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Effect of wildfire on soil physical and chemical properties in a *Nothofagus glauca* forest, Chile

Efecto del fuego en las propiedades físicas y químicas en un bosque de *Nothofagus glauca* en Chile

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ABSTRACT

Effects of a wildfire on soil chemical and physical properties in a *Nothofagus glauca* (Phil.) Krasser forest in the Coastal Mountain Range of south-central Chile were investigated. Response of the soil during the first two years following a wildfire was examined, where data from soil in a burned forest were compared to that in an adjacent, unburned stand. The effects that wildfire have on soil properties in this highly fragmented ecosystem are not well understood, but results from this study suggest similar responses to those found in other mediterranean forest systems. Both physical (bulk density, percent soil moisture, and soil organic matter content) and chemical properties (exchangeable inorganic nitrogen, extractable phosphorus, exchangeable potassium, and soil pH) were examined, and data presented here suggest that soil properties vary in their initial response to fire in this ecosystem. Soil organic matter content and soil moisture decreased following fire and remained lower than values from unburned plots for the duration of the study. Exchangeable potassium increased initially after burning, but values in burned plots decreased with time and by the end of two years were significantly lower than in unburned soil. In turn, extractable phosphorus and soil pH both increased immediately following wildfire and values in burned plots remained significantly higher than unburned plots for the entire measurement period. Exchangeable inorganic nitrogen reached higher levels in soil of burned plots for the autumn measurements (April 1997 and 1998) and lower values in burned plots for the spring measurements (November 1997 and 1998). Soil bulk density remained unchanged following fire. In general, changes in soil properties following fire were greatest at the 0-5 cm layer and more modest at the 5-10 cm sampling depth. These changes were related primarily to oxidation of the detrital layer during fire and concurrent changes in the soil environment following fire (e.g., a reduction in organic matter content of the soil, decreased soil moisture, and increased soil pH). The results of this study have implications for the productivity and sustainable management of the native forest remnants in this region.

Key words: *Nothofagus glauca*, soil chemical properties, soil physical properties, wildfire.

RESUMEN

Se investigó el efecto de un incendio forestal sobre las propiedades físicas y químicas de un bosque de *Nothofagus glauca* (Phil.) Krasser en la zona costera de la zona centro sur de Chile. Durante los dos primeros años después de ocurrido el incendio, se comparó la respuesta de ese suelo con otro de las mismas características, pero por donde no pasó el fuego, ubicado en forma adyacente. A pesar de que el efecto del fuego en las propiedades del suelo en este ecosistema altamente fragmentado son poco conocidas, ellas son comparables a otros ecosistemas forestales de zonas mediterráneas. Se examinaron tanto las propiedades físicas (densidad aparente, porcentaje de humedad y contenido de materia orgánica) como las químicas (nitrógeno inorgánico intercambiable, fósforo extraíble, potasio intercambiable y pH del suelo). La información recogida sugiere que las propiedades del suelo en el ecosistema varían en su respuesta inicial. El contenido de materia orgánica y la humedad del suelo decrecen después del incendio y se mantienen en valores menores que en el sector no quemado, al menos en el tiempo de duración de este estudio. El potasio intercambiable inicialmente se incrementa después del incendio, pero luego decrecen con el tiempo y al final de dos años los valores son significativamente menores que en el sector no quemado. En cambio, tanto el fósforo intercambiable como el pH del suelo se incrementan inmediatamente después del incendio y permanecen en valores significativamente más altos que en el sector no quemado durante todo el tiempo de duración del estudio. El nitrógeno inorgánico intercambiable alcanza niveles más altos en el sector quemado en las mediciones de otoño (abril de 1997 y 1998) y valores más bajos en las realizadas en primavera (noviembre de 1997 y 1998). La densidad se mantiene sin variaciones en forma posterior al incendio. En general, después de ocurrido el incendio los cambios en las propiedades del suelo fueron más grandes en la capa de 0-5 cm de profundidad y más modestos en la de 5-10 cm. Estos cambios, durante el incendio se relacionaron principalmente con la combustión/oxidación de la capa superficial del suelo (horizonte A) y en forma posterior con los cambios simultáneos en el ambiente (e.g., una reducción en el contenido de materia orgánica del suelo, disminución de la humedad del suelo y aumento del pH del suelo). Los resultados de este estudio tienen implicancias para la productividad y sustentabilidad del manejo de los remanentes de bosque nativo que aún quedan en esta región.

Palabras clave: *Nothofagus glauca*, propiedades químicas del suelo, propiedades físicas del suelo, fuego.

INTRODUCTION

Fire is an important natural disturbance in most forest ecosystems and can lead to rapid changes in soils and biogeochemical cycling which, in turn, can have important implications for long-term ecosystem dynamics (Chandler et al. 1983, Aber & Melillo 1991, Martins et al. 1995, Pyne et al. 1996, Schmoldt et al. 1999). Effects of fire on chemical and physical properties of forest soils vary from minimal to profound, depending on factors such as intensity and duration of the fire, soil type, soil moisture content at the time of the fire, and duration and intensity of postfire precipitation events (Chandler et al. 1983, Pyne et al. 1996).

This paper investigates the effects of a wildfire on physical (bulk density, percent soil moisture, and soil organic matter content) and chemical properties (exchangeable inorganic nitrogen, extractable phosphorus, exchangeable potassium, and soil pH) of the soil in a *Nothofagus glauca* (Phil.) Krasser forest in the Coastal Range of south-central Chile. Response of the soils during the first two years following a wildfire are examined, where data from soils in a burned forest are compared to those in an adjacent, unburned stand. Specifically, the study examines the following questions: (1) What soil properties are influenced by wildfire in this ecosystem, and (2) Are these effects short-lived or do they remain apparent for up to two years following the fire?

The temperate deciduous hardwood *Nothofagus glauca* exhibits a thick, scaly bark (Santelices 1997) and is a prolific sprouter after clearcuts (Donoso 1993), characteristics that are often found in fire adapted species. However, there exists no documentation of the frequency of fire in the coastal mountain range of central Chile prior to European settlement. Although the region is characterized by a mediterranean climate with warm, dry summers, the low incidence of lightning and lack of historical documentation would seem to indicate an ecosystem not subjected historically to frequent fires (Donoso 1981). Fire is known to be an important natural disturbance in other Mediterranean climates (Archibold 1995) but, unfortunately, no paleoecological studies documenting historical fire frequency have been conducted in this region to date.

While the role that fire has played over the long-term history of the native vegetation in central Chile is questionable, it has long been an important tool in agricultural and forestry activities where it is used for crop residue elimination and site preparation (Armesto et al. 1994). Utilization of fire as a management tool for the elimination of forest residues in plantations has been widespread due to its simplicity and the relatively low cost of its implementation. In spite of its common use as a management tool, potential effects of fire on soil properties in this area are not well known. Most studies that do exist have concentrated on the effects of fire on the soils present in forest plantations of exotic species (Altieri & Rodríguez 1975, Toro 1987), and the effect of fire on the soil in the native forests has received little attention. While native forests of this region are not necessarily burned deliberately, fires used in the agricultural and plantation areas frequently burn into native habitat, with unknown effects on the vegetation and soils.

Common thought, particularly from an economic point of view, holds that the use of fire in Chile brings more advantages than disadvantages. However, productivity of the vegetation is intimately tied to the soil and the role it plays in important ecosystem functions (e.g., nutrient cycling, energy flow). Alterations to soil physical and chemical properties may well have important implications for ecosystem productivity and function. Moreover, sustainable management of these forests requires information on the consequences that common management practices have for ecosystem structure and function. The effects of wildfire on early postfire succession in this area were explored in an earlier study (Litton & Santelices 2002). Here we describe the effects, beneficial and/or detrimental, that fire has on soil physical and chemical properties in the native forests of the Coastal Range of south-central Chile.

STUDY AREA

Native vegetation in the Coastal Mountain Range of central Chile consists of temperate deciduous forests dominated by *Nothofagus glauca* ("hualo") at higher elevations (100-900 m), with other species of *Nothofagus* sp. and hydrophytes in moister ravines, and sclerophyllous vegetation at lower elevations (Donoso 1993). Central Chile was recently listed as one of 25 global biodiversity hotspots for conservation, making studies of the management and conservation of native vegetation in this region not only important but urgent as well (Myers et al. 2000).

Extensive areas of native vegetation in the coastal mountains of south-central Chile had been cleared and converted to agriculture by the turn of the nineteenth century (Lara & Veblen 1993, San Martín & Donoso 1995). Within the past 50 years, former agricultural lands and much of the remaining native forests have experienced widespread replacement with fast growing exotic plantation species, principally *Pinus radiata* D. Don and *Eucalyptus globulus* Labill (Lara & Veblen 1993). Agricultural and forestry activities have resulted in a highly fragmented landscape, where small patches of native vegetation are dispersed within a matrix of agricultural lands and exotic forest plantations. The native forests have undergone such drastic reductions that the dominant overstory species of the forests examined in this study, *Nothofagus glauca*, is currently considered vulnerable to extinction by the Chilean Forest Service (Benoit 1989).

One of the consequences of replacement of native forests with exotic plantations has been an increased frequency of forest fires (CONAF 1998). *Pinus radiata* is particularly susceptible to fire due to the often-extensive plantations the species occupies, its high flammability, the dry summer months of the Mediterranean-type climate, and the uninterrupted fuel loads characteristic of these sites (Lara & Veblen 1993). While the number of wildfires has more or less remained constant in Chile over the past 6 years, the area of burned plantations has been drastically reduced (CONAF 1998). In contrast, the area of native vegetation affected by fire has increased more than two-fold over the same period. Fires that occur in the native vegetation normally start as human caused wildfires or site preparation fires in the *Pinus radiata* plantations. Increased fire frequency, as a direct result of anthropogenic influence, can alter landscape patterns and disrupt ecosystem structure and function, with unknown short- and long-term consequences (Schmoldt et al. 1999).

The study was conducted in the forest "Costa Azul", property of the Universidad Católica del Maule, located in the Coastal Mountain Range of Chile (35°37' S, 72°45' W) (Fig. 1). The forest is representative of the present-day landscape in the Coastal

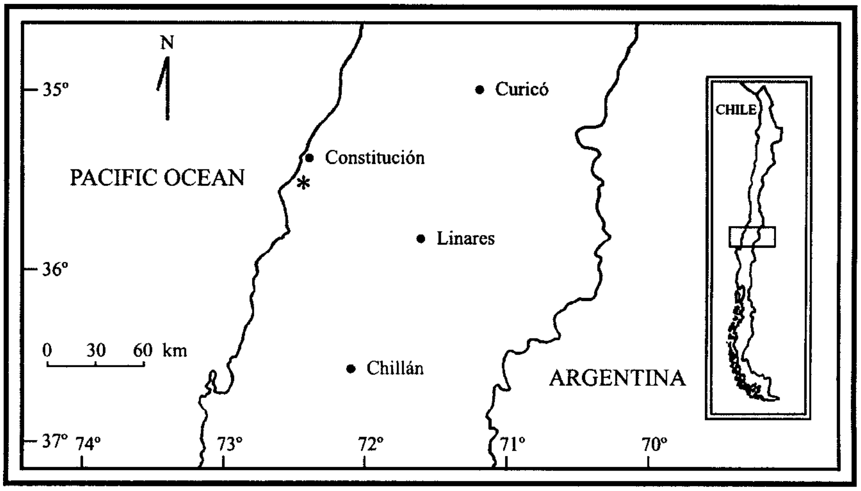

Fig. 1: Map of south-central Chile and location of the study area (*) in the Coastal Mountain Range.

Mapa de la zona centro sur de Chile, representando el área de estudio (*) en la Cordillera de la Costa.

Mountains, with 195 ha in exotic plantations, principally *Pinus radiata*, and 85 ha of native forests, principally *Nothofagus glauca*, located along stream courses and on steep slopes.

The regional climate is typical of Mediterranean areas and is characterized by a conspicuous summer drought of 2-4 months duration and a mild winter rainy season (Amigo & Ramírez 1998). The dry summer months representative of the Mediterranean region are attenuated in the Coastal Mountain Range by increased winter precipitation, high relative humidity, and humid, cool winds from the Humboldt Current of the Pacific Ocean (San Martín & Donoso 1995, Litton & Santelices 1996). Annual precipitation is 943 mm, all falling as rain, and the average annual relative humidity is 73 %. Average annual temperature is 13.8 ° C, with a mean maximum of 24.4 ° C in the hottest month (January) and a mean minimum of 6.0 ° C during the coldest month (July) (Ulriksen et al. 1979, Specht 1988).

The geologic substrate of the coastal mountain range in central Chile has its origins over 245 million years ago in the Paleozoic Era and consists principally of metamorphic rock with occasional granitic intrusions (San Martín & Donoso 1995). The reddish-brown lateritic soils typical of the region are a result of ancient origin and the dry, hot climate prevalent during interglacial periods (Pinochet 1991). Soils in the study area are in the fine, kaolinitic, thermic xeric Haplohumults family (Soil Survey Staff 1999).

MATERIAL AND METHODS

On February 19, 1997 a fire of human origin started in a recently harvested pine plantation. The fire spread onto University property and resulted in a high-intensity surface/crown fire. A total of 19 ha burned, including 6 ha of native forest. In the *Nothofagus glauca* forest, fires burned 100 % of the fine fuels in the standing vegetation, the vast majority of understory biomass, and the litter layer down to the mineral soil. No vegetative regrowth was observed until the following spring (November 1997).

In April of 1997, six 5 x 25 m permanent plots were established, three in the burned forest and three in an adjacent, unburned *Nothofagus glauca* forest. Each 5 x 25 m plot was divided into five 5 x 5 m sub-plots. Soil measurements, as described below, were taken in April and November of 1997 (two and nine months following the fire), and again in April and November of 1998 (14 and 21 months following the fire). April measurements represent autumn and November represents early spring. For soil organic matter and all chemical analyses, soils were collected during each measurement period in all 5 x 5 m sub-plots from the mineral soil (0-5 cm and 5-10 cm depths). Five samples from each of the five sub-plots were taken at both depths with a standard soil corer (i.e., 25 samples at each depth per plot for all measurement periods). The 25 samples for any one depth were then composited within each plot for analysis. For bulk density and percent soil moisture, five cores were taken to 10 cm in each plot (one from each sub-plot) and analyzed separately for the April 1997, November 1997 and April 1998 measurement periods.

All soil analyses were conducted in the Universidad Católica del Maule laboratory in Molina, Chile. Soil bulk density was determined with a standard core method (Culley 1993). Soil moisture (mass water percentage) was calculated using wet and dry weights of cores, where soils were dried at 105 ºC for 48 h (Topp 1993). To calculate soil organic matter content (expressed as a percentage of soil by weight), the soil organic carbon content was first determined with the Walkley-Black method (Nelson & Sommers 1996). The organic carbon values were then multiplied by a factor of 2.0 to estimate soil organic matter content. Exchangeable inorganic nitrogen was analyzed with extraction in potassium chloride and steam distillation (Bremner & Keeney 1965), extractable phosphorus with sodium bicarbonate at a pH = 8.5 (Olsen et al. 1954), and exchangeable potassium using ammonium acetate at pH = 7.0 (Thomas 1982). Soil pH was determined in a 1:2.5 solution (soil:distilled water) and was measured with a standard glass electrode.

Comparisons between unburned and burned sites were made using a non-parametric two-sample t-test (Mann-Whitney U test for difference in medians) in the statistics package NCSS 97 (Hintze 1996). As a result of the small population sample (n = 3), data could not be accurately tested for normality (Hintze 1996). Thus, a non-parametric equivalent of the equal variance two-sample t-test was used. Because seasonal interactions were evident for all parameters measured and the focus of the study was on treatment effects, separate analyses were performed for each property measured at each measurement date. Results were considered statistically significant when the null hypothesis was rejected at P = 0.05.

Ideally, the most reliable approach to studies of this type is to compare changes in a given site over time, including site observations from before the disturbance. A second, more opportunistic approach is to compare post-disturbance sites with nearby, undisturbed areas. Since no data were collected on the burned forest prior to the fire, comparisons between the unburned and burned areas are contingent upon the assumption that the unburned forest is an accurate proxy of the prefire conditions in the burned area.

Burned and unburned areas used in this study are geographically proximate (≈ 1 km), as well as similar in environmental (elevation, slope and aspect) and stand characteristics (composition, age, density and basal area), and should represent a legitimate comparison (Litton & Santelices 2002). In both areas, forests are second-growth stands (~ 60-yrs-old) that have regenerated following logging and minor surface fires. While it is possible that the site history could affect the biogeochemical response of these stands following a wildfire, it is likely that 60 years of recovery would minimize any such effects. In addition, comparisons between burned and unburned forests, and conclusions drawn from those comparisons, should not be affected by site history as historical accounts indicate that all of our stands were subjected to the same disturbance regime.

The experimental design used here represents, in its strictest sense, a pseudoreplicated study. With this in mind, the reader is cautioned that “significant results” should be viewed as nothing more than an indication of the variability across experimental units. Despite this shortcoming, we feel that the results presented contain useful information for scientists and managers, especially in light of the paucity of information available on the subject matter for this region.

RESULTS

Soil organic matter content

Results from this study indicate lower levels of organic matter in burned areas, in both the 0-5 cm and the 5-10 cm depths (Fig. 2). For all measurement periods, at both depths, soil

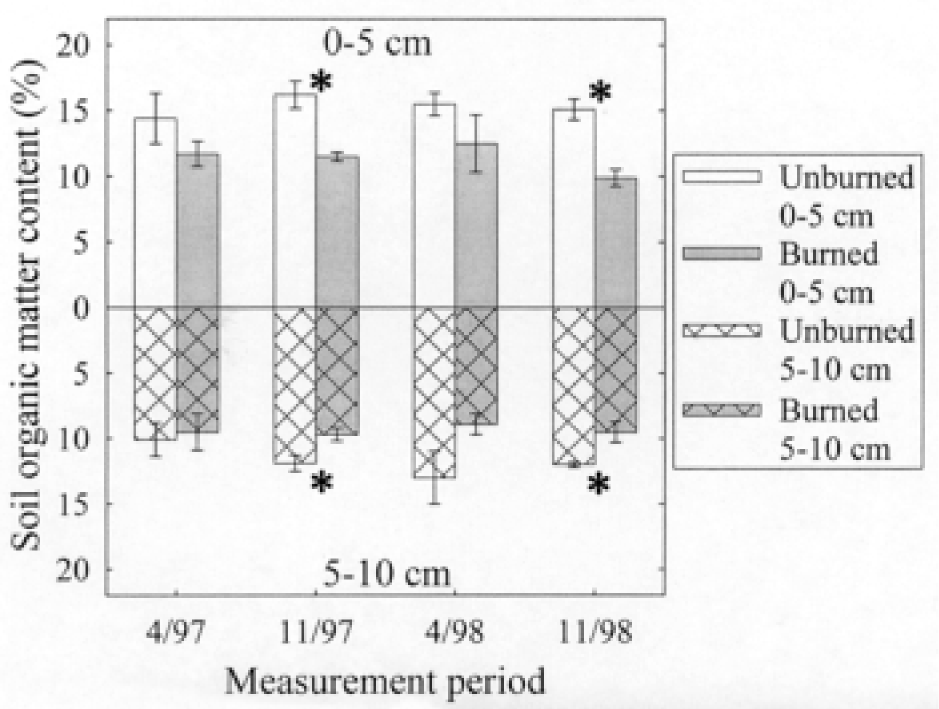

Fig. 2: Soil organic matter content (percentage of soil by weight; Mean ± 1 SE) from 0-5 and 5-10 cm in burned and unburned plots. Statistically significant differences at either depth for each measurement period are indicated by an asterisk (a= 0.05).

Contenido de materia orgánica del suelo (porcentaje de suelo por peso; media ± 1 EE) de 0-5 y 5-10 cm en parcelas quemadas y no quemadas. Diferencias estadísticamente significativas para ambas profundidades en cada período de medición están señaladas por un asterisco (a = 0,05).

organic matter content was higher in the unburned plots. In the spring of 1997 and 1998, nine and twenty-one months after the fire, respectively, soil organic matter content at both depths was significantly higher in the unburned plots than in the burned plots (P < 0.013 at 0-5 cm for 11/97; P < 0.008 at 0-5 cm for 11/98; P < 0.049 at 5-10 cm for 11/97; P < 0.035 at 5-10 cm for 11/98). Levels of soil organic matter varied from 14.4-16.2 % and 9.9-12.5 % at 0-5 cm and 10.1-13 % and 8.9-9.7 % at 5-10 cm in the unburned and burned plots, respectively.

Bulk density and percent soil moisture

No significant differences in the bulk density of soils from unburned and burned plots were found. Mean bulk density of unburned plots varied between 0.72 and 0.82 g cm^{-3}, while that of the burned plots varied from 0.79 to 0.89 g cm^{-3}. Lack of difference between the treatments is surprising in light of the decreased soil organic matter content in soils from the burned sites, which was expected to result in increased bulk density for these soils.

Soil moisture content was higher in the unburned plots for all measurement periods, and was significantly higher in the unburned plots for both April 1997 (P < 0.028) and 1998 (P < 0.001) (Fig. 3). April represents the end of the long dry summer characteristic of Mediterranean regions in the Southern Hemisphere.

Exchangeable inorganic nitrogen

In general, exchangeable inorganic soil nitrogen in this study was higher in the burned plots at both depths for the April 1997 and 1998 measurements and lower in the burned plots at both depths for the November 1997 and 1998 measurements (Fig. 4). For the 0-5 cm depth, exchangeable nitrogen was significantly higher in the burned plots for April of 1997 (P < 0.007) and April of 1998 (P < 0.004). Likewise, for the 5-10 cm depth exchangeable nitrogen was significantly higher in the burned plots for April of 1997 (P < 0.015). Over the duration of the study, exchangeable nitrogen at 0-5 cm varied from 15.8-23.9 ppm in the burned soils and 7.0-25.1 ppm in the unburned soils, and at 5-10 cm it varied from 14.6-16.9 ppm in the burned soils and 7.0-47.5 ppm in the unburned soils.

Extractable phosphorus

Extractable soil phosphorus was higher in burned plots at the 0-5 cm depth and the 5-10 cm depth for all measurement periods (Fig. 5). For the 0-5 cm depth, burned plots had significantly higher concentrations of phosphorus for April 1997 (P < 0.036), November 1997 (P < 0.023), April 1998 (P < 0.029), and November 1998 (P < 0.038). For the 5-10 cm depth, statistically significant

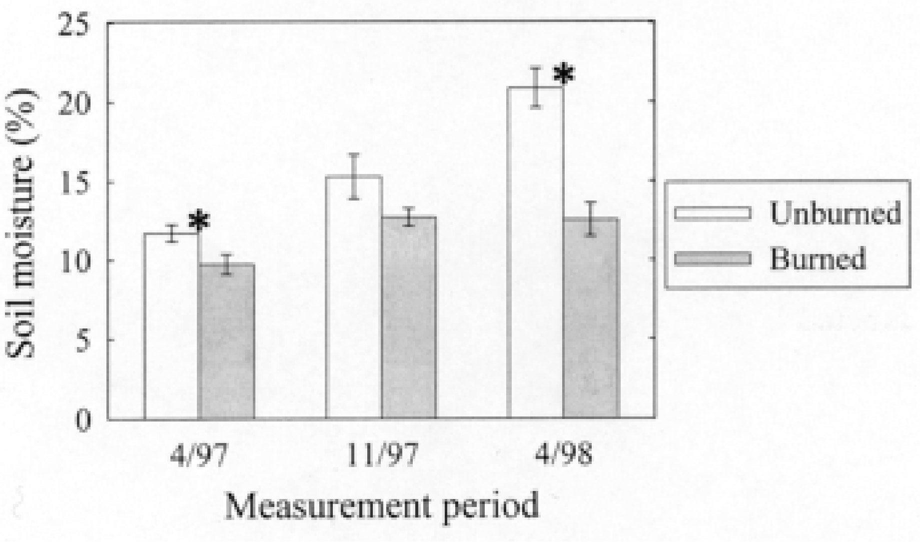

Fig. 3: Soil moisture (%; Mean ± 1 SE) in burned and unburned plots to 10 cm depth. Statistically significant differences for each measurement period are indicated by an asterisk (a = 0.05).

Humedad del suelo (%; media ± 1 EE) para parcelas quemadas y no quemadas a 10 cm de profundidad. Diferencias estadísticamente significativas para cada período de medición son señaladas con un asterisco (a = 0,05).

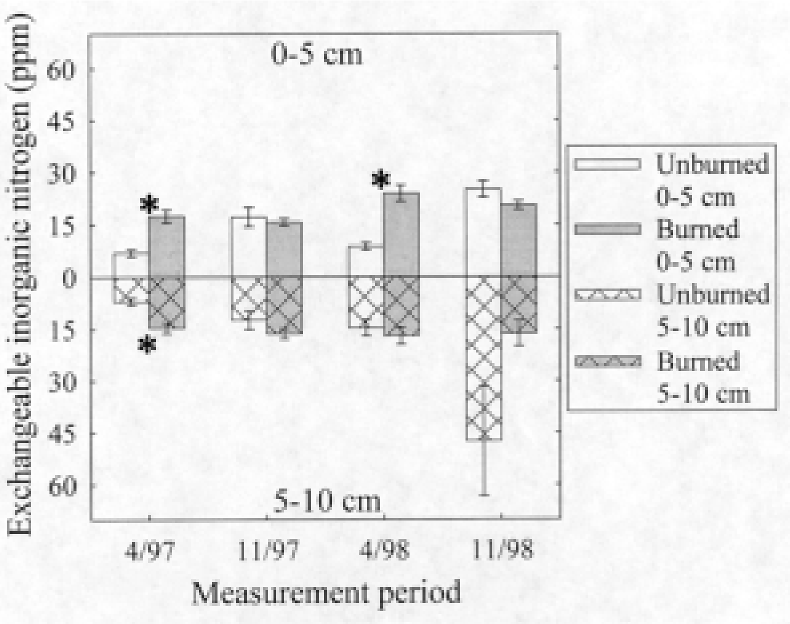

Fig. 4: Exchangeable inorganic soil nitrogen (ppm; Mean ± 1 SE) from 0-5 and 5-10 cm in burned and unburned plots. Statistically significant differences at either depth for each measurement period are indicated by an asterisk (a = 0.05).

Nitrógeno inorgánico intercambiable del suelo (ppm; media ± 1 EE) de 0-5 y 5-10 cm en parcelas quemadas y no quemadas. Diferencias estadísticamente significativas para ambas profundidades en cada período de medición están señaladas por un asterisco (a = 0,05).

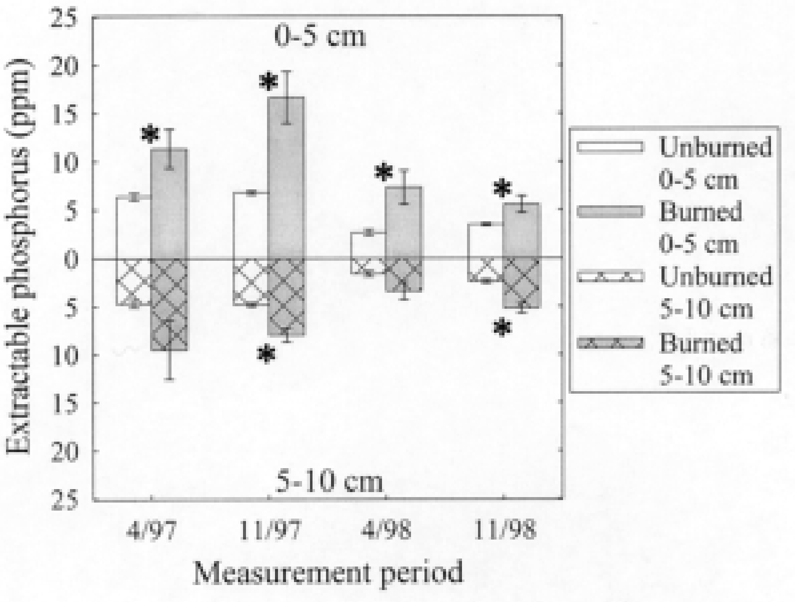

Fig. 5: Extractable soil phosphorus (ppm; Mean ± 1 SE) from 0-5 and 5-10 cm in burned and unburned plots. Statistically significant differences at either depth for each measurement period are indicated by an asterisk (a = 0.05).

Fósforo extraíble del suelo (ppm; media ± 1 EE) de 0-5 y 5-10 cm en parcelas quemadas y no quemadas. Diferencias estadísticamente significativas para ambas profundidades en cada período de medición están señaladas por un asterisco (a = 0,05).

differences were observed only for the November 1997 (*P* < 0.012) and November 1998 (P < 0.006) measurements. Highest measurements for extractable soil phosphorus at both depths in the burned plots were recorded during the April 1997 and November 1997 measurements, two and nine months following the fire, respectively (Fig. 5). Phosphorus levels at both depths decreased with time after the fire.

Exchangeable potassium

Exchangeable soil potassium was initially similar between unburned and burned plots, but decreased with time in the burned plots at both the 0-5 cm depth and the 5-10 cm depth (Fig. 6). Significantly higher levels of potassium were observed in the unburned plots at 0-5 cm for April 1998 (P < 0.041) and November 1998 (P < 0.045), while significant differences at the 5-10 cm depth were observed for the November 1998 measurement (P < 0.045).

Soil pH

Soil pH was significantly higher for all measurement periods in the burned plots for both the 0-5 cm depth and the 5-10 cm depth (Fig. 7). Soil pH over the duration of the study ranged from 5.2-5.5 for the unburned plots and 6.1-6.4 for the burned plots at 0-5 cm, while that at 5-10 cm varied between 4.9-5.4 for the unburned plots and 5.6-6.0 for the burned plots. For both burned and unburned plots, soil pH was lower at the 5-10 cm depth than the 0-5 cm depth (Fig. 7).

DISCUSSION

The wildfire that occurred in February 1997 consumed the vast majority of organic matter on the forest floor, although areas of light burn did occur on the margins of the fire. Measuring wildfire behavior (e.g., intensity, duration, rate of spread) is problematic in that most measurement techniques use sampling procedures requiring knowledge about when and where a fire is to occur. A rough estimate of fire intensity can be made, however, by judging the percentage of forest floor consumed during the fire (De Ronde 1990). Consequently, complete consumption of the organic material on the forest floor in the area studied here indicates that a very high intensity fire occurred in the study area in February 1997.

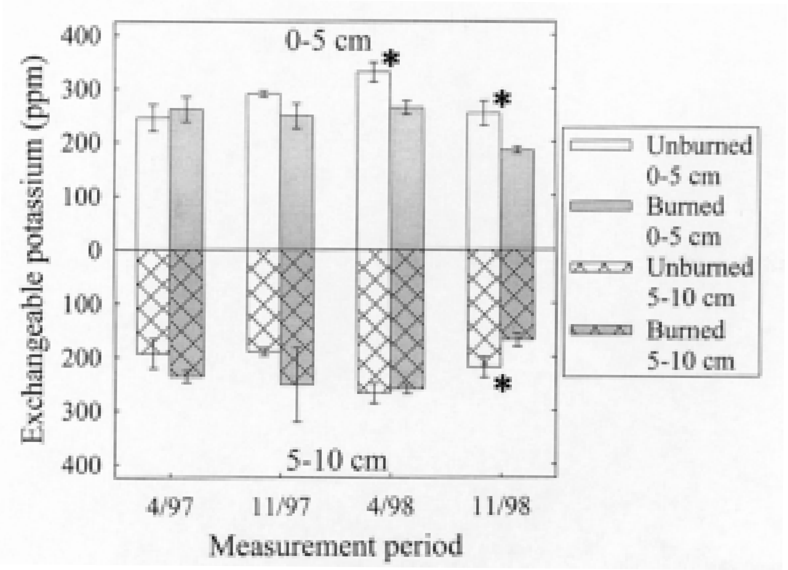

Fig. 6: Exchangeable soil potassium (ppm; Mean ± 1 SE) from 0-5 and 5-10 cm in burned and unburned plots. Statistically significant differences at either depth for each measurement period are indicated by an asterisk (a = 0.05).

Potasio intercambiable del suelo (ppm; media ± 1 EE) de 0-5 y 5-10 cm en parcelas quemadas y no quemadas. Diferencias estadísticamente significativas para ambas profundidades en cada período de medición están señaladas por un asterisco (a = 0,05).

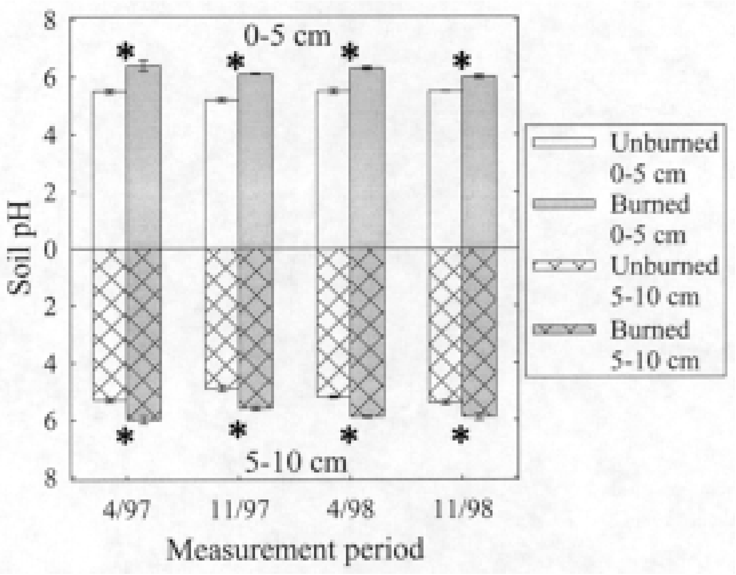

Fig. 7: Soil pH (Mean ± 1 SE) from 0-5 and 5-10 cm in burned and unburned plots. Statistically significant differences at either depth for each measurement period are indicated by an asterisk (a = 0.05).

pH del suelo (ppm; media ± 1 EE) de 0-5 y 5-10 cm en parcelas quemadas y no quemadas. Diferencias estadísticamente significativas para ambas profundidades en cada período de medición están señaladas por un asterisco (a = 0,05).

Soil organic matter content

The loss of the detrital layer from the forest floor represents one of the more obvious alterations to soil physical properties after a fire. The litter layer is an important source of nutrients and organic matter, providing a carbon and nutrient substrate for microbial activity (Wagner & Wolf 1998), as well as acting as insulation from abrupt changes in soil temperature and moisture content. Areas experiencing wildfire after prolonged absence of fire can lose as much as 4,000-9,000 kg ha^{-1} of organic matter from the forest floor (Pritchett & Fisher 1987). Wells (1971) and Olsen (1981) observed that a reduction in the litter layer can result in an increase in organic matter in the first 5 cm of soil, offsetting the reduction of organic matter on the soil surface. Trabaud (1983) also documented an increase in mineral soil organic matter content following fire, but these levels decreased to prefire conditions within a year after burning. In contrast, results from this study show a reduction of organic matter in the mineral soil of burned plots for all measurement periods (Fig. 2). A study conducted by Diaz-Fierros et al. (1990) in a *Ulex europaeus* shrubland in Southern Spain revealed a reduction in organic matter content in the 5-10 cm layer following a prescribed fire. Moreover, other studies conducted in Mediterranean regions have documented reductions in organic matter content in the mineral soil following fire (Naveh 1973, Kutiel et al. 1990).

Results presented in this study on soil organic matter likely represent data only for non-carbonized soil carbon, since the Walkley and Black wet oxidation method that was employed does not oxidize charcoal carbon (Nelson & Sommers 1996). A recent study by Johnson & Curtis (2001) points out that the incorporation of charcoal to soils following fire can, in some cases, partially offset soil organic carbon lost during fire. However, charcoal is a highly recalcitrant form of soil carbon that is essentially inert and unavailable to microbes.

Soil organic matter imparts many desirable biological, physical, and chemical properties to soil, including higher infiltration rates and reduced erosion, better soil aeration, and increased aggregation of soil particles. Moreover, soil organic matter can contribute 20-80 % of the cation exchange capacity (CEC) of a soil, strongly influencing site fertility in regards to cation retention and plant nutrient availability (Wagner & Wolf 1998). Distribution and abundance of the soil microbial community responsible for nutrient cycling and other beneficial attributes of soil is also intimately tied to the amount of organic matter present in a soil (Bottomley 1998). The decreased levels of soil organic matter observed in the burned plots in this study suggest important ramifications for other soil biological, chemical and physical properties. Establishment of postfire vegetation, through both resprouting and seedling establishment, has been rapid on the burned plots (Litton & Santelices 2002). However, it is not likely that litterfall rates in burned forests will approximate those on unburned sites for some time and, thus, soil organic matter content in burned plots will more than likely remain low for some time period.

Bulk density and percent soil moisture

Bulk density, which is directly related to the amount of pore space and to the infiltration rate of a soil, is not affected by wildfire in this system in the two years following the initial disturbance. This has important implications for potential soil erosion on these sites. Fire can contribute to soil erosion by lowering infiltration rates and increasing the water repellency of soil (Díaz-Fierros et al. 1990), both of which can lead to increased surface flow. Díaz-Fierros et al. (1990) reported lower values of bulk density in burned soils which, in turn, led to increased rates of superficial water flow and soil erosion. *Nothofagus glauca* forests in this study do not appear to be at risk for soil erosion, despite the fact that the plots were located on steep slopes (40–81 %). This is more than likely due to the rapid re-establishment of vegetation following fire that was observed in the burned plots (Litton & Santelices 2002).

The thick detrital layer common in deciduous forests can be important for conserving soil moisture through its role in insulating the mineral soil, and in absorbing and retaining water. As a result of the elimination of the detrital layer during fire, the soils in the burned area apparently dry out much faster in the summer. Removal of the litter layer likely resulted in increased soil temperatures which, in turn, led to increased evaporation rates and drying of soils in burned plots. This is interesting in light of reduced plant cover in burned plots (Litton & Santelices 2002), which should result in reduced transpiration rates. Apparently, an increase in evaporation rates from burned forests where the litter layer has been eliminated results in drier soils than in unburned areas with higher transpiration rates, but an intact litter layer. This has important implications for the productivity of these areas, as water may well become limiting in burned forests during dry periods long before it does so in unburned areas.

Changes in soil chemical properties during a fire are related to rapid oxidation of nutrients contained in the living and dead organic matter in the vegetation and detrital layer (Pritchett & Fisher 1987). Likewise, changes in chemical properties following a fire are primarily related to changes in the quantity and quality of the organic matter on the soil surface. Burning can lead to a rapid loss of nutrients from the system as a result of volatilization, leaching, runoff, and/or ash convection (Trabaud 1983). Long-term losses of nutrients from forests following fire, however, have not been widely demonstrated.

Exchangeable inorganic nitrogen

Other studies have reported variable results in relation to fire effects on the nitrogen content of soils (e.g., Johnson & Curtis 2001, Wan et al. 2001). Wan et al. (2001) point out that published responses of inorganic nitrogen to fire are significantly affected by sampling depth, fire type, and time since fire. Kutiel et al. (1990) observed a reduction in total soil nitrogen of 42 % following fire and the lower levels of nitrogen persisted for two years after burning. This is contradictory to the increase in inorganic nitrogen observed in this study two and fourteen months after the fire. Results of Trabaud (1983) and the pattern identified in a meta-analysis by Wan et al. (2001) agree with our study wherein inorganic nitrogen increased in the upper layer of soil in burned plots 15-180 days following burning.

Interesting trends in nitrogen dynamics are apparent for both burned and unburned plots. Burning appeared to result in decreased inorganic soil nitrogen at the beginning of the growing season followed by an increase late in the growing season. A likely explanation for decreased soil nitrogen in spring (November) in burned plots is through increased leaching of NO_3^- during the rainy winter season that is characteristic of the region. Consumption of the litter layer during fire likely leads to increased infiltration rates for burned soils in winter that, in turn, could lead to increased leaching of nitrogen in the form of NO_3^-. Increased nitrogen contents in the burned soils at the end of the growing season are best explained by a possible increase in activity of nitrogen fixing microbes as a result of increased temperatures and elevated pH in the burned soils. For unburned plots, the opposite trend seems to hold in that autumn measurements of inorganic nitrogen are lower than spring measurements for both years. One possible explanation for decreased soil nitrogen during the autumn measurement period in unburned plots pertains to the large input of detritus (i.e., leaf senescence) that occurs during this time period. This could lead to a strong immobilization of nitrogen in soil organic matter during autumn, a pattern that would be absent from burned plots due to greatly reduced litterfall rates as a result of decreased plant biomass.

Nitrogen is easily lost from systems during an intense fire, as it volatilizes at temperatures as low as 200 °C (White et al. 1973). Actual losses of nitrogen due to volatilization have been estimated to vary from 75 kg ha^{-1} (Klemmedson 1976) to 907 kg ha^{-1} (Grier 1975), depending upon the vegetation and detritus present and the intensity and duration of the fire. The amount of nitrogen in the mineral soil after fire, however, has been found to increase, decrease, or remain unchanged, despite the sometimes-large quantities lost through volatilization (Wan et al. 2001). Evidence exists that increased biological nitrogen fixation along with increased mineralization rates following burning may replace much of the nitrogen lost through volatilization during fire (Rundel 1983, Kutiel et al. 1990). Prevailing soil conditions following fire (principally increased soil temperature, moisture, nutrient supply, and pH) may favor symbiotic and, possibly, non-symbiotic fixation of nitrogen (Zuberer 1998). *Sophora macrocarpa* J.E.Sm., a common understory shrub in *Nothofagus glauca* forests, is a nodulated legume that may play an important role in nitrogen fixation following fire in these sites.

Extractable phosphorus

Other studies conducted on effects of wildfire on phosphorus content of forest soils are similar to those found here. Wells (1971) reported significant increases in extractable phosphorus in the 0-10 cm layer of a coastal plains pine system after 20 years of annual burning. Likewise, De Ronde (1990) found that a high intensity wildfire resulted in an immediate increase in phosphorus levels from the 0-5 cm layer of a *Pinus pinaster* forest in the Southern Cape Forest Region of South Africa.

A large portion of the nutrient reserve in most forest ecosystems is contained in the organic material on the forest floor and that distributed throughout the soil profile (Wagner & Wolf 1998). Nutrients contained in this organic material are slowly released into the soil through biological oxidation (i.e., decomposition) (Fuhrmann 1998). While fire can eliminate a large portion of the organic material in the litter layer, it speeds up the process of oxidation and can result in readily available nutrients in the ash left after a fire has passed. Following a precipitation event, these nutrients can dissolve and enter the soil in readily available forms. Increases in nutrients in this way are greatest immediately following a fire, but increases in certain elements can persist for five years or longer (Pritchett & Fisher 1987). Volatilization of phosphorus is not common, and DeBano and Conrad (1978) have suggested that 100 % of the phosphorus found in the plants and litter that are consumed during a fire is returned to the soil surface as ash. If this ash is not removed from the site by wind and surface runoff, it will be incorporated into the mineral soil, resulting in increased levels of extractable phosphorus following fire.

Exchangeable potassium

Much like phosphorus, potassium levels decreased with time since fire. Contrary to the results obtained for phosphorus, however, at the 0-5 cm depth levels of potassium were higher in unburned plots for three out of four measurement periods, and levels at the 5-10 cm depth were higher in the unburned plots for both 1998 measurements. Potassium appears to decrease in concentration in this system with time since fire. These results correspond with those found by Trabaud (1983), but differ from those of De Ronde (1990) who reported significantly higher levels of exchangeable potassium in burned forests for a period of 21 months following a wildfire.

Soil pH

Increases in soil pH following fire have been widely reported (e.g., Wells 1971, De Ronde 1990, Diaz-Fierros et al. 1990, Kutiel et al. 1990), and are due primarily to increases in base elements contained in the ash residue and a decrease in organic acids produced during the biological oxidation of organic matter in the detritus (Wells 1971). The magnitude and duration of change is dependent on the amount and base content of the ash, and the texture and organic matter content of the soil (Pritchett and Fisher 1987). Kutiel et al. (1990) found that soil pH decreased to prefire conditions eight months after a low intensity fire in a pine forest in Israel. Following a high intensity fire, we found that soil pH values remained significantly higher in burned plots for at least two years.

One potentially important implication of increased pH in the burned soils is the possibility for increased nitrogen fixation under environmental conditions favoring both symbiotic and free-living nitrogen fixers. Exchangeable nitrogen concentrations in this study were not significantly higher in the unburned plots for any measurement period at either depth, despite the potential for loss of nitrogen from the burned plots through volatilization during the fire and leaching of NO_3^- following the fire. In fact, concentrations of exchangeable nitrogen were significantly higher in the burned plots for April 1997 at both depths and during April 1998 at the 0-5 cm layer (Fig. 4). While mineralized forms of nitrogen in the ash layer deposited by the fire may account for increased nitrogen in the burned plots immediately after a fire, this reserve of nutrients was more than likely rapidly depleted through microbial and vegetative uptake, as well as leaching during the rainy winter season that occurred within a few months of the fire. The most plausible explanation, then, for continued increases in exchangeable nitrogen in the burned plots is through increased nitrogen fixation as a direct result of changes in the soil environment, including increased soil pH.

CONCLUSIONS

Effects of wildfire on soil in this highly fragmented ecosystem are not well understood. Data from this study suggest soil properties vary in their response to fire over a period of two years. Soil pH and soil moisture content changed notably after fire, with higher values of pH and lower values of soil moisture in burned soils. Nitrogen and phosphorus became more available following fire, while potassium levels were found to be lower in the burned forest. Changes in soil properties were more than likely a result of the oxidation of the detrital layer during the fire and concurrent changes in the soil environment following the fire. Nitrogen availability seemed to change in response to changes in the soil environment that resulted in conditions more favorable for N-fixation, while phosphorus levels probably increased as a result of ash deposition following the fire. Organic matter content of the soils was lower in burned plots for all measurement periods. Changes observed in the organic matter content of the soils and the availability of nutrients to plants and soil microorganisms have short-term implications for the postfire development of the *Nothofagus* forests in central Chile, as well as long-term implications for their productivity and sustainable management.

The widespread use of fire as a management tool in plantation forestry in Chile is likely to continue due to its low cost and ease of implementation. However, we found that fire can significantly affect some soil chemical and physical properties, as well as plant species composition (Litton & Santelices 2002), in these native forest remnants. In light of these findings, we recommend that more attention should be placed on preventing and fighting human-caused fires in native vegetation, and fire breaks should be established around remnants of native forest to prevent further degradation of this ecosystem.

In addition, further research is needed on the effects of fire on soils and vegetation in the *Nothofagus glauca* remnants in the coastal mountains of Chile. Specifically, studies are needed on the long-term effects (i.e., > 2 years) of fire on ecosystem dynamics in the region. Moreover, the effects of short time intervals between burning need to be addressed in order to assess the stability (i.e., resistance and resiliency) of these systems to disturbance. Widespread replacement of native forests with exotic plantation species implores further investigation on ecosystem structure and function as well. A better understanding of the role that fire plays as a natural disturbance in these native forests should allow for intelligent management of this important, yet rapidly vanishing ecosystem.

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