral-N, PO₄-P and MB-N, and decreased for NH₄-N, NO₃-N and DON.

4. Discussion

Processes that explain the increase in the spatial structure of organic and inorganic-N and P pools after a wildfire should coincide, at least partially, with those that explain changes in overall soil nutrient concentrations. Most authors explain the rise in mineral-N by the rapid decomposition of organic-N compounds produced by the combustion of organic matter. Decomposition of these newly formed organic-N compounds is favored by increases in temperature, pH and moisture after the wildfire; where these factors may promote both N mineralization and nitrification (Raison, 1979; Certini, 2005). The increase of mineral-P also occurs as a result of the burning of organic matter, although the release of P bonded to aluminum oxides because of a pH increase may also play an important role (Debano and Klopatek, 1988). The 1-month increase that we noted in soil microbial biomass after a fire may be explained by the increase in soil temperature, humidity and nutrient availability that promotes a favorable environment for the activity of soil microbes, leading to increases in soil microbial biomass (Dumontet et al., 1996; Fisher and Binkley, 2000; Liu et al., 2007). However, decreases in soil microbial biomass after a fire have also been reported because of the increase in organic contaminants, and both a reduction and modification of organic substrates (Fritze et al., 1993; Hernández et al., 1997; Prieto-Fernández et al., 1998; Kim et al., 2003). Unlike soil microbial biomass, DON mean values decreased up to three-fold in all burned plots, suggesting that DON may be actively immobilized or mineralized by the soil microbial biomass after a fire. Other authors have reported a decrease in labile organic carbon after a fire (Fernández et al., 1997). Dissolved organic nitrogen is composed of amino acids and other light organic molecules, and may represent a labile C and N source for soil microorganisms (Chapin et al., 1993; Jones and Kielland, 2002). However, after the fire, the increase in the microbial biomass-N was higher than the decrease in DON, suggesting that DON was not the only C and N source for soil microbes, and that soil microbial biomass was not Climited after the fire.

The geostatistical analysis performed on *P. canariensis* plots showed that, as stated in our hypothesis, fire led to a more clustered pattern in soil mineral-N. labile organic-N and extractable-P. This more clumped spatial pattern may occur because of ash and organic matter accumulation around large P. canariensis canopies, resulting in a more clumped spatial pattern with higher spatial dependence in burned plots. The alternative hypothesis suggesting that ash and plant material would distribute uniformly over the soil surface, thereby causing a decline in the pre-fire spatial pattern, was rejected in P. canariensis plots, because an increase in the spatial dependence of most variables was observed after the fire. The loss of spatial structure for DON concentration after the fire may be explained by DON uptake by plant and soil microorganisms, proportionally decreasing more soil DON concentrations at microsites with the highest DON content, and consequently reducing the spatial pattern intensity.

Except for PO₄-P and DON, differences found in the spatial pattern in the *A. viscosus* plots (smaller individuals) before and after the fire were much lower than in the *P. canariensis* plots (larger individuals) and, because the lack of replicate plots, we can not conclude that these smaller differences can be explained by the

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Fig. 3. Semivariograms for all soil properties measured in *P. canariensis* and *A. viscosus* plots before and after the wildfire. All variables are expressed as mg kg⁻¹ soil.

effect of fire. Several authors have emphasized the importance of the effect that plant size exerts on the spatial pattern of soil nutrients (Zinke, 1962; Jackson and Caldwell, 1993b; Gallardo, 2003a). Thus, differences in plant size between *P. canariensis* trees and *A. viscosus* shrubs may explain the different effect of fire on N and P spatial properties. Furthermore, while *P. canariensis* individuals survive fire, and maintain their ability to intercept materials, *A. viscosus* die, losing a significant part of their aerial biomass. For PO₄-P, we observed a 60% loss in spatial dependence after the fire. As a legume, *A. viscosus* likely has a high phosphorus demand (Dixon and Wheeler, 1983). Before a fire, these individuals may be actively taking up phosphorus below their canopy, generating a spatial structure that disappears after a fire. The disappearance of the spatial structure of phosphorus coincides with a significant increase in soil concentration. Because of the death of *A. viscosus* individuals after a fire, the recovery of the spatial pattern by plant uptake is unlikely. Unlike *P. canariensis* plots, DON concentration in *A. viscosus* plots showed the highest spatial dependence after the fire. However, the small scale (a few centimeters) of this increased spatial dependence suggested that A. Rodríguez et al. / Forest Ecology and Management 257 (2009) 739-746



Fig. 4. Interpolation maps (kriging) for NH₄-N, NO₃-N, PO₄-P and MB-N measured in *P. canariensis* plots before and after the wildfire. All variables are expressed as mg kg⁻¹ soil. Dotted line shows the projection of tree canopy.

this might be due to microbial processes that act on DON production and mineralization more than to the presence of an individual.

In *P. canariensis* plots, the spatial range (the distance over which variables showed autocorrelation) for most variables increased

after the fire. This increase in the spatial scale is consistent with the effect of trees on the spatial distribution of these variables (concentration of burned materials under their canopies). Accordingly, changes in the spatial range of soil variables in *A. viscosus* plots, with smaller individuals, are inconsistent.

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Fig. 5. Interpolation maps (kriging) for PO₄-P and DON measured in *A. viscosus* plots before and after the wildfire. All variables are expressed as mg kg⁻¹ soil. Dotted line shows the projection of tree canopy.

We are not aware of other studies examining short-term changes in the spatial structure of soil N and P pools after a fire. Long-term changes in spatial structure after a fire have been observed by Hirobe et al. (2003) and Smithwick et al. (2005), and these changes have been explained by the effect of vegetation changes on soil nutrient availability.

Our results suggest that, on a short-term basis, the physical structure of the plant community may determine the new spatial structure after fire, with a more clumped distribution around large surviving trees and shrubs. We realize, however, that our experimental design is limited by the lack of replicated plots and the small spatial scale based on sampling on a focal individual, and further experimentation is needed to confirm these changes in spatial pattern. These results may have interesting consequences for restoration of burned sites. As suggested by Gallardo et al. (2006), the spatial patch size of limiting resources has important consequences for forest regeneration, since it determines the probability of finding a favourable site. For example, given a known patch size of the limiting resource, the choice of planting seedlings or large plants in forest restoration may determine how many plants will survive and how many will grow on either a rich or poor nutrient patch during initial stages.

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