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RESEARCH ARTICLE

Effect of wildfires on soil properties of agricultural lands of Mediterranean-climate region in Chile

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ABSTRACT

The frequency and severity of wildfires in Mediterranean climate regions have increased in the last decades due to changes in climatic conditions and land use. This change in the fire regime has increased the threat to forest, shrublands and agricultural lands. To evaluate to what extent wildfires could affect agricultural soils, we evaluated 40 properties of soil samples collected at two depths (0-5 and 5-10 cm) in areas affected by moderate severity wildfires 14 mo prior, and the immediately neighboring unburned area. The overall most relevant soil properties to differentiate between burned and unburned soil, regardless its sampling depth, were selected as soil quality indicators and used to compute a soil quality index. Accordingly, carboxylesterase activity, available soil moisture, pH, Ca, P, Fe, B, S and Cu were selected using a two-way ANOVA. The results showed that carboxylesterase activity decreased from 0.49 ± 0.18 to 0.26 ± 0.16 μmol h^{-1} g^{-1} dry soil, and available soil moisture was reduced from 9.85 ± 0.83 to 8.33 ± 0.52 cm in burned soils. Also, pH significantly decreased from 7.30 ± 0.14 to 6.27 ± 0.23 which affected the subsequent nutrient availability. Thus, Ca and P decreased from 6.50 ± 1.78 to 3.95 ± 0.91 $cmol_{(+)}$ kg^{-1} and from 10.72 ± 2.84 to 7.44 ± 0.91 mg kg^{-1} respectively, whereas Fe increased from 3.89 ± 0.97 to 16.75 ± 3.13 mg kg^{-1}, Cu and S availability doubled, and B content increase by 29%. The overall soil quality index revealed a nonsignificant decreased between unburned (0.59 ± 0.03) and burned (0.55 ± 0.04) soils 14 mo after the fire.

Key words: Mediterranean-climate, soil properties, soil quality, wildfire.

INTRODUCTION

Ecosystems in Mediterranean climate regions are highly fire-prone due to winter precipitation with mild temperatures that promotes plant growth and then summer droughts under high temperatures that enhance biomass flammability (Keeley, 2012). Although high severity wildfires are natural occurrences in these regions, they have lately become a major hazard for these land areas because of their increased frequency and severity (and thus the alteration of the natural fire regime) because of changes in climatic conditions (drier and hotter climate) and land use (Moreira et al., 2020).

Specifically, in Chile, the South-Central Mediterranean region is characterized by hot, dry summers, and cool wet winters (warm-summer Mediterranean climate – Csb; Sarricolea et al., 2017), there are large extensions of monocultural, exotic, forest plantations (Urrutia-Jalabert et al., 2018) that replaced native forests, and other extensive areas of agriculture that have degraded the soils. Both land use changes have increased the fuel load and potential flammability of the landscape (Taylor et al., 2017). In this Mediterranean climate region, as well as the others around the globe, the length of the fire season, heat waves, and fire duration and frequency has notably increased in the last 30 yr (González et al., 2018; CONAF, 2021).

Wildfires in Chile are a threat to forest plantations, native forests, shrublands, and agricultural lands in the coastal range within the Mediterranean climate region. Particularly, in January 2017, wildfires were driven by extreme and unprecedented fire promoting weather conditions (or Fire Weather Index which includes vapor pressure deficit, daily maximum temperature, and summer average temperature). The 2017 fires were the most severe of the last four decades, because they were preceded by a previous severe multiannual drought and were responsible for burning of 266 728 ha forest plantations, 212 830 ha native forest shrublands and grasslands, and 28 729 ha agricultural land, mainly on the coastal range between 33°50' and 38°29' S lat (Bowman et al., 2019; CONAF, 2021) (Figure 1).

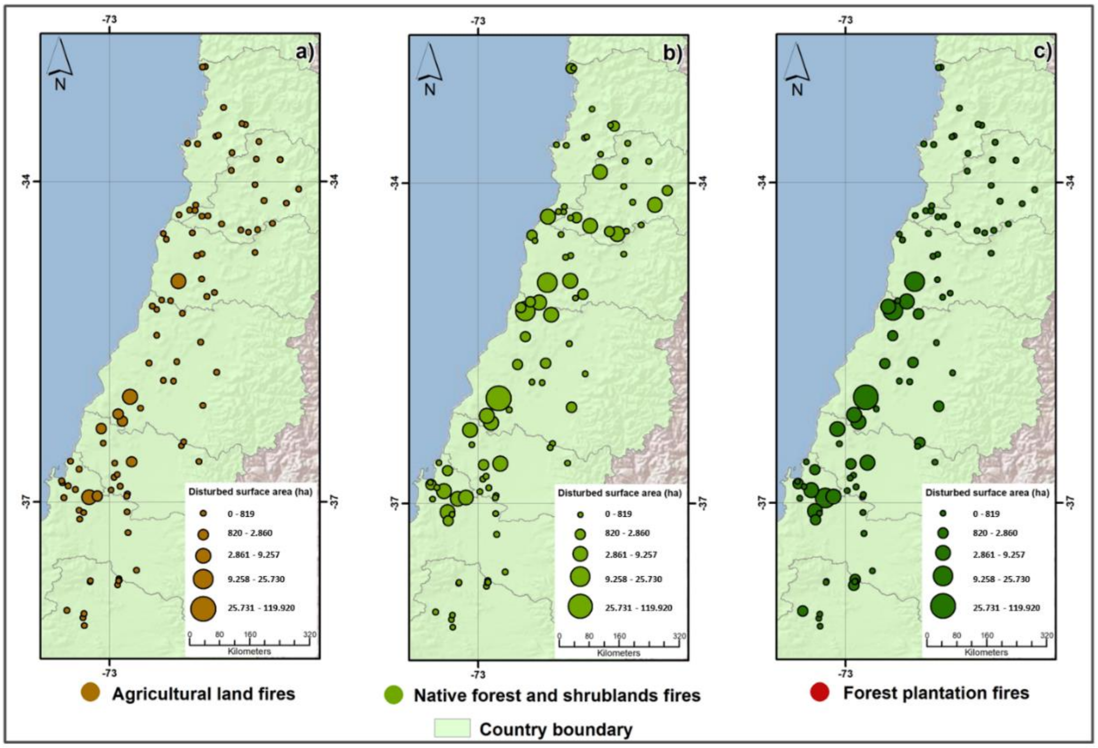

Figure 1. Distribution of disturbed surface area of the 2017 major fire in South-Central Chile. (a) Agricultural lands, (b) native forest and shrublands, and (c) forest plantation.

Even though the 2017 fires were unprecedented, every year several hundreds of hectares of agricultural land are affected by wildfires in Chile and result in an associated total loss of seasonal production. Furthermore, in addition to seasonal production losses, wildfires might increase soil degradation (Moya et al., 2019) and thereby affect agricultural productions in the following seasons in these already degraded agricultural lands comprised of small-scale, non-irrigated, traditional agricultural enterprises that are run by poor rural landowners (Bowman et al., 2019).

While there has been much research that has evaluated wildfire impacts on soil degradation in forests, shrublands, and grasslands, there has been, to date, no study over wildfire effects on the soil of rain-fed (dryland) agriculture in Chile’s coastal range ecoregion.

Although agricultural lands do not accumulate as much biomass (fuel) as forests and shrublands and thus high severity fires are unusual, in the 2017 fires, 33% of agricultural lands were affected by moderate severity fires (de la Barrera et al., 2018).

Several studies suggest fire effects are negligible below 5 cm (Moya et al., 2019). However, fire can indirectly influence soil properties in deeper layers through redistribution of soil due to erosion, infiltration and leaching (Certini et al., 2021). Thus, changes in soil properties below 5 cm in the mid-term (≥ 1 yr) have also been reported (Fonseca et al., 2017; Raiesi and Pejman, 2021).

Most soil properties are unaffected 1 yr after low severity fires, such as prescribed fires. However, important changes in soil's physical and chemical properties are commonly reported in moderate severity fires (Araya et al., 2016). Fire or burn severity can be defined based on loss or decomposition of organic matter aboveground and belowground which is directly related to fire intensity (Certini et al., 2021). Thus, low-intensity fires may reach surface temperatures of up to 250 °C, whereas moderate-intensity fires reach surface temperatures up to 450 °C (Araya et al., 2016).

Usually, changes in soil properties during a fire are related to soil organic matter (SOM) loss and alterations. The charring of SOM starts at 250 °C and at 450°C most of the SOM is combusted (Araya et al., 2016). The decrease of SOM and biomass C losses (Granged et al., 2011; Fernández-García et al., 2019) are associated with other changes in soil biological properties after moderate severity fires of Mediterranean climate regions such as decrease in soil respiration (Vega et al., 2013) and soil enzymatic activity of acid phosphatase, β-glucosidase (Fernández-García et al., 2019), and urease (Moya et al., 2019).

On the other hand, the most significant changes of soil chemical properties that are reported after a moderate severity fire the in Mediterranean climate region are: i) Increased pH (Granged et al., 2011; Vega et al., 2013; Gómez-Rey and González-Prieto, 2014; Heydari et al., 2017; Fernández-García et al., 2019); ii) increased total N (NO_3-N and NH_4-N) (Vega et al., 2013; Gómez-Rey and González-Prieto, 2014; Heydari et al., 2017); iii) increased electric conductivity (EC) (Granged et al., 2011; Heydari et al., 2017); and also greater nutrients availability such as P (Vega et al., 2013; Gómez-Rey and González-Prieto, 2014; Heydari et al., 2017; Moya et al., 2019), K (Gómez-Rey et al., 2013; Heydari et al., 2017), Ca (Gómez-Rey and González-Prieto, 2014) and Mg (Gómez-Rey et al., 2013). Usually, pH and nutrient availability changes are ephemeral (≤ 1 yr) due to the formation of new humus, leaching of bases and removal of ash by erosion process (Alcañiz et al., 2016).

The fire induced changes on soil physical properties such as decreased aggregate stability (AS) (Granged et al., 2011), and an increase in soil bulk density (SBD) and soil water repellency (SWR) (Heydari et al., 2017; Plaza-Álvarez et al., 2018) enhance the post fire risk of erosion and losses of nutrient availability thereby increasing soil degradation (Heydari et al., 2017). Therefore, we can infer that moderate severity fires (wildfires) in Mediterranean climate region may be drivers of agricultural soil degradation.

Our study aimed to identify to which extent a moderate severity wildfire may influence soil degradation on agricultural lands of the coastal range in the Mediterranean climate region of Chile. Therefore, we hypothesized that soil quality of agricultural lands in Mediterranean-climate region decreases 14 mo after a moderate severity wildfire.

MATERIALS AND METHODS

Study site description

This study was conducted within a Mediterranean climate (Csb) on a dry land vineyard affected by wildfires in the coastal range of the administrative Biobío Region in central Chile (Figure 2).

The mean annual precipitation in this area is 1633 mm with summer mean temperature of 18.1 °C and winter mean temperature of 8.9 °C (Santibáñez et al., 2016). The elevation corresponds to 255 m a.s.l. with a slope between 9% and 15%.

The study site was partially burned in January 2017 by moderate severity wildfire according to the indicators defined by Heydari et al. (2017). Thus, the study site was composed of two plots: i) Unburned vineyard (UBV) (700656 E, 5932780 S) and ii) Burned vineyard (BV) (700577 E, 5932763 S).

The soil order is Alfisols with a clay loam texture and was developed from saprolitic granitic materials, mapped as Cauquenes Soil Association, and classified as Ultic Palexeralfs.

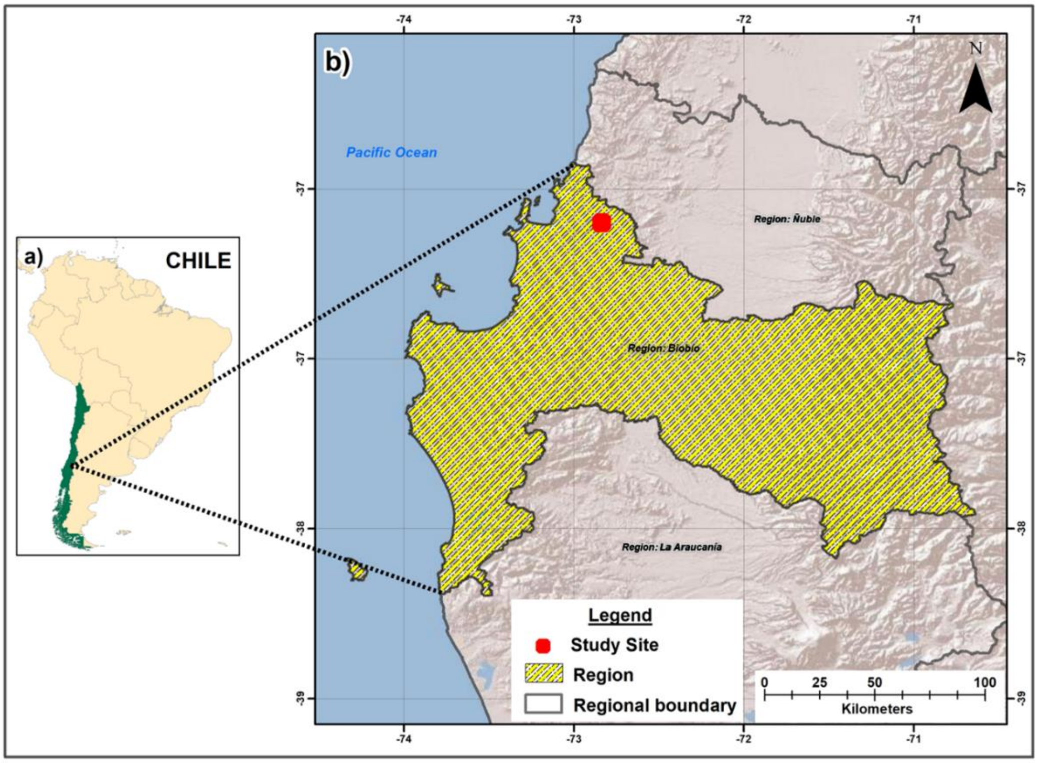

Figure 2. Location of the study site. (a) Regional location, (b) national location.

Experimental design and sample collection

Samples were collected in March 2018, 14 mo after the wildfire. Three sample plots (150 m^2 each) were randomly selected inside the burned area and the immediately adjacent unburned area. The burned and unburned areas had the same edaphic development, topography, land use and agricultural management. Thus, the unburned areas were used as a control to determine wildfire effect on soil properties, assuming that the unburned areas were at steady state and the burned areas had no further disturbances after the fire (Raiesi and Pejman, 2021). In each plot, 25 subsamples were collected at two depths: 0-5 and 5-10 cm. The subsamples were mixed to obtain a composite sample for each treatment. Thus, 12 composite soil samples (2 treatments × 2 depths × 3 plots) were stored in plastic bags and transported to the Soil Department Laboratory, Universidad de Concepción, and kept at 4 °C until analysis.

Laboratory analysis

The main physicochemical and biological soil properties (n = 40) were determined for each sample, as follows:

Soil organic matter (SOM) was determined by reducing the C in SOM with dichromate in an acid media (Sadzawka et al., 2006). Soil microbial C mineralization was measured by the incubation of triplicate 20 g soil for 56 d. Small vials with 7.5 mL 0.5 M NaOH were placed in the incubations chambers and the solution was changed after 3, 7, 14, 28 and 56 d and titrated with 0.1 M HCl in the presence of $BaCl_2$ (El-Saeid and Usman, 2022).

Acid phosphatase (AcP), β-glucosidase (Glu), urease (Ure), protease (Prot), dehydrogenase (Deh), and carboxylesterase (CbE) activities were measured in 1:50 (w/v) soil-water suspensions. Sodium azide (1 mM) was added to soil water suspension for AcP, Glu, Ure and Prot measurement to prevent microbial growth due to longer reaction times. Enzyme activities were analyzed following the procedures described by Sanchez-Hernandez et al. (2017).

Chemical properties were determined according to the methods recommended for Chilean soils by Sadzawka et al. (2006), and included: Electric conductivity (EC) (conductivity cell and direct reading digital bridge); cation exchange capacity (CEC) (sum of the exchangeable basic cations), pH (potentiometric measurements in suspension), NO_3-N, NH_4-N (Kjeldahl method), Available P (Olsen method), exchangeable K, Al, Ca, Mg, Na, Mn, Fe, Zn, Ca, and B (spectrophotometry).

Physical properties were determined according to Sandoval et al. (2012), and included: Soil texture (hydrometer method), soil bulk density (SBD) (core method), field capacity (FC), permanent wilting point (PWP) and available soil moisture (ASM) (pressure plates method), macro and micro-aggregates (set of sieves underwater) and saturated hydraulic conductivity (K_s) (single-ring infiltrometer).

Statistical analysis

The Shapiro-Wilk test was used to test for data normality. Soil properties were separated into two sets, 0-5 and 5-10 cm depth to select soil quality indicators to evaluate changes due to fire. To identify significant differences in soil properties between the burned and unburned groups at each depth, we compared samples using a T-test independent variable ($p > 0.05$). Soil properties that significantly differed between unburned and burned treatment were considered sensitive to the wildfire effect (Raiesi and Pejman, 2021).

To estimate the overall changes in soil properties between burned and unburned vineyards we used a two-way ANOVA with fire treatment and depths as the sources of variation (Raiesi and Pejman, 2021). Soil properties with significant difference between burned and unburned soil and nonsignificant interaction (Fire treatment × Soil sampling depth) were selected as soil quality indicators and pooled from both sampling depth to conduct an overall T-test independent variable ($p > 0.05$).

The soil quality indicators were normalized using three soil functions: i) Linear scoring (LS) where “more is better” (Equation 1), and each observation was divided by the highest observed value, ii) LS where “less is better” and the lowest observed value was divided by each observation (Equation 2), and iii) non-linear scoring (NLS) following a sigmoidal type of curve (Equation 3) (Raiesi and Pejman, 2021):

$$LS = \frac{X}{X_{max}} \tag{1}$$

$$LS = \frac{X_{min}}{X} \tag{2}$$

$$NLS = \frac{1}{\left(1+\left(\frac{X}{X_0}\right)^{-2.5}\right)} \tag{3}$$

where LS is the linear score and NLS is the non-linear score varying from 0 to 1, X is the soil property and X_{max}, X_{min} and X_0 are the maximum, minimum and mean value of each soil property obtained in burned and unburned soils.

A soil quality index (SQI) was calculated using an additive equation of the normalized quality indicators. The SQI was finally divided by the number of quality indicators to obtain values ranging from 0 to 1.

Finally, a T-test was performed to evaluate if the SQI reflected differences of quality between burned and unburned soils. All quantitative results were expressed as the means of three and six replicates ± standard deviation.

RESULTS AND DISCUSSION

Soil properties sensitive to wildfire

Overall, the soils were clay loam with high bulk density between 1.54 and 1.60 g cm^{-3}. These soils are considered unstable (potentially erodible) with mean weight diameter (MWD) < 0.5 cm and excessive drainage (K_s >15 cm h^{-1}). Moreover, considering their slope (9%-15%), the high precipitation in winter and scant vegetation, theses soils have already been degraded by soil erosion and thus the soil nutrient content in them is considered low (Table 1).

Table 1. Nutrient content in soils of the study site. SOM: Soil organic matter.

Soil property	Content	Level
SOM, %	1.73 ± 0.15	Low
pH (1:1 H_2O)	7.28 ± 0.20	Neutral
NO_3-N, mg kg^{-1}	2.03 ± 0.27	Very low
NH_4-N, mg kg^{-1}	5.92 ± 1.67	Very low
P, mg kg^{-1}	13.02 ± 2.74	Moderate
K, $cmol_{(+)}$ kg^{-1}	0.52 ± 0.08	High
Ca, $cmol_{(+)}$ kg^{-1}	7.87 ± 1.96	Moderate
Mg, $cmol_{(+)}$ kg^{-1}	0.64 ± 0.09	Moderate
Na, $cmol_{(+)}$ kg^{-1}	0.03 ± 0.02	Very low
Bases, $cmol_{(+)}$ kg^{-1}	9.07 ± 1.93	Moderate
Al, $cmol_{(+)}$ kg^{-1}	0.05 ± 0.03	Very low
S, mg kg^{-1}	2.99 ± 0.48	Low
Fe, mg kg^{-1}	3.73 ± 1.61	Very low
Zn, mg kg^{-1}	0.41 ± 0.09	Low
Cu, mg kg^{-1}	0.41 ± 0.05	Low
B, mg kg^{-1}	0.31 ± 0.07	Low

Wildfire significantly affected 14 soil properties 14 mo after the fire. At a 0-5 cm depth, six soil properties changed in burned soils, whereas from 5-10 cm, 11 soils properties were significantly different between burned and unburned soils. Thus, more changes in soil properties were observed below 5 cm, suggesting that 14 mo after a wildfire, indirect changes related to erosion and leaching are relevant in deeper soil layers (Table 2).

Although soil enzymes have been identified as sensitive indicators of ecological change (Singh et al., 2021), nonsignificant difference on these soil biological properties was observed for the first 5 cm, where fire can directly influence soil properties through heating and combustion processes (Certini et al., 2021) (Table 2). Considering soil C is one of the main drivers of changes in enzyme activities (Yan et al., 2020), one of the reasons for this result could be the low SOM content of these highly weathered soils. Thus, SOM content and C mineralization did not change between burned and unburned soils, which is consistent with other previous studies in Mediterranean climate region, where unchanged SOM and C mineralization 1 yr after a moderate severity fire have been reported (Heydari et al., 2017).

Prot and CbE activity were the only biological soil properties that significantly decreased 14 mo after the wildfire ($p < 0.05$) at a 5-10 cm depth. A decrease in Prot activity has been reported immediately after a fire (Fioretto et al., 2005) while there are not reports on CbE activity after a fire. Furthermore, among biological soil properties, only for CbE activity the effect of fire was independent of the effect of sampling depth (no interaction) (Table 3).

Table 2. T test independent variable to determined significant differences in soil properties between burned and unburned soils at 0-5 and 5-10 cm depths. UBV: Unburned vineyard; BV: burned vineyard. *Significant difference at $\alpha = 0.05$. **Significant difference at $\alpha = 0.01$. Boldface p values mean significant difference between burned and unburned vineyard. SBD: Soil bulk density; FC: field capacity; PWP: permanent wilting point; ASM: available soil moisture; MWD: mean weight diameter; K_s: saturated hydraulic conductivity; INTF: iodonitrotetrazolium formazan; SOM: soil organic matter; CEC: cation exchange capacity.

Soil property	0-5 cm			5-10 cm		
	UBV	BV	*p*	UBV	BV	*p*
Sand, %	0.46 ± 0.00	0.39 ± 0.14	0.5447	0.38 ± 0.00	0.54 ± 0.21	0.3368
Silt, %	0.21 ± 0.03	0.20 ± 0.01	0.8188	0.22 ± 0.02	0.21 ± 0.06	0.8734
Clay, %	0.32 ± 0.03	0.39 ± 0.13	0.4514	0.39 ± 0.02	0.24 ± 0.14	0.7523
SBD, g cm^{-3}	1.60 ± 0.05	1.59 ± 0.02	0.7736	1.54 ± 0.06	1.59 ± 0.07	0.3504
FC, %	20.64 ± 1.61	18.27 ± 1.24	0.1153	21.41 ± 0.88	18.74 ± 1.51	0.0575
PWP, %	11.29 ± 0.97	10.05 ± 0.68	0.1465	11.06 ± 1.49	10.31 ± 0.83	0.4896
ASM, cm	9.35 ± 0.64	8.22 ± 0.56	0.0838	10.35 ± 0.95	8.43 ± 0.68	**0.0473***
Macroaggregates, %	22.80 ± 2.06	34.88 ± 1.19	**0.0009****	18.50 ± 1.20	42.32 ± 1.13	**0.0001****
Microaggregates, %	4.02 ± 0.97	7.59 ± 0.48	**0.0048****	6.07 ± 1.44	6.03 ± 0.81	0.9713
MWD, cm	0.40 ± 0.04	0.47 ± 0.02	0.1128	0.23 ± 0.04	0.48 ± 0.09	**0.0140***
K_s, cm s^{-1}	32.94 ± 3.30	27.80 ± 2.60	0.1004	21.61 ± 3.58	29.43 ± 3.76	0.0604
Carboxylesterase, µmol h^{-1} g^{-1} dry soil	0.61 ± 0.22	0.40 ± 0.04	0.1838	0.36 ± 0.10	0.11 ± 0.11	**0.0442***
Acid phosphatase, µmol h^{-1} g^{-1} dry soil	0.14 ± 0.05	0.35 ± 0.17	0.1247	0.06 ± 0.00	0.16 ± 0.07	0.1768
Glucosidase, µmol h^{-1} g^{-1} dry soil	0.21 ± 0.02	0.19 ± 0.05	0.673	0.10 ± 0.04	0.04 ± 0.01	0.1064
Urease, µ NH_4^+-N h^{-1} g^{-1} dry soil	2.93 ± 0.11	2.53 ± 0.25	0.0672	2.54 ± 0.19	2.21 ± 0.25	0.1600
Deshydrogenase, µmol INTF h^{-1} g^{-1} dry soil	9.81 ± 7.18	24.64 ± 10.26	0.1098	6.88 ± 0.49	4.70 ± 2.25	0.1767
Protease, µmol tyr-equivalents h^{-1} g^{-1} dry soil	211.93 ± 85.51	465.53 ± 227.85	0.1454	353.39 ± 23.30	256.94 ± 34.09	**0.0155***
C Mineralization, µg CO_2 g soil^{-1}	353.60 ± 64.72	418.12 ± 104.99	0.4442	120.12 ± 22.56	181.13 ± 77.96	0.2628
pH (1:1 H_2O)	7.28 ± 0.20	6.31 ± 0.33	0.0722	7.32 ± 0.14	6.23 ± 0.23	**0.0103***
SOM	1.73 ± 0.14	1.92 ± 0.44	0.5268	1.10 ± 0.03	1.47 ± 0.40	0.2516
NO_3-N, mg kg^{-1}	2.03 ± 0.26	5.98 ± 1.25	**0.0060****	1.29 ± 0.34	1.92 ± 0.81	0.2844
NH_4-N, mg kg^{-1}	5.91 ± 1.66	6.45 ± 0.34	0.6161	3.4 ± 0.76	2.94 ± 0.75	0.5026
P, mg kg^{-1}	13.01 ± 2.73	8.97 ± 0.85	0.0709	8.43 ± 0.98	5.90 ± 0.33	**0.0135***
K, mg kg^{-1}	0.52 ± 0.07	0.53 ± 0.13	0.9167	0.49 ± 0.01	0.42 ± 0.13	0.4949
Ca, cmol$_{(+)}$ kg^{-1}	7.87 ± 1.96	4.58 ± 0.87	0.0564	5.13 ± 0.32	3.32 ± 0.75	**0.0193***
Mg, cmol$_{(+)}$ kg^{-1}	0.63 ± 0.09	0.89 ± 0.32	0.2614	0.71 ± 0.04	0.80 ± 0.25	0.5869
Na, cmol$_{(+)}$ kg^{-1}	0.03 ± 0.02	0.05 ± 0.01	0.3982	0.02 ± 0.00	0.02 ± 0.00	0.3739
Bases	9.06 ± 1.93	6.05 ± 1.29	0.0891	6.36 ± 0.32	4.58 ± 1.15	0.0628
Exchangeable Al, cmol$_{(+)}$ kg^{-1}	0.05 ± 0.02	0.05 ± 0.02	0.9999	0.02 ± 0.01	0.07 ± 0.02	0.0798
CEC, cmol$_{(+)}$ kg^{-1}	9.11 ± 1.94	6.11 ± 1.26	0.0885	6.39 ± 0.31	4.65 ± 1.13	0.0628
Al saturation, %	0.01 ± 0.00	0.00 ± 0.00	0.1161	0.00 ± 0.00	0.00 ± 0.00	0.9999
K saturation, %	0.09 ± 0.01	0.08 ± 0.00	0.4216	0.07 ± 0.00	0.05 ± 0.01	0.1890
Ca saturation, %	0.71 ± 0.01	0.75 ± 0.01	0.0835	0.80 ± 0.01	0.85 ± 0.03	0.0864
Mg saturation, %	0.16 ± 0.01	0.14 ± 0.02	0.2182	0.11 ± 0.00	0.07 ± 0.02	0.0514
S, mg kg^{-1}	2.99 ± 0.48	5.74 ± 0.83	**0.0078****	3.29 ± 0.79	7.66 ± 3.42	0.0979

Table 3. Two-way ANOVA to determined significant differences in soil properties for wildfire effect and soil sampling depth (sources for variation). Boldface p values mean: i) Significant difference between burned and unburned vineyard (for fire treatment), ii) significant difference between 0-5 and 5-10 cm depth, and iii) significant difference between burned and unburned vineyard regardless of depth for interaction (Fire treatment×Depth). ASM: Available soil moisture; MWD: mean weight diameter; CbE: carboxylesterase.

Soil property	P value		
	Fire treatment	Depth	Fire treatment×Depth
ASM, cm	**0.0066**	0.1841	**0.3729**
Macroaggregates, %	0.0010	0.0966	0.0001
Microaggregates, %	0.0151	0.6722	0.0137
MWD, cm	0.0017	0.0510	0.0239
CbE, µmol h^{-1} g^{-1} dry soil	**0.0186**	**0.0087**	**0.7900**
Protease, µmol tyr-equivalents h^{-1} g^{-1} dry soil	0.3022	0.6502	0.0396
pH (1:1 H_2O)	**0.0010**	0.9063	**0.6567**
NO_3-N, mg kg^{-1}	0.0010	0.0007	0.0062
P, mg kg^{-1}	**0.0057**	**0.0024**	**0.4159**
Ca, $cmol_{(+)}$ kg^{-1}	**0.0049**	**0.0169**	**0.2943**
S, mg kg^{-1}	**0.0097**	**0.3216**	**0.4626**
Fe, mg kg^{-1}	**0.0001**	**0.4490**	**0.5774**
Cu, mg kg^{-1}	**0.0001**	**0.1148**	**0.7924**
B, mg kg^{-1}	**0.0456**	**0.3533**	**0.5707**

The Glu and Ure activities showed nonsignificant decreases of about 34% and 13%, respectively. Some studies have reported a decrease in Glu activity immediately after a fire and 1 to 3 yr after a wildfire the Glu activity remains low (Fontúrbel et al., 2012; Fernández-García et al., 2019). Regarding Ure, several studies report a decrease in its activity after wildfires (Fontúrbel et al., 2012; Fernández-García et al., 2019; Moya et al., 2019).

The AcP activity showed a nonsignificant increase that is contrary to most studies that report a decreased in its value (Fontúrbel et al., 2012; Fernández-García et al., 2019; Singh et al., 2021), which is linked to an increase of pH. Furthermore, AcP activity play a key role in the release of P whenever required in the soil (Adetunji et al., 2017), thus the decrease of available P in burned soil also might have triggered an increase of its activity.

Regarding chemical properties, while available P and exchangeable Ca significantly decreased, NO_3-N, available S, Cu, Fe content increased. In burned plots available Fe increased about four times, NO_3-N was nearly three times higher, while available S and Cu were two times higher, compared to the unburned plots (Table 2).

Even though the decrease of soil pH was nonsignificant in the first 5 cm, there was an overall decrease in this soil property in burned soil regardless of its sampling depth (Table 3). Soil pH decreases after a fire are likely to occur in the long term due to soil leaching (Alcañiz et al., 2016; Francos et al., 2019) but most studies in Mediterranean climate regions report no changes or increase of pH in the first 2 yr after a low to moderate severity fire (Garrido-Ruiz et al., 2022). Soils in our study site have an excessive drainage (K_s >15 cm h^{-1}), along with receiving high precipitation during winter, causing the leaching of basic cations after a wildfire event, which might partially explain the decrease in pH. However, in our study, base cations decreased in burned soil solely by decreases of exchangeable Ca, whereas there was no change in the status of other basic cations such as Mg, K, Na. In addition, this decrease of pH could be responsible for leaching of Ca and P due to the precipitation of Ca phosphates that may have been retained by carbonates at the higher pH of the unburned soils (Penn and Camberato, 2019). Thus, the decreases of Ca and P availability follow the decrease of pH, which are in contrast with most reports of the soil effects 1 yr after a fire in Mediterranean climate regions (Gómez-Rey et al., 2013; Gómez-Rey and González-Prieto, 2014; Heydari et al., 2017; Francos et al., 2019) where such decreases have been associated with long term effects after wildfires (Alcañiz et al., 2016; Francos et al., 2019). Furthermore, the decrease of P is related to increase of availability of Al and Fe ions that result in P fixation (Ng et al., 2022).

The pH decrease after the wildfire can explain the increase of micronutrients such as Fe, S, B, Mn and Cu that usually are reported to have decreased in soil (Gómez-Rey and González-Prieto, 2014). However, in agreement with our results, there are other studies in Mediterranean climate region that have reported increases in B, Cu, Mn (Gómez-Rey et al., 2013; Gómez-Rey and González-Prieto, 2014). Thus, the pH changes in the present study were likely responsible for triggering the unlikely effects on most macro and micronutrients.

Although Fe is a key element in Alfisols, its content in unburned soils was below critical levels, but the lower pH in burned soils promoted the release of Fe minerals (Colombo et al., 2014), increasing tenfold in the first 5 cm.

Available N increased in the form of NO_3-N, whereas NH_4-N did not change. The increase of NO_3-N agrees with most reports (Gómez-Rey and González-Prieto, 2014; Heydari et al., 2017) whereas NH_4-N has been reported to increase in the first year after the fire (Gómez-Rey et al., 2013; Vega et al., 2013; Gómez-Rey and González-Prieto, 2014).

Except NO_3-N, depth does not influence the fire effect on soil chemical properties (Table 3). Thus, in our study, regardless of depth, the chemical properties were more sensitive to distinguish burned from and unburned soils than the biological properties which failed to identify effects from fire disturbances in the first 5 cm (Table 2).

Four physical properties were significantly changed by fire. The ASM decreased while macroaggregates, microaggregates and MWD were higher in burned soils after 14 mo (Table 2). For ASM, there was no interaction between depth and fire treatment, but for soil aggregate percentage and MWD the effect of fire depends on the effect of depths (Table 3).

The improvement of soil structure through the observed increase of the percentage of macroaggregates could be related to a strong aggregation that was a product of the high clay content of the samples and a recrystallization of some Fe and Al minerals (which both increased after the fire) as cementing substances when exposed to high temperatures (Mataix-Solera et al., 2011).

Soil quality indicators

Soil properties that were sensitive to wildfire in the first 5 cm (n = 6), were highly correlated with each other (Table 2), thus any sensitive soil property can be potentially used as a soil quality indicator. Considering that NO_3-N, Fe and S are usually reported on soil test results, they might be more convenient to be used as soil quality indicators than the less commonly reported Cu content and percent soil aggregates.

In total, there were nine soil properties where the effect of fire was independent of soil sampling depth (no interaction), which were pooled to compare burned and unburned vineyards using a paired T-test regardless of sampling depth. The CbE activity, ASM, pH, P and Ca significantly decreased in burned soils, regardless of sampling depth, while micronutrients such a Fe, S, Cu and B increased 14 mo after the wildfire (Figure 3).

We normalized the soil properties as follows: i) LS where "more is better" was used for CbE activity, ASM, P, Ca, Fe, B and S, ii) LS where "less is better" was used for Cu, and iii) non-linear scoring was used for pH. Thus, we estimated an overall SQI with an additive equation of the normalized variables. The overall SQI did not vary between burned and unburned soils (Figure 4). This is because some soil quality indicators improved in the burned vineyard such as Fe, S, B, while others like ASM, P, Ca and CbE worsened with the fire. Thus, the SQI had a nonsignificant decrease in burned soil from 0.55 to 0.59 (Figure 4).

Soil response to fire is often linked to fire severity and recurrence. Therefore, even though our results showed that fire had an apparent mix of positive and negative effects 14 mo after the fire, this is pertinent only to an already highly degraded soil with no recurrence of fire over the years. Also, our result show that the impacts of moderate severity fire did not disappear after 14 mo, even when vegetation had been regenerated, as had been reported by other studies.

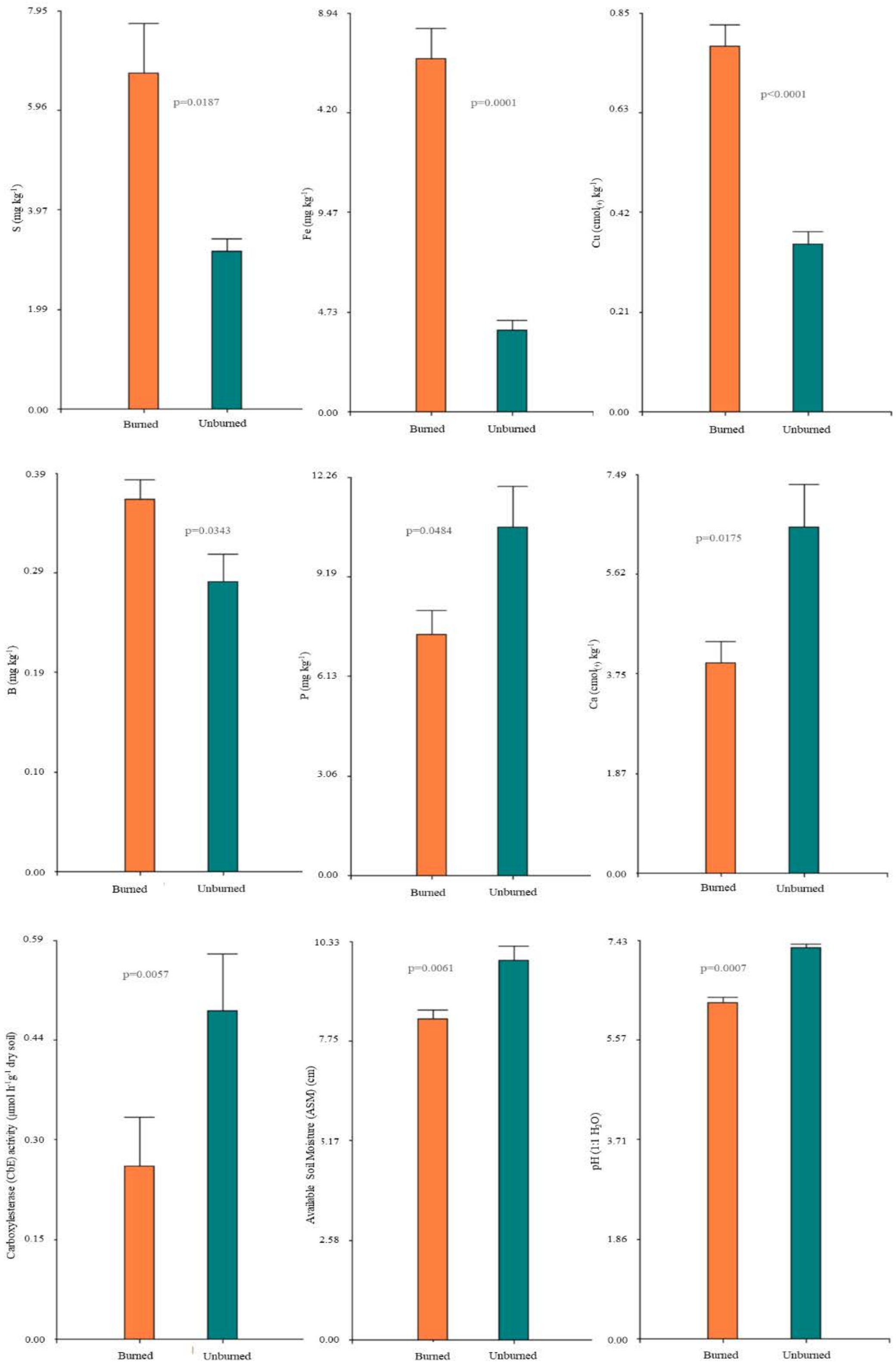

Figure 3. Mean values of soil properties 14 mo after a wildfire in a burned and unburned vineyard regardless its sampling depth. P values according to T-test independent variables ($p < 0.05$). Vertical bars correspond to standard error.

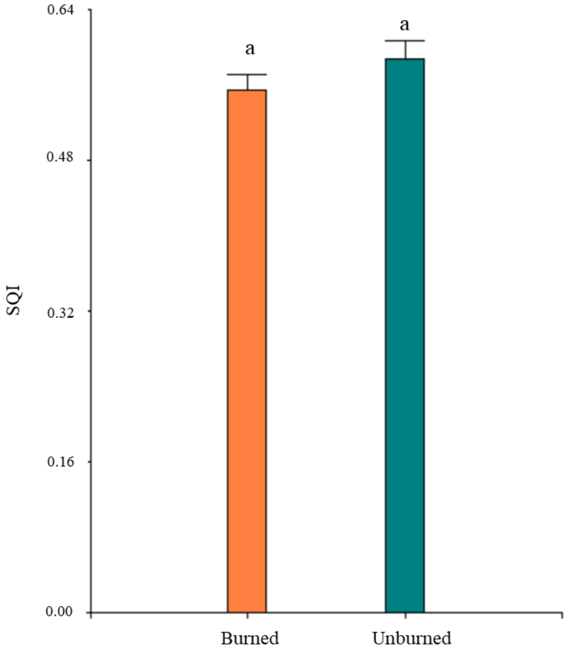

Figure 4. Mean values of soil quality index (SQI) in a burned and unburned vineyard 14 mo after the wildfire. Vertical bars correspond to standard error. Distinct letters indicate significant differences according to T-test independent variable test (P ≤ 0.05).

CONCLUSIONS

Our results do not support our first hypothesis. Even though fire causes non ephemeral alterations on specific soil properties, moderate severity wildfires did not reduce the overall soil quality of this agricultural land in the Mediterranean coastal range of Chile at 14 mo after the fire.

It is important to consider that we investigated the wildfire effect on soil quality in the short term in a rainfed vineyard and further investigation needs to be done to evaluate the immediate, mid-, and long-term effects of wildfires on these already degraded soils.

Although carboxylesterase activity was a biological property that was selected as a soil quality indicator due to its sensitivity to fire change, in soils with very low organic matter, chemical indicators can be more appropriate to evaluate the effect of fire in the short term.

Regarding the sensibility of soil properties to wildfires is important to note that most changes occur between 5-10 cm depth, thus it is important to evaluate not only the first few centimeters that are allegedly directly affected by heat but also deeper layers that are indirectly affected by fire through redistributive processes of soil.

Author contribution

Conceptualization: M.S., C.G. Methodology: M.S., C.G., J.S., N.S., C.C. Validation: M.S., J.S., N.S., C.C. Formal analysis: M.S., C.G, Investigation: M.S., C.G., J.S. Data curation: M.S., C.G. Writing-original draft: C.G. Writing-review & editing: M.S., J.S., N.S., C.C. Supervision: M.S. Project administration: M.S. Funding acquisition: M.S. All co-authors reviewed the final version and approved the manuscript before submission.

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