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ORIGINAL PAPER

Contrasting Organic Amendments Induce Different Short-Term Responses in Soil Abiotic and Biotic Properties in a Fire-Affected Native Mediterranean Forest in Chile

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Abstract

This study aimed to evaluate contrasting organic amendments as a strategy to promote the recovery of biotic and abiotic edaphic conditions central to the reestablishment of soil ecosystem functions at a site in south-central Chile affected by megafires in the 2016–2017 summer season. We analyzed the effects of the application of fresh (poultry and swine manure) and stabilized (compost of agricultural waste origin) organic amendments on microbial parameters, including basal respiration, microbial biomass, the carbon mineralization coefficient, and the microbial metabolic quotient, along with soil physicochemical properties related to soil fertility and stability. All organic amendments improved soil fertility and stimulated soil microbial activity. Fresh amendments, particularly swine manure, promoted the immediate recovery of the microbial conditions evaluated. However, greater mineralization rates and thus presumably shorter periods of carbon (C) source consumption were related to the application of such organic amendments. Soils treated with compost accumulated the most organic carbon and nitrogen, ensuring long-term nutrient release and thus long-term soil function recovery. Choosing the type of organic amendment to use to sustain ecosystem resilience will highly depend on the restoration goals over time.

Keywords Compost · Ecosystem restoration · Poultry manure · Swine manure · Wildfires

Abbreviations

CFU	Colony-forming unit
EC	Electrical conductivity
GLMs	Generalized linear models
qCO2	Metabolic quotient
OC	Organic carbon
PCA	Principal component analysis
SIR	Substrate-induced respiration

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1 Introduction

Fires in Chilean Mediterranean ecosystems have increased over the last two decades, coinciding in the last 10 years with a period deemed as "megadrought" due to consecutive dry years, causing major socioeconomic and environmental impacts (Garreaud et al. 2020). The latest fire of vast magnitude, the so-called extreme fire event or megafire, occurred in the 2016–2017 summer season in central and south-central areas of Chile (32–40° S latitude) and reached a historical maximum affected area of approximately 600,000 ha (De la Barrera et al. 2018).

Although Mediterranean landscapes are prone to fires (Pausas et al. 2009), the intensity and severity of wildfires increase dramatically in megafire events, endangering the resilience of forest ecosystems (Moreira et al. 2020). In this context, where the natural recovery of native vegetation is hampered, restoration efforts towards post-fire recovery of ecosystem services become crucial (Muñoz-Rojas 2018). Thus, restoration of belowground functions, such as biological productivity, nutrient cycling, physical stability, carbon sequestration, and support for plant growth

(Keesstra et al. 2016), is essential to sustain aboveground ecosystem conditions. These efforts not only should take into account the characteristics of the landscape to be restored, but also the processes or components aimed to recover in the short and long term (Costantini et al. 2016).

The effects of fires on soil properties depend primarily on pre-fire edaphic conditions, the type of ecosystem affected, the severity and intensity of fires, and post-fire meteorological conditions (Neary et al. 2005). Microbial dynamics and growth can be strongly affected by frequent fires and droughts (Guénon and Gros 2016), hindering the recovery of microbially driven ecosystem functions, including nitrogen and carbon cycling (Pérez-Valera et al. 2019). Moreover, high-severity fires damage soils mainly due to the combustion of organic matter, a critical component of terrestrial ecosystems, since it plays key roles in nutrient cycling, microbial activity, and soil structure formation (González-Pérez et al. 2004). Thus, considering a key component in the restoration process as soil organic matter has cascading effect implications in multiple components in a perturbed ecosystem (Heneghan et al. 2008). The reestablishment of organic matter levels in post-fire restoration efforts, for example, by applying organic amendments, is an effective strategy to promote vegetation reestablishment and the recovery of soil health, thus restoring its ecosystem functions and services (Hueso-González et al. 2018; Larney and Angers 2012). In the short term, an increase in organic matter through the addition of organic amendments boosts soil fertility and nutrient cycling, stimulates soil microbial growth and activity, and favors a rapid plant establishment, whereas in the long term, soil structure and stability and water holding capacity improve, hence reducing the risks of erosion and nutrient loss (Larchevêque et al. 2005; Ojeda et al. 2003).

In soil restoration plans, choosing the type of organic amendment to use is an important step, as this decision dictates decomposition rates and has transient and durable implications on soil conditions (González-Ubierna et al. 2012). The application of fresh organic amendments adds a high amount of labile, easy-to-degrade organic carbon to soils with short turnover times, which promotes the rapid growth of microorganisms and vegetation (Haynes 2005). However, fresh organic amendments can have potential adverse effects, including increases in autochthonous soil organic carbon mineralization, short-term CO_2 emissions, salinity or acidity, nitrogen immobilization, and/or the addition of potential pollutants and pathogens into soil and bodies of water (Bernal et al. 2009). In contrast, stabilized materials, such as compost, provide a high proportion of stable organic substances contributing to enduring soil fertility (Larney and Angers 2012). Consequently, the amendment selection will depend on the goals of the soil restoration plan. While fresh amendments with high contents of labile organic matter might enhance biological activity by acting as a fast release of C in recently burned soils, the more stabilized organic amendments would ensure carbon and nutrient storage with slow mineralization rates over time (Kowaljow and Mazzarino 2007).

This study aimed to evaluate the effect of contrasting organic amendments in the restoration of biotic and abiotic edaphic conditions, which are key to the recovery of ecosystem functions, in a fire-affected sclerophyllous forest in the Mediterranean zone of central Chile. For this purpose, microbial parameters, including basal respiration, microbial biomass, the carbon mineralization coefficient, and the microbial metabolic quotient, along with soil physicochemical properties, such as organic carbon, nutrient, and metal contents, were studied after the application of fresh (poultry or swine manure) and stabilized (compost of agricultural waste origin) organic amendments. We hypothesize that fresh amendments, poultry and swine manure, would promote immediate, but transient, microbial conditions recovery, enhancing microbial biomass and activity in a short term. On the contrary, the compost amendment, characterized by stabilized organic matter, would impact long-term soil function recovery by increasing organic matter and nutrient contents in soils.

2 Materials and Methods

2.1 Research Site

The study was conducted in the Chilean Mediterranean zone of the O'Higgins Region, one of the most affected regions during the 2016–2017 summer megafire (CONAF 2017). The study site is located in the Pumanque commune (34° 36.502′ S, 71° 42.281′ W; altitude: 130 m.a.s.l.), in the region's dryland coastal zone. According to information provided by local residents, within the last 30 years, the site was mainly used by small farmers for livestock pasture and wood charcoal production and had not experienced fire events until January 2017. The average annual precipitation is 451 mm, with an average temperature of 15.4 °C (summer: 29.9 °C, winter: 5.3 °C). The site is mainly covered by native sclerophyllous forest species, dominated by *Quillaja saponaria* Molina, *Lithraea caustica* Hook. & Arn., and *Peumus boldus* Molina in the canopy, and *Trevoa trinervis* Miers, *Azara serrata* Ruiz & Pav., and *Colliguaja odorifera* Molina in the understory. Soils are classified as Aquic Dystroxerepts (Soil Survey Staff 2014) with low depth (40 cm on average) and sandy loam texture (58% sand, 34% silt, and 8% clay) located on a 10% slope facing south.

2.2 Experimental Design

The application of organic amendments and different vegetation establishment methods were implemented in early June of 2018, as part of a previous study, to evaluate the effect of them on early soil biological conditions (Marín and Rojas 2020). Poultry and swine manure were organic materials easily available at the site location, while compost consisted of a commercial product originating from agricultural wastes. Chemical analyses of organic amendments have been previously reported (Marín and Rojas 2020). Briefly, organic carbon and total nitrogen contents were 10.38% and 0.83% in compost, 23.47% and 1.92% in poultry manure, and 12.89% and 0.75% in swine manure (further information on the amount of OM, OC, and N added by each organic amendment is provided in Table S1). The pH (1:5 w/v water extract) values varied from 6.77 (in poultry manure) to 8.8 (in swine manure), while electrical conductivity (1:5 w/v water extract) fluctuated from 1.12 (in compost) to 3.56 mS cm^{-1} (in poultry manure). These amendments were incorporated over the upper 30 cm of soil, with a 1-cm mulch layer consisting of a wheat and oat straw mix (except for the reference and control treatments), following rototilling at the same depth (Marín and Rojas 2020).

For the present work, soils receiving organic amendments and plants were revisited in January of 2019. Six treatments were evaluated, these consisted of T0, reference (unburned area); T1, control (burned); T2, mulch (burned + mulch); T3, compost (burned with 200 m^3 ha^{-1} or 78.77 t dry weight ha^{-1} + mulch); T4, poultry manure (burned with 200 m^3 ha^{-1} or 150 t dry weight ha^{-1}+ mulch); and T5, swine manure (burned with 200 m^3 ha^{-1} or 95.67 t dry weight ha^{-1}+ mulch). Treatments were each distributed in four parcels (3 m × 1.5 m) within (1) a burned area of 50 m × 50 m (T1–T5) and (2) an unburned area of 20 m × 20 m (T0), located within the research site at a distance of approximately 500 m from the burned area.

2.3 Soil Sampling and Analyses

Soil sampling was conducted 8 months after organic amendment application in January 2019, which coincided with the summer season in the Southern Hemisphere. Four composite soil samples (1 kg each sample approx.) were taken per experimental parcel (3 m × 1.5 m). These samples were collected at a 6-cm depth in the A horizon following the removal of organic debris (including mulch when applied). In total, 96 composite soil samples were analyzed (six treatments × four parcels per treatment × four technical replicates per parcel). Each technical replicate consisted of five subsamples taken at the corners and center of each parcel. For each composite soil sample, an aliquot was used to measure microbiological parameters (using samples kept at 4 °C) and to perform the aggregate stability test (using samples dried at room temperature and sieved apart between 4 and 0.25 mm). The remaining aliquot was sieved at 2 mm for the rest of the physico-chemical analyses.

Soil organic carbon (OC) was determined by the potassium dichromate oxidation method by the Walkley-Black procedure (Nelson and Sommers 1983); total nitrogen was determined by the Kjeldahl method (Bremner and Mulvaney 1982); and available phosphorus was determined by the Burriel-Hernando method (Burriel and Hernando 1950; Díez 1982). Soil pH and electrical conductivity (EC) were determined in a 1:2.5 and a 1:5 (w/v) water extract, respectively. Aggregate stability was measured using the method of Roldán et al. (1994) based on the method of Benito and Díaz-Fierros (1989). This method examines the proportion of aggregates that remain stable after a soil sample is subjected to an artificial rainfall of known energy (279 J min^{-1} m^{-1}). Water-soluble carbohydrates were determined in a 1:5 (w/v) aqueous extract, using the anthrone method as reported by Brink et al. (1960). EDTA-extractable trace elements (Fe, Zn, Cu, and Mn as available micronutrients and Ni, Cr, Pb, and Cd as potential pollutants) were obtained from a 1:10 (w/v) extract with 0.05 M EDTA (pH 7), following shaking for 1 h at room temperature (Quevauviller et al. 1998), determined by an atomic absorption spectrophotometer.

Regarding the microbial parameters used in this study, the basal respiration was measured based on the CO_2 emission from 4 g of fresh soil adjusted to 60% water holding capacity and incubated for 24 h at 30 °C. The microbial biomass was estimated by the substrate-induced respiration (SIR) method using glucose (3 mg per gram of soil, the optimum rate of glucose determined after calibration as the available substrate (Anderson and Domsch 1978), based on the CO_2 emission from 4 g of fresh soil adjusted to 60% water holding capacity and incubated for 6 h at 30 °C). The amount of CO_2 emitted during both incubations was detected by indirect impedance measurement in an automated impedance meter (BacTrac 4200 Microbiological Analyzer, Sylab, Austria) based on the changes in the impedance of a KOH solution (2%) after potassium carbonate formation (García-Carmona et al. 2020; Mengual et al. 2014; Rodríguez et al. 2018). In addition, two biological indices were calculated with these values: the coefficient of carbon mineralization, determined as the basal respiration divided by total organic carbon, to assess the mineralizing capacity of soil in the presence of the amendments (Fernández et al. 2007), and the metabolic quotient (qCO_2) determined as the basal respiration divided by microbial biomass carbon, to estimate the efficiency of C decomposition by the microorganisms (Anderson and Domsch 1990).

2.4 Statistical Analysis

To test whether soil characteristics differed among treatments, we fitted generalized linear models (GLMs) using the soil properties analyzed as response, followed by multiple comparisons performed with the Tukey test ($p < 0.05$). The relationship between the soils parameters measured regarding the treatments applied was analyzed using principal component analysis (PCA). These statistical analyses were performed in RStudio v.3.6.2 (RStudio Team 2020) using the RStudio base function *glm* and the *FactoMineR* package (Lê et al. 2008).

In order to test the effects of soil physicochemical parameters on microbial parameters, and then the effect of organic amendments (T1–T5) on these same parameters, linear regressions were performed. First, stepwise regressions independent of treatment with all physicochemical parameters were performed in both directions in order to identify those abiotic parameters that better explained microbial parameters. Then, in a new model (that included physicochemical parameters selected in the first model), the effect of treatments with organic amendments was included as a predictor. Analyses were performed using the RStudio base function *lme*.

3 Results

The soils under study showed variable responses in physicochemical conditions following fire occurrence and the incorporation of treatments (Table 1). Eight months after the treatment establishment, amended soils showed the highest OC contents (Table 1): those receiving compost showed significantly higher values (5.19%), followed by poultry manure (4.73%), and swine manure (4.14%) amended soils. The same pattern was observed for N contents, where soils amended with compost had significantly higher values (0.54%) than those receiving fresh amendments in the form of poultry manure (0.47%) and swine manure (0.36%). Thus, a more stable material as compost, although providing fewer initial amounts of OC and N than manures (Table S1), resulted in greater amounts of these elements in amended soils. In addition, phosphorus contents registered a noticeable increase due to the addition of compost and manures, especially in soils treated with poultry manure, which showed approximately one to two orders of magnitude greater values than in mulch (burned + mulch) and control (burned) soils, respectively. Carbohydrate contents increased significantly in soils receiving not only compost and manure but also mulch, while high aggregate stability levels were observed for all soils. Increases in salinity and metal contents were registered in all amended soils; nevertheless, they were still under toxic levels for most plants (Kabata-Pendias 2011) (Table 1).

Soil microbial processes responded differently to the effect of land burning and established treatments (Fig. 1). Basal respiration particularly responded to organic amendments, showing higher values in soils receiving swine manure and poultry manure than in soils amended

Table 1 Means ± standard deviation of the main physicochemical properties analyzed in the soil treatments

	T0	T1	T2	T3	T4	T5
OC (%)	3.99±*0.58* bc	3.27±*0.52* a	3.66±*0.38* ab	5.19±*1.22* d	4.73±*0.57* cd	4.14±*0.51* bc
N (%)	0.31±*0.03* ab	0.27±*0.04* a	0.26±*0.03* a	0.54±*0.12* d	0.47±*0.07* c	0.36±*0.04* b
P (mg kg^{-1})	22.03±*8.08* a	8.08±*3.88* a	20.78±*10.19* a	169.14±*38.90* b	625.79±*151.68* d	302.42±*138.80* c
Carbohydrates (mg kg^{-1})	16.67±*3.58* a	31.48±*7.60* a	66.56±*29.53* b	58.32±*12.47* b	57.17±*8.53* b	64.39±*19.85* b
Aggregate stability (%)	75.32±*6.12* b	74.41±*7.16* b	71.48±*7.86* ab	65.81±*5.44* a	73.27±*6.79* b	73.13±*6.95* b
pH	6.94±*0.10* cd	6.49±*0.19* a	7.12±*0.33* d	7.43±*0.10* e	6.89±*0.11* ab	6.69±*0.22* bc
EC (µS cm^{-1})	56.6±*6.7* a	54.9±*5.7* a	115.8±*59.9* b	164.7±*25.4* c	286.6±*52.4* d	199.0±*49.4* c
Zn (mg kg^{-1})	4.52±*1.93* a	3.51±*1.11* a	4.56±*1.01* a	28.91±*6.74* c	31.59±*6.73* c	18.64±*5.99* b
Cu (mg kg^{-1})	1.16±*0.22* a	2.15±*0.76* ab	3.55±*0.67* bc	11.76±*2.45* e	7.29±*1.08* d	5.48±*2.51* c
Mn (mg kg^{-1})	0.23±*0.06* ab	0.27±*0.03* ac	0.29±*0.06* c	0.23±*0.05* a	0.27±*0.04* bc	0.27±*0.04* ac
Fe (mg kg^{-1})	0.21±*0.04* a	0.21±*0.03* a	0.18±*0.02* a	0.45±*0.10* c	0.31±*0.05* b	0.32±*0.05* b
Ni (mg kg^{-1})	0.11±*0.09* a	0.27±*0.08* bc	0.31±*0.10* c	0.22±*0.10* ac	0.12±*0.05* bc	0.26±*0.16* ab
Cr (mg kg^{-1})	3.90±*2.38* b	2.54±*1.13* a	1.41±*0.73* a	2.05±*0.47* a	3.21±*0.74* a	2.02±*0.75* a
Pb (mg kg^{-1})	0.49±*0.53* a	0.56±*0.33* a	1.08±*1.14* a	1.72±*0.95* a	7.37±*2.72* b	3.16±*2.61* a
Cd (mg kg^{-1})	0.05±*0.04* ab	0.02±*0.02* a	0.13±*0.04* b	0.26±*0.09* c	0.34±*0.02* c	0.21±*0.13* c

T0, reference (unburned); T1, control (burned); T2, mulch (burned +mulch); T3, compost (burned + compost + mulch); T4, poultry manure (burned + p.manure + mulch); and T5, swine manure (burned + s.manure + mulch). Lowercase letters represent significant differences among mean groups after GLMs models (Tukey test $P < 0.05$)

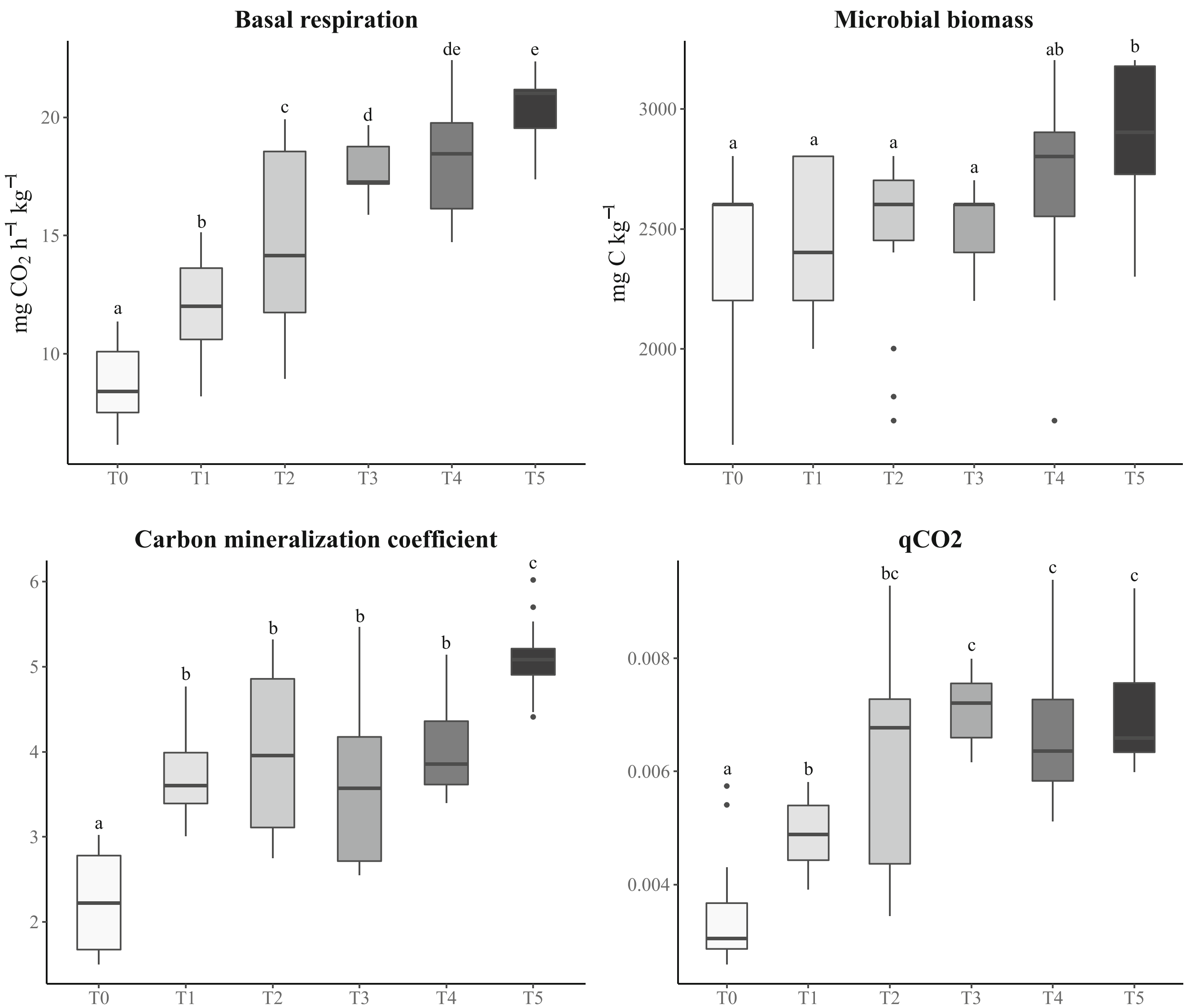

Fig. 1 Box-plot of **a** basal respiration (mg h^{-1} kg^{-1}); **b** microbial biomass (mg kg^{-1}); **c** coefficient of carbon mineralization; and **d** microbial metabolic quotient, qCO_2, measured in soils treatments: T0, reference (unburned); T1, control (burned); T2, mulch (burned + mulch); T3, compost (burned + compost + mulch); T4, poultry manure (burned + p.manure +mulch); and T5, swine manure (burned + s.manure +mulch). Points represent outliers, lowercase letters represent significant differences among mean groups after GLM models (Tukey test $P < 0.05$)

with compost (Fig. 1a). Although soil covered with mulch showed significantly lower respiration rates than soils receiving compost or manure, it had significantly greater values than control and reference soils. In contrast to basal respiration, microbial biomass showed few differences among treatments; however, the greatest values were observed in soils receiving fresh amendments in the form of swine manure and poultry manure, although the latter did not show a significant increase when compared to the rest of the treatments (Fig. 1b). Regarding the microbial indices, the coefficient of carbon mineralization showed an increase in all fire-affected soils, including the control (Fig. 1c). Similarly, the metabolic quotient (qCO_2) also increased in all fire-affected treated soils and the control, with significantly higher values in compost- and manure-amended soils (Fig. 1d).

According to the PCA, soils receiving organic amendment were grouped apart from those at the reference (unburned) forest, control (burned), and mulch (burned + mulch) parcels (Fig. 2), with the first two components explaining 56% of the variation. All soil parameters grouped towards the first PCA component were positively correlated and highly influenced by the treatments tested in this study. The ordination of soils amended with compost was highly influenced by N and OC contents and Fe, Cu, and Zn micronutrients. These micronutrients, along with the basal respiration, qCO_2, EC, and P, highly influenced the ordination of poultry manure-amended soils,

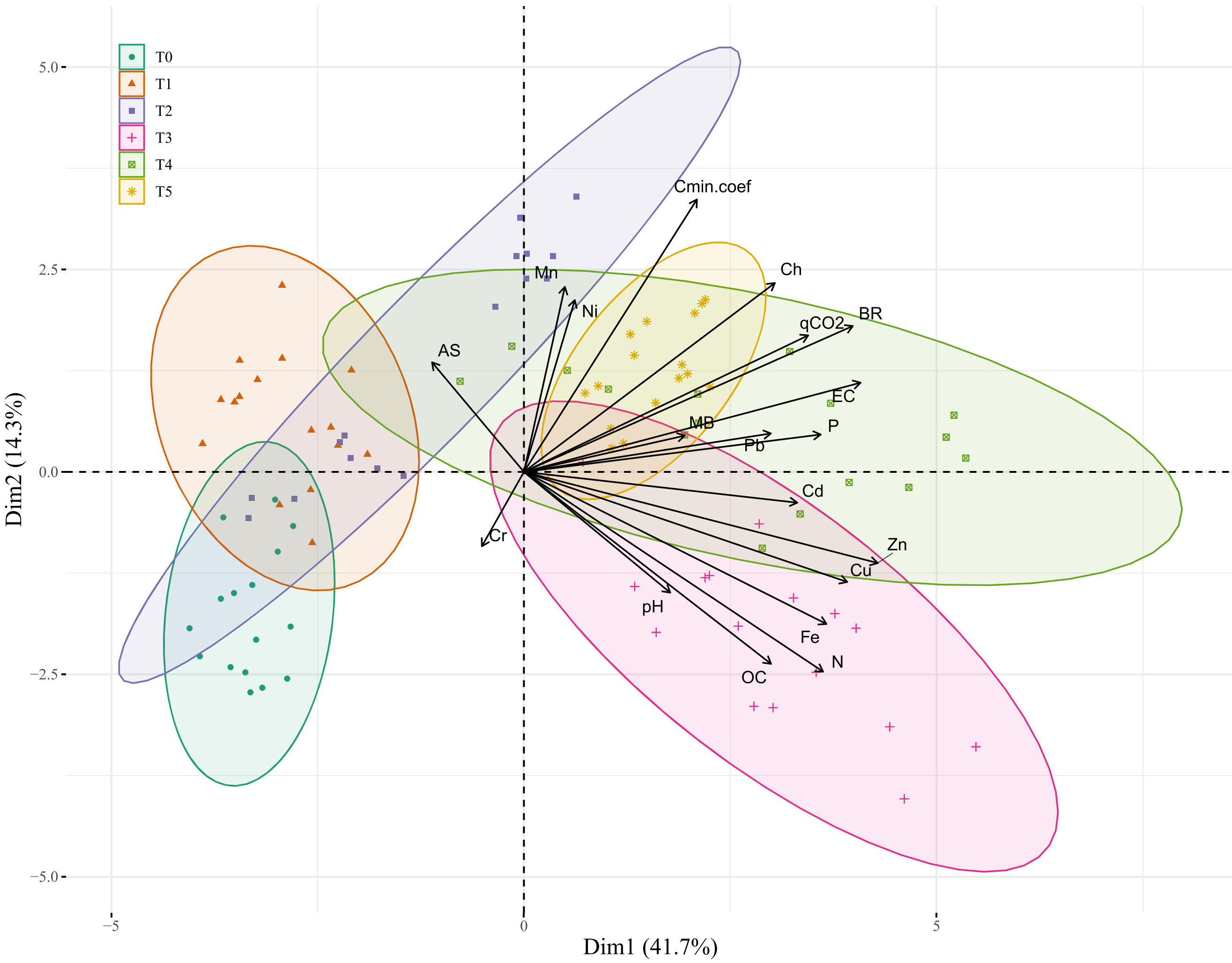

Fig. 2 Scores and loadings for PCA performed for soil treatments: T0, reference (unburned); T1, control (burned); T2, mulch (burned +mulch); T3, compost (burned + compost +mulch); T4, poultry manure (burned + p.manure + mulch); and T5, swine manure (burned + s.manure +mulch). (OC, organic carbon; N, total nitrogen; P, available phosphorous; AS, aggregate stability; Ch, carbohydrates; BR, basal respiration; MB, microbial biomass; qCO_2, microbial metabolic quotient; Cmin.coef., coefficient of carbon mineralization; EC, electrical conductivity)

while microbial parameters, especially the coefficient of carbon mineralization, also highly influenced poultry manure-amended soils (Fig. 2).

After performing stepwise regressions (Table S2), models including the treatments and soil physicochemical parameters were run to test their effects on the indicators of microbial activity used in this study (Table 2). The organic treatment had a significantly higher effect than the soil physicochemical parameters on these four microbial parameters (Table 2). Among soil physicochemical parameters, EC had an effect on all measurements except for qCO_2; in addition, all treatments (except T2) had a strong effect on EC (F value: 73.195: p value: >0.001). Some micronutrients (Fe and Mn) and potential pollutants (Pb and Cd) also slightly affected some of the microbial parameters (Table 2). Among treatments, T1 (burned control) also had effects on microbial parameters except for microbial biomass, thus showing that while lower, the effects of the aforementioned chemical parameters were still important.

4 Discussion

4.1 Responses of Biotic Soil Conditions Following Organic Amendments

Soil microbial conditions showed different responses following fire and the application of the treatments evaluated. Similar microbial biomass observed between unburned and burned soils (with no amendments) could be due to soil heating, which increases easily mineralizable compounds that can promote microbial activity and biomass growth immediately after land burning (Goberna et al. 2012). Indeed, our

Table 2 **a** ANOVA of linear models for microbial parameters (basal respiration, microbial biomass, coefficient of carbon mineralization, and qCO2, microbial metabolic quotient) that included treatments as a predictor, in addition to those abiotic parameters that better explained microbial parameters (Table S2) and **b** specific effects of each treatment (T1, control (burned); T2, mulch (burned +mulch); T3, compost (burned + compost + mulch); T4, poultry manure (burned + p.manure + mulch); and T5, swine manure (burned + s.manure + mulch))

	Basal respiration	Microbial biomass	Mineralization C coefficient	qCO_2
a. ANOVA of the models				
Model AIC	1615.496	1940.612	286.888	478.328
Treatments	129.019***	48.380***	51.187***	8.733***
EC	74.460***	44.624***	25.756***	0.486 ns
Cu	0.639 ns			0.214 ns
Mn	9.823**	1.174 ns	1.322 ns	0.053 ns
Fe	0.171 ns	0.292 ns	11.781***	0.247*
Cr	10.530**	0.168 ns	2.018 ns	
Pb	<0.001 ns	0.140 ns	11.711***	9.213**
Cd	0.959 ns		7.537**	
pH		8.734**		2.151 ns
N		1.714 ns		
OC			2.582 ns	
Ni				3.272 ns
b. Specific treatments effects				
T1	6.628***	1.476^{ns}	8.012***	2.614*
T2	6.403***	5.973***	5.039***	3.096**
T3	4.794***	2.801**	2.416*	0.862^{ns}
T4	1.813^{ns}	−2.287*	1.535^{ns}	1.572^{ns}
T5	8.063***	2.156*	5.860***	1.146^{ns}

Model AIC (Akaike Information Criterion) values of the model that best fit the data according to the physicochemical parameter selected are shown

a F-values$^{p\text{-values}}$ are indicated; empty cells indicate that the variable was not included in the model (Table S2). b t-values$^{p\text{-values}}$ are indicated. *P*-values: *** = <0.001; ** = <0.01; * = <0.05; *ns* non-significant

findings are consistent with those by Fuentes-Ramirez et al. (2018), who reported an increase in soil microbial activity 1 year after wildfires in mixed temperate rainforests of *Araucaria araucana* and *Nothofagus pumilio* ((Poepp. & Endl.) Krasser) in southern Chile due to changes in organic matter mineralization rates and the contribution of nutrients from ashes. Although wildfires usually result in a reduction in soil microbial biomass (Holden and Treseder 2013), our findings suggest that the fire severity occurred at the studied site was likely of low to moderate. Nevertheless, the application of organic amendments significantly influenced soil microbial conditions, especially those related to basal respiration, reflecting its importance as an indicator of soil recovery, along with other soil parameters (Bastida et al. 2008). This finding was particularly significant for soils receiving swine manure, where the values obtained were significantly higher than those registered from reference unburned ecosystems, suggesting great short-term effects on the microbial population due to the high release of labile C compounds. Although less marked than basal respiration, microbial biomass also showed short-term responses to fresh organic amendments, which is consistent with results obtained in previous comparable studies (Ros et al. 2003). These observations were supported by previous findings within the same study system, where colony-forming unit (CFU) counts showed higher values in both fresh material-amended soils, reaching levels closer to the reference unburned ecosystem after 6 months of organic treatment establishment (Marín and Rojas 2020).

4.2 Influence of Organic Amendment Type on Soil Organic Carbon

As opposed to microbial conditions, OC evidenced a decrease following land burning, which could reflect a symptom of soil degradation and potential loss of ecosystem resilience (Keeley 2009). The fire-affected soils behaved differently depending on the type of organic matter used, which supports the idea that restoration success greatly depends on the characteristics of the organic amendment applied to soils (Hueso-González et al. 2018). The organic matter contents in animal manures were originally greater than in compost, but soils treated with the latter material showed the highest OC content at the end of this study. This fact relates to the coefficient of carbon mineralization values observed, where rates from soils amended with animal manures, particularly those with swine manure, evidenced greater mineralization rates and thus presumably shorter periods of C source consumption. Along with short-term activation in soil biological parameters following the addition of fresh materials, it is important to consider the priming effect, i.e., the mineralization of autochthonous soil organic matter driven by the input of fresh organic matter. Fresh materials could induce this phenomenon as a consequence of increased microbial activity (Kuzyakov 2006), which could be a problem in soils impoverished in organic matter (Bastida et al. 2013), such as those affected by high-severity wildfires. Therefore, the use of more stabilized organic amendments such as compost in fire-affected soils could ensure greater long-term positive impacts on edaphic conditions due to greater turnover times (Haynes 2005), for example, strongly influencing nutrient cycling and storage over time, soil structure stability, or water holding capacity, thus improving soil health and productivity. Despite the organic matter mineralization rates observed in all treatments, OC remained above the control burned soil at the end of the study.

4.3 Soil Nutrient Conditions After Treatment Application

Despite the greatest amount of total N in the poultry manure, when compared to compost and swine manure, all of the organic amendments added significant N contents into soils compared to reference (unburned) soils. However, considerable N loss was detected for soils receiving fresh materials, notably poultry manure, presumably via volatilization or leaching (Cellier et al. 2014). Usually, the use of fresh materials stimulates N immobilization in soils due to the high concentrations of easily degradable C compounds (Paul 2014), but the nutritional balance of all organic amendments was adequate, as the C/N ratios were < 30; therefore, mineralization could have prevailed over immobilization (Bernal et al. 2009). Greater available P levels were also detected in soils amended with poultry manure, but these levels do not represent environmental risks over time, as P tends to accumulate in the topsoil layer without mobilization into the subsoil following long-term poultry manure application (Hoover et al. 2019). In addition, different responses to organic amendments between the microbial biomass and the basal respiration highlight the variable sensitivity of these biological parameters to these additions, which could be attributed in part to the toxicity produced by elements supplied with the organic amendments, which some studies have registered to affect soil microbial biomass (Tejada and Gonzalez 2006). However, despite potential inhibitory effects in microbial biomass caused by the increase in salinity and Pb content, particularly those observed in the poultry manure amendment and soils treated with it, the levels of potentially toxic elements (Cu, Zn, Cr, Cd, Pb) in our study were very low and far from any problem of toxicity (Kabata-Pendias 2011).

4.4 Recovery of the Soil Ecosystem Following Fires

In the context of global change and an increase in the severity and frequency of wildfires, it is crucial to understand how soil functions are recovered following fires so that the resilience potential of ecosystems vulnerable to land degradation is better understood. In this study, we observed different responses in soil properties with different types of organic amendments; our findings suggest that the addition of fresh materials has rapid and noticeable effects in soil microbial properties. Nevertheless, compost addition may provide the maintenance of the soil biogeochemical cycles over time, which would later result in higher microbial biomass and in the establishment of a plant cover indispensable for the long-term recovery of Mediterranean soils (Guénon and Gros 2016; Kowaljow and Mazzarino 2007). The consequences of restoration efforts in Chilean sclerophyllous forests affected by the increasing occurrence of wildfires need to be further investigated due to the importance of soil recovery to ecosystem functioning and to provide a better understanding of post-fire management plans.

5 Conclusions

The results obtained in our study suggest that swine manure had the most noticeable microbial response in the short term, reaching values above the reference unburned ecosystem. However, greater mineralization rates and thus presumably shorter periods of C source consumption related to such organic amendments might condition the recovery of ecosystem functions over time. Soils amended with compost accumulated the most OC, ensuring long-term nutrient release. Nevertheless, monitoring the evolution of microbial responses to contrasting organic amendments would be necessary to elucidate the implications of C as an energy source to sustain soil recovery in the long term. Wildfire increases in intensity and severity, as predicted for Mediterranean ecosystems under a global change scenario, demand a better understanding of the short- and long-term implications of restoration efforts. Thus, a good comprehension of contrasting organic amendment effects in soil functions and their implications on overall ecosystem recovery is central to sustaining the resilience of sclerophyllous forests following fires.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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Table S1. Total content of organic matter (OM), organic carbon (OC), and total nitrogen added to the soil by the organic amendments (dry weight) in a volume of 200 m^3 ha^{-1} of amendment.

Organic amendment	**Amendment** **(t ha^{-1})**	**OM** **(t ha^{-1})**	**OC** **(t ha^{-1})**	**N** **(t ha^{-1})**
Compost	78,77	14,7	8,18	0,65
Poultry manure	150,91	63,7	35,41	2,89
Swine manure	95,67	22,2	27,64	0,717

Table S2. Linear models resulting of stepwise linear regressions for basal respiration, microbial biomass, microbial metabolic coefficient (qCO_2), and coefficient of carbon mineralization, independently of treatment. The order of the variables indicates their importance (OC: organic carbon; N: total nitrogen; P: available phosphorous; EC, electrical conductivity).

Response	Model	AIC
Basal respiration	EC+Cu+Mn+Fe+Cr+Pb+Cd	157.68
Microbial biomass	pH+EC+N+Mn+Fe+Cr+Pb	536.07
Coefficient of C mineralization	EC+OC+Mn+Fe+Cr+Pb+Cd	-108.38
qCO2	pH+EC+Cu+Mn+Fe+Ni+Pb	-1198.52