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Evaluación de la calidad química, física y microbiológica de suelos de uso agropecuario afectados por incendios forestales

Tesis para optar al grado de Doctor en Ciencias de la Agronomía

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DEDICATORIA

A mi esposo y mis dos hijas.

Claudia Garrido Ruiz

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Resumen

La frecuencia y severidad de los incendios en regiones de clima Mediterráneo ha incrementado en las últimas décadas debido a cambios de las condiciones climáticas y uso de la tierra. Este cambio en el régimen del fuego se ha convertido en una amenaza tanto para bosques y vegetación arbustiva como para tierras agrícolas.

En este contexto, existe mucha investigación para evaluar los impactos de incendios en la degradación del suelo en bosques, vegetación arbustiva y praderas, sin embargo, estudios del efecto de incendios en tierras agrícolas de secano en la cordillera de la costa de Chile no existen a pesar de ser estás altamente vulnerables a los incendios.

Aunque las tierras agrícolas no acumulan tanta biomasa (combustible) como los bosques y por ende los incendios de alta severidad no son usuales, el 33% de las tierras agrícolas afectadas fueron afectadas por incendios de severidad media durante el año 2017.

Basados en el contexto anterior, en el presente proyecto de investigación se realizó una extensa revisión bibliográfica del efecto de los incendios en las propiedades físicas, químicas y biológicas del suelo en zonas de clima Mediterráneo y se evaluó el efecto de incendios de media severidad en las

propiedades fisicoquímicas y biológicas de suelos de uso agrícola en la cordillera de la costa de Chile.

Para determinar el efecto a corto plazo (14 meses después del incendios) de los incendios de media severidad en tierras de uso agropecuario, se evaluaron 40 propiedades de muestras de suelos afectados por incendios de severidad moderada y suelos no afectados por incendios en dos profundidades: i) 0-5 cm y ii) 5-10 cm.

Las propiedades del suelo más sensibles a los incendios en los primeros 5 cm de acuerdo con la prueba T ($p<0.05$) son el porcentaje de micro agregados y macro agregados y el contenido de NO_3-N, Fe, Cu y S. Además, las propiedades del suelo que diferencian entre suelos quemados y no quemados independientemente de la profundidad del muestreo fueron seleccionados como indicadores de calidad de suelo. Entonces, la actividad de la Carboxilesterasa, la humedad disponible del suelo, el pH y el contenido de Ca, P, Fe, B, S y Cu fueron seleccionados mediante un análisis de varianza de dos factores con el efecto del fuego y profundidad de muestreo como fuentes de variación.

La actividad de la enzima Carboxilesterasa y la humedad disponible del suelo disminuyeron después de 14 meses. También, el pH disminuyó significativamente afectando así la disponibilidad de nutrientes. El contenido de Ca y P disminuyeron mientras que la disponibilidad de Fe, Cu, S y B incrementaron en los suelos afectados por el incendio.

Para estimar los cambios impulsados por los incendios se calculó un índice de calidad del suelo mediante la sumatoria de los indicadores de calidad del suelo normalizados. A pesar de encontrar efectos no efímeros del fuego en múltiples propiedades del suelo, estos efectos fueron positivos y negativos. Por lo tanto, el índice de calidad de suelo no varió entre los suelos afectados por incendios y los suelos no afectados por incendios 14 meses después del incendio.

Abstract

The frequency and severity of wildfires in Mediterranean climate regions have increased in the last decades due to changes in climate conditions and land use. This change in fire regime has become a threat to forest, shrublands and agricultural lands.

Much research has been conducted to evaluate wildfire impacts on soil degradation in forests, shrublands, and grasslands, but studies of wildfire effects on the soil of rain-fed (dryland) agriculture in Chile’s coastal range ecoregion are nonexistent, although its high vulnerability to wildfire.

Even though agricultural lands do not accumulate as much biomass (fuel) as forests and shrublands and thus high severity fires are unusual, in 2017 fires, 33% of agricultural lands were affected by moderate severity fires.

Based on the above context, in this research project we conducted an extensive literature review of impact of moderate severity wildfires on physical, chemical, and biological properties of soil in Mediterranean-climate regions. Furthermore, we evaluate the effect of moderate severity wildfires in soil properties of agricultural lands in the coastal range of Chile.

To assess the short-term effect (14 months after the wildfire) of moderate severity wildfires we evaluated 40 properties of soils samples from burned (by a

moderate severity wildfire) and unburned soils at two depths: i) 0-5 cm and ii) 5-10 cm.

The most sensitive soil properties to wildfire in the top 5 cm according to a T-test independent variable ($p<0.05$) were Microaggregates, Macroaggregates, and content of NO_3-N, Fe, Cu, and S. Furthermore, the overall most relevant soil properties to differentiate between burned and unburned soil regardless its sampling depth were selected as soil quality indicators. Thus, Carboxylesterase activity, Available Soil Moisture, pH, Ca, P, Fe, B, S and Cu were selected using a two-way analysis of variance with fire treatment and sampling depth as sources of variation.

Carboxylesterase activity and Available Soil Moisture decrease after the wildfire. Also, pH significantly decreased 14 months after the fire affecting the behavior of nutrient availability. Thus, Ca and P decreased whereas Fe, Cu, S and B availability increased in burned soils.

To assess these changes driven by wildfires, a soil quality index was computed adding normalized soil quality indicators. Even though fire effects were not ephemeral in several soil properties, some effects were positive and other negatives. Therefore, the overall soil quality index did not differ between burned and unburned soils 14 months after the fire.

I. INTRODUCCIÓN GENERAL

1.1 Introducción

El fuego causa alteraciones fisicoquímicas y biológicas en el ambiente a través del calor y oxidación, así como mediante la creación de nuevas fuentes de compuestos fisicoquímicos y biológicos en la forma de carbón, destilados, óxidos metálicos y residuos vegetales (Alcañiz et al., 2018; Satín & Doerr, 2016)

Los incendios forestales son fuegos no controlados de gran intensidad debido a la gran cantidad de combustible seco (biomasa). En este contexto, la intensidad del fuego se asocia con la temperatura y el tiempo de residencia (duración) y depende de la cantidad de combustible (biomasa), la flamabilidad del paisaje, las condiciones climáticas y la topografía (Keeley, 2009; Mataix-Solera et al., 2011).

Sin embargo, la intensidad de fuego frecuentemente es desconocida en los incendios forestales por lo que se usa el término severidad para describir como el incendio afectó al ecosistema. La severidad del incendio se refiere al grado de pérdida o descomposición de la materia orgánica bajo y sobre el suelo y presentan una correlación positiva con la intensidad del fuego, pero también depende de las características y condiciones del suelo (Keeley, 2009; Mataix-Solera et al., 2011).

Los ecosistemas en las regiones de clima Mediterráneo son altamente propensas a incendios forestales debido a las precipitaciones de invierno junto con temperaturas suaves que promueven el crecimiento de las plantas y veranos muy secos con altas temperaturas que incrementan la flamabilidad de la biomasa (Keeley, 2012). Aunque los incendios forestales son naturales en estas regiones, el incremento de su frecuencia y severidad debido a cambios en las condiciones climáticas y uso de la tierra supone una gran amenaza tanto para bosques como tierras no boscosas.

Particularmente en Chile, la región Mediterránea Centro Sur caracterizada por veranos calurosos y secos e invierno húmedos y frescos (clima Mediterráneo de verano cálido- Csb) contiene las mayores extensiones de plantaciones forestales en el país (Urrutia-Jalabert et al., 2018) que han reemplazado a bosques nativos y tierras agrícolas degradadas y como resultado han incrementado la cantidad de combustible y flamabilidad del paisaje (Taylor et al., 2017), acrecentando así la vulnerabilidad de estos ecosistemas a los incendios forestales.

En enero del año 2017, los incendios forestales fueron responsables de quemar 266,728 ha de plantaciones forestales, 212,830 ha de vegetación natural (bosque nativo, vegetación arbustiva y praderas) y 28,729 ha de tierras agrícolas principalmente en la cordillera de la costa entre las latitudes 33°50´y 38°39´ (Bowman et al. 2019; CONAF, 2021).

A pesar de que la magnitud de los incendios forestales del año 2017 fueron un hecho sin precedente, cientos de hectáreas de tierras agrícolas son afectadas por incendios forestales cada año en Chile que representa además de pérdida total de la producción estacional, una causa adicional que reduce la calidad del suelo en estos suelos altamente degradados.

La tierras agrícolas no acumulan tanta biomasa (combustible) como las plantaciones forestales por lo que los incendios de alta severidad son inusuales. Sin embargo, el año 2017, el 33% de los incendios que afectaron las tierras de uso agrícola fueron de severidad moderada (de la Barrera et al., 2018). En este contexto, se han identificado importante cambios (impacto) en las propiedades de suelo un año después de un incendio de severidad moderada (Araya et al., 2016), indicando que el efecto no es efímero como las quemas controladas (baja severidad).

En los incendios de severidad moderada se pueden alcanzar temperaturas en la superficie hasta de 450 °C en las cuales gran parte de la materia orgánica del suelo (MOS) ha sido incinerada (Araya et al., 2016). En este contexto, muchos cambios en las propiedades del suelo durante un incendios se vinculan a la alteración y pérdida de la MOS. Por lo tanto, la pérdida de la MOS se asocia con la reducción de la respiración del suelo (Vega et al., 2013) y reducción de actividad enzimática (Fernández-García et al., 2019; Moya et al., 2019).

Por otro lado, los cambios más significativos en las propiedades químicas del suelo reportados un año después de un incendios de severidad moderada en regiones de clima Mediterráneo son: i) incremento de pH (Granged et al., 2011; Vega et al., 2013; Gómez-Rey y González-Prieto, 2014; Heydari et al., 2017; Fernández-García et al., 2019); ii) incremento del N total (NO_3-N and NH_4-N) (Vega et al., 2013; Gómez-Rey y González-Prieto, 2014; Heydari et al., 2017); iii) incremento de la conductividad eléctrica (CE) (Granged et al., 2011; Heydari et al., 2017;); y iii) mayor disponibilidad de nutrientes como P (Vega et al., 2013; Gómez-Rey & González-Prieto, 2014; Heydari et al., 2017; Moya et al., 2019), K (Gómez-Rey et al., 2013; Heydari et al., 2017), Ca (Gómez-Rey & González-Prieto, 2014) y Mg (Gómez-Rey et al., 2013).

Los cambios inducidos por los incendios de severidad moderada en las propiedades físicas del suelo incluyen una disminución de la estabilidad de los agregados (Granged et al., 2011) y un aumento de la densidad aparente del suelo y repelencia (Heydari et al., 2017; Plaza-Álvarez et al., 2018). Estos cambios en las propiedades físicas intensifican el riesgo de erosión y consecuente pérdida de los nutrientes del suelo (Heydari et al., 2017). Específicamente en regiones de clima Mediterráneo, la pérdida por escorrentía en de 1-4 veces mayor en suelos afectados por incendios debido a diversos factores como ser: i) la presencia de cenizas que produce una obstrucción de los macroporos del suelo (Bodí et al., 2012), ii) los cambio en las propiedades físicas del suelo que reducen la tasa de infiltración y la capacidad de retención de agua (Jordán et al., 2013; Zavala et al., 2014; Heydari et al., 2016; Weninger et al., 2019) y iii) la ausencia de cobertura de la tierra (suelo desnudo) (Bodí et al., 2012; Jordán et al., 2013).

Considerando los cambios en las propiedades del suelo afectados por incendios de severidad moderada, como ser un detrimento de las propiedades biológicas, un incremento de las disponibilidad de nutrientes y un aumento del riesgo de la pérdida de estos nutrientes por erosión, podemos inferir que los incendios de severidad moderada en regiones de clima Mediterráneo son causales de degradación de suelo agrícolas.

Los índices de calidad del suelo (ICS) ha sido ampliamente utilizados para cuantificar el impacto del cambio de uso de la tierra, uso de agroquímicos entre otras perturbaciones. Más recientemente, estos ICS están siendo utilizados para medir el impacto de incendios sobre el suelo (Raiesi y Pejman 2021; Memoli et al., 2020). Por lo tanto, el objetivo de nuestro estudio es identificar mediante un ICS en qué medida los incendios forestales de severidad moderada influencian la degradación de suelos de uso agrícolas en la cordillera de la costa (región de clima Mediterráneo) de Chile.

1.2 Hipótesis

La calidad de los suelos de tierras agrícolas afectados por incendios de severidad moderada disminuye 14 meses después del incendio.

1.3 Objetivos

1.3.1 Objetivo general

- Seleccionar de las propiedades físicas, químicas y biológicas del suelo un set de indicadores de calidad de suelo capaces de discriminar entre suelos no afectados por incendios y suelos afectados por incendios de severidad moderada con el fin de determinar un índice de calidad del suelo (ICS) que evalúe el impacto de estos incendios en la calidad del suelo.

1.3.2 Objetivos específicos

- Identificar los principales cambios (impactos) de los incendios de severidad moderada en las propiedades del suelo.
- Evaluar y seleccionar indicadores de calidad de suelo que cuantifiquen los efectos de los incendios de severidad moderada en las propiedades del suelo.
- Estimar un ICS en suelos agrícolas afectados que permitan cuantificar el impacto general de los incendios de severidad moderada en la calidad del suelo.

Capítulo I: Glosario de Abreviaturas, siglas y acrónimos

CE	Conductividad Eléctrica
CONAF	Corporación Nacional Forestal
ICS	Índice de Calidad del Suelo
MOS	Materia Orgánica del Suelo

1.4 Referencias bibliográficas

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II. FIRE IMPACTS ON SOIL AND POST FIRES EMERGENCY STABILIZATION TREATMENT IN MEDITERRANEAN-CLIMATE REGIONS

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Fire impacts on soil and post fire emergency stabilization treatments in Mediterranean-climate regions

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Abstract

Wildfires are non-controlled large-scale fires of various vegetation types that have long affected the Mediterranean-climate regions, but their increased frequency and severity has led to the degradation of the ecosystems. Particularly in Chile, 147 major wildfires in 2017, were responsible of burning 546,678 ha, which included 28,729 ha of traditional small-scale non irrigated agricultural systems, highlighting the vulnerability of these agricultural soils to wildfires. Soil biological properties are more sensitive to heating than physicochemical properties. Thus, a reduction of microbial communities and associated enzyme activities generally occur in low-intensity fires (< 200 °C). Most significant changes in physicochemical properties of soil occurring in moderately intense fires (250 to 450 °C) are increases of soil pH, nutrient availability, bulk density and soil water repellency, whereas soil aggregate stability and water holding capacity generally decrease. When vegetation cover is completely destroyed by fire, emergency stabilization treatments such

as mulching and seeding provide an immediate ground cover to reduce soil erosion and preserve nutrients. Therefore, it is important to define the impacts of wildfire on soil properties of agricultural lands to establish a roadmap to implement an adequate and viable restoration.

Keywords: Erosion, fire, Mediterranean-climate, mulching, seeding, soil properties, wildfire.

2.1. Introduction

Fire intensity relates to temperature and fire duration (residence time) and represents the energy output from a fire. Thus, fire intensity mainly depends on fuel amount and flammability, weather conditions and topography (Keeley, 2009; Mataix-Solera et al., 2011). Low intensity fires reach surface temperature of up to 250 °C, whereas moderate and high intensity fires reach surface temperature up to 450 and 650 °C, respectively (Araya et al., 2016).

Because fire intensity is often not known for most wildfires, fire severity is used to describe how fire intensity affected ecosystems. Fire severity emphasized the degrees of organic matter loss or decomposition both aboveground and

belowground and is positively correlated to fire intensity but also depends on the type of vegetation and soil characteristics and conditions (texture, water content and organic matter) (Keeley, 2009; Mataix-Solera et al., 2011). Fire severity can be assessed using burn severity mapping (spectral indices)

(Fernández-García et al., 2019b) and/or ground variables such as coloration of ash, twig diameter on terminal branches and charring depth among other metrics (Keeley, 2009; Francos et al., 2018). Ground variables differ depending on the ecosystem but in general, severity varies from low severity fires (light) where non woody vegetation cover is consumed, ash is black and charring is limited to a few millimeters depth, to high severity fire (deep burning) where all vegetation is killed, ash is white/gray and charred organic matter reach several centimeters depth (Keeley, 2009).

Wildfires or uncontrolled fires generally occur in the presence of an abundant and dry fuel load (Certini, 2005). In Mediterranean-climate regions the frequency of wildfires is related to fuel flammability conditions and that is projected to increase around the globe if climate variables were the only driver (McWethy et al., 2018; Urrutia-Jalabert et al., 2018; Gómez-González et al., 2019).

Particularly, in Chile more than 95% of the wildfires occur in the Mediterranean-climate (warm summer) region between 33° and 42° S lat (Figure 2.1), i.e., the South-Central region (Sarricolea et al., 2017; de la Barrera et al., 2018; CONAF, 2020). These Mediterranean-climate regions are fire prone due to hot, dry summers and cool wet winters (Castillo et al., 2020). Furthermore, this area is characterized by an increase of extensive monoculture of exotic, fire prone, forest plantations, which have changed the vegetative landscape in just a few decades, replacing agricultural lands, grasslands, native shrublands and forests (Heilmayr et al., 2016).

In the last three decades, the frequency of major wildfires (≥ 200 ha) in Chile have increase from an annual average of 40 (1991-2000) to 63 (2011-2020) (Figure 2). Moreover, the length of fire season as well as the fire duration increased in the last 30 yr, evidencing that fire regime in central Chile has been altered (González et al., 2018; CONAF, 2020).

The main reasons identified for the higher frequency and severity of wildfire in Chile are: i) climatic variables such as summer drought, winter precipitation, and spring and summer mean temperature that promotes fuel accumulation and flammability (González et al., 2018; McWethy et al., 2018; Urrutia-Jalabert et al., 2018; Gómez-González et al., 2019), ii) increase of the area of fire prone exotic forest plantations (Pinus and Eucalyptus) and the adoption of intensive forest management practices, which result in the accumulation of a high fuel load (de la Barrera et al., 2018; Gómez-González et al., 2018; McWethy et al., 2018; Bowman et al., 2019), and iii) increase in population density and thus human occupation of the urban-rural interface and human-driven land use change that generates fires and intensify drought (McWethy et al., 2018; Gómez-González et al., 2019; Castillo et al., 2020).

In 2017, 147 major fires (each with an affected surface area ≥ 200 ha), driven by extreme climatic conditions (Bowman et al., 2019), were responsible for burning 546 678 ha (CONAF, 2020), making it by far the worst year of wildfires in the last three decades in Chile (Figure 2.2).

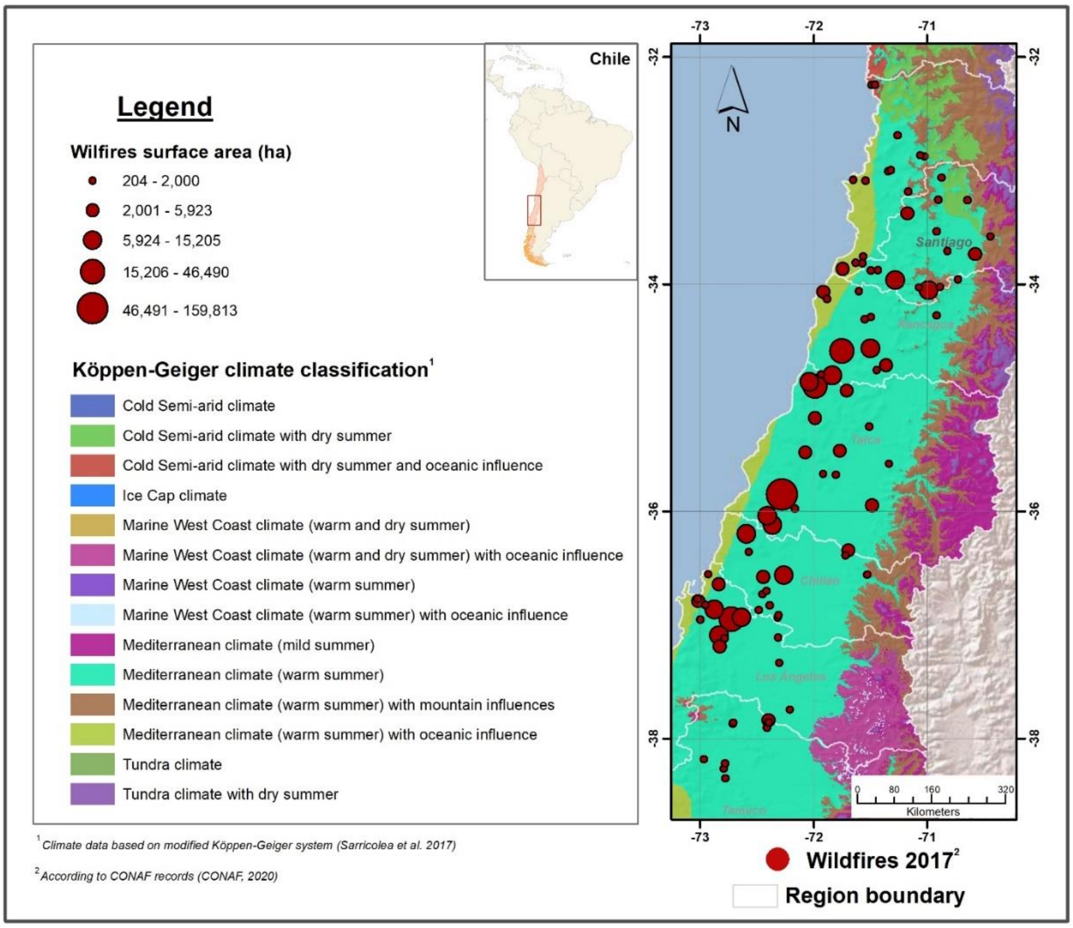


Figure 2.1. Köppen-Geiger climate classification (adapted by Sarricolea et al., 2017) and locations of 2017 major wildfires in central Chile (CONAF, 2020).

These major fires burned down forest plantations, native forests, shrublands, agricultural crops and buildings; forest plantations (223.605 ha) whereby the native shrublands (187.906 ha) were the most affected ecosystems (de la Barrera et al., 2018). Likewise, 28.729 ha of agricultural lands between 33°50' and 38º29' S lat were affected by these fires (CONAF, 2020).

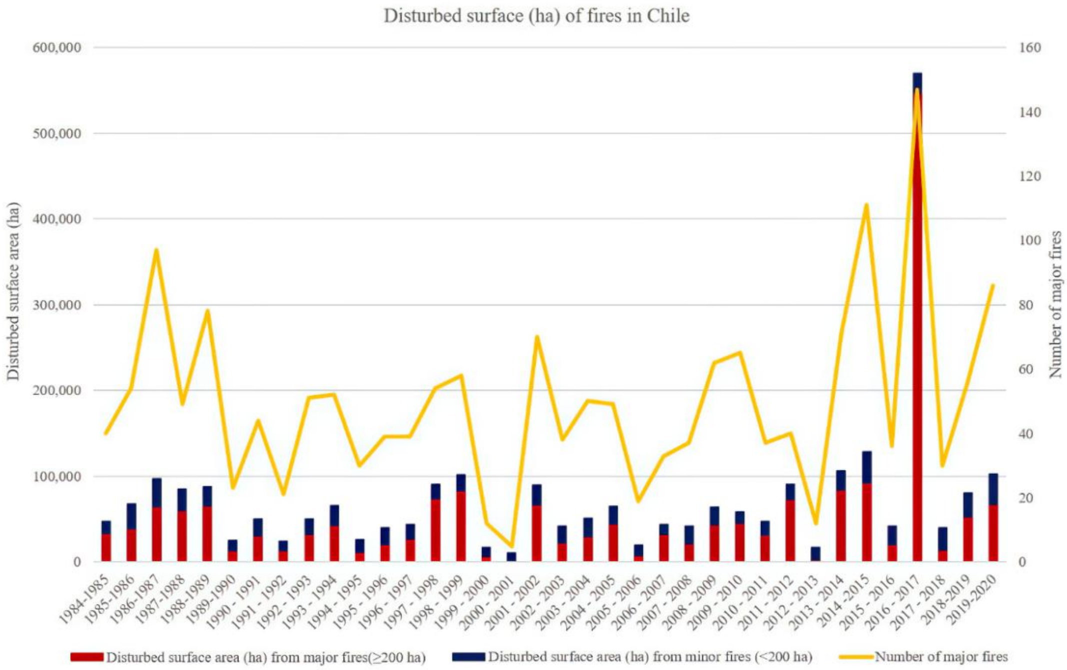


Figure 2.2. Fire affected surface area (ha) and the frequency (number) of major fires (≥ 200 ha) for the last three decades in Chile (CONAF, 2020).

Wildfires that affect agricultural soils behave differently than prescribed (planned) fires that are used in agriculture that may have neutral or even positive effects (Armas-Herrera et al., 2016). However, high severity fires are not common in agricultural land because of a reduced fuel quantity (Certini, 2005) compared to fire-prone forest lands.

Fire causes an alteration of soil through heating and oxidation, thus generating new sources of physicochemical and biological inputs into the soil system in the form of charcoal, organic distillates, metal oxides and plant litter (Hart et al., 2005; Alcañiz et al., 2018). The capacity of a soil to recover from the fire-induced degradation depends on the type of ecosystem, fire severity (Fernández-García et al., 2019a), fire history, ash properties, topography, postfire weather, plant resilience, and postfire management (Pereira et al., 2018). Mediterranean ecosystems are vulnerable to the increase in fire frequency and severity, with a relative long natural recovery (passive restoration) period of 15-21 yr if not intervened (Moya et al., 2018). Thus, planned interventions such as emergency stabilization treatment are fundamental to prevent soil degradation and recover soil productivity in the short and midterm in agricultural lands.

Postfire emergency stabilization treatments such as mulching and seeding along with organic amendments applications, can be used for decreasing soil degradation (Pereira et al., 2018) and restoring productivity, but the lack of economic incentives for these practices (mulching and organic amendments) may make soil recovery difficult for most of the small landowners. Thus, the aim of this review is to describe the potential impact of wildfires on Mediterranean agricultural soils, and to analyze the inclusion of postfire emergency stabilization techniques into an incentive system with some projections to the case of Chile.

2.2 Fires and Soil Properties

To assess the potential effects of wildfires on soils from Mediterranean-climate agricultural lands, we analyzed 34 studies. All the studies were conducted in Mediterranean-climate region and evaluated short (≤ 1 yr) and midterm (> 1 yr and ≤ 5 yr) post fire effects of low to moderate severity fires in field conditions (Table 2.1).

Table 2.1 Studies that were considered to identify the effects of low to medium severity fires on soil properties in the short and mid-terms in Mediterranean climates.

						Type of soil property		
Authors	Country	Ecosystem	Soil texture	Climate	Type of fire	Biological	Chemical	Physical
Alcañiz et al., 2016	Spain	Forest	Not specified	Csa	Prescribed fire	0	16	0
Faría et al., 2015	Portugal	Forest	Loam	Csb	Wildfire	0	5	0
Fernández-García et al., 2019a	Spain	Forest	Sandy	Csb	Wildfire	11	4	0
Fernández-García et al., 2019b	Spain	Forest	Sandy loam	Csb	Wildfire	11	8	0
Fonseca et al., 2017	Portugal	Shrublands	Loam	Csb	Prescribed fire	9	81	0
Fontúrbel et al., 2012	Spain	Shrublands	Not specified	Csb	Experimental burning	24	12	8
Francos et al., 2018	Spain	Forest	Not specified	Csa	Wildfire	2	6	0
Francos et al., 2019	Spain	Forest	Not specified	Csa	Prescribed fire	4	14	0
Gimeno García et al., 2000	Spain	Shrublands	Sandy loam	Csa	Experimental burning	1	9	0
Goméz-Rey et al., 2013	Spain	Forest	Sandy loam	Csb	Wildfire	0	21	0
Goméz-Rey and González-Prieto, 2014	Spain	Forest	Silty loam	Csb	Wildfire	0	56	0
Granged et al., 2011	Spain	Heathland	Loam	Csa	Experimental burning	4	8	16
Gutknecht et al., 2010	USA	Grassland	Loam	Csa	Wildfire	12	0	0
Hernández et al., 1997	Spain	Matorral	Loam	Csa	Wildfire	14	16	0
Heydari et al., 2016	Iran	Forest	Loam	Csa	Wildfire	2	14	2
Hosseini et al., 2017	Portugal	Forest	Loam	Csb	Wildfire	0	12	0
Hubbert et al., 2006	USA	Chaparral	Loam	Csa	Prescribed fire	0	0	5
Hueso-González et al., 2018	Spain	Shrublands	Sandy loam	Csa	Prescribed fire	2	6	6
Jiménez-González et al., 2016	Spain	Forest	Not specified	Csa	Wildfire	16	32	8
Jiménez-Morillo et al., 2020	Spain	Forest	Sandy	Csa	Wildfire	4	0	0
Jiménez-Pinilla et al., 2016	Spain	Shrublands	Silty loam	Csa	Wildfire	0	0	4
Mataix-Solera and Doerr, 2004	Spain	Forest	Sandy loam	Csa	Wildfire	1	0	2
Mataix-Solera et al., 2013	Spain	Forest	Loam	Csa	Wildfire	5	0	5
Meira-Castro et al., 2014	Portugal	Forest	Clayey	Csb	Prescribed fire	2	2	2
Miesel et al., 2011	USA	Forest	Loam	Csa	Prescribed fire	10	0	0
Moya et al., 2019	Spain	Forest	Sandy clay loam	Csa	Wildfire	18	2	0
Otero et al., 2015	Portugal	Forest	Sandy loam	Csb	Wildfire	1	7	0
Plaza-Álvarez et al., 2018	Spain	Forest	Clayey	Csa	Prescribed fire	6	0	12
Plaza-Álvarez et al., 2019	Spain	Forest	Clayey	Csa	Prescribed fire	6	6	10
Romanyá et al., 2001	Spain	Grassland	Not specified	Csa	Experimental burning	5	3	0
Romeo et al., 2020	Spain	Forest	Clay loam	Csb	Wildfire	6	4	0
Úbeda et al., 2005	Spain	Grassland	Not specified	Csa	Prescribed fire	0	10	0
Varela et al., 2015	Spain	Forest	Sandy loam	Csa	Wildfire	2	0	8
Vega et al., 2013	Spain	Shrublands	Loam	Csa	Wildfire	12	210	0
Total						190	564	88

Csa: Hot summer Mediterranean climate; Csb: warm-summer Mediterranean climate.

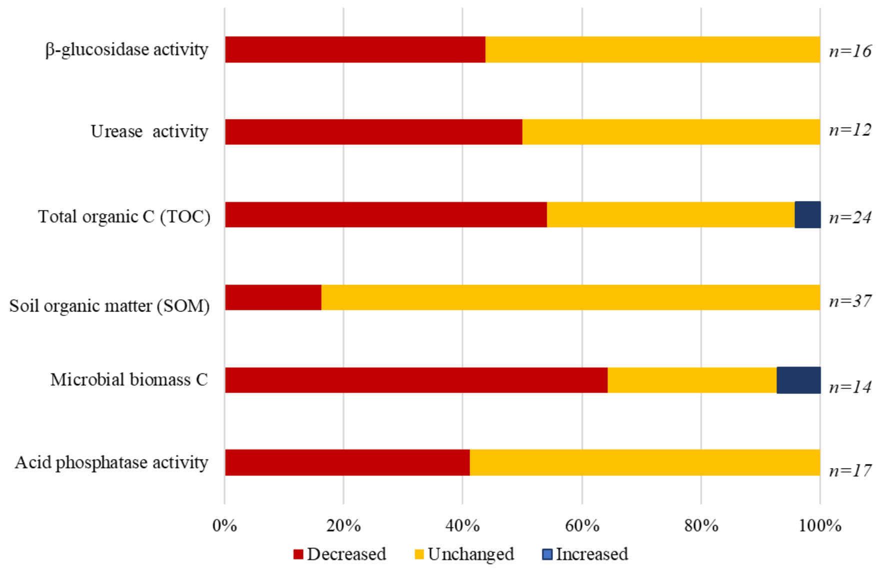
2.2.1. Effect of fire on soil properties

Low to moderate severity fire primarily impacts the topsoil. Consequently, the loss of soil organic matter (SOM) rather than alteration of soil minerals, has been the property most related to fire-induced changes in soil physico-chemical properties (Mataix-Solera et al., 2011; Araya et al., 2016)

Soil biological properties are more sensitive than chemical and physical properties to heat, which decreases microbial C through the direct mortality of microorganisms exposed to lethal temperatures (Hart et al., 2005; Muñoz-Rojas et al., 2016) and extracellular enzyme activities by enzyme denaturation (Fultz et al., 2016). Furthermore, changes in chemical and physical properties indirectly alter microbial communities and the decomposing and mineralization processes that they catalyze (Hart et al., 2005).

Occasionally, there is an immediate net increase in available nutrient after a fire, leading to a short-term increase in microbial activity (Caon et al., 2014), but most authors report a decrease of this activity. Furthermore, a meta-analysis of below ground biological community responses to fire concluded that fire reduced the richness, evenness, and diversity of soil microorganisms and mesofauna by up to 99% (Pressler et al., 2019).

Substantial oxidation of SOM begins in the 200-250 °C temperature range (Certini et al., 2011). Although SOM quantity and quality may change with elevated heat (Faría et al., 2015; Jiménez-Morillo et al., 2020), low to moderate severity fires have greater effect over the microbial communities and associated enzyme activities. Not surprisingly then, most studies in Mediterranean-climate region report no effect on SOM quantity (Mataix-Solera et al., 2013; Meira-Castro et al., 2014; Fonseca et al., 2017; Francos et al., 2019; Moya et al., 2019; Plaza-Álvarez et al., 2019) while others showed a significantly decrease on microbial biomass C (Vega et al., 2013; Fernández-García et al., 2019a; 2019b; Moya et al., 2019; Romeo et al., 2020) and the activity of urease, β-glucosidase and acid phosphatase (Miesel et al., 2011; Fernández-García et al., 2019a; 2019b; Moya et al., 2019) (Figure 2.3).



n: Number of significant effects reported per soil property.

Figure 2.3. Short and mid-term effects of low and moderate severity fire on soil biological properties in Mediterranean climate areas (based on the 34 studies described in Table 1).

Near 60% of the studies carried out in forest ecosystems report a decrease in enzyme activities in the short and midterm even with low severity fires (Miesel et al., 2011; Fernández-García et al., 2019a; 2019b; Moya et al., 2019), whereas low severity fires in grasslands and matorral report a neutral effect of fire on these properties (Gutknecht et al., 2010; Fontúrbel et al., 2012; Vega et al., 2013).

Soil chemical properties are generally more affected by the peak temperature than the fire residence time (Thomaz, 2017). Some studies report that the most significant changes of soil chemistry occur between 250 and 450 °C (Araya et al., 2016) and are linked to the SOM combustion and its by-products such as ash, pyrogenic organic compounds, increased pH, and transformation of Fe oxyhydroxide into Fe oxides (Caon et al., 2014; Thomaz, 2017). However, most studies on Mediterranean climate report no change in the mid-term of soil pH, electrical conductivity (EC) and cation exchange capacity (CEC) and an increase in available P, and NH4-N (Figure 2.4).

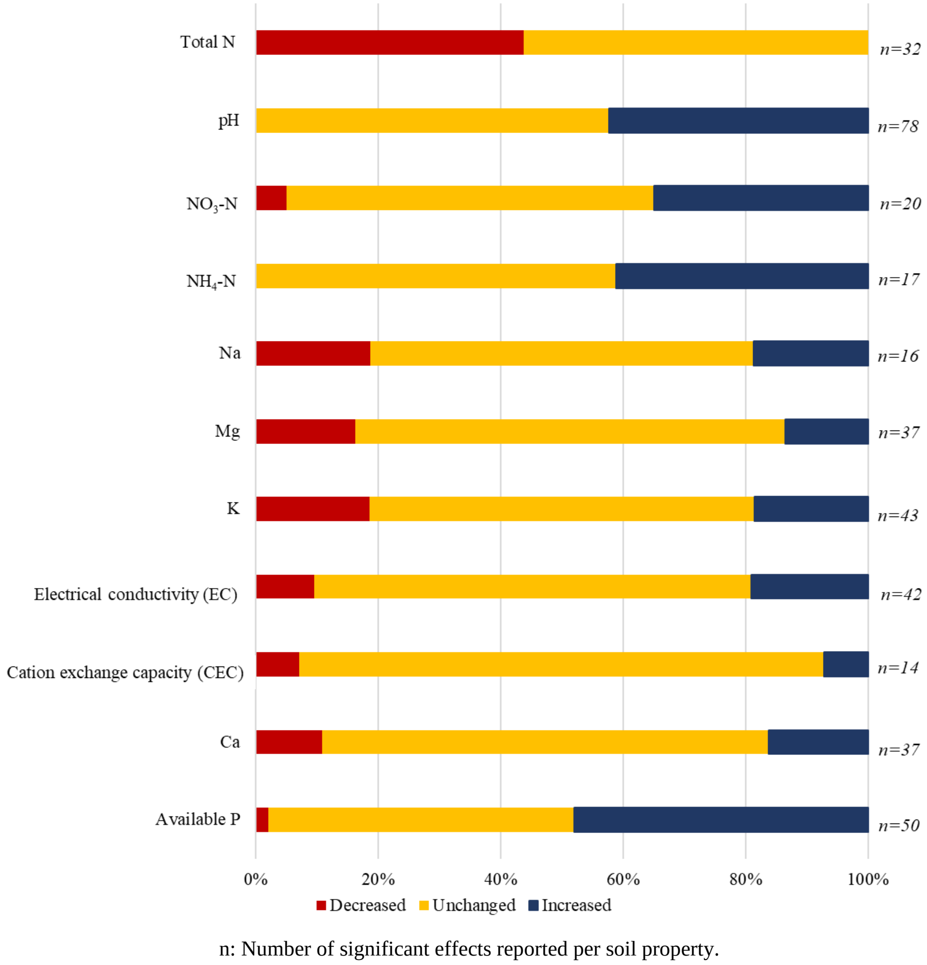


Figure 2.4. Short and mid-term effects of low and moderate severity fire on soil chemical properties in Mediterranean climate areas (based on the 34 studies described in Table 1).

Fire usually increases soil pH in the short term because of i) the release of alkaline cations (Ca, Mg, K, Na) that are bound to organic matter (Certini, 2005; Alcañiz et al., 2018), ii) the destruction of organic acids, and iii) the contribution of carbonates and oxides from ash (Granged et al., 2011; Bodí et al., 2012; Zavala et al., 2014; Alcañiz et al., 2016). This increase is ephemeral due to the formation of new humus, leaching of bases and removal of ash by erosion processes (Zavala et al., 2014). Thus, fire has no lasting effect on pH in the midterm.

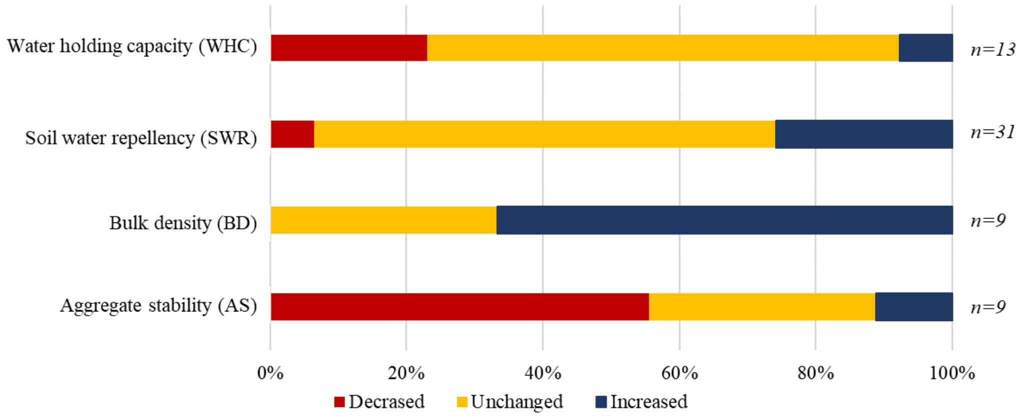
An increase of soil EC is associated to the soluble inorganic ions released during SOM combustion as well as the formation of black carbon and the incorporation of ash into the soil. Conversely, a decrease of CEC after fire is mainly associated with the net loss of SOM (Certini, 2005; Alcañiz et al., 2016; Araya et al., 2016). Some experimental studies have indicated that CEC is altered as far as the fire temperature exceed 300 °C to 350 °C (Thomaz, 2017). However, nonsignificant CEC changes are observed under low-severity fires because of unaffected SOM (Heydari et al., 2016; Fonseca et al., 2017; Plaza-Álvarez et al., 2018; Francos et al., 2019). Significant changes of EC have been reported in the midterm (Hueso-González et al., 2018) but most studies agree in a neutral effect of fire in CE and CEC after 1 yr (Granged et al., 2011; Jiménez-González et al., 2016; Hosseini et al., 2017; Fernández-García et al., 2019b).

Nitrogen content is another chemical parameter that experience notable variations in post-fire soils. The total N concentration tends to increase after a fire due to: i) release of the element from dead roots and N-containing organic compounds (Rivas et al., 2012), ii) nitrification enhancement in acid soil, and iii) the addition of partially pyrolyzed materials (Grogan et al., 2000). Similar to pH total N increase is ephemeral, thus most studies report a neutral effect in this property in the midterm.

Generally, positive changes in nutrient availability (P, Mg, K, Ca) occur after a fire; however, the recovery of prefire nutrient concentrations can take approximately 1 yr (Úbeda et al., 2005; Alcañiz et al., 2016), thus, usually there are negligible mid-term effects regarding nutrient availability after a fire (Figure2. 4).

The main physical changes at low to moderate fire temperatures are an increase of soil water repellency (SWR) and bulk density (BD) and a decrease of aggregate stability (AS) and water holding capacity (WHC). Most studies report an increase of SWR during the first year after following the fire event, and no changes in the midterm (Hubbert et al., 2006; Jiménez-Pinilla et al., 2016; Plaza-Álvarez et al., 2018). Furthermore, SWR is common in long-term unburned Mediterranean calcareous soils (Bodí et al., 2013), thus, fire might not have the same impact as in other types of soil. However, the degree of postfire SWR in the short term depends on fire severity, vegetation type, soil texture, rainy season, soil moisture and land use (Alcañiz et al., 2018).

The AS usually decreases after fire in the short and midterm (Granged et al., 2011; Varela et al., 2015), WHC decreases immediately a fire but has no change in the short and midterm (Jiménez-González et al., 2016; Plaza-Álvarez et al., 2018) and BD increases in the short and midterm after a fire (Hubbert et al., 2006; Granged et al., 2011; Heydari et al., 2016) (Figure 2.5).



n: Number of significant effects reported per soil property.

Figure 2.5. Short and mid-term effects of low and moderate severity fire on soil physical properties in Mediterranean climate areas (based on the 34 studies described in Table 1).

2.2.2. Postfire erosion risk

In Mediterranean ecosystems around the world, runoff and sediment yields are around 1-4 orders of magnitude higher on burnt soils compare to unburnt soils, resulting in serious soil degradation (Shakesby, 2011) due to extreme soil erosion rates (Lucas-Borja et al., 2019). After a fire event, a set of factors enhance the postfire risk of erosion: i) the presence of ash that causes the clogging of macropores and surface sealing (Larsen et al., 2009; Bodí et al., 2012), ii) the reduction of AS and increase of SWR and BD which reduces both the rate of infiltration and WHC (Certini, 2005; Jordán et al., 2013; Zavala et al., 2014; Heydari et al., 2016; Weninger et al., 2019), iii) the absence of vegetation cover and superficial litter layer (amount of bare soil exposed) (Bodí et al., 2012; Jordán et al., 2013), iv) the reduction of SOM (Wittenberg et al., 2020), v) the occurrence of intense rainfall immediately after a fire (Pereira et al., 2018), vi) slope, and vii) tillage (Larsen et al., 2009; Vieira et al., 2018) (Figure 2.6).

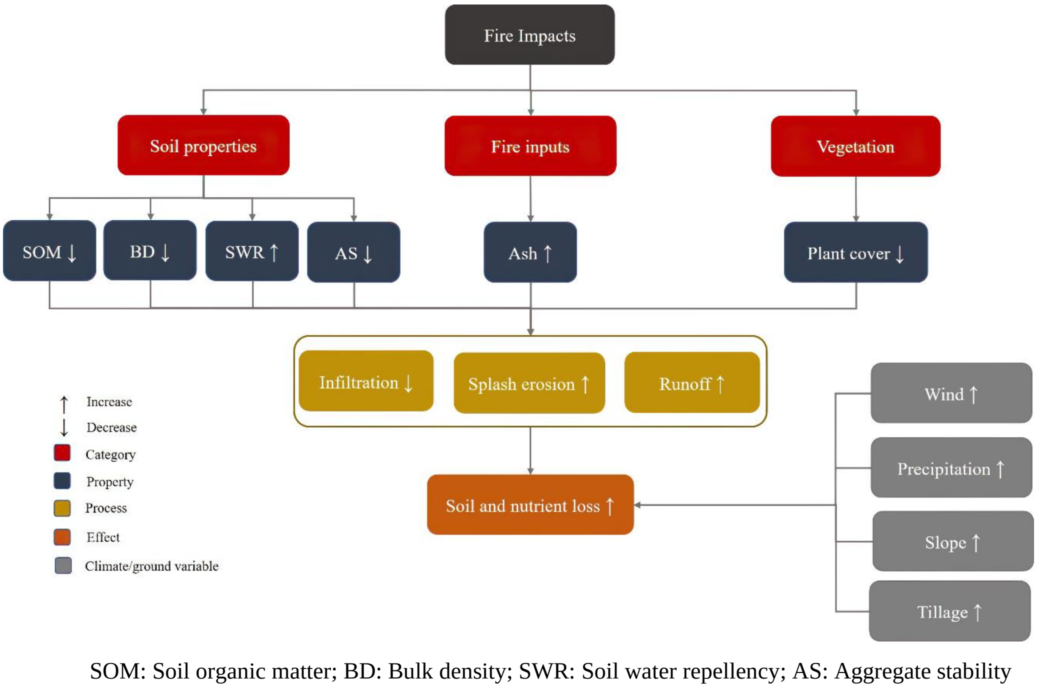


Figure 2.6. Changes of soil properties, processes and site variables that increased soil and nutrient losses after a wildfire (adapted from Wittenberg et al., 2020).

Therefore, postfire interventions are needed to reduce runoff and soil erosion in order to prevent losses of SOM, nutrients and avoid sediment transport. In addition to addressing the risk of runoff and erosion, the improvement of SOM quantity and quality is fundamental in the process of restoring other physical-chemical and biological soil properties (Varela et al., 2011).

2.2.3. Postfire soil management

In most Mediterranean-climate regions, where wildfires are considered a main soil degradation driver, passive restoration (letting Nature do it) is not a viable strategy for most areas affected, were naturally vegetation recovery takes 5-10 times longer than wetter environments (Caon et al., 2014).

When vegetation cover is completely destroyed by fire, emergency stabilization treatments such as seeding for plant cover and/or mulching must be applied as soon as possible in the burned area to reduce runoff and soil erosion and nutrient losses (Caon et al., 2014; Fernández et al., 2019). Thus, ash deposition and persistence on the soil surface is essential to limiting nutrient losses and fostering vegetation recovery after a fire (Caon et al., 2014)

Plant seeding is a soil stabilization technique to accelerate the reestablishment of a vegetation cover in burnt areas (Fernández-Fernández and González-Prieto, 2020) and is used to reduce erosion and preserve soil nutrient after a fire (Table 2). However, this technique can be ineffective in increasing ground cover or reducing erosion rates and sediment yields, especially during the first critical rain events following a fire (Wagenbrenner et al., 2006; Vega et al., 2014) when it fails to achieve 50%-70% coverage of the ground necessary to mitigate post fire erosion (Robichaud et al., 2013). Furthermore, considering that wildfires in Mediterranean-climate region usually occur during hot dry summers, the establishment of plant seeding after a fire of rainfed agriculture in central Chile might not be viable.

As an alternative, dry mulching (using wheat and rice straw, wood strand and coconut fibers among others) can provide immediate effectiveness in increasing ground cover (Fernández et al., 2011; Wittenberg et al., 2020), reducing runoff speed, increasing water infiltration, and retaining sediments (Fernández-Fernández and González-Prieto, 2020).

Mulching therefore is increasingly employed to reduce postfire runoff and soil and SOM losses (Wagenbrenner et al., 2006; De la Rosa et al., 2019; Lucas-Borja et al., 2019). Although in burned areas with low precipitation, mulching might not decrease the losses of eroded sediment and nutrient (Fernández-Fernández et al., 2016). However, in Mediterranean climate with wet winters (and high precipitation) mulching is highly efficient to reduce erosion and sediment yield (Wagenbrenner et al., 2006; Fernández et al., 2011; Díaz-Raviña et al., 2013; Robichaud et al., 2013; Vega et al., 2014; De la Rosa et al., 2019; Lucas-Borja et al., 2019). In addition to reducing erosion and thus preserving SOM, N, and nutrients after a fire, mulching has others benefits that enable soil restoration after a fire such as increase in soil moisture and recovery of plan cover and preserve activity and diversity of soil microorganism (Fernández et al., 2016; De la Rosa et al., 2019) (Table 2.2).

Table 2.2 Effects of mulching and seeding on soil erosion after a fire.

Mulching effects on soil
• Provide immediate ground cover for exposed soil and protection from raindrop impact and overland flow (Wagenbrenner et al., 2006; Robichaud et al., 2013; Wittenberg et al., 2020) • Increases soil moisture (Fernández et al., 2016) and for coconut fiber mulching also increases soil water retention (Wittenberg et al., 2020) • Preserve N and nutrients increase after a fire (Gómez-Rey et al., 2013; Gómez-Rey and González-Prieto, 2014; Fernández-Fernández and González-Prieto, 2020) • Reduce SOM losses and improved SOM quality of the topsoil (De la Rosa et al., 2019) • Improve the recovery rate of plan cover (Fernández et al., 2016) • Preserve pyrogenic organic matter (De la Rosa et al., 2019) • Preserve biomass and the activity and diversity of soil microorganisms (Fontúrbel et al., 2012)
Seeding effects on soil
• Reduce N losses by erosion (Díaz-Raviña et al., 2013; Gómez-Rey et al., 2013) • Preserve the biomass and the activity and diversity of soil microorganisms (Fontúrbel et al., 2012) • Mitigate the fire triggered negative effects on soil characteristics related with soil fertility and quality (Fernández-Fernández and González-Prieto, 2020)

2.2.4. Fire management and planning tools in Chile

National environmental policies should consider the projected increase of wildfires frequency under expected climate variables, to help reduce the future risk of wildfires (Urrutia-Jalabert et al., 2018). Management options of potentially flammable biomass should be developed and optimized by risk-based modeling approaches and should be mandatory in wildland-urban transition lands (Gómez-González et al., 2018) as well as agricultural land-forest interfaces in order to ensure the long-term sustainability of agricultural land.

In Chile, the Law 20.283 Recovery of Native Forest and Forest Promotion, which has an annual fund of 8 million dollars, was established for the protection, recovery and improvement of native forests, and includes economic incentives for postfire recovery and the prevention and suppression of forest fires. The law provides subsidies for various activities and structures such as soil improvement, rainfall infiltration ditches, and forest thinning and firewalls.

For agricultural lands, the Law 20.412 Agri-environmental Soil Sustainability Incentive System (SIRSD-S) which has an annual budget of 60 million dollars, was established to promote practices that ensure the soils sustainable management in the long term for agricultural and livestock production. The SIRSD-S integrates five subprograms, which include among them plant cover establishment. This subprogram provides financing of 70%-90% of the total costs (depending on farm size) of plant cover establishment for bare soils, which can be used to prevent soil erosion and associated nutrient loss after a fire. But there are no economic incentives for mulching which is the most effective stabilization technique after a fire and could be used in rainfed agriculture which constitutes up to 90% of the total agricultural land that is affected by wildfire in Chile, and where plant cover cannot be easily established after a fire due to long-term droughts during the summer. Inorganic fertilizers are also financed by the sub-program, but organic amendments needed to recover these soils are not included thereby leaving aside degraded agricultural lands affected by wildfires in rainfed agriculture of Central Chile.

2.3. Conclusions

Mediterranean climate regions are prone to wildfires due to hot, dry summers and cool wet winters. Furthermore, considering that wildfire frequency is projected to increase in these regions, fire prevention and suppression efforts must go hand in hand with post fire restoration of these soils. Countries with agricultural lands vulnerable to wildfires such as Chile, should consider economic incentives to restore these soils affected for wildfires and guarantee its sustainable management in the long term.

Fire impacts on soil properties vary among the studies. However, most wildfires enhance the postfire risk of erosion due to the presence of ash, reduction of aggregate stability, and increase of soil water repellency and bulk density. Thus, after a fire the use of emergency stabilization techniques are essential to limit nutrient and soil losses in agricultural lands that need to recover its productivity in the short term.

Much research has been conducted to evaluate wildfire impacts and post fire restoration in forest soils, but there are not studies for agricultural soils affected by wildfires. Further research is needed to define the impacts of wildfire on agricultural soil properties and to evaluate the use of emergency stabilization techniques particularly in rainfed agriculture were the restoration or establishment of plant cover after a fire is not viable. To define the impacts of fire and post fire stabilization techniques will contribute to construct an adequate restoration strategy or guidelines to facilitate the post fire soil restoration in agricultural lands vulnerable to wildfire in the Mediterranean climate regions.

2.4. Acknowledgements

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Capítulo II: Glosario de Abreviaturas, siglas y acrónimos

AS	Aggregate Stability
BD	Bulk Density
Csa	Hot summer Mediterranean climate
Csb	Warm summer Mediterranean climate
CEC	Cation Exchange Capacity
EC	Electrical conductivity
SIRSD-S	Agri-environmental Soil Sustainability Incentive System
SOM	Soil Organic Matter
SWR	Soil Water Repellency
TOC	Total Organic Carbon
WHC	Walter Holding Capacity

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III. EFFECT OF WILDFIRES ON SOIL PROPERTIES OF AGRICULTURAL LANDS OF MEDITERRANEAN-CLIMATE REGION IN CHILE

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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 soils samples that were collected at two depths (0-5 cm and 5-10 cm) in areas that were affected by moderate severity wildfires 14 months prior and the immediately neighboring unburned area. The most sensitive soil properties to wildfire in the top 5 cm according to a T-test independent variable ($p<0.05$) were Microaggregates, Macroaggregates, and contents of NO_3-N, Fe, Cu, and S. Furthermore, the overall most relevant soil properties to differentiate between burned and unburned soil regardless its sampling depth were selected as soil quality indicators. Accordingly, Carboxylesterase activity, Available Soil Moisture, pH, Ca, P, Fe, B, S and Cu were selected using a two-way analysis of variance with fire treatment and sampling depth as sources of variation. The results showed that Carboxylesterase activity and Available Soil Moisture decreased after a wildfire. Also, pH significantly decreased 14 months after a fire which affected the subsequent nutrient availability. Thus, Ca and P decreased whereas Fe, Cu, S and B availability increased in burned soils. To assess these changes that are driven by wildfires, a soil quality index was computed adding normalized soil quality indicators. Even though the fire effects were not ephemeral in several soil properties, some individual effects were both positive and other negative. Therefore, the overall soil quality index did not differ between burned and unburned soils 14 months after the fire.

Keywords: Soil properties, soil quality, wildfire, Mediterranean-climate, Agriculture

3.1 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 sever wildfires are natural occurrences in these regions, they have lately become a major hazard for these lands 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 climate region is characterized by hot, dry summers, and cool wet winters (Warm-summer Mediterranean climate – Csb), 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. This 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 others around the globe, the length of the fire season, heat waves, and fire duration and frequency has notably increased in the last 30 years (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 wildfires were the most severe of last four decades, because they were preceded by a previous severe multiannual drought and were responsible for burning of 266,728 ha of forest plantations, 212,830 ha of native forest shrublands and grasslands and, 28,729 ha of agricultural land mainly on the coastal range between 33°50' and 38°29' (Bowman et al., 2019; CONAF, 2021) (Figure 3.1).

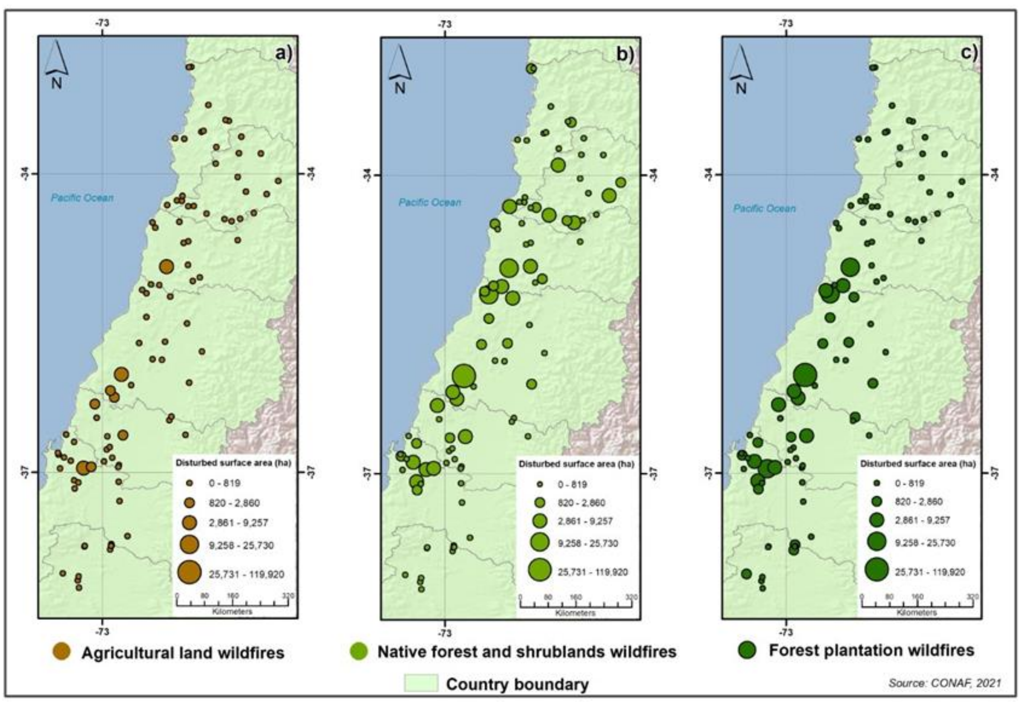

Figure 3.1 Distribution of disturbed surface area of the 2017 major fire in South-Central Chile. a) Agricultural lands b) native forest and shrublands, and c) forest plantation (CONAF, 2021)

Even though the 2017 fires were unprecedented, every year several hundreds of hectares of agricultural land are affected by wildfires in Chile with 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. Many areas of these degraded agricultural lands are 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 wildfires (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 year) have also been reported (Fonseca et al., 2017; Raiesi and Pejman, 2021).

Most soil properties are unaffected 1 year 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 (NO3-N and NH4-N) (Vega et al., 2013; Gómez-Rey & 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 & González-Prieto, 2014; Heydari et al., 2017; Moya et al., 2019), K (Gómez-Rey et al., 2013; Heydari et al., 2017), Ca (Gómez-Rey & González-Prieto, 2014) and Mg (Gómez-Rey et al., 2013). Usually, pH and nutrient availability changes are ephemeral (≤ one year) 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 bulk density (BD) 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 aims 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 hypothesize that the soil quality of agricultural lands in Mediterranean-climate region decreases 14 months after a moderate severity wildfire.

3.2. Materials and methods

3.2.1. 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 region of Bíobio in central Chile (Figure 3.2).

The mean annual precipitation in this area is 1,633 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 masl with a slope between 9 to 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 is of the Alfisols Order with a clay loam texture and was developed from saprolitic granitic materials, mapped as Cauquenes Soil Association, and classified as Ultic Palexeralfs.

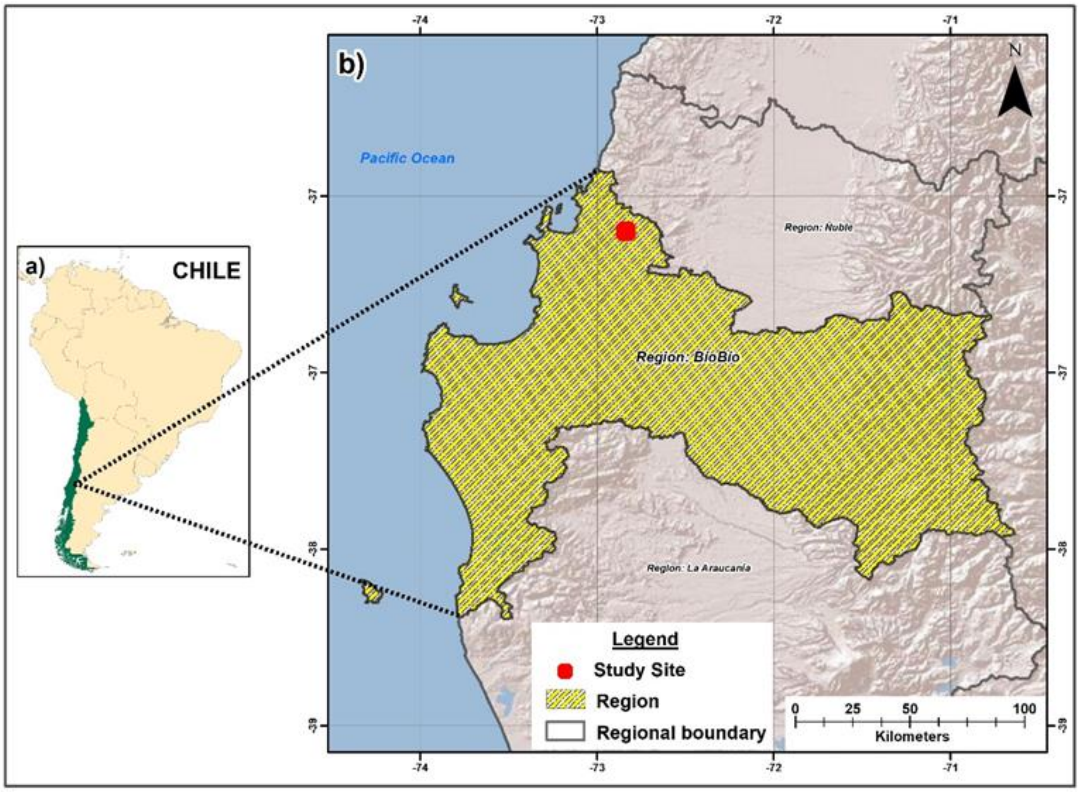

Figure 3.2 Location of the study site. (a) Regional location, (b) National location.

3.2.2. Experimental design and sample collection

Samples were collected in March 2018, 14 months after the wildfire. Three sample plots (150 m^2 each) were selected randomly inside the burnt area and the immediately adjacent unburnt 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 sub samples were collected at two depths: i) 0-5 cm depth, and ii) 5-10 cm. The sub samples were mixed to obtain a composite sample for each treatment. Thus, 12 composite soil samples (2 treatments x 2 depths x 3 plots) were stored in plastic bags and transported to the Soil Department Laboratory, Universidad de Concepción, and kept at 4°C until analysis.

3.2.3. Laboratory analysis

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

SOM was determined by reducing the carbon in SOM with dichromate in an acid media (Sadzawka A. 2006). Soil Microbial C mineralization was measured by the incubation of triplicate 20 g of soil for 56 days. Small vials with 7.5 ml of 0.5M NaOH were placed in the incubations chambers and the solution was changed after 3, 7, 14, 28 and 56 days and titrated with 0.1 M HCl in the presence of BaCl2 (El-Saeid & 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 (1mM) was added to soil water suspension for AcP, Glu, Ure and Prot to prevent microbial growth due to longer reaction times (Turner Benjamin 2010). Enzyme activities were analyzed following the procedures described by Sanchez-Hernández et al., (2017).

Chemical properties were determined according to the methods recommended for Chilean soils by Sadzawka et al., (2006). 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), NO3-N, NH4-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), Permanente Wilting Point (PWP) and Available Soil Moisture (ASM) (Pressure plates method), macro and micro-aggregates (set of sieves underwater) and Saturated hydraulic conductivity (Ks) (single-ring infiltrometer).

3.2.4. Statistical analysis

The Shapiro-Wilk test was used to test for data normality. Soil properties were separated in two set: i) 0-5 cm depth and ii) 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 analysis of variance (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 no significant interaction (fire treatment x 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” (Eq. 1), and each observation was divided by the highest observed value, ii) Linear scoring where “less is better” and the lowest observed value was divided by each observation (Eq. 2), and iii) Non-linear scoring (NLS) following a sigmoidal type of curve (Eq. 3) (Raiesi and Pejman, 2021).

$$LS = \frac{X}{Xmax} \quad (1)$$

$$LS = \frac{Xmin}{X} \quad (2)$$

$$NLS = \frac{1}{1 + \left(\frac{x}{x0}\right)^{-2.5}} \quad (3)$$

Where LS is the linear score and NLS is the nonlinear score varying from 0 to 1, x is the soil property and xmax, xmin and x0 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 indicators. The SQI was finally normalized using the LS “more is better” 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 replicates ± standard deviation.

3.3 Results and Discussion

3.3.1 Soil properties sensitive to wildfire

Overall, the soils were clay loam with high bulk density between 1.60 and 1.54 g cc-1. These soils are considered unstable (potentially erodible) with Mean Weight Diameter (MWD) <0.5 cm and excessive drainage (Ks >15 cm hr-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 nutrient content in them is considered low (Table 3.1).

Table 3.1 Nutrient content in soils of the study site.

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 months after the wildfire. At a 0-5 cm depth, 6 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 months after a wildfire, indirect changes related to erosion and leaching are relevant in deeper soil layers (Table 3.2)

Table 3.2 T test independent variable to determined significant differences in soil properties between burned and unburned soils at 0-5 cm and 5-10 cm depth. UBV;Unburned vineyard, BV; Burned vineyard.

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 cc^{-1})	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***
Ks (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 (µNH_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	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	5.898 ± 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
Fe (mg kg^{-1})	3.73 ± 1.61	15.70 ± 3.76	**0.0071****	4.06 ± 0.41	17.8 ± 3.44	**0.0204***
Mn (mg kg^{-1})	26.73 ± 2.21	44.60 ± 15.93	0.1943	6.6 ± 1.11	22.4 ± 9.98	0.1125
Zn (mg kg^{-1})	0.41 ± 0.09	0.40 ± 0.06	0.9220	0.27 ± 0.09	0.26 ± 0.10	0.9380
Cu (mg kg^{-1})	0.40 ± 0.05	0.81 ± 0.11	**0.0052****	0.30 ± 0.01	0.74 ± 0.11	**0.0215***
B (mg kg^{-1})	0.30 ± 0.07	0.36 ± 0.06	0.3630	0.25 ± 0.05	0.35 ± 0.01	**0.0423***

Although soil enzymes have been identified as sensitive indicators of ecological change (Singh et al., 2021), no significant 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 carbon 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 one year 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 months 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 was the effect of fire found to be independent of the effect a sampling depth (no interaction) (Table 3.3).

Table 3.3 Two-way ANOVA to determined significant differences in soil properties for wildfire effect and soil sampling depth (sources for variation).

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

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

AcP activity showed a non-significant increase which 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 phosphorus 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 2 times higher, compared to the unburned plots (Table 3.2).

Even though the decrease of soil pH was non-significant 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 years after a low to moderate severity fire (Garrido-Ruiz et al. 2022). Soils in our study site have an excessive drainage (Ks >15 cm hr^{-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 soil 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 one year after a fire in Mediterranean climate regions (Gómez-Rey and González-Prieto 2014; Gómez-Rey et al., 2013; 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 NH4-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 3.3). Thus, in our study the chemical properties showed greater sensitivity to differentiate between burned and unburned soils regardless its depth than the biological properties that were unable to identify effects from fire disturbances in the first 5 cm.

Four physical properties were significantly changed by fire. ASM decreased while macroaggregates, microaggregates and MWD were higher in burned soils after 14 months (Table 3.2). 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 3.3).

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).

3.3.2 Soil quality indicators

Soil properties that were sensitive to wildfire in the first 5 cm (n=6), were highly correlated with each other, 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), were pooled to compare burned and unburned vineyards using a paired t-test regardless of sampling depth. 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 months after the wildfire (Figure 3.3).

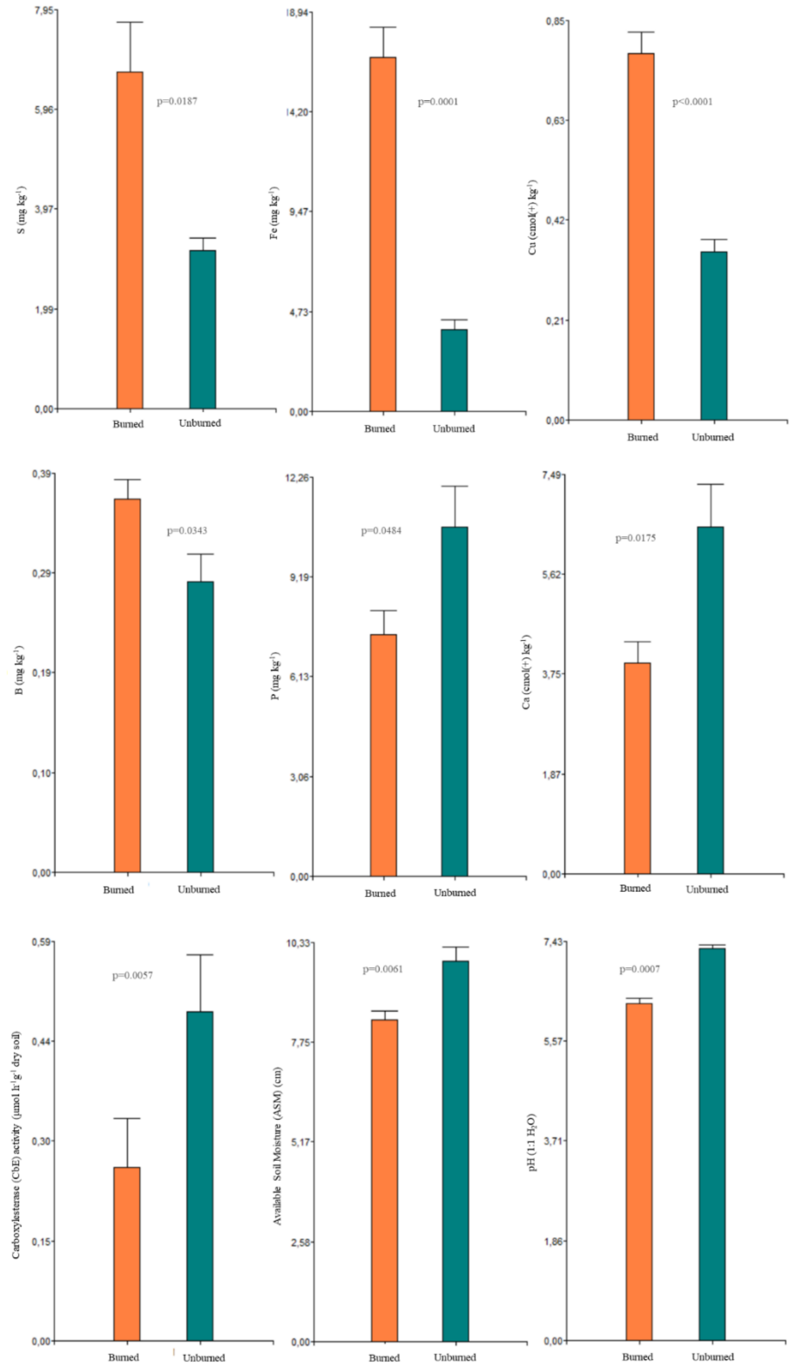

Figure 3.3 Mean values of soil properties 14 months after a wildfire in a burned and unburned vineyard regardless its sampling depth. P values according to T-test independent variables ($p < 0.05$). Vertical bars correspond to standard error.

We normalized the soil properties as follows: i) linear scoring where “more is better” was used for CbE activity, ASM, P, Ca, Fe, B and S, ii) linear scoring where “less is better” was used for Cu and iii) non-linear scoring was used for pH. Thus, we estimated an overall soil quality index with an additive equation of the normalized variables. The overall soil quality index was once more normalized with linear scoring “more is better” which did not vary between burned and unburned soils. This is because some soil quality indicators improved in burned soils such as Fe, S, B, while others like ASM, P, Ca and CbE worsened with the fire. Thus, the SQI had a non-significant decrease in burned soil from 0.88 to 0.83 (Figure 3.4).

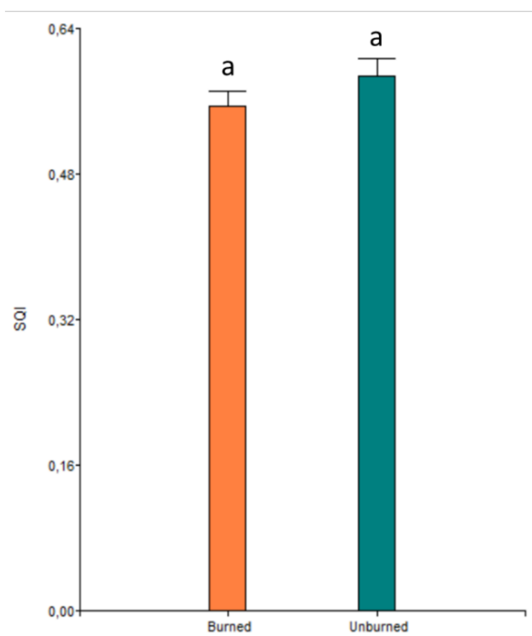

Figure 3.4 Mean values of Soil Quality Index (SQI) in a burned and unburned vineyard 14 months after the wildfire Vertical bars correspond to standard error. Distinct letters indicate significant differences according to T-test independent variable (P ≤ 0.05).

Soil response to fire is often linked to fire severity and recurrence. Therefore, even though our results showed that fire had an apparent a mix of positive a negative effects 14 months 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 months, even when vegetation had been regenerated, as had been reported by other studies.

3.4. 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 months after the fire.

It is important to consider that 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.

CbE activity was the only biological property selected as a soil quality indicator due to its sensitivity to fire change. Thus, in soils with very low SOM, 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 importance to evaluate not only the first few cm that are allegedly directly affected by heat (Strydom et al. 2019) but also deeper layers that are indirectly affected by fire through redistributive processes of soil.

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Capítulo III: Glosario de Abreviaturas, siglas y acrónimos

AcP	Acid phosphatese
ANID	Agencia Nacional de Investigación y Desarrollo
ANOVA	Analysis of Variance
AS	Aggregate Stability
ASM	Available Soil Moisture
BD	Bulk Density
CbE	Carboxylesterase
CE	Electric Conductivity
CEC	Cation Exchange Capacity
CONAF	Corporación Nacional Forestal
Csb	Warm-summer Mediterranean climate
Glu	Glucosidase
LS	Linear scoring
MWD	Mean Weight Diameter
NLS	Nonlinear scoring
Prot	Protease
SQI	Soil Quality Index
SOM	Soil Organic Matter
SWR	Soil Water Repellency
Ure	Urease

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IV. CONCLUSIONES GENERALES

El impacto de incendios de severidad moderada sobre las propiedades del suelo en regiones de clima Mediterráneo no es efímera, por lo que los efectos causados por el fuego persisten 14 meses después del incendio. Debido a que estos efectos del fuego pueden ser positivos y negativos el impacto global de incendios de severidad moderada en la calidad del suelo puede ser imperceptible.

Particularmente los nutrientes que disminuyeron (Ca y P) en los suelos afectados por incendios de severidad moderada se encontraban en un nivel moderado, mientras que los nutrientes que incrementaron como el NO_3-N, Fe, S y B se encontraban en niveles bajos y muy bajos. En este contexto es necesario asociar estos cambios con la capacidad del suelo de sustentar la productividad de plantas y animales.

Los mejores indicadores para monitorear la calidad del suelo afectada por incendios de severidad moderada, por su capacidad de discriminar los suelos quemados independiente de la profundidad de muestreo son: Humedad del Suelo Disponible, actividad de la CbE, pH, P, Ca, S, fe, Cu, B. El ICS estimado con estos indicadores demuestra que no existe diferencia en la calidad del suelo en general, sin embargo, es fundamental evaluar la importancia de cada indicador con un enfoque de productividad y evaluar el comportamiento de estos indicadores en el tiempo (medio y largo plazo).

En general las propiedades biológicas son mejores indicadores de calidad del suelo después de una perturbación, sin embargo, en el caso de suelos de uso agrícolas de secano altamente degradados (con contenido de materia orgánica muy bajo), los incendios de severidad moderada no causan efectos significativos duraderos en la materia orgánica ni en las propiedades biológicas del suelo asociadas. En contraparte, en estos suelos, las propiedades químicas de suelos son más sensibles a los efectos de los incendios y por ende tiene mayor poder discriminante entre suelos afectados por incendios de aquellos que no han sido afectados.

Al evaluar el impacto post incendios no inmediato es importante considerar profundidades del suelo mayores a los primeros 5 cm. Si bien a estas profundidades no existe efecto directo de fuego (por calor o combustión), existen impactos indirectos asociados a procesos de redistribución de los suelos mediante erosión, infiltración y lavado de bases.

Los resultados obtenidos en este estudio se deben acotar a suelos agrícolas de secano en regiones de clima Mediterráneo, altamente degradados y con alto riesgo a erosión (debido a las altas precipitaciones y pendiente).