Annals of Silvicultural Research
47(2), 2022: 104-115
https://creajournals.crea.gov.it/asr/

Research paper

# A preliminary study of chemical properties in temperate forest fire of the Chilean Andean range for planning of ecosystems restoration

Roberto Moreno[1,2*], Claudia Rabert[3], Daisy Tapia-Valdebenito[3], Julian Sàez[3], Rodrigo Castro[4], Carlos Esse[5], Juan Ramòn Molina Martìnez[6]

*Received: 20/12/2021 Accepted: 30/07/2022 Published online: 01/09/2022*

**ABSTRACT** Despite vegetation in fire-prone landscapes having different fire adaptations, a change in the worldwide fire regime could affect all ecosystem processes and systems. In this sense, soil systems play a key role in ecosystems, not only providing inorganic nutrients to plants, but also serve as filter water and carbon storage. The aim of this research was to identify the effects of wildfire on the chemical properties of young volcanic soils over the medium-term in two natural protected areas of Andean Mountain range. A comparative statistical analysis was performed to identify significant differences in different soil parameters between forty-eight unburned and burned soil samples. Therefore, significant differences were identified between evaluated samples in organic matter, macronutrients, micronutrients, and cation exchange capacity. Whilst organic soil matter and potassium content substantially increased due to incomplete vegetation combustion; the presence of calcium content and cation exchange capacity decreased with the occurrence of fire. Our findings showed that there were significant differences between unburned soils or a soil that had been burned once and soil that had been burned twice in thirteen years. These findings should support decision making, improving the selection of passive or active restoration actions and thus efficiency in forest management.

**KEYWORDS**: Fire impact, soil properties, forest restoration.

## Introduction

Large forest fires have short-term and long-term impacts on soil system (Giovannini et al. 1990, Doerr and Cerdà 2005, Jhariya et al. 2014, Pereira et al. 2019). Physical, chemical, and biological changes have been previously recorded based on soil properties (Doerr and Cerdà 2005, Alcañiz et al. 2018). The effects depend on the properties of the soil, but also on the frequency and intensity of rainfall events, geomorphology, vegetation resilience, time lapsed and the severity of the fire (Vega et al. 2013a, Zavala et al. 2014, Francos et al. 2018, Urretavizcaya et al. 2018, Chavez et al. 2020). Whilst low and moderate severity fires are generally associated with incomplete vegetation combustion, high severity fires are related to complete vegetation combustion (Castillo et al. 2017, Pereira et al. 2019). Incomplete vegetation combustion generates a large amount of semi-pyrolyzed ashes with high potassium, calcium, and magnesium contents (Kanna et al. 1994, Escudey et al. 2015, Santin et al. 2016, Doerr et al. 2018). Therefore, when there is not a complete combustion of canopy layer, branches and litterfall fall onto the forest ground due to thermal pruning (Stephens et al. 2012). As a result, complete vegetation combustion usually increases chemical soil changes (Bodí et al. 2014, Fernandez and Veg 2016, Ulery et al. 2017, Bridges et al. 2019). Additionally, severe fires also modify the water repellency (MacDonald and Huffman 2004, Mataix-Solera et al. 2013, Pereira et al. 2019) and the cation exchange capacity (Ulery et al. 2017, Garcia-Chevesich et al. 2019, Smettem et al. 2021).

Despite the small and short-term differences that have been reported in pH level, significant differences were found between unburned and burned soils according to organic matter content and macronutrient contents (Certini 2005). The carbon, nitrogen, and potassium cycles are also modified by fire events (Grogan et al. 2000, Johnson and Curtis 2001, Fuentes-Ramirez et al. 2018, Merino et al. 2019).

The soil effects may persist over the short and medium term and that they can be affected by the fire regime (Zavala et al. 2014, Francos et al. 2018). Therefore, a succession of fire events could directly influence the biological parameters of soil over the medium to long term (Fernández et al. 2020).

The effects of wildfires on young volcanic soils are not often the subject of forest fire studies. Many fire-prone areas are instead characterized by old, strongly weathered soils and this is a key part of the ecological role of fire in such ecosystems (Orians and Milewski 2007). Fire might have different effects on volcanic soils which are recent soils formed from ash, scoria and dark brown lava. These soils are characterized by

1 - Universidad de Córdoba - Campus de Rabanales, Grupo de Investigación Botánica Sistemática y Aplicada, Campus de Excelencia Internacional Agroalimentario - Spain

2 - Universidad Cientifica del Sur - Facultad de Arquitectura y Urbanismo Ambiental Miraflores – Perù

3 - Universidad Autónoma de Chile Instituto de Ciencias Biomédicas. Facultad de Ciencias de la Salud Temuco – Chile

4 - Universidad de La Frontera, Laboratorio de consevación y dinámica de suelos volcánicos Temuco – Chile

5 – Universidad Autónoma de Chile Ringgold, Instituto Iberoamericano de Desarrollo Sostenible (IIDS) Temuco – Chile

6 - Universidad de Córdoba, Laboratorio de incendios forestales. Departamento de Ingenieria Forestal, Cordoba, Andalucía - Spain

*corresponding author: z82mogar@uco.es

 http://dx.doi.org/10.12899/asr-2409

a coarse texture, medium depth, good infiltration rate, exceptionally low edaphization and a high content of aluminum hidrosilicates (CIREN 2010, Casanova et al. 2013). Rapid weathering of the volcanic ash means that the soils are rich in organic matter, aluminum, and iron. However, they usually contain low levels of some macro- and micro-nutrients (Borie and Rubio 2008, La Manna and Barroetaveña 2011) and the conversion of organic compounds to inorganic compounds has been previously reported (La Manna and Barroetaveña 2011, Rivas et al. 2012a). Frequent rainfall events on the volcanic soils of the Andean Range rises both the surface runoff and the nutrient infiltration rate (Escudey et al. 2015).

In disturbed ecosystems, such as fire affected forests, several factors (ecosystem resilience, land-use history, landscape context, goals and available resources) should be considered for selecting the most effective management strategy to facilitate forest recovery (Holl and Aide 2011). Two main methods for restoration have been defined: active restoration, that involves human intervention and is focused on accelerated recovery and passive restoration, where the recovery is done by natural regeneration of the forest ecosystem (Meli et al. 2017).

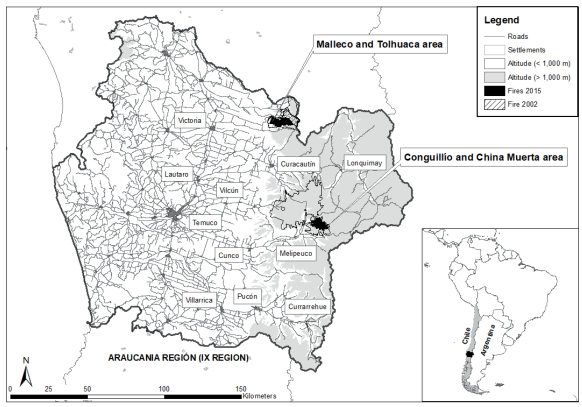
The aim of this research was to identify the effects of wildfire on the chemical properties of young volcanic soils over the medium-term (approximately three years) in two natural protected areas of Andean Mountain range. A comparative statistical analysis was performed to identify significant differences in pH, soil organic matter, macronutrient contents, micronutrient contents, and cationic exchange capacity between unburned soils and burned soils. The novelty of this study is the assessment of the succession of wildfire events on the chemical properties of volcanic soils. One of the study areas has been affected by two fires in only thirteen years (2002 and 2015). Under new climate change scenarios, this change of frequency of large fires has already been noted by other Chilean authors (Ubeda and Sarricolea 2016) and similarly in other countries. The succession of wildfire events could play a key role when evaluating the impact of fire on the chemical properties of soil. Hence, considering the risk of chemical soil degradation is essential when attempting to prioritize restoration and soil conservation measures, as it is an important parameter associated with factors pertaining to land-use history.

## Material and methods

### *Study area and field inventory*

The study was carried out in two natural protected areas located in the IX Region of Chile: Malleco National Reserve (MNR) and Conguillio National Park (CNP) (Fig. 1). Large fires spread across CNP and MNR in March-April 2015. Whilst CNP has been affected by more than 50 volcanic eruptions (the last one in 2009), MNR was burned previously in 2002, 1956, 1928 and 1912 (Iglesias 2011). Although 1912, 1928 and 1956 fire events could have residual effects in MNR, a considerable time has already passed considering the fire-prone nature of these landscapes (Donoso 1993, González et al. 2005). The last CNP eruption did not affect the sampling area.

**Figure 1** - Study area location.




The MNR and CNP soils are derived from ash produced by volcanic activity in the area (Llaima, Lonquimay and Tolhuaca volcanos). The soil type of the study area was characterized as an Andosol (IUSS Working Group WRB, 2015). Generally, these Andosols are resistant to erosion because they have a high aggregative stability and a low runoff response when subjected to important rainfall events. In this sense, the two study areas have a steep topography with slopes of more than 40% and altitudes higher than 1,000 m in many cases (Tab. 1).

**Table 1** - Location, forest type, fire regime and topographical conditions for each sampling area.

| Sampling unit | Location (UTM) | Forestry type | Fire Severity (2015) | Altitude (m) | Slope (%) |
|---|---|---|---|---|---|
| CNP1 | 279,630 5,707,067 | Nothofagus | Unburned | 1,250- 1,300 | 30-50 |
| CNP2 | 279,446 5,707,519 | Nothofagus | Moderate | 1,150 – 1,220 | 20-30 |
| CNP3 | 279,922 5,708,522 | Araucaria | Unburned | 1,275 – 1,310 | 25-35 |
| CNP4 | 280,050 5,707,690 | Araucaria | Moderate | 1,250 – 1,300 | 20-30 |
| MNR1 | 253,838 5,772,918 | Nothofagus | Burned in 2002; unburned in 2015 | 1,025 – 1,075 | 25-35 |
| MNR2 | 253,791 5,771,851 | Nothofagus | Moderate | 875 – 1,025 | 40-50 |
| MNR3 | 254,706 5,773,273 | Nothofagus | Burned in 2002; unburned in 2015 | 825 - 875 | 30-45 |
| MNR4 | 255,057 5,722,813 | Nothofagus | Moderate | 850 - 900 | 40-60 |

According to Curacautin weather station, the mean annual precipitation ranged from 1,275 mm to 1,706 mm in both study areas over the years following the fires (2015-2018) (Dirección Meteorológica de Chile 2020). In 2015 and 2016, immediately after the fires, precipitation was higher than during the other years before sample collection (Fig. 2). The MNR and CNP fires affected protected *Nothofagus-Araucaria* forests. *Araucaria araucana* (Molina) K. Koch is a "National Monument" due to its ecological, cultural, and socioeconomic importance, whereas *Nothofagus* spp. forests are strongly representative of the temperate rainforests in the Andean Range (Donoso 1993). During the MNR fire 5,469 ha of forest was burned, which was made up of 54.68% *Nothofagus* forest and 0.62% *Araucaria* Forest (CONAF 2015a). Meantime, during the CNP fire was affected 3,765 ha, which was made up of 66.7% *Araucaria* Forest and almost 20% Nothofagus forest (CONAF 2015b).

Forest fires show different severities and effects at all levels (Bowman et al. 2019, De la Barrera et al. 2018). For this study, the chemical properties were analyzed only in moderate fire severity areas according to official general technical reports (CONAF 2015a, 2015b), due to that is the situation with more surface in the natural areas in study.

Further studies should consider high severity areas with total Araucaria loss even where soil organic matter and nutrient conditions could be favorable. The moderate severity classification was based on incomplete vegetation combustion and the generation of semi-pyrolyzed ashes (Pereira et al. 2019). Fire severity will be visually confirmed by measuring the effects on vegetation and soil (Appendix I). Five visual levels (layer partially intact, layer totally charred, bare soil and soil structure unaffected, bare soil and soil structure affected, and bare soil and surface soil structure and color altered) adequately reflected chemical soil changes (Vega et al. 2013a).

The sampling plots in CNP and MNR were located based on the 2002 and 2015 fires, to contain soils which had been burned once or twice in 13 years. Four sampling plots in CNP (CNP1, CNP2, CNP3 and CNP4) and four sampling plots in MNR (MNR1, MNR2, MNR3 and MNR4) were sampled according to forest type and fire regime (Tab. 1). *Araucaria* and *Nothofagus* forests were sampled in CNP, but only *Nothofagus* forest was considered in MNR because of the small *Araucaria* area involved (0.62% of the burned area). All sampling plots were georeferenced using GPS to improve spatial-temporal monitoring (Tab. 1). The maximum distance among sampling plots ranged from 1,500 m in CNP to 1,700 m in MNR. The sampling plots were in areas that had no border effects. Although sampling plots were characterized by a good accessibility, the sampling plots were located at least 50 m away from roads or trails. On the other hand, fire regime of the sampling plots was characterized as follows: regime without fire occurrence (CNP1), regime with fire occurrence in 2002 (MNR1 and MNR3), regime with fire occurrence in 2015 (CNP2 and CNP4) and regime with fire occurrence in 2002 and 2015 (MNR2 and MNR4).

### Soil sampling

The soil inventories were developed between October and November 2018, which was 42–43 months (over approximately three years) after the occurrence of fire. Six soil samples from each sampling plot were labeled and transported in hermetically sealed bags to the laboratory. The forty-eight soil samples (approximately 5 cm of soil depth) were manually collected using a shovel according to the (1999) Cambardella and Karlen method. The soil analysis strictly complied with the obligations imposed by the National Accreditation Commission and Chilean Soil Society according to U.S.D.A (USDA 1996).

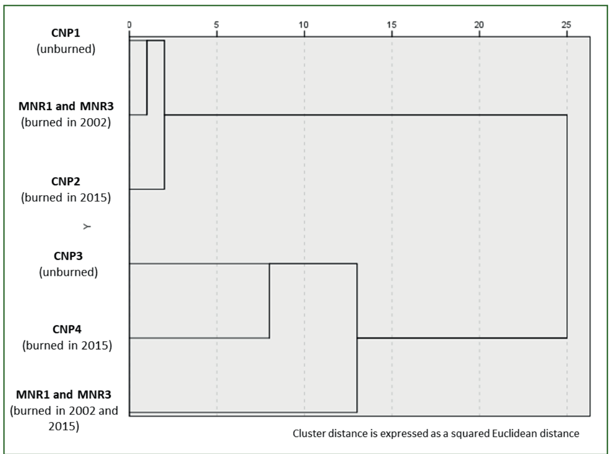
The field inventory included the following chemical properties: pH that was potentiometrically measured in water by soil suspension at a 1:2.5 soil: solution ratio; soil organic matter or SOM (%) that was estimated by wet digestion through a modified Walkley-Black method; total nitrogen or T-N (mg $kg^{-1}$) that was calculated by Kjeldahl method; extractable phosphorus or E-P (mg $kg^{-1}$) that was extracted according to Olsen P procedure with 0.5 M $NaHCO_3$ at pH 8.5 and analyzed by the Murphy and Riley method and turbidimetry; exchangeable potassium or E-K (mg $kg^{-1}$), exchangeable sodium or Na (cmol+ $kg^{-1}$), exchangeable calcium or Ca (cmol+$kg^{-1}$), exchangeable magnesium or Mg (cmol+ $kg^{-1}$) were extracted with 1 M NH4Ac at pH 7.0 and exchangeable Al was extracted by 1 M KCl, analyzed by atomic absorption spectrophotometry.

Base saturation or BS (cmol+ $kg^{-1}$) was calculated as the sum of exchangeable Ca, Mg, K and Na; cation exchange capacity or CEC (cmol+ $kg^{-1}$) was calculated from the total exchangeable bases plus Al exchangeable; aluminum saturation or Al-S (%) was calculated by the formula 1: ((Al exchangeable x 100)/CEC). In further studies, SOM analysis should be supplemented by a study of the quality or composition of carbon pools in volcanic soils affected by wildfires (Rivas et al. 2012b). Soil radiation exposure may have changed the soil properties due to the fire occurrence

### Statistical analysis

The statistical analysis was carried out using SPSS© software. Statistical analysis was performed to identify significant differences amongst unburned soils (CNP1, CNP3), soils burned in 2002 (MNR1 and MNR3), soils burned in 2015 (CNP2 and CNP4) and soils burned twice in 13 years (MNR2 and MNR 4). Firstly, a hierarchical variance analysis (clustering analysis) was considered in both protected natural areas (CNP and MNR) to divide the sampling plot into separate groups or clusters that share common characteristics. Later, an analysis of variance of the unburned soils was used to identify significant differences in soil chemical parameters among the three unburned areas (*Nothofagus* in MNR, Nothofagus in CNP, and *Araucaria* in CNP). If significant differences were performed between *Nothofagus* and *Araucaria* soils, an ANOVA and a Tukey's test (normal distribution) or Mann-Whitney´s test (non-normal distribution) would be used to compare the chemical properties of the unburned soils for each forest type. While the Shapiro test was used to test the normality distribution of the variables, the Levene test was used to assess the equality of variances. The equality or inequality results were used to establish the comparability assumption, and then the t-statistic and significance level was used to identify the bilateral hypothesis ($p < 0.05$). Finally, a Principal Component Analysis (PCA) was performed to analyze the set of variables. PCA is a method for minimizing information loss using different components or a combination of the variables. The creation of a PCA scatter-plot allowed us to disentangle the connections amongst the soil properties.

**Figure 2** - Hierarchical cluster analysis among sampling plots of Conguillio National Park (CNP1, CNP2, CNP 3 and CNP4) and Malleco National Reserve (MNR1, MNR2, MNR3 and MNR4).



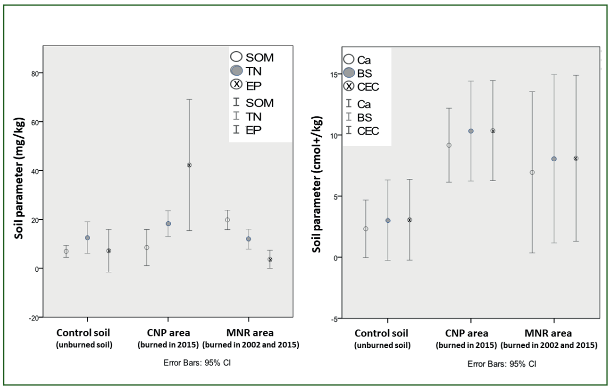

## Results

### *Nothofagus and Araucaria soil*

Although non-significant chemical differences were observed between the unburned MNP and the CNP *Nothofagus* burned in 2002 (CNP1, MNR1 and MNR3), discrepancies were found between the *Nothofagus* and the *Araucaria* unburned soils (CNP3). Cluster analysis allowed us to identify four hierarchical groups: Group I (CNP1, MNR1 and MNR3 and CNP2), Group II (CNP3), Group III (CNP4) and Group IV (MNR2 and MNR4) (Fig. 3). Whilst the most important soil parameter differences and maximum cluster distance was observed between Group I and Group IV, minimum soil parameter differences or least cluster distance was Observed between Group II and Group III. Therefore, the t-test identified significantly differs in the *Araucaria* soils compared to the *Nothofagus* soils. There were differences in SOM ($t = 3.95$, $p < 0.05$), T-N ($t = 4.72$, $p < 0.05$), E-K ($t = 2.81$, $p < 0.05$), Na ($t = 2.36$, $p < 0.1$), and Mg ($t = 3.93$, $p < 0.1$).

We used visual classification based on Vega et al. (2013) considering distinct levels (layer partially intact, layer totally charred, bare soil and soil structure unaffected, bare soil and soil structure affected, and bare soil and surface soil structure and color altered) that adequately reflected chemical soil changes.

**Figure 3** - Box-plots analysis (SOM, T-N, E-P, Ca, BS and CEC) for unburned soils and *Nothofagus* soils that were burned once (CNP) or twice (MNR).




### *Nothofagus soil*

The statistical analysis showed significant differences ($p < 0.05$) in Ca, BS, and CEC between CNP and MNR burned in 2015 and the unburned Nothofagus soils, mainly in MNR (Fig. 4). There were also significant differences ($p < 0.05$) in SOM and E-K from MNR location compared to the unburned soil (Tab. 2). The modification was higher for SOM than E-K. Finally, the CNP burned soil contained significantly ($p < 0.05$) more T-N and E-P than the unburned and burned soils from MNR (Tab. 2). The change was higher for E-P, which showed a 5-fold increase after burning (Fig. 4). The PCA analysis identified the simultaneous changes between SOM and E-K and the connections among BS, CEC, Ca, and Mg (Fig. 5).

### *Araucaria soil*

There were significant differences in E-K ($t = -2.43$, $p < 0.1$), Na ($t = 2.36$, $p < 0.1$), Ca ($t = 2.73$, $p < 0.1$), SB ($t = 2.79$, $p < 0.05$), and CEC ($t = 2.79$, $p < 0.05$) between the unburned and burned soils (Tab. 3). PCA showed a connection amongst BS, CEC, Ca, Mg and Na (Fig. 5). Specifically, Na, Ca, BS, and CEC decreased in the burned soil, but E-K increased after the fire (Tab. 3). The difference in chemical properties in the burned soil ranged from 0.4-fold (Ca) to

0.58-fold (Na). The E-K changed 1.42-fold in the burned soil compared to the unburned soil. There were also non-significant differences in pH, SOM, E-P, T-N, Mg and Al-S.

**Figure 4a 4b** - PCA scatter-plots for *Nothofagus* soils (a) and *Araucaria* soils (b).

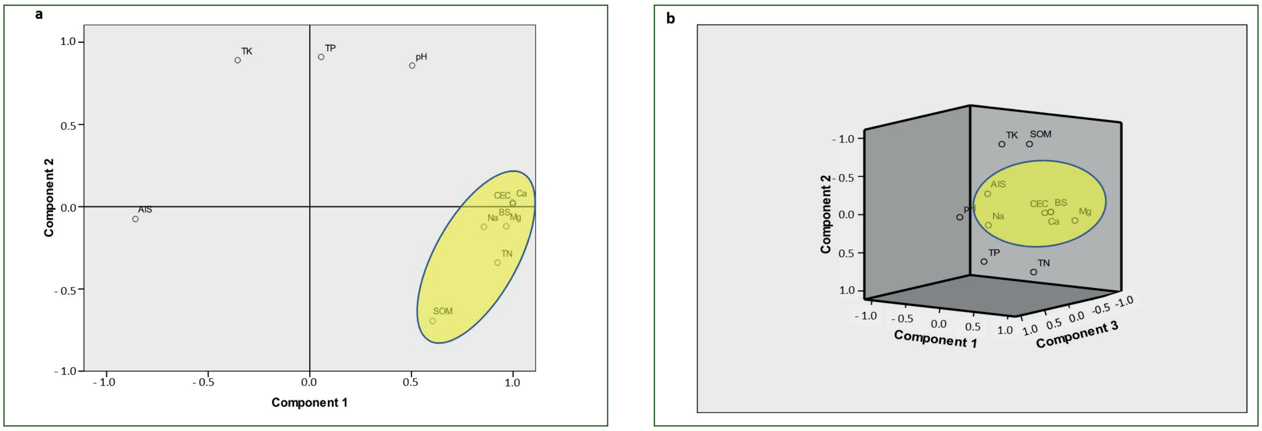



**Table 2** - Comparative analysis between unburned soil and *Nothofagus* burned soils for each natural protected area.

| Properties | Control soil | CNP burned area (burned once) | MNR burned area (burned twice) |
|---|---|---|---|
| pH ($H_2O$) | 6.07(±0.26)$^{a}$ | 6.41(±0.57)$^{a}$ | 6.18(±0.37)$^{a}$ |
| SOM (%) | 6.92(±1.54)$^{a}$ | 8.5(±4.65)$^{a}$ | 19.79(±2.51)$^{b**}$ |
| T-N (mg/kg) | 12.55(±4.06)$^{a}$ | 18.25(±3.30)$^{b**}$ | 11.90(±2.56)$^{a}$ |
| E-P (mg/kg) | 7.17(±5.49)$^{a}$ | 42.25(±16.87)$^{b**}$ | 3.65(±2.32)$^{a}$ |
| E-K (mg/kg) | 55.22(±24.77)$^{a}$ | 63.75(±24.70)$^{a}$ | 116.83(±15.16)$^{b**}$ |
| Na (cmol+/kg) | 0.0375(±0.01)$^{a}$ | 0.035(±0.005)$^{a}$ | 0.0325(±0.03)$^{a}$ |
| Ca (cmol+/kg) | 2.32(±1.47)$^{a}$ | 9.16(±1.90)$^{b**}$ | 6.94(±4.14)$^{ab**}$ |
| Mg (cmol+/kg) | 0.57(±0.40)$^{a}$ | 0.96(±0.72)$^{a}$ | 0.74(±0.24)$^{a}$ |
| BS (cmol+/kg) | 3.02(±2.07)$^{a}$ | 10.32(±2.56)$^{b**}$ | 8.05(±4.32)$^{ab**}$ |
| CEC (cmol+/kg) | 3.06(±2.07)$^{a}$ | 10.35(±2.57)$^{b**}$ | 8.09(±4.26)$^{ab**}$ |
| AlS (%) | 1.55(±1.42)$^{a}$ | 0.37(±0.07)$^{a}$ | 1.44(±1.69)$^{a}$ |

Mean values in a row followed by the same letter are not significantly different (**$p < 0.05$).

Note: SOM is the soil organic matter (%); T-N is the total nitrogen (mg/kg) was done by Kjeldahl method; E-P is extractable P and was estimated by Olsen-method (mg/kg); Ca, Mg, K and Na exchangeable, were determined at pH 7,0 extraction; BS is the base saturation (cmol+/kg); CEC is the cation exchange capacity (cmol+/kg) Ca+Mg+K+Na+Al exchangeable and Al-S is the aluminum saturation (Al exchangeable x100/CEC).

**Table 3** - Comparative analysis between unburned soil and *Araucaria* burned soil.

| Properties | Control | Burned area | Increase or decrease (%) |
|---|---|---|---|
| pH ($H_2O$) | 6.13(±0.73)$^{a}$ | 6.18(±0.27)$^{a}$ | +0.82 |
| SOM (%) | 14.5(±3.53)$^{a}$ | 7.25(±0.96)$^{a}$ | -50.00 |
| T-N (mg/kg) | 31(±5.65)$^{a}$ | 16.25(±0.5)$^{a}$ | -47.58 |
| E-P (mg/kg) | 56.5(±40.30)$^{a}$ | 95.50(±44.84)$^{a}$ | +69.03 |
| E-K (mg/kg) | 123.5(±36.06)$^{a}$ | 176(±19.86)$^{b*}$ | +42.51 |
| Na (cmol+/kg) | 0.065(±0.02)$^{a}$ | 0.0375(±0.01)b* | -42.31 |
| Ca (cmol+/kg) | 14.19(±5.34)$^{a}$ | 6.23(±2.34)$^{b*}$ | -56.10 |
| Mg (cmol+/kg) | 2.615(±0.97)$^{a}$ | 1.215(±0.07)$^{a}$ | -53.54 |
| BS (cmol+/kg) | 17.18(±6.43)$^{a}$ | 7.93(±2.42)$^{b**}$ | -53.84 |
| CEC (cmol+/kg) | 17.21(±6.41)$^{a}$ | 7.98(±2.41)$^{b**}$ | -53.63 |
| Al-S (%) | 0.205(±0.16)$^{a}$ | 0.65(±0.29)$^{a}$ | +217.07 |

Mean values in a row followed by the same letter are not significantly different (** $p < 0.05$, * $p < 0.1$).

Note: SOM is the soil organic matter (%); T-N is the total nitrogen (mg/kg) was done by Kjeldahl method; E-P is extractable P and was estimated by Olsen-method (mg/kg); Ca, Mg, K and Na exchangeable, were determined at pH 7,0 extraction; BS is the base saturation (cmol+/kg); CEC is the cation exchange capacity (cmol+/kg) Ca+Mg+K+Na+Al exchangeable and Al-S is the aluminum saturation (Al exchangeable x100/CEC).

### *Effects of a succession of wildfire events*

Our results showed that the succession of fire events (comparative analysis between one and two large fires in 13 years) in *Nothofagus* forests led to significant differences after three years in the following soil parameters: SOM, T-N, E-P, E-K, Ca, BS, and CEC (Tab. 4). The SOM increased with one and two fires in 13 years, mainly in this last fire regime. The T-N and E-P only increased with one fire, but they decreased after the succession of two fires in 13 years. In addition, a significant Ca, BS and CEC increase was found with one and two fires, but it was more prominent with only one fire (Tab. 4).

**Table 3** - Increase or decrease (%) of chemical soil parameters based on the fire frequency in *Nothofagus* forest.

| Properties | Wildfire events | |
|---|---|---|
| | 1 large fire in 13 years | 2 large fires in 13 years |
| pH (%) | +5.60 | +1.81 |
| SOM (%) | +22.83 | +185.98 |
| T-N (%) | +45.42 | -5.18 |
| E-P (%) | +489.26 | -49.09 |
| E-K (%) | +15.45 | +111.57 |
| Na (%) | -6.67 | -13.33 |
| Ca (%) | +294.83 | +199.14 |
| Mg (%) | +68.42 | +29.82 |
| BS (%) | +241.72 | +166.56 |
| CEC (%) | +238.24 | +164.38 |
| Al-S (%) | -76.13 | -7.10 |

Note: SOM is the soil organic matter (%); T-N is the total nitrogen (mg/kg) was done by Kjeldahl method; E-P is extractable P and was estimated by Olsen-method (mg/kg); Ca, Mg, K and Na exchangeable, were determined at pH 7,0 extraction; BS is the base saturation (cmol+/kg); CEC is the cation exchange capacity (cmol+/kg) Ca+Mg+K+Na+Al exchangeable and Al-S is the aluminum saturation (Al exchangeable x100/CEC).

## Discussion

### *Changes in soil chemical properties*

Forest fires cause structural, physical, and chemical changes in the soil, mainly in the uppermost soil horizon (Pereira et al. 2019, Chavez et al. 2020). Although the natural regeneration and root system may greatly influence soil properties, mainly in infiltration capacity, little is known about the relationship among root biomass and infiltration capacity after wildfires (Wang et al. 2021).

Although this study only evaluated chemical changes in the soil, the results will be supplemented by physical and structural further studies. The pH tends to be moderately alkaline for at least three years after a fire due to carbohydrate, sodium, and potassium oxide production (Certini 2005). In our study, the pH increase in three years was not significant, although it was higher in *Nothofagus* forests. *Nothofagus* soils were generally covered by a thin ash layer that was blackish-grey in color. This fact could be related to the incomplete vegetation combustion and the fall of leaves, twigs, and branches on the ground. Despite some authors (Arocena and Opio 2003, Girona-García et al. 2018) finding significant pH differences in Spanish and sub-boreal soils, Fonseca et al. (2017) and Bridges et al. (2019) did not find any significant pH increase in Spanish and Hungarian soils in a similarly to our findings.

Post-fire SOM in the uppermost soil horizon is dependent on fire severity, SOM volatilization, carbonization and oxidation processes (Vega et al. 2013a, Merino et al. 2019). Many studies (Certini 2005, Bodí et al. 2014, Francos et al. 2018) have associated significant SOM decreases with high severity fires. A non-significant decrease was observed in our *Araucaria* soils, confirming the results of other volcanic soils studies (Le Manna and Barroeteveña 2011, Fuentes-Ramirez et al. 2018).

The *Araucaria* undergrowth, which could range up to 23 t/ha (Castillo 2013), was totally consumed because the dominant understory species (*Chusquea* spp.) were highly flammable (Kitzberger et al. 2016). In this sense, Araucaria soils were classified as "moderate-high severity" (Vega et al. 2013b) due to its dark color. This elevated surface fuel consumption increased the probability of transition from a surface fire to a crown fire (Veblen et al. 2003). The very high canopy base height of A. *araucana* mitigated the effects of thermal pruning and, consequently, crown scorch and the fall of leaves and branches due to convective flux heating (Stephens et al. 2012).

On the other hand, the SOM content had significantly increased in the *Nothofagus* forests 3 years after the fire. These forests have a large number of vegetation strata (Moreno et al. 2014) that were not totally burned under moderate fire severity. Whilst the canopy biomass of the study in *Nothofagus* forests may represent up to 126.11 t/ha (Moreno et al. 2019), the surface biomass can be as much as 35 t/ha (Castillo 2013). In this sense, the incomplete consumption of *Nothofagus* provided organic matter in the form of semi-pyrolyzed ashes (Santin et al. 2016), which could protect the SOM from biochemical decomposition (Johnson and Curtis 2001).

Forest fires can change T-N transformation, but not its total mineralization (Grogan et al. 2000, Choromanska and Deluca 2002, Pereira et al. 2019). Whilst some studies (Rivas et al. 2012a) did not find significant T-N differences between burned and unburned

Nothofagus soils, they did record differences in the levels of $NO_3^-$ and $NH_4^+$. Giovannini et al. (1990) pointed out that the effects depend on the temperature reached by the soil. Although T-N decreases have been reported on severe fires with complete vegetation combustion in Spain and Canada (Girona-García et al. 2018, Doerr et al. 2018), these changes were not significant in our study. This small T-N change could be related to the nitrogen absorption to volcanic soil phase (Bornemisza and Pineda 1969).

The E-P increased in soils burned once in comparison to the unburned soils, as found in other studies (Bodí et al. 2014, Bridges et al. 2019) in European soils. The P can be easily retained by volcanic soils due to their low content and high precipitation value (Stevenson and Cole 1999, Escudey et al. 2015). The E-K increase was significant for *Araucaria* forests due to the presence of forest residues and semi-pyrolyzed ashes in a similar way to other volcanic soil studies (Fuentes-Ramirez et al. 2018).

The Na, Ca, and Mg levels are affected by fire severity (Vega et al. 2013a). The high annual precipitation in volcanic soils of the Andean Range facilitates the absorption of micronutrients, especially Ca (Escudey et al. 2015). Na levels significantly decreased after fire in volcanic soils (La Manna and Barroeteveña 2011). Francos et al. (2018) identified a significant decrease in Ca and Mg levels in Spanish soils, as observed in the *Araucaria* soils. However, other studies (Bodí et al. 2014, Bridges et al. 2019) in European soils reported an increase of Ca and Mg, similarly to our *Nothofagus* soils.

Our contrasting results could be caused by a lower ash presence and leaching processes (Pereira et al. 2019) in *Araucaria* forests due to complete consumption of the understory and low crown scorch (Appendix I).

The BS and CEC significantly increased in the *Nothofagus* soils but significantly decreased in *Araucaria* soils after burning. These responses were due to the direct relationship between CEC and positive cations, such as Ca and Mg (Pereira et al. 2019). This relationship was clearly confirmed by our PCA scatter-plots. A decrease in the cation content (e.g., in Araucaria soils) leads to a reduction in BS and CEC. The BS and CEC are higher when there is incomplete consumption of the vegetation (La Manna and Barroeteveña 2011, Ulery et al. 2017).

However, our findings showed that BS and CEC were much higher than in other studies. This increase could be related to the volcanic singularity of the soils and soil washing due to the topography of the area and high annual precipitation (between 1,706 and 2,560 mm).

Finally, Al has been identified as a limiting element in volcanic soils (Borie and Rubio 2008). The Al-S level tends to decrease after fire, although it can increase over the medium term (Pereira et al. 2019). Nevertheless, no significant Al differences were noted between the unburned soils and soils that were burned once or twice.

### *Effects of a succession of wildfire events*

Most of the studies dealing with fire in A. *araucana* forests have focused on fire effects several years after fire. The innovative aspect of this study is the assessment of the succession of wildfire events on the chemical properties of volcanic soils. Fernández et al. (2020) have reported that the biochemical soil properties change when succession of wildfire events occur. Our SOM increase with a succession of large fires in 13 years could be related to the progressive incorporation of leaves, twigs, and branches from the tree crowns due to thermal pruning. Therefore, the protection of this layer on the ground versus biochemical decomposition, the lower mineralization ratio, and the growth of nitrogen fixing species should improve carbon sequestration from the soil (Johnson and Curtis 2001). This modification in soil sequestration would lead to an increase in SOM and T-N.

The T-N increase was due to N transformation from organic to inorganic forms ($NO_3^-$ and $NH_4^+$) which increases after a fire due to the accumulation of ashes and the nitrification process (Hernández et al. 1997). However, this process had decreased after the succession of a second wildfire in 13 years. This fact could be related to the presence of a low amount of biomass, and therefore, of ashes. The P cycle, which transforms organic P in orthophosphates and increases pH alkalinity (Certini 2005, Orians and Milewski 2007), could be modified by the slight losses caused by volatilization and lixiviation (Pereira et al. 2019).

Wildfires promote a reduction of organic P and an increase of inorganic P due to the mineralization effect (Saa et al. 1993, Grogan et al. 2020). The E-P decrease with two fires in 13 years might occur due to complete vegetation combustion (Girona-García et al. 2018, Doerr et al. 2018) and its low content (Escudey et al. 2015). Our E-P values under the succession of wildfire events were similar to the maximum values obtained in burned Canada soils (Doerr et al. 2018).

Semi-pyrolyzed ashes are rich in nutrients, such as K, Ca, and Mg, because they are a product of incomplete combustion (Escudey et al. 2015, Santin et al. 2016). Potassium is highly soluble in this kind of ash (Khanna et al. 1994). In this sense, the succession of two wildfire events could increase ash levels and K dilution in the soil. Furthermore, the *Nothofagus* litter has high Ca and Mg contents (Goh and Phillips 1991).

A moderate fire or crown scorch would imply higher litterfall biomass levels on the ground. The higher Ca, Mg, BS, and CEC values after one fire compared to two fires could be due to the higher periodic litterfall since 2002 (Pereira et al. 2019). Although the AI-S is only a proportion regarding the total of soil exchangeable cations, its change after a succession of wildfires could be due to the lower pH or soil acidification, which would cause an increase in aluminum hydroxysulfates (Violante et al. 1996).

Fire regimes across the globe have been modified by climate change and socioeconomic changes (Batllori et al. 2013, Rogers et al. 2020), which have made forest soils more vulnerable (Fernández-García et al. 2020). The presence of more frequent fire could result in an important decrease in soil aggregative stability, which would lead to increased erosion (Morales et al. 2013, Neris et al. 2013).

Although in our *Nothofagus-Araucaria* forests, fire regime was classified as being one large fire every 35–60 years in the 20th century (González et al. 2005, Veblen et al. 2008), one of our study areas had a succession of wildfire events in 13 years. This succession of events has already affected the dynamics of the vegetation system in the study area (Molina et al. 2017). Our study analyzed the soil system to obtain a global ecosystem perspective of the succession of wildfire events.

The applied methodology in this study could be extrapolated to any spatial and temporal scale. On one hand, our findings suggested that SOM, E-P, E-K, Na, Ca, BS, and CEC were affected over the medium term (3 years) in volcanic soils after a fire. On the other hand, the succession of wildfire events substantially modified the evolution of soil properties such as SOM, T-N, E-P, E-K, and Ca. Further studies on other soil typologies and fire severities should supplement the approach used in this study, and complex factors, e.g., leaching, volatilization, and soil washing from the uppermost soil horizon, should be investigated.

All this information seeks to contribute to plans for the recovery of ecosystems that have lost wildlife habitat and biodiversity (Braun et al. 2021, Morales et al. 2021). Taking into account that natural regeneration becomes more complex after fires due to the loss of nutrients, erosion, loss of litter that provides protection to seeds and loss of forest structure that protects the first phase of development, amongst other situations (Bonilla et al. 2014, Donoso 1994, Litton and Santelices 2003). Which generates a low resilience to fires, especially those repeated in short periods (Armesto et al. 2009, Valderrama et al. 2018).

These changes in soil chemistry discussed above shorten the time and incremental success of the natural regeneration of burned forests, especially in areas that suffer repeated fires in short periods of time.

This information shows the limits of passive restoration in identified zones with significant problems in nutrient levels. Previous studies showed that successful recovery was obtained without human intervention or even more when human activities in the area has been limited or declined (Duffy and Meier 1992, Guariguata et al. 1997, Jones and Schmitz 2009) but success will depend on the recuperative capacity of the soil present.

Active restoration is the method more widely used for the restoration of ecosystems (Bustamante-Sánchez et. al 2013, Bannister et al. 2018, Meli et al. 2017), in this process the application of the information from this research mainly concerns the elimination of mycorrhized plant systems present in the soil (Godoy and Marín 2019, Torres-Díaz et al. 2021) which has shown positive effects on plant establishment. As well as extended research of the microbiota associated with species that have shown rapid and good resilience to the effects of forest fires, in such a way as to provide information and actions that provide an improvement to the capacities of the damaged soil to recover more quickly and effectively

The restoration of these ecosystems is highly relevant, especially in the current context of climate change and the commitments to reduce emissions and contribute to mitigation, which, thanks to the fixing capacities of forests, make them essential to meet sustainability objectives. Therefore, having information to improve these plans is a great contribution to sustainable development.

In addition to the above, the temperate forests of southern Chile are a global biodiversity hotspot, which would benefit from active restoration over passive recovery or rehabilitation processes, since these forests are the habitat of different bioindicator species that require specific structural and compositional conditions of their native forests for their conservation. Therefore, in order to accelerate the recovery of biodiversity in these forests, the recommended action for active restoration could be implemented, but restricted to areas with accessibility and high degradation level, where this action will positively affect the recovery rate.

## Conclusions

A comparative analysis between burned and unburned soils, which were burned once or twice in 13 years, is a versatile tool that can be used to identify fire severity and soil vulnerability. Soil chemical changes after fire depend on the time elapsed, the soil properties, and the fire severity.

The incomplete consumption of the canopy layer provided organic matter in the form of semipyrolyzed ashes. However, the succession of wildfire events caused significant changes in soil properties. In our study area, the occurrence of two large wildfires in thirteen years led to medium term changes in SOM, macronutrients (T-N, E-K, and E-P) and Ca.

These changes should be complemented with indicators of the ecosystem status.

In disturbed forests, the land management should first consider the biological components, main goals and available resources before defining the actions of a restoration project. The restoration planning should also include the possible succession of wildfire events because the fire regime may promote changes at soil and ecosystem levels. Data about soil systems and fire regimes is of great value to forest managers, particularly when attempting to manage fire vulnerability. Therefore, the fire regime should be obligatory and complemented with supplementary data that can be used when making decisions about post-fire restoration projects.

Choosing the type and activities associated with restoration processes requires as much information and analysis as possible. Therefore, continuing to monitor information such as the one presented, deepening and broadening the analysis of variables, as it is intended to be carried out in the area studied, is essential to provide a better response in the restoration processes.

When choosing between the passive and active restoration actions, and the recently recommended combined or cluster actions, it is necessary to integrate all the information available to ensure the success and speed of the ecological restoration processes.This is especially important not only for the conservation of biodiversity for also for the tasks and commitments of adaptation and mitigation of climate change.

## References

Alcañiz M., Outeiro R., Francos M., Úbeda X. 2018 - *Effects of prescribed fires on soil properties: A review*. Science of the Total Environment 613–614: 944-957.

Armesto J.J., Bustamante-Sánchez M.A., Díaz M.F., González M.E., Holz A., Nuñez-Avila M., Smith-Ramírez C. 2009 - *Fire disturbance regimes, ecosystem recovery and restoration strategies in mediterranean and temperate regions of Chile*. In “Fire Effects on Soils and Restoration Strategies”. Enfield, New Hampshire: 537–567. https://doi.org/10.1201/9781439843338-c20.

Arocena J.M., Opio C. 2003 - *Prescribed fire-induced changes in properties of sub-boreal forest soils*. Geoderma 113: 1–16.

Bustamante-Sánchez M., Bannister A., Caracciolo A., Echeverría J., Suárez J., Zambrano C. 2013 - *Experiencias de restauración en los bosques nativos del sur de Chile: Una mirada desde la Isla Grande de Chiloé*. Revue Bosque Nativos 52: 35–43.

Bannister J.R., Kremer K., Schlegel B., Carrasco-Farias N. V. 2018 - *Silvicultura para la restauración de ecosistemas forestales Norpatagónicos en la Isla Grande de Chiloé, Chile*. In “Silvicultura En Bosques Nativos Experiencias En Silvicultura y Restauración En Chile, Argentina y El Oeste de Estados Unidos”: 215–231.

Batllori E., Parisien M.A., Krawchuk M.A., Moritz M.A. 2013 - *Climate change-induced shifts in fire for Mediterranean ecosystems*. Global Ecology and Biogeography 22 (10): 1118-1129.

Bodí M., Martin D., Balfour V., Santín C., Doerr S., Pereira P., Cerdá A., Mataix-Solera J. 2014 - *Wildland fire ash: Production, composition and eco-hydro-geomorphic effects*. Earth-Science Reviews 130: 103-127.

Bonilla C.A., Pastén P.A., Pizarro G.E., González V.I., Carkovic A.B., Céspedes R.A. 2014 - *Forest Fires and Soil Erosion Effects on Soil Organic Carbon in the Serrano River Basin (Chilean Patagonia)*. In: “Soil Carbon”. https://doi.org/10.1007/978-3-319-04084-4_24.

Borie F., Rubio R. 2008 - *Effects of arbuscular mycorrhizae and liming on growth and mineral acqquisition of aluminum-tolerant and aluminum-sensitive barley cultivars*. Journal of Plant Nutrition 22: 121-137.

Bornemisza E., Pineda R. 1969 - *Minerales amorfos y mineralización de nitrógeno en suelos derivados de cenizas volcánicas*. Panel sobre suelos derivados de cenizas volcánicas de América Latina. Costa Rica: FAO.

Bowman D.M.J.S., Moreira-Muñoz A., Kolden C.A., Chávez R.O., Muñoz A.A., Salinas F., González-Reyes Á., Rocco R., de la Barrera F., Williamson G.J., Borchers N., Cifuentes L.A., Abatzoglou J.T., Johnston F.H. 2019 - *Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires*. Ambio 48: 350–362. https://doi.org/10.1007/s13280-018-1084-1

Braun A.C., Faßnacht F., Valencia D., Sepulveda M. 2021 - *Consequences of land-use change and the wildfire disaster of 2017 for the central Chilean biodiversity hotspot*. Regional Environmental Change 21. https://doi.org/10.1007/s10113-021-01756-4.

Bridges J.M., Petropoulos G.P., Clerici N. 2019 - *Immediate Change in Organic Matter and Plant Available Nutrients of Haplic Luvisol Soil Following Different Experimental Burning Intensities in Damak Forest, Hungary*. Forest 10: 453. doi:10.3390/f10050453.

Cambardella C.A., Karlen D.L. 1999 - *Spatial Analysis of Soil Fertility Parameters*. Precision Agriculture 1: 5–14.

Casanova M., Salazar O., Seguel O., Luzio W. 2013 - *The soils of Chile*. Springer Science & Business Media.

Castillo M. 2013 - *Integración de variables y criterios territoriales como apoyo a la protección contra incendios forestales*. Área *piloto: Valparaíso – Chile Central*. Doctoral Thesis, University of Córdoba, Spain, Córdoba, 247 pp.

Castillo M., Molina J-R., Rodríguez y Silva F., García-Chevesich P., Garfias R.A. 2017 - A *system to evaluate fire impacts from simulated fire behavior in Mediterranean areas of Central Chile*. Science of the Total Environment 579: 1410-1418.

Certini G. 2005 - *Effects of fire on properties of forest soils: a review*. Oecologia 143: 1–10.

Chávez D., Machuca A., Fuentes-Ramírez A., Fernández N., Cornejo P. 2020 - *Shifts in soil traits and arbuscular mycorrhizal symbiosis represent the conservation status of* Araucaria Araucana *forests and the effects after fire events*. Forest Ecology and Management 458: 117806.

Choromanska U., Deluca TH. 2002 - *Microbial activity* *and nitrogen mineralization in forest mineral soils following heating: evaluation of post-fire effects.* Soil Biology and Biochemistry 34: 263–271.

Chuvieco E., Martínez S., Román M.V., Hantson S., Pettinari M.L. 2014 - *Integration of ecological and socio-economic factors to assess global vulnerability to wildfire.* Global Ecology and Biogeography 23: 245–258.

CIREN 2010 - *Determinación de la erosión actual y potencial de los suelos de Chile. Centro de Información De Recursos Naturales.* Santiago, Chile: Ministerio de Agricultura.

CONAF 2015a - *Informe: Diagnóstico y Evaluación Incendio Forestal - R.N. Malleco (Niblinto) - P.N. Tolhuaca 2015. Plan de Restauración Ecológica R.N. Malleco - P.N. Tolhuaca.* Temuco, Chile: Corporación Nacional Forestal. Región de la Araucanía.

CONAF 2015b - *Informe: Diagnóstico y Evaluación Incendio Forestal - China Muerta 2015. Plan de Restauración Ecológica China Muerta.* Temuco, Chile: Corporación Nacional Forestal. Región de la Araucanía.

De la Barrera F., Barraza F., Favier P., Ruiz V., Quense J. 2018 - *Megafires in Chile 2017: Monitoring multiscale environmental impacts of burned ecosystems.* Science of the Total Environment 637–638: 1526–1536. https://doi.org/10.1016/j.scitotenv.2018.05.119

Doerr S., Cerdà A. 2005 - *Fire effects on soil system functioning: new insights and future challenges.* International Journal of Wildland Fire 14 (4): 339-342.

Doerr S., Santín C., Merino A., Belcher C., Baxter G. 2018 - *Fire as a Removal Mechanism of Pyrogenic Carbon from the Environment: Effects of Fire and Pyrogenic Carbon Characteristics.* Frontiers in Earth Science 6: 127. doi: 10.3389/feart.2018.00127.

Donoso C. 1993 - *Bosques templados de Chile. Colección Nueva Técnica.* Santiago de Chile, Chile: Editorial Universitaria.

Donoso C. 1994 - *Bosques templados de Chile y Argentina : variación, estructura y dinámica.* Colección Nueva técnica. Santiago de Chile, Chile: Editorial Universitaria.

Duffy D.C., Meier A.J. 1992 – *Do Appalachian herbaceous understories ever recover From clearcutting?* Conservation Biology 6: 196–201.

Escudey M., Arancibia-Miranda N., Pizarro C., Antilén M. 2015 - *Effect of ash from forest fires on leaching in volcanic soils.* Catena 135: 383–392.

Fernández C., Vega J.A. 2016 - *Modelling the effect of soil burn severity on soil erosion at hillslope scale in the first year following wildfire in NW Spain.* Earth Surface Processes and Landforms 41: 928–935.

Fernández V., Marcos E., Reyes O., Calvo L. 2020 - *Do Fire Regime Attributes Affect Soil Biochemical Properties in the Same Way under Different Environmental Conditions?* Forests 11: 274. doi:10.3390/f11030274.

Fonseca F., De Figueiredo T., Nogueira C., Queirós A. 2017 - *Effect of prescribed fire on soil properties and soil erosion in a Mediterranean mountain area.* Geoderma 307: 172-180.

Francos M., Úbeda X., Pereira P., Alcañiz M. 2018 - *Long-term impact of wildfire on soils exposed to different fire severities. A case study in Cadiretes Massif (NE Iberian Peninsula).* Science of the Total Environment 615: 664-671.

Fuentes-Ramírez A., Barrientos M., Almonacid L., Arriagada-Escamilla C., Salas-Eljatib C. 2018 - *Short-term response of soil microorganisms, nutrients and plant recovery in fire-affected* Araucaria Araucana *forests.* Applied Soil Ecology 131: 99-106.

Garcia-Chevesich P., Martínez E., García A., Castillo M., Garfias R., Neary D., Pizarro R., Valdés-Pineda R., González L., Venegas-Quiñones H., Magni C. 2019 - *Formation of Post-Fire Water Repellent Layers on* Nothofagus glauca *(Hualo) Forests, After the Historical? Las Máquinas? Wildfire in South-Central Chile.* American Journal of Environmental Sciences 15 (1): 1-6. https://doi.org/ 10.3844/ajessp.2019.1.6

Giovannini C., Lucchesi S., Giachetti M. 1990 - *Effects of heating on some chemical parameters related to soil fertility and plant growth.* Soil Science 149 (6): 344-350.

Girona-García A., Badía-Villas D., Martí-Dalmau C., Ortiz-Perpiñá O., Mora J.L., Armas-Herrera C.M. 2018 - *Effects of prescribed fire for pasture management on soil organic matter and biological properties: A 1-year study case in the Central Pyrenees.* Science of the Total Environment 618: 1079-1087.

Godoy R., Marín C. 2019 - *Mycorrhizal Studies in Temperate Rainforests of Southern Chile.* In "Mycorrhizal Fungi in South America. Fungal Biology", Pagano M., Lugo M. (eds). Springer, Cham. https://doi.org/10.1007/978-3-030-15228-4_16.

Goh K., Phillips M.J. 1991 - *Effects of clearfell logging and clearfell logging and burning of a* Nothofagus *forest on soil nutrient dynamics in South Island, New Zealand—changes in forest floor organic matter and nutrient status.* New Zealand Journal of Botany 29: 367–384.

González M.E., Veblen T.T., Sibold J.S. 2005 - *Fire history of* Araucaria-Nothofagus *forests in Villarrica National Park, Chile.* Journal of Biogeography 32 (7): 1187–1202.

Grogan P., Bruns T.D., Chapin F.S. 2000 - *Fire effects on ecosystem nitrogen cycling in a California bishop pine forest.* Oecologia 122: 537-544.

Guariguata M.R., Chazdon R.L., Denslow J.S., Dupuy J.M., Anderson L. 1997 - *Structure and floristics of secondary and old-growth forest stands in lowland Costa Rica.* Plant Ecology 132: 107–20.

Hernández T., García C., Reinhardt I. 1997 - *Short-term effect of wildfire on the chemical, biochemical and microbiological properties of Mediterranean pine forest soils.* Biology and Fertility of Soils 25 (2): 109-116.

Holl K.D., Aide T.M. 2011 – *When and where to actively restore ecosystems?* Forest Ecology and Management 261: 1558-1563.

Iglesias W. 2011 - *Reconstrucción de 500 años de incendios en bosques de* Araucaria araucana *en la primera Área protegida por el Estado: Reserva Nacional Malleco, Región de la Araucanía.* Final Degree Project. Universidad Austral de Chile. Valdivia, Chile. 32 p.

IUSS Working Group WRB 2015 - *World Reference Base for soil resources 2014.* International soil classification system for naming soils and creating legends for soil maps. Update 2015. World Soil Resources Report 106. FAO, Rome.188 p.

Jhariya M., Raj A. 2014 - *Effects of wildfires on flora, fauna and physico-chemical properties of soil-An overview.* Journal of Applied and Natural Science 6 (2): 887 – 897.

Johnson D.W., Curtis P.S. 2001 - *Effects of forest management on soil C and N storage: meta analysis.* Forest Ecology and Management 140: 227–238.

Jones H.P., Schmitz O.J. 2009 - *Rapid recovery of damaged ecosystems.* PLoS One 4: e5653

Khanna P.K., Raison R.J., Falkiner R.A. 1994 - *Chemical properties of ash derived from Eucalyptus litter and its effects on forest soils.* Forest Ecology and Management 66: 107–125.

Kitzberger T., Perry G.L.W., Paritsis J., Gowda J.H., Tepley A.J., Holz A., Veblen T.T. 2016 - *Fire vegetation feedbacks and alternative states: common mechanisms of temperate forest vulnerability to fire in southern South America and New Zealand.* New Zealand Journal of Botany 54 (2): 247-272.

La Manna L., Barroetaveña C. 2011 - *Propiedades químicas del suelo en bosques de* Nothofagus antarctica *y* Austrocedrus chilensis *afectados por fuego.* Revista de Ciencias Agrarias 43 (1): 41-55.

Litton C.M., Santelices R. 2003 - *Effect of wildfire on soil physical and chemical properties in a* Nothofagus glauca *forest, Chile.* Revista Chilena de Historia Natural 76: 529–542. https://doi.org/10.4067/S0716-078X2003000400001

Mataix-Solera J., Arcenegui V., Tessler N., Zornoza R., Wittenberg L., Martínez C., Caselles P., Pérez-Bejarano A., Malkinson D., Jordán M. 2013 - *Soil properties as key factors controlling water repellency in fire-affected areas: evidence from burned sites in Spain and Israel.* Catena 108: 9-16.

MacDonald L., Huffman E. 2004 - *Post-fire Soil Water Repellency: Persistence and Soil Moisture Thresholds.* Soil Science Society of America 68: 1729-1734.

Meli P., Holl K.D., Rey J.M., Jones H.P., Jones P.C., Montoya D., Moreno Mateos D. 2017 - *A global review of past land use, climate, and active vs. passive restoration effects on forest recovery.* PLoS ONE 12(2): e0171368.

Merino A., Jiménez E., Fernández C., Fontúrbel M.T., Campo J., Vega J.A. 2019 - *Soil organic matter and phosphorus dynamics after low intensity prescribed burning in forests and shrubland.* Journal of Environmental Management 234: 214-225.

Molina J.R., Moreno N., Moreno R. 2017 - *Influence of fire regime on forest structure and restoration of a native forest type in the southern Andean Range.* Ecological Engineering 102: 390–396.

Morales D.V., Rostagno C.M., La Manna L.A. 2013 - *Runoff and erosion from volcanic soils affected by fire: the case of* Austrocedrus chilensis *forests in Patagonia, Argentina.* Plant and Soil 370: 367-380.

Morales N.S., Fernández I.C., Duran L.P., Venegas-González A. 2021 - *Community driven post fire restoration initiatives in Central Chile when good.* Restoration Ecology 29: 1–6.

Moreno R., Moreno R., Molina J.R. 2019 - *Optimal harvest cycle on* Nothofagus forests *including carbon storage in Southern America: An application to Chilean subsidies in temperate forests.* Land Use Policy 81: 705-713.

Moreno R., Zamora R., Herrera M.A. 2014 - *Habitat selection of endemic birds in temperate forests in a biodiversity "Hotspot". Forest systems* 23 (2): 216–224.

Neris J., Tejedor M., Fuentes J., Jiménez C. 2013 - *Infiltration, runoff and soil loss in Andisols affected by forest fire (Canary Islands, Spain).* Hydrol Processes 27 (19): 2814-2824.

Orians G.H., Milewski A.V. 2007 - *Ecology of Australia: the effects of nutrient-poor soils and intense fires.* Biological Reviews 82: 393-423.

Pereira P., Mataix-Solera J., Úbeda X., Rein G., Cerdà A. 2019 - *Fire effects on soil properties.* Florida, United States: CRC Press.

Rivas Y., Huygens D., Knicker H., Godoy R., Matus F., Boeckx P. 2012a - *Soil nitrogen dynamics three years after a severe* Araucaria-Nothofagus *forest fire.* Austral Ecology 37: 153-163.

Rivas Y., Matus F., Cornelia R., Knicker H., Garrido E. 2012b - *Black carbon contribution in volcanic soils affected by wildfire or stubble burning.* Organic Geochemistry 47: 41-50.

Rogers B.M., Balch J.K., Goetz S.J., Lehmann C.E.R., Turetsky M. 2020 - *Focus on changing fire regimes: Interactions with climate, ecosystems, and humans.* Environmental Research Letters 15: 030201. https://doi.org/10.1088/1748-9326/ab6d3a.

Saa A., Trasar-Cepeda M.C., Gil-Sotres F., Carballas T. 1993 - *Changes in soil phosphorus and acid phosphatase activity immediately following forest fires.* Soil Biology and Biochemistry 25 (9): 1223-1230.

Santin C., Doerr S., Kane E., Masiello C., Ohlson M., De la Rosa J.M., Preston C.M., Dittmar T. 2016 - *Towards a global assessment of pyrogenic carbon from vegetation fires.* Global Change Biology 22: 76–91.

Smettem K.R.J., Rye C., Henry D.J., Sochacki S.J., Harper R.J. 2021 - *Soil water repellency and the five spheres of influence: A review of mechanisms, measurement and ecological implications.* Science of the Total Environment 787: 147429. https://doi.org/10.1016/j.scitotenv.2021.147429.

Stephens S.L., McIver J.D., Boerner R.E., Fettig C.J., Fontaine J.B., Hartsough B.R., Kennedy P.L., Schwilk D.W. 2012 - *The Effects of Forest Fuel-Reduction Treatments in the United States.* BioScience 62 (6): 549–560.

Stevenson F.J., Cole M.A. 1999 - *Cycles of soil.* Second Edition. London: John Wiley & Sons.

Torres-Díaz C., Valladares M.A., Acuña-Rodríguez I.S., Ballesteros G.I., Barrera A., Atala C., Molina-Montenegro M.A. 2021 - *Symbiotic Interaction Enhances the Recovery of Endangered Tree Species in the Fragmented Maulino Forest.* Frontiers in Plant Science 12: 1–13. https://doi.org/10.3389/fpls.2021.663017.

Ubeda X., Sarricolea P. 2016 - *Wildfires in Chile: A review.* Global Planet Change 146: 152-161.

Ulery A.L., Graham R.C., Goforth B.R., Hubbert K.R. 2017 - *Fire effects on cation exchange capacity of California forest and woodland soils.* Geoderma 286: 125-130.

USDA (United States Department of Agriculture)1996 - *Soil survey laboratory methods manual.* Soil Survey Investigations Reports N°42. Version 3.0. U.S. Department of Agriculture, Washington DC, USA. 693 p.

Urretavizcaya M.F., Peri P.L., Monelos L., Arriola H., Oyharçabal M.F., Contardi L., Defosse G. 2018 - *Condiciones de suelo y vegetación en tres bosques quemados de* Nothofagus pumilio *en Argentina y experiencias para su restauración activa.* Ecología Austral 28 (2): 383–399.

Valderrama L., Contreras-Reyes J.E., Carrasco R. 2018 - *Ecological impact of forest fires and subsequent restoration in Chile.* Resources 7: 1–10. https://doi.org/10.3390/resources7020026.

Veblen T., Baker W., Montenegro G., Swetnam T. 2003 - *Fire and climatic change. In temperate ecosystems of the Western Americas*. Verlag, New York: Springer.

Veblen T.T., Kitzberger T., Raffaele E., Mermoz M., González M.E., Sibold J.S., Holz A. 2008 - *The historical range of variability of fires in the Andean Patagonian* Nothofagus *forest region*. International Journal of Wildland Fire 17 (6): 724–741.

Vega J.A., Fontúrbel T., Merino A., Fernández C., Ferreiro A., Jiménez E. 2013a - *Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland.* Plant Soil 369: 73–91.

Vega J.A., Fontúrbel T., Fernández C., Díaz-Raviña M., Carballas M.T., Martín A., González-Prieto S., Merino A., Benito E. 2013b - *Acciones urgentes contra la erosión en áreas forestales quemadas.* Guía para su planificación en Galicia. Santiago de Compostela, Galicia: Tórculo Artes Gráficas.

Violante A., Rao M.A., Chiara A., Gianfreda L. 1996 - *Sorption of phosphate and oxalate by a synthetic aluminium hydroxysulphate complex.* European Journal of Soil Science 47 (2): 241-247.

Wang L., Zhang J., Zhaod Z., Fu Q., Li T. 2021 - *Vegetation restoration and plant roots improve soil infiltration capacity after a severe forest fire in Daxing'anling, northeast China.* Journal of Soil and Water Conservation 00059. DOI: 10.2489/jswc.2022.00059

Zavala L.M., De Celis R., Jordán A. 2014 - *How wildfires affect soil properties. A brief review.* Geophysical Research Letters 40 (2): 311-333.