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Soil amendments from recycled waste differently affect CO₂ soil emissions in restored mining soils under semiarid conditions

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ABSTRACT

Drylands affected by serious disturbances such as mining activities lose their vegetation cover and organic soil horizons, becoming CO_2 emissions sources. Applications of organic amendments could be a good restoration solution that favours vegetation establishment and soil carbon sequestration; however, they are also associated with CO₂ emissions. Experimental plots with different organic amendments (sewage sludge, garden and greenhouse vegetable composts, and mixtures of both) and unamended soils were installed in a quarry in southeast Spain. The aim of this study was: i) to evaluate the magnitude and changes of *in situ* CO₂ emission from each experimental plot during a year and a half, and ii) to assess the effects of several physical–chemical (total organic carbon, total nitrogen, water retention, pH and electrical conductivity) and environmental parameters (moisture and temperature) in CO_2 emissions. The results showed an initial CO_2 emission (priming effect), produced from all restored plots just after the application of the organic amendment, which was significantly higher $(P < 0.05)$ in soils with sewage sludge and their mixtures in comparison to vegetable compost. Garden compost had low emission rates, similar to soils without amendment and showed lower CO_2 emission rates than the rest of the restoration treatments. Nevertheless, CO_2 emissions decreased in each field campaign over time, showing that all restored soils had lower emissions than natural soils at the end of the sampled period. The different composition of organic amendments had a different effect on soil CO_2 emissions. DistLM analysis showed that soil properties such as total organic carbon, total nitrogen, pH and soil moisture, associated with rainfall periods, strongly influenced CO₂ emissions, whereas temperature did not affect the CO_2 flow. In conclusion, the compost from plant remains could serve better as treatment to restore degraded soils in drylands than sewage sludge because of its lower CO_2 emissions and concomitant effect on climate warming and carbon balance.

1. Introduction

Arid and semiarid areas are characterized by extreme climatic conditions, with high temperatures, low rainfall, high evaporation rates and strong winds (Luna et al., 2016a). Currently, they occupy 45.36% of the Earth's surface (Lal, 2019) and are estimated as storing 32% of the earth's carbon (Dacal et al., 2020). Drylands are the most severely threatened ecosystems on the planet because of their increasing aridity (Berdugo et al., 2020; Lal, 2019). Drivers of global change such as human activities (such as land use change) and climate change (Huang et al., 2016; Schlesinger et al., 1990) can accelerate the expansion of arid and semiarid areas (Huang et al., 2016; Yao et al., 2020) and increase desertification processes (Hueso-González et al., 2018; Lavee et al., 1998; Reynolds et al., 2007).

Mining is a widespread activity in arid and semiarid areas because of its economic and social benefits (Gratzfeld, 2003), but it has serious consequences for soil degradation (Moreno-de las Heras, 2009). Soil processes are closely linked to temperature and precipitation patterns, which exert strong control over vegetation productivity and composition (Booker et al., 2013; Gravuer et al., 2019), making it difficult to restore ecosystems degraded by mining in arid and semiarid environments (Josa et al., 2012; Rodríguez-Berbel et al., 2021). Despite difficulties in achieving success in restoration, it is important to choose an appropriate strategy to restore these fragile degraded environments to

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recover their functionality, improve, such as their capacity for carbon sequestration (Lal, 2009, 2015) and reduce CO₂ emissions. Soil management practices can influence the carbon cycle by affecting the soil's CO₂ emissions (Ray et al., 2020).

In this context, the incorporation of organic waste has shown improvements in physical, chemical and biological soil properties (Abdelhafez et al., 2018; Breton et al., 2016; Luna et al., 2016b; Ros et al., 2003) and consequently improves the soil functionality (Mondini et al., 2018; Soria et al., 2021). Organic amendments derived from different types of waste can improve degraded soils, and their correct selection could provide a good opportunity to successfully restore mined areas (Hernández et al., 2016; Jordán et al., 2008; Ros et al., 2003). In addition, soil loss causes a depletion of organic carbon that negatively affects the nutrient cycle and soil biological activity, whereas increasing the carbon input of biomass through the addition of organic amendments can increase soil organic carbon sequestration and nutrient cycling (Ghimire and Khanal, 2020). All in all, soil amendment is considered a good strategy for recovering soil functions related to carbon sequestration (Coyne et al., 1998; Diacono and Montemurro, 2011; Lal, 2019; Montiel-Rozas et al., 2016; Paustian et al, 2000, 2007; Tits et al., 2014; Vinson et al., 1999). Moreover organic amendments also favours development of a stable plant cover that contributes to the fixation of CO_2 through photosynthesis (Shrestha and Lal, 2006) and soil microorganisms (Rossi et al., 2015) with consequent positive feedback on global change.

Several authors have researched the effect of organic amendments in soil CO₂ emission rates (Chen et al., 2015; Li et al., 2013; Ray et al., 2020; Rochette and Gregorich, 2011). Despite all the benefits that organic amendments contribute to soil restoration, the variability of organic amendment types resulting from the different origins of organic waste, the variability of their organic matter composition, which can generate different organic matter decomposition rates (Hueso-González et al., 2018) and their long-term maintenance (Larney and Angers, 2012), makes it difficult to select the type of amendment. Thus, Albiach et al. (2000) reported that organic amendments of different plant and sheep compositions, anaerobic digestion sludge, and vermicompost significantly increased CO₂ emissions with respect to commercial amendments. Li et al. (2013), noted the impact on CO₂ emissions was greater in applying organic amendments derived from pig manure than in residue amendments from corn cultivation in Molisols in North-East China. Chaker et al. (2019) observed that in arid soils the application of amendments derived from olive pruning and palm leaves did not impact soil respiration, whereas amendments from oil mill waste water and fermented sheep manure increased the emission rate to 7.6 g CO₂ m^{-2}. Quemada and Menacho (2001) observed an increase in CO₂ fluxes with application of sewage sludge versus unamended soils one year after implementation.

Because arid and semiarid ecosystems cover a significant area of the planet and are expected to increase in the future, the projected increase in aridity as a result of climate change therefore makes restoring these fragile ecosystems a major challenge and selecting appropriate methodologies that are both successful and an adequate response to CO₂ emissions and climate change mitigation is of crucial importance. Therefore, improving our understanding of the use of organic amendments for the ecological restoration of mining areas, as well as understanding their impact on CO₂ emissions and in turn knowing the environmental and soil factors influencing CO₂ emissions from restored soils, is of crucial importance for selecting appropriate soil management techniques. This research's main objective was to evaluate the impact of different types of amendments on the CO₂ emission of fully degraded semiarid soils in a limestone quarry restored with organic amendments from local organic waste over a year and a half from their application, comparing these emission rates with degraded soils without organic amendments from the quarry and surrounding natural soils. The influence of environmental factors (soil temperature, soil moisture and precipitation) and physical and chemical soil properties on the CO_2 emission rates from different types of soils (restored, degraded and natural) in the medium term was also analysed. We hypothesised that organic amendments would increase CO_2 emissions, but these rates would differ depending on the chemical composition of the amendments applied to soils. Moreover, environmental factors and physical and chemical soil properties would also influence the magnitude and trends of CO_2 emissions from restored soils.

2. Material and methods

2.1. Study site

The study zone was located in completely degraded soils from a limestone quarry located in the Gádor mountain-range in Almería (SE, Spain) (N 36° 55′ 18″, 02° 30′ 40″ W). The experimental area was in a flat completely exploited site, at an elevation of 362 m.a.s.l. The initial substrate was formed by a mixture of fragments of calcareous rock and loams derived from mining activity. In adjacent, unexploited locations, shallow soils are found over limestones and dolomites with calcareous sandstones and marly and loamy marls forming Regosols (IUSS Working Group WRB, 2015). Irregular temperatures and rainfall are characteristic of the dominant semiarid Mediterranean climate, where the average annual rainfall is 242 mm in the autumn and winter seasons. Summers are hot and dry with maximum temperatures recorded in August of 31 °C and minimum temperatures of approximately 8 °C in January and high rates of evapotranspiration that reach 1225 mm $year^{-1}$ (data recorded at the weather station from Alhama of Almería, a city near the study area, as described in Luna et al. (2018). Native vegetation corresponds to *Macrochloa tenacissima* (L.) Kunth *(= Stipa tenacissima* L.*)* as main species, accompanied by small shrubs such as *Ulex parviflorus* Pourr. and *Anthyllis cytisoides* L., as well as dispersed individuals of *Maytenus senegalensis* (Lam.) Exell., *Pistacia lentiscus* L. and *Rhamnus lycioides* L. (Luna et al., 2016b). Also, the presence of other species such as *Olea europaea* L., *Genista umbellata* (L'Hér.) Poir. or *Ephedra fragilis* Desf. has been verified, among others, in the thermomediterranean belt at an altitude between 200 and 800 m.a.s.l. (Carrión et al., 2003).

2.2. Experimental design

A total of 18 experimental plots with dimensions of 50 m^2 (10 m × 5 m) were installed in a selected flat degraded area in the quarry. A first mechanical pre-treatment to homogenization and decompaction of the marl substrate was carried out using the machinery available at the mine, such as mechanical excavators and bulldozers. Subsequently, five restoration treatments consisting of different organic amendments from wastes of different origin and chemical composition were applied in the experimental plots, increasing the organic matter content in each plot by 3% in the first 20 cm depth. The five restoration treatments used were: i) organic amendment from a 100% vegetable compost obtained from garden waste (CG), ii) organic amendment consisting in a vegetable compost from greenhouse crop waste (CC), iii) organic amendments from sewage sludge waste treated by mesophilic digestion, thermal dehydration at 70 °C, and centrifugation (SS), iv) organic amendments made from the mixture CG + SS (Mix1), and v) organic amendments made from the mixture CC + SS (Mix2). In addition, unamended experimental plots were used as control experimental plots (CON).

Three experimental plots per each restoration treatment and control soils were randomly applied in the study area using a mechanical backhoe available in the quarry facilities (3 replicates of experimental plots per each treatment x 5 restoration treatments = 15 experimental plots plus 3 replicates of control plots = 18 experimental plots). Fig. 1 shows a diagram of all the experimental plots and the treatments applied in each plot. Moreover, surrounding natural soils close to the experimental plots not affected by mining activities were chosen as quality reference (NAT). This experimental condition allowed us to establish a reference system for comparison among soil types (restoration

Fig. 1. Location study site and experimental design. On the right, a diagram of the experimental plots distribution with the different soil restoration treatments and unmodified soils is shown, as well as location of natural reference soil plots. Font photography: Sentinel2 (July-2019) and Spain's National Aerial Orthophotography Plan (PNOA).

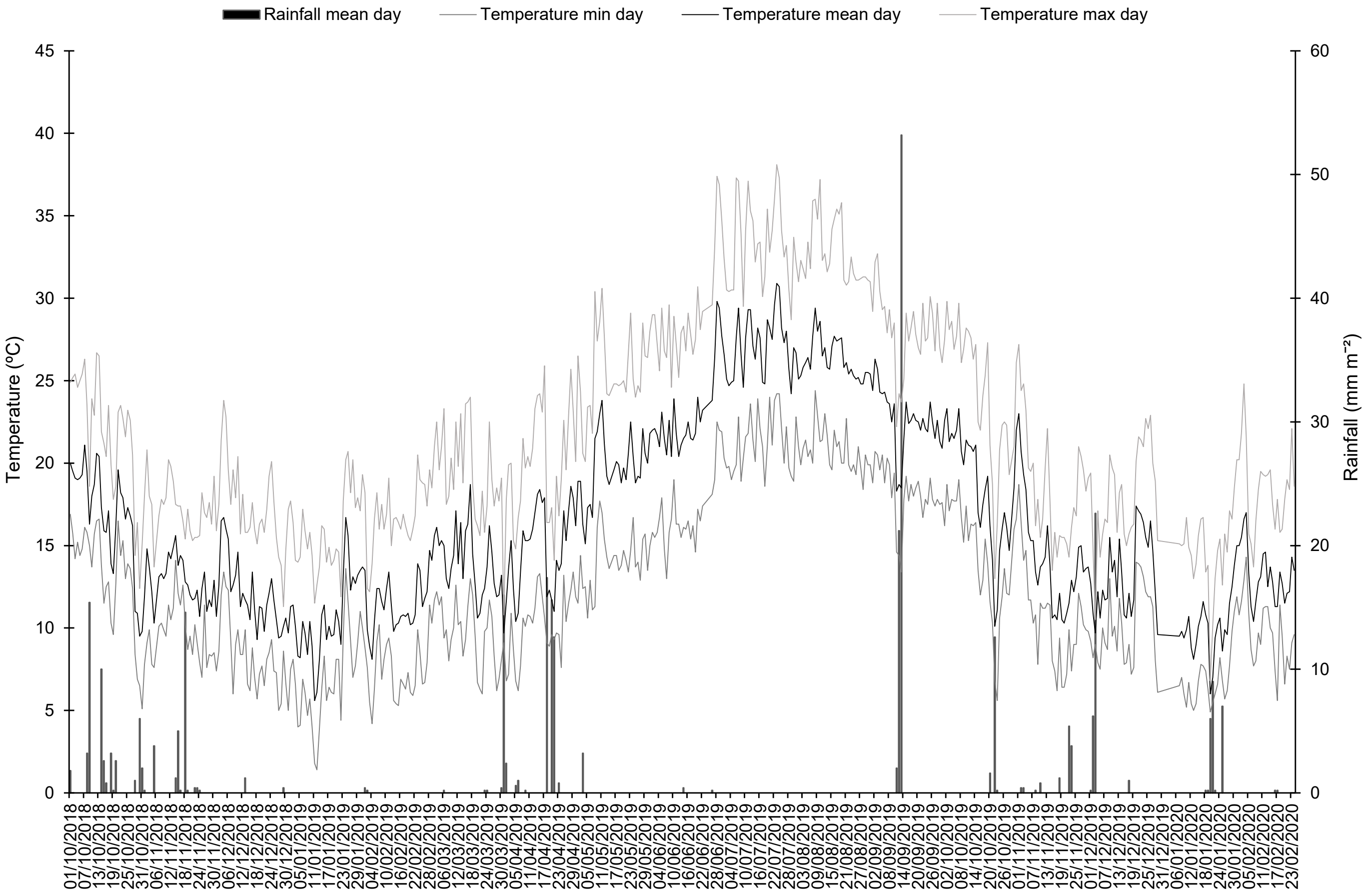


Fig. 2. Local climate diagram of the experiment site during the experiment. Precipitation (rainfall) monitored by a rain sensor (Rain-O-Matic Small, Pronamic ApS, Denmark) located in the experimental area; temperature mean daily, maximum and minimum from weather station RAIFALL003 of Junta de Andalucía.

treatments and control soils) (Miralles et al., 2009).

Two species of native plants in the study area were selected for the restoration, planting 40 plants of *Macrochloa tenacissima* L. Kunth and 10 plants of *Olea europaea* L. var *sylvestris* Brot. in each experimental plot (restored and control soils), spaced 1 m apart. An establishment irrigation after planting was done to ensure the vegetation's survival in the first summer because of the harsh climatic conditions typical of the Mediterranean semiarid areas, which include long summer droughts and high temperatures (Luna et al., 2018; Sánchez et al., 2004).

Six field samplings by season, from the end of summer 2018 to autumn 2019, were taken to collect soil samples to analyze for their physical-chemical properties. The first soil sampling was approximately four months after the application of the organic amendments in late summer 2018 (15-10-2018; FieldS1). The following field samplings took place in late autumn 2018 (17-12-2018; FieldS2), winter 2018 (18-03-2018; FieldS3), spring 2019 (02-07-2019; FieldS4), summer 2019 (19-09-2019; FieldS5) and autumn 2019 (25-11-2019; FieldS6). In each field sampling, one composite soil sample from mixing 10 randomly subsamples were collected from the soil surface (0–10 cm) in each experimental plot (3 replicates of soil treated samples x 5 restoration treatments = 15 soil samples) plus 3 soil samples from unamended control experimental plots and 3 soil samples from surrounding natural soils, for a total of 21 soil samples in each field sampling. Thus, 6 field sampling x 21 total soil samples per sampling = 126 soil samples which were analysed in the laboratory.

Rainfall was continuously monitored with a pluviometry sensor located at the experiment site and also the ambient temperature was taken daily from a nearby station (distance of 4 km) and at the same height above sea level (RAIFALL003, Junta de Andalucía) at least for the duration of the experiment to obtain the local environmental climate context (Fig. 2).

2.3. *Physical-chemical properties of restored soils*

Soil samples were air-dried and sieved to a 2 mm separating fine soil fraction and were used to, the following physical and chemical properties were analysed: (1) soil pH was measured in a distilled water solution with a ratio of 1:2.5 w/v as measured with a pHmeter (LAQUA PH1100, Horiba, Tokyo, Japan); (2) electrical conductivity (EC) was measured in an aqueous suspension 1:2.5 soil/water suspensions with a digital conductivity meter (LAQUA EC1100, Horiba, Tokyo, Japan); (3) total organic carbon (TOC) was determined by wet oxidation with dichromate according to Walkley and Black's method (1934) (rectified by Mingorance, 2007); (4) total nitrogen content (TN) was analysed with an elemental analyser TCD detector (ELEMENTAR Rapid N; Elemental Analysen systems GmbH, Hanau, Germany); and (5) water retention was determined at −33 and −1500 KPa using the Richards membrane method (Richards, 1941).

2.4. *In situ field campaigns of CO_2 emission and monitoring of climatic variables*

In situ measurements of dark respiration (CO_2 emission) were taken using a handheld, portable dark chamber connected to an infrared gas analyzer system PP-systems (EGM-4, IRGA, Hitchin, UK) with the measurement time set for 90 s. The chamber had a volume of 1170 cm^3 and a flat surface of 78 cm^2. A total of 18 field measurement campaigns were conducted for each experimental plot [soils restored with amendments (CG, CC, SS, Mix1 and Mix2) and un-amendments control plots (CON) and surrounding natural soils (NAT)]. Three randomly distributed replicas of PVC soil-borne collars (5 cm high by 10 cm diameter) were inserted into the soil one month before field measurements began, leaving 2–3 cm above ground in each experimental plot and in NAT soils, where they remained for the duration of the experiment. The inside of each soil-borne collar was kept free from vegetation to eliminate the effect of plant or root respiration on CO_2 emission measurements at each experimental plot. The field campaigns were conducted monthly from autumn 2018 to winter 2020 in the different seasons under different environmental conditions. Supplementary Table 1 provides detailed description of the environmental conditions in which the field measurement campaigns were done.

Soil moisture (M) and temperature (T) were measured at a depth of 3 cm next to each soil-borne collar with a handheld readout sensor (Pro-Check, Decagon Devices, Inc., Pullman, WA, USA) during each field CO_2 measurement campaign. Rainfall events were registered daily every 20 min by a pluviometer with rain sensor with tipping bucket technology Rain-O-Matic Small (Pronamic ApS, Denmark) connected to a data logger in the middle of experimental area.

2.5. *Statistical analyses*

First, significant differences in physical, chemical, environmental and emission CO_2 were analysed for all restoration treatments and control and natural reference soils using a two-way multivariate permutational analysis of variance (hereinafter PERMANOVA) (Anderson, 2001) that included two factors: date of field sampling and soil treatment. In cases where PERMANOVA detected a significant effect of the organic amendment treatments ($P < 0.05$), the source of the differences was evaluated by comparing the treatment pairs with the PERMANOVA posttest pairs, and the results with $P < 0.05$ were reported as significant. Pearson's correlation coefficients (r) were used to assess the relationship among physical and chemical properties and environmental parameters between different treatment and dates of field sampling. To observe the different trends in the evolution of CO_2 emissions over time, a Mann-Kendall (MK) linear regression trend test was applied (MK) (Kendall, 1948; Mann, 1945).

Physical, chemical and environmental variables with the highest importance in CO_2 emission correlation were identified using step-wise analysis DistLM (Distance-based Linear Models). For the DistLM routine we developed a "marginal" test for the relationship between variable response (CO_2 emissions) and an individual variable (EC, pH, TOC, TN and water retention at −1500 and −33 KPa) to identify independent variables that explain the variations in soil samples both by treatment and over time. Subsequently, the Akaike Information Criterion (AICc) (Akaike, 1974) was established to select the best model, and the step-by-step procedure to build the model was followed. Finally, a "sequential" test of the individual variables was performed to assess whether adding an individual variable contributes significantly to the explanation. Ordination and visualisation of the model was performed in distance-based redundancy analysis (dbRDA). The statistical package PRIMER + PERMANOVA software (PRIMER-E Ltd., Plymouth Marine Laboratory, UK) for Windows was used for PERMANOVA, DistLM and dbRDA analysis (Anderson et al., 2008), as well as for AICc analysis. The trends had been performed using TREND V1.0.2. software (Cooperative Research Centre for Catchment Hydrology, Australia). Pearson's correlations were performed with Statgraphic Centurion XVIII-X64 software.

3. Results

3.1. *Changes in physical and chemical soil properties in the medium-term. Differences between restored, natural and degraded soils*

In general, the results showed progressive changes in physical and chemical properties (TOC, TN, EC, pF at −1500 KPa, pF at −33 KPa) in all restored soils throughout the field sampling campaigns carried out from application of organic amendments until the end of sampled period. Nevertheless, the values of these physical and chemical soil properties hardly changed in un-amendments control soils (CON) and natural soils (NAT) during the sampled period (Table 1).

Two-way PERMANOVA analysis showed significant differences ($P < 0.05$) in the physical and chemical soil parameters attending to date of field campaign (in different environmental conditions), soil treatment

Table 1
Main chemical and physical characteristics of soils with restored organic amendments, control soils without addition of amendments and natural reference soils on six dates distributed along the studied chronological sequence. Average of three replicated samples (mean ± standard error).

	EC (mS/cm)	pH	TOC (%)	TN (%)	*pF* -1500 KPa	*pF* -33 KPa
FieldS1 15/10/2018						
CG	3.46 ± 0.27a	7.58 ± 0.06a	3.43 ± 0.52a	0.57 ± 0.05a	17.05 ± 0.21 ab	36.55 ± 1.93a
SS	3.76 ± 1.35abc	7.21 ± 0.04b	6.51 ± 1.07 ab	0.89 ± 0.09b	25.92 ± 3.57ac	39.58 ± 3.67a
CC	5.46 ± 0.32abc	8.57 ± 0.04c	4.77 ± 0.81 ab	0.62 ± 0.01 ab	19.18 ± 0.44c	33.67 ± 2.52a
Mix1	5.18 ± 0.93a	7.61 ± 0.09a	6.23 ± 1.27 ab	0.68 ± 0.05 ab	18.57 ± 1.57abc	35.41 ± 0.95a
Mix2	4.15 ± 0.13b	8.06 ± 0.07d	5.56 ± 0.31b	0.62 ± 0.02 ab	20.36 ± 1.70abc	33.61 ± 0.93a
CON	1.84 ± 0.33c	8.25 ± 0.08d	0.34 ± 0.12c	0.05 ± 0.01c	15.64 ± 0.89b	32.59 ± 2.99a
NAT	0.07 ± 0.00d	8.54 ± 0.05c	1.37 ± 0.04d	0.20 ± 0.00d	15.73 ± 0.44 ab	33.09 ± 0.93a
FieldS2 17/12/2018						
CG	2.56 ± 0.28 ab	7.97 ± 0.20 ab	1.71 ± 0.31a	0.32 ± 0.07a	18.14 ± 0.80 ab	29.47 ± 1.51a
SS	3.42 ± 0.40 ab	7.45 ± 0.04a	2.67 ± 0.38b	0.60 ± 0.12b	21.45 ± 1.06a	34.34 ± 1.80a
CC	3.30 ± 0.25a	8.5 ± 0.12b	2.94 ± 0.10b	0.40 ± 0.03 ab	18.59 ± 0.28 ab	30.70 ± 0.95a
Mix1	3.25 ± 0.12a	7.52 ± 0.03a	2.45 ± 0.09b	0.51 ± 0.02b	19.46 ± 0.69a	31.61 ± 0.60a
Mix2	3.08 ± 0.41 ab	7.65 ± 0.04a	2.82 ± 0.09b	0.51 ± 0.01b	19.42 ± 0.67a	32.40 ± 1.40a
CON	1.72 ± 0.00b	8.59 ± 0.06b	0.46 ± 0.08c	0.02 ± 0.00c	16.34 ± 0.14bc	32.36 ± 0.62a
NAT	0.07 ± 0.00c	8.64 ± 0.06b	1.31 ± 0.08d	0.11 ± 0.00d	14.91 ± 0.14c	36.32 ± 0.62a
FieldS3 14/03/2019						
CG	3.72 ± 0.39 ab	8.06 ± 0.52abcd	2.62 ± 0.26a	0.44 ± 0.06a	15.16 ± 0.58a	34.21 ± 1.04a
SS	3.79 ± 0.17a	7.91 ± 0.10a	2.55 ± 0.34a	0.63 ± 0.05 ab	19.22 ± 6.00a	33.08 ± 0.87a
CC	2.8 ± 0.09b	8.81 ± 0.04a	4.40 ± 0.54b	0.56 ± 0.03a	12.80 ± 2.60a	30.71 ± 0.98a
Mix1	3.77 ± 0.30a	8.01 ± 0.00b	3.62 ± 0.49 ab	0.66 ± 0.06 ab	19.76 ± 0.37a	33.08 ± 1.31a
Mix2	2.47 ± 0.46 ab	8.28 ± 0.16ac	4.42 ± 0.55b	0.71 ± 0.00b	19.01 ± 1.02a	33.47 ± 1.30a
CON	3.54 ± 0.55 ab	9.19 ± 0.08d	0.28 ± 0.03c	0.06 ± 0.00c	13.83 ± 0.62a	31.96 ± 1.95a
NAT	0.10 ± 0.01c	8.62 ± 0.07bc	1.34 ± 0.01d	0.15 ± 0.01d	13.22 ± 0.34a	35.28 ± 1.18a
FieldS4 02/07/2019						
CG	2.31 ± 0.28a	7.88 ± 0.05a	3.11 ± 0.46a	0.39 ± 0.09a	19.61 ± 1.73a	35.99 ± 1.83a
SS	3.06 ± 0.53a	8.12 ± 0.03b	3.59 ± 0.46a	0.60 ± 0.12b	21.56 ± 1.08a	36.78 ± 1.90a
CC	2.04 ± 0.33a	8.75 ± 0.05c	4.21 ± 0.17a	0.50 ± 0.05 ab	19.23 ± 0.50a	34.19 ± 0.96a
Mix1	2.93 ± 0.58a	7.48 ± 0.09d	3.24 ± 1.87a	0.57 ± 0.02 ab	19.36 ± 0.75a	35.34 ± 1.17a
Mix2	3.34 ± 0.52a	7.71 ± 0.02ad	5.64 ± 0.06abc	0.59 ± 0.00b	19.95 ± 0.47a	36.37 ± 1.00a
CON	3.57 ± 0.00a	7.62 ± 0.08d	0.79 ± 0.12b	0.04 ± 0.00c	17.53 ± 1.18a	33.65 ± 1.80a
NAT	0.08 ± 0.00b	8.36 ± 0.08b	1.64 ± 0.12c	0.15 ± 0.00d	18.78 ± 1.18a	33.77 ± 1.80a
FieldS5 19/09/2019						
CG	2.25 ± 0.03a	7.89 ± 0.11a	2.29 ± 0.19a	0.28 ± 0.03a	18.78 ± 1.27 ab	32.26 ± 1.34a
SS	2.55 ± 0.12a	7.79 ± 0.06a	3.41 ± 0.69ba	0.60 ± 0.12b	19.59 ± 0.26a	34.50 ± 2.82a
CC	1.72 ± 0.05 ab	8.38 ± 0.22b	3.03 ± 1.16abc	0.35 ± 0.18abcd	18.35 ± 1.85abc	33.47 ± 4.87a
Mix1	3.12 ± 0.09a	7.83 ± 0.09a	3.02 ± 0.70abc	0.48 ± 0.13 ab	16.82 ± 1.37bcd	31.59 ± 1.65a
Mix2	2.46 ± 0.03a	7.86 ± 0.16ac	3.27 ± 0.53b	0.48 ± 0.07b	18.12 ± 0.45b	33.92 ± 2.28a
CON	1.96 ± 0.06 ab	8.9 ± 0.06d	0.75 ± 0.13d	0.05 ± 0.01c	14.95 ± 0.89c	33.29 ± 0.47a
NAT	0.06 ± 0.06b	8.17 ± 0.11bc	1.83 ± 0.19c	0.16 ± 0.02d	15.83 ± 0.74cd	31.06 ± 1.26a
FieldS6 25/11/2019						
CG	2.23 ± 0.43 ab	7.99 ± 0.09a	2.65 ± 0.03a	0.38 ± 0.00a	18.21 ± 2.13a	35.78 ± 0.94a
SS	3.24 ± 0.04a	7.88 ± 0.06a	3.08 ± 0.20 ab	0.60 ± 0.12b	17.38 ± 0.51a	36.02 ± 1.52a
CC	1.75 ± 0.35b	8.87 ± 0.16b	3.37 ± 0.17b	0.40 ± 0.01a	16.40 ± 1.09a	36.45 ± 2.10a
Mix1	2.75 ± 0.68 ab	8.07 ± 0.09a	2.46 ± 0.39abc	0.42 ± 0.04 ab	16.41 ± 1.13a	34.65 ± 0.94a
Mix2	2.6 ± 0.42 ab	7.97 ± 0.08a	2.90 ± 0.21 ab	0.42 ± 0.05 ab	16.78 ± 0.69a	43.92 ± 6.80a
CON	1.64 ± 0.35b	8.67 ± 0.06b	0.81 ± 0.16d	0.06 ± 0.00c	14.89 ± 0.99a	33.40 ± 1.22a
NAT	0.08 ± 0.01c	8.70 ± 0.01c	1.81 ± 0.14c	0.15 ± 0.01d	13.21 ± 0.84a	33.76 ± 1.24a

CG: 100% vegetable compost from garden waste; CC: vegetable compost from greenhouse crop residues: SS: wastewater treatment station sludges from anaerobic mesophilic digestion, dehydrated by centrifuges and heat-dried at 70 °C; Mix1 (CG + SS) and Mix2 (CC + SS): mixture amendment of different vegetal compost and sludge compost; CON: unamended control soils; NAT: natural reference soil. EC: electrical conductivity; TOC: total organic carbon; TN: total nitrogen; C/N: carbon to nitrogen ratio; pF: water retention determined at −33 and −1500 KPa. Across treatments, data with different lowercase letters are significantly different, $P < 0.05$ [PERMANOVA].

(SS, CG, CC, Mix1, Mix2, CON and NAT) and their interaction (Supplementary Table 2). Amended soils showed significantly higher TOC and TN contents than CON and NAT soils in all campaigns, being those soil properties significantly higher in FieldS1, just after the application of the organic amendments (Table 1). The highest values of TOC and TN were reached in SS, Mix1, Mix2 and CC soils followed by CG, whereas CON soils presented the significantly lowest values of TOC and TN in all field campaigns (Table 1). However, TOC and TN in all restored soils with organic amendments decreased progressively in successive field campaigns, with their values approaching those of NAT soils somewhat more closely in the last field campaign (FieldS6; Table 1). The organic

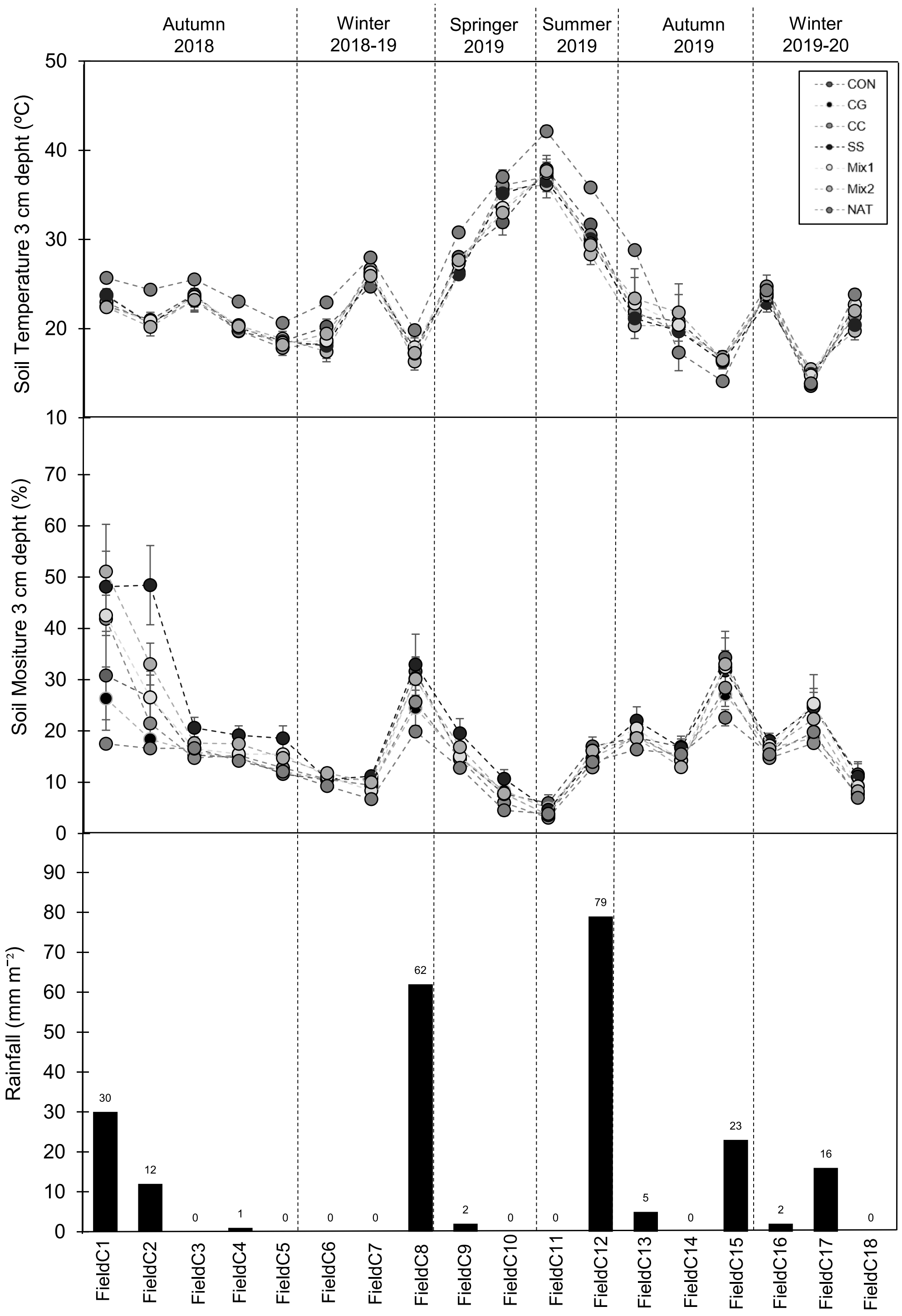


Fig. 3. Temporal distribution of rainfall, soil moisture and soil temperature during the experiment in different field campaigns and different seasons.

amendments also significantly increased EC content with respect to the CON and NAT soils, although EC values decreased rapidly throughout the sampled period, approaching EC values that were more similar to those of CON soils. On the contrary, NAT soils showed the significantly lowest values of EC in all the sampled campaigns (Table 1). Restored soil showed a significantly lower pH than that in NAT and CON soil, especially in FieldS1 and FieldS2, then increased in subsequent measurement campaigns, minimising their differences with control and reference soils in the last sampling campaign (FieldS6) (Table 1). Soils with organic amendments showed higher water retention at pF −1500 KPa than CON and NAT soils only in the FieldS1 and FieldS2 campaigns (Table 1).

3.2. Environmental conditions and microclimatic parameters in field CO_2 measurement campaigns

The main precipitation events were recorded in autumn and spring months throughout the experimental period (Fig. 2), although the total accumulated rains were very scarce (173.4 mm). In these seasons, temperatures were generally mild (average temperatures ranged between 19 and 24 °C), reaching maximums of about 28–30 °C in autumn and minimums of about 8 °C in spring (Fig. 2). Winter was cold, with low rainfall (24.2 mm) and minimum average temperatures of about 5 °C and maximum average temperatures of 18 °C. The summer period was generally very dry, registering some light rain and occasional rainstorms at the end of the season (Fig. 2). The long summer period coincided with mild temperatures in spring and high temperatures in the summer seasons (maximum of 38 °C and minimums of 14 °C; Fig. 2).

During the period under study, the FieldC1, FieldC2, FieldC8, FieldC13, FieldC15 and FieldC17 campaigns took place after rain events (accumulated precipitation 10 days before the campaign) and generally mild temperatures. Supplementary Table 1 provides a detailed description of the environmental conditions of each field campaign. In these field campaigns, the soils restored with organic amendments presented higher soil moisture than natural (NAT) and control (CON) soils. Among all restored soils with organic amendments, SS, Mix1, and Mix2 presented higher soil moisture contents than CC and CG soils (Fig. 3).

In FieldC8, FieldC9, and Field10 campaigns, which took place in spring, the soil moisture content decreased progressively in all restored, control, and natural soils, as temperatures increased progressively (average temperatures of about 18 °C and maximum of about 27 °C); and only one major rain event was recorded in the first measurement campaign (Supplementary Table 1). However, the soil moisture content in the restored soils was still comparatively higher than in the NAT soils (Fig. 3). During the summer campaigns, FieldC11 and FieldC12, the soil samples were dry at first, but soil moisture increased during the second campaign from a rainfall event recorded at the end of the season coinciding with that campaign. Nevertheless, there were almost no differences in soil moisture content between the restored, control and natural soils (Fig. 3). On the contrary, temperatures were higher in the control (about 38 °C) and natural (about 42 °C) soils than in the restored soils with organic amendments (about 36 °C; Fig. 3).

3.3. In situ CO_2 emission pattern and relationship between CO_2 emission, environmental parameters, physical and chemical soils properties

The MK statistical test showed that the CO_2 emission trend decreased significantly during the experimental period (from FieldC1 to FieldC18) (Table 2) in all restored soils with organic amendments. Two-way PERMANOVA analysis showed significant differences ($P < 0.05$) in CO_2 rates between the different field campaigns on different dates with organic amendment treatment (CC, CG, SS, Mix1 and Mix2) (Supplementary Table 2).

Table 2
Soil CO_2 emissions (soil respiration) trends shown by different organic amendments treatments, control soils and natural reference soil (Mann-Kendall test).

Treatment	Trend	Z-statistic	Critical value (a = 0.01)	Result
CG	Decreasing	−1.87	0.64	Signifincant
SS	Decreasing	−2.25	0.64	Signifincant
CC	Decreasing	−2.25	0.64	Signifincant
Mix-1	Decreasing	−2.25	0.64	Signifincant
Mix-2	Decreasing	−2.25	0.64	Signifincant
Control	Decreasing	−2.25	0.64	Signifincant
NAT	Decreasing	−2.25	0.64	Signifincant

CG: 100% vegetable compost from garden waste; CC: vegetable compost from greenhouse crop residues: SS: wastewater treatment station sludges from anaerobic mesophilic digestion, dehydrated by centrifuges and heat-dried at 70 °C; Mix1 (CG + SS) and Mix2 (CC + SS): mixtures amendments of different vegetal compost and sludge compost; CON: unamended control soils; NAT: natural reference soils.

The CO_2 emission pattern spiked after the organic amendment treatment was applied and gradually decreased over time, although CO_2 emission changed little for NAT and CON soils in the different field campaigns (Fig. 4). At the beginning of the field experiment, the first campaign (FieldC1), conducted in the fall (15-10-2018) and coinciding with the first rain event after a long dry period in summer, showed a higher soil moisture and CO_2 emission than the rest of the field campaigns until the end of the period under study (Supplementary Figure 1). Specifically, in FieldC1 the soils SS, Mix1 and Mix2 had the significantly highest CO_2 emission rates ($P < 0.05$) (average values of CO_2 emissions of about 40 μmol m^{-2} s^{-1}) (Table 3; Fig. 4). In contrast, CC soils had significantly lower CO_2 emissions than the experimental plots with sludge although both had a similar soil moisture, whereas these CO_2 emissions were similar to those of NAT soils with a soil moisture around 25% lower than CC (Supplementary Figure 1). CG soils and CON soils showed the significantly lowest CO_2 emission values (Supplementary Table 2; Fig. 4). The CO_2 emission rate from the restored soils, especially SS, Mix1 and Mix2, beginning with the second measurement campaign (FieldC2), also conducted in the same season, was significantly lower than that produced in FieldC1. Interestingly, there was a slight difference in the CO_2 emissions from NAT and CON soils between FieldC1 and FieldC2 that did not recur throughout the entire period studied.

In the following field campaign (FieldC3) conducted in a period without rain and with low temperatures in the winter, the CO_2 emission rates from all soil types (restored, CON and NAT soils) were lower than in previous campaigns. However, in the following spring and late summer field campaigns after the rain events (between FieldC8 and FieldC12), although the CO_2 emissions were significantly lower than in FieldC1, there were slight peaks in CO_2 emissions, especially from SS (Table 3; Fig. 4). In those field campaigns, CO_2 emissions from the restored soils did not differ significantly from NAT soils in general and were only slightly higher than those from CON soils at the end of the study period (FieldC11) coinciding with the lowest values of soil moisture (Supplementary Figure 1). CO_2 emissions were low; and, in general, there were no significant differences between all soil types (restored, natural and control) in the field campaigns conducted in dry periods of winter and summer with low and very high temperatures, respectively (Figs. 3 and 4).

The CO_2 emission showed significant positive correlations ($p < 0.05$) with TOC, TN, pF −1500, EC, and soil moisture (M), which showed the highest significant correlations ($r = 0.74$), whereas pH had negative significant correlation with CO_2 emission (Table 4).

DistLM analysis selected of all the environmental variables and soil properties variables measured the most important influencing CO_2 emission were M (59.27%), TOC (9.02%), pH (8.7%) and TN (8.09%), while the significant predictor with the lower impact on CO_2 emission were water retention at pF −1500 KPa (5.9%). Nevertheless, pF −33 KPa, EC and T did not have a statistically significant ($P < 0.05$) effect on CO_2 emission in the different field measurement campaigns under different environmental conditions (Table 5). A global model with the four predictor variables of CO_2 emission, which solved best for R^2 value,

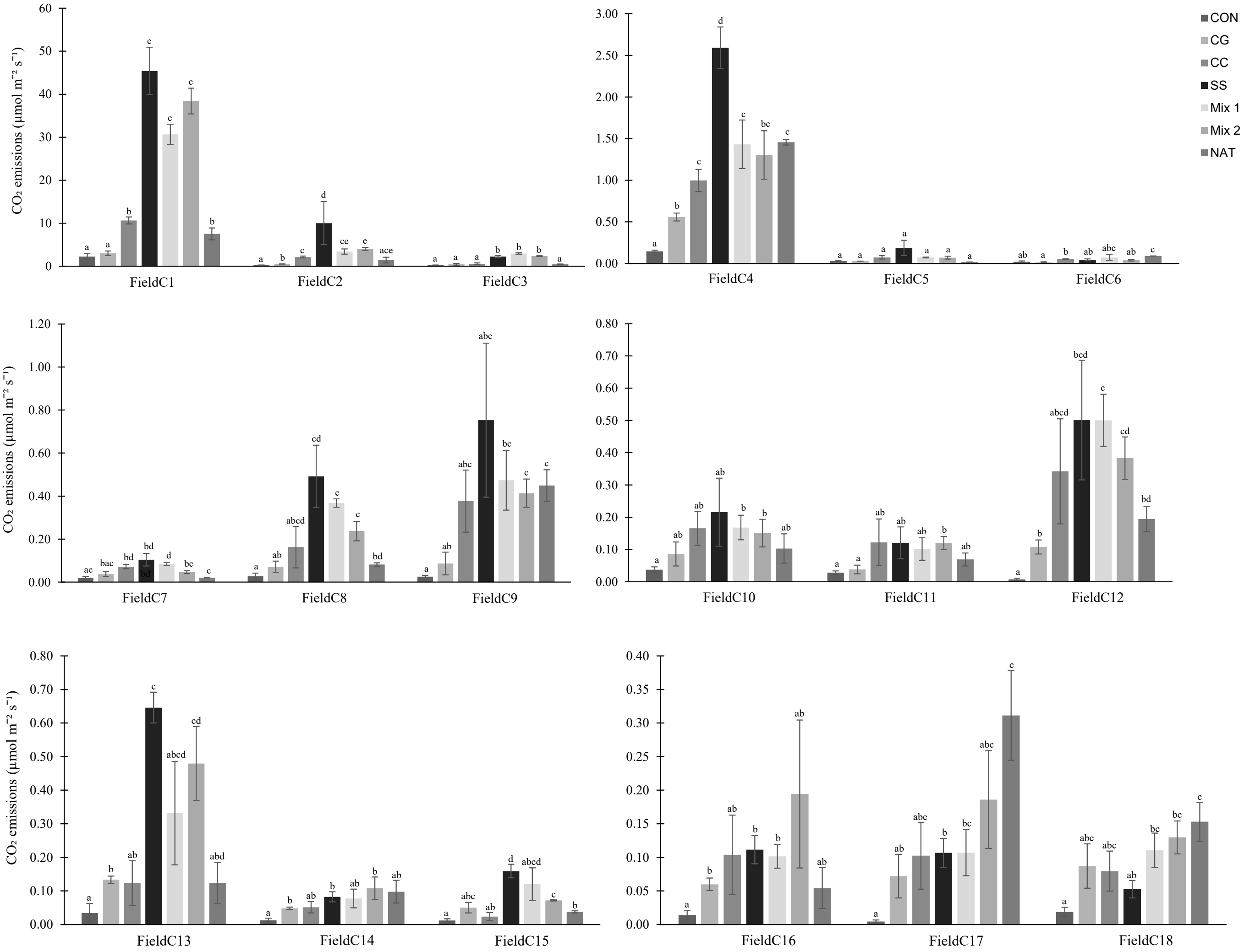


Fig. 4. Comparison of soil CO₂ emissions to differently treated soils, control soil, and natural reference soil during the experiment (x-axis field measurement campaign) to evaluate the impact of organic amendments after application.

Table 3

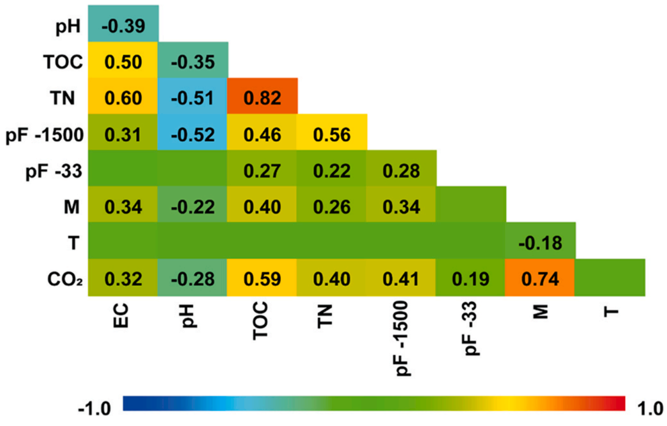
Measurements of CO₂ emissions, in experimental plots with organic amendments, control and natural reference soils (average ± standard error).

Date	CON	CG	CC	SS	Mix1	Mix2	NAT
15/10/2018	2.25 ± 0.69a	3.02 ± 0.52a	10.65 ± 0.81b	45.39 ± 5.52c	30.65 ± 2.36c	38.41 ± 0.98c	7.52 ± 1.36b
29/10/2018	0.25 ± 0.04a	0.52 ± 0.05b	2.14 ± 0.22c	14.12 ± 0.96d	3.42 ± 0.61ce	4.05 ± 0.33e	1.42 ± 0.67abc
05/12/2018	0.23 ± 0.06a	0.43 ± 0.19a	0.50 ± 0.22a	2.24 ± 0.25b	2.97 ± 0.19b	2.38 ± 0.15b	0.38 ± 0.05a
17/12/2018	0.14 ± 0.01a	0.55 ± 0.05b	0.99 ± 0.13c	2.59 ± 0.25d	1.43 ± 0.29c	1.30 ± 0.29bc	1.37 ± 0.03c
16/01/2019	0.03 ± 0.01a	0.03 ± 0.00a	0.07 ± 0.01a	0.18 ± 0.08a	0.07 ± 0.00a	0.07 ± 0.02a	0.01 ± 0.00a
18/02/2019	0.02 ± 0.01 ab	0.01 ± 0.01a	0.05 ± 0.00b	0.04 ± 0.01 ab	0.07 ± 0.03abc	0.04 ± 0.01 ab	0.09 ± 0.00c
14/03/2019	0.02 ± 0.01ac	0.03 ± 0.01abc	0.07 ± 0.01bd	0.10 ± 0.03bd	0.08 ± 0.01d	0.05 ± 0.01bc	0.02 ± 0.00c
23/04/2019	0.3 ± 0.01a	0.07 ± 0.03 ab	0.16 ± 0.10abcd	0.49 ± 0.15cd	0.37 ± 0.02c	0.24 ± 0.05c	0.08 ± 0.01bd
02/05/2019	0.03 ± 0.00a	0.09 ± 0.05 ab	0.38 ± 0.14abc	0.75 ± 0.36abc	0.47 ± 0.14bc	0.41 ± 0.07c	0.45 ± 0.07c
11/06/2019	0.04 ± 0.01a	0.09 ± 0.04 ab	0.17 ± 0.05 ab	0.22 ± 0.11 ab	0.17 ± 0.04b	0.15 ± 0.04b	0.10 ± 0.05 ab
23/07/2019	0.03 ± 0.01a	0.04 ± 0.01a	0.12 ± 0.07 ab	0.12 ± 0.05 ab	0.10 ± 0.04 ab	0.12 ± 0.02b	0.07 ± 0.01 ab
19/09/2019	0.01 ± 0.00a	0.11 ± 0.02b	0.34 ± 0.16abcd	0.50 ± 0.19bcd	0.50 ± 0.08c	0.38 ± 0.07cd	0.19 ± 0.04bd
25/10/2019	0.03 ± 0.03a	0.13 ± 0.01b	0.12 ± 0.07 ab	0.65 ± 0.05c	0.33 ± 0.15abcd	0.48 ± 0.11cd	0.12 ± 0.06abc
24/11/2019	0.01 ± 0.01a	0.05 ± 0.00b	0.05 ± 0.02 ab	0.08 ± 0.02b	0.08 ± 0.03 ab	0.11 ± 0.03b	0.10 ± 0.03 ab
04/12/2019	0.01 ± 0.00a	0.05 ± 0.02abc	0.02 ± 0.01 ab	0.16 ± 0.02d	0.12 ± 0.05abcd	0.07 ± 0.00c	0.04 ± 0.00b
23/12/2019	0.01 ± 0.01a	0.06 ± 0.01b	0.10 ± 0.06 ab	0.11 ± 0.02b	0.10 ± 0.02b	0.19 ± 0.11 ab	0.05 ± 0.03 ab
24/01/2020	0.01 ± 0.00a	0.07 ± 0.03 ab	0.10 ± 0.05abc	0.11 ± 0.03b	0.11 ± 0.03bc	0.19 ± 0.07abc	0.31 ± 0.07c
24/02/2020	0.02 ± 0.01a	0.09 ± 0.03abc	0.08 ± 0.03abc	0.05 ± 0.01 ab	0.11 ± 0.03bc	0.13 ± 0.02bc	0.15 ± 0.03c

CG: 100% vegetable compost from garden waste; CC: vegetable compost from greenhouse crop residues: SS: wastewater treatment station sludges from anaerobic mesophilic digestion, dehydrated by centrifuges and heat-dried at 70 °C; Mix1 (CG + SS) and Mix2 (CC + SS): mixture amendments of different vegetal compost and sludge compost; CON: unamended control soils; NAT: natural reference soils. Number with different lowercase letters are significantly different treatments in the same date, $P < 0.05$ (one-way analysis of variance with permutations [PERMANOVA].

Table 4

Significant positive and negative Pearson correlations ($p < 0.05$) between physical and chemical soils properties, environmental parameters and CO_2 emissions. Empty boxes obtain non-significant correlations ($p > 0.05$). EC: electrical conductivity; TOC: total organic carbon; TN: total nitrogen; pF: soil water content at different pressures; M: moisture 3 cm depth; T: Temperature 3 cm depth; CO_2: emission of CO_2.



	EC	pH	TOC	TN	pF -1500	pF -33	M	T
pH	-0.39							
TOC	0.50	-0.35						
TN	0.60	-0.51	0.82					
pF -1500	0.31	-0.52	0.46	0.56				
pF -33			0.27	0.22	0.28			
M	0.34	-0.22	0.40	0.26	0.34			
T							-0.18	
CO_2	0.32	-0.28	0.59	0.40	0.41	0.19	0.74	

Table 5

Results of DistLM analysis showing the physical, chemical and environmental variables that describe significant and independent proportions of the variation in CO_2 emissions between sampling date in restored soil with organic amendment.

MARGINAL TESTS

Variable	SS(trace)	Pseudo-F	P	Prop.
EC	4272.30	2.78	0.063	0.02
pH	12912.00	8.79	0.001	0.07
TOC	13233.00	9.02	0.001	0.07
pF - 1500	8861.30	5.90	0.004	0.05
pF −33	1952.50	1.25	0.284	0.01
TN	11940.00	8.09	0.002	0.06
M	63080.00	59.27	0.001	0.32
T	4288.80	2.79	0.064	0.02

SEQUENTIAL TESTS

Variable	AICc	SS (trace)	Pseudo-F	P	Prop.	Cumul.
M	880.31	63,080	59.27	0.001	0.32	0.32
M + TOC	877.32	5219.4	5.06	0.005	0.03	0.35
M + TOC + pF −33	875.43	3987.8	3.96	0.012	0.02	0.37
M + TOC + pF −33 + pH	873.99	3469.5	3.52	0.023	0.02	0.39
M + TOC + pF −33 + pH + EC	872.68	3279.8	3.39	0.039	0.02	0.41

Best solution

AICc	R^2	RSS	Variable Selections
872.68	0.41	116020.00	5: M, TOC, pF −33, EC, pH

Percentage of variation explained by individual axes RDA

Axis	% explained variation out of fitted model		% explained variation out of total variation	
	Individual	Cumulative	Individual	Cumulative
1	87.98	87.98	35.65	35.65
2	8.37	96.35	3.39	39.04
3	3.54	99.89	1.43	40.48
4	0.08	99.97	0.03	40.51
5	0.03	100	0.01	40.52

EC: electrical conductivity; TOC: total organic carbon; TN: total nitrogen; pF: water retention determined at -33 and -1500 Kpa.

explained the 40.52% of the total variation to AICc of 872.68 and identified a combination of 5 significant factors M, TOC, pF-33, pH and EC (Table 5). According to the variations (outside the adjusted model and outside the total variation) explained by the dbRDA graphs, applied to the CO_2 emissions from soils as a function of the treatment applied (Fig. 5a) and as a function of the sampling date (different environmental conditions) (Fig. 5b) for restored soils, untreated soils and natural reference soils explained 96.35% of the adjusted model accumulated in the first two axes (dbRDA1 87.98% and dbRDA2 8.37%) of the total variation of the physical, chemical and environmental variables analysed. The dbRDA analysis results showed that M, TOC, pH, pF −33 and EC best explained CO_2 emissions both by dates of campaigns under different environmental conditions and restoration treatment types (Fig. 5a and b) and thus explained a large part of the variation.

4. Discussion

In this work, the effect of five restoration treatments from organic wastes on CO_2 emission compared with CO_2 emission from un-amended soils from a quarry under semiarid conditions and surrounding natural soils was monitored for a one and a half years after amendments were applied. All the restoration treatments with the different types of organic amendments produced CO_2 emissions just after their soil application, which was especially high from soils treated with sewage sludge (Fig. 4). This CO_2 emission from the restored soil could have been due to interactions between soil microorganisms, transformation of added organic substances, and the natural soil C-cycle (Fangueiro et al., 2007; Kuzyakov, 2010). These interactions cause intense short-term changes in the native soil organic matter cycle, resulting in an additional release of CO_2 known as a “priming effect” (Kuzyakov et al., 2000). The positive priming effect is normal in soils with low organic matter content after receiving inputs (Zimmerman et al., 2011). Other authors have already pointed out that the type of amendment applied conditions soil respiration, causing CO_2 output flows (Ray et al., 2020).

The CO_2 emission from the restored experimental plots was due to complex interactions between physical, chemical and biological soil properties and environmental factors conditioning the soil climate, as was supported by our statistical analysis. DistLM analysis indicated that soil moisture, TOC, pH and TN were the most influential factors in the CO_2 emissions (Table 5). The high positive correlations between CO_2 emissions and TOC, TN, soil moisture (M) and pF −1500 and negative correlation with pH (Table 4) corroborated the key importance of these factors in the dynamics of CO_2 fluxes in the restored and control soils in the quarry and in surrounding natural soil. Soil moisture and these physical and chemical properties are considered key drivers for the soil bacterial communities (Miralles et al., 2020; Miralles et al., 2020; Rodríguez-Berbel et al., 2020; Sánchez-Marañón et al., 2017); and therefore their effect on CO_2 emission after the application of amendments is due to the priming effect. Nevertheless, our results also showed interesting differences in the magnitude of CO_2 emission depending on the restoration treatment used in comparison with natural soils (NAT) and unamended control soils (CON), especially in the first months of monitoring. In FieldC1, restored soils with sludge (SS, Mix1 and Mix2) emitted CO_2 rates approximately 80% higher than in NAT and CC soils and 90% higher than in GC and CON soils (Fig. 4). Given that the magnitude of microbial activity is associated with TOC content and the bioavailability of organic compounds, there will be an increase in soil CO_2 emissions in soils with easily mineralizable organic matter (González-Ubierna et al., 2012), causing the priming effect. Therefore, our results showed that differences in the CO_2 emission magnitude between the restoration treatments could have been due in large part to the chemical composition of the organic amendment rather than to the amount of organic matter, given that there were no significant differences between all restored soils in the TOC content (Table 1).

The soils restored with sludge (SS, Mix1, and Mix2) contributed a high amount of labile organic matter to the soils, with significantly

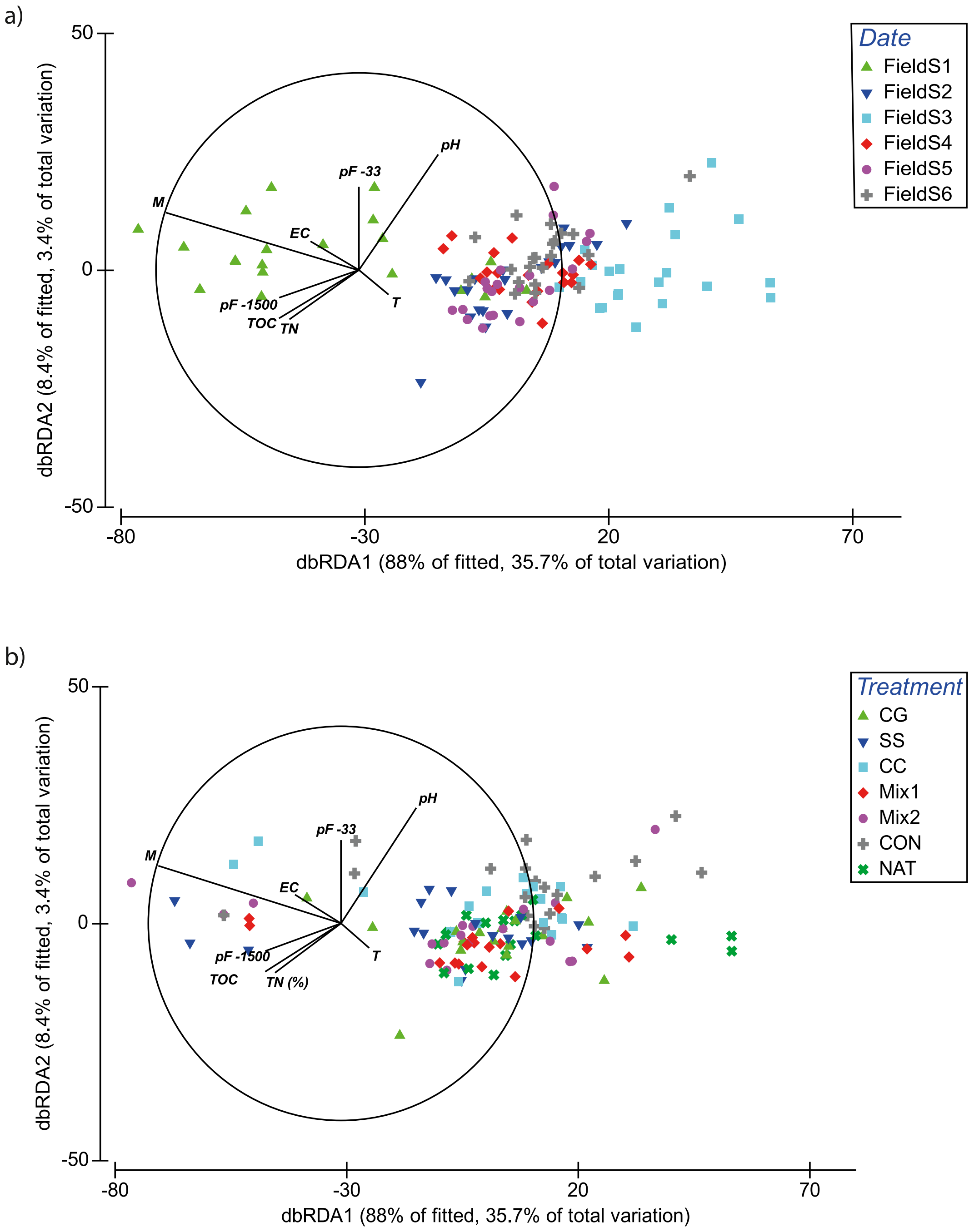


Fig. 5. Distance-based RDA bi-plot of different soil treated, control soil and natural reference soil, showing projections of samples from different soil sampling along the experiment with various significant chemical properties as explanatory variables as a date sample function (a) and treatment function (b). Footnotes: CON: unamended control soils; CG: 100% vegetable compost from garden waste; CC: vegetable compost from greenhouse crop residues: SS: wastewater station sludges from anaerobic mesophilic digestion, dehydrated by centrifuges and heat-dried at 70 °C; Mix1 (CG + SS) and Mix2 (CC + SS): mixture amendments from different vegetal compost and sludge compost. NAT: natural reference soils. EC: electrical conductivity; TOC: total organic carbon; TN: total nitrogen; pF: water retention determined at −33 and −1500 KPa.

higher carbohydrate content than in the other types of restored, control and natural soils (Soria et al., 2021). The contribution of easily biodegradable organic matter favours the proliferation of soil bacteria capable of mineralizing the excess of labile organic matter applied to the soil by increasing the production of C-cycle enzymes, a direct cause of CO_2 emission (Bastida et al., 2008b; Blagodatskaya and Kuzyakov, 2008; Mondini et al., 2006). In addition to stimulating soil microbial communities, organic amendments contribute to increasing the growth of soil microbial biomass by providing new bacterial communities associated with soil amendments (Bastida et al., 2008a; García-Gil et al., 2000; García et al., 1998; Rodríguez-Berbel et al., 2020). Therefore, the changes in the composition and structure of soil bacteria communities could be associated with the high increase in soil respiration and CO_2 production (Blagodatskaya et al., 2007; Fontaine et al., 2003; Razanamalala et al., 2018) just after the application of organic amendments in the restored soils. In this sense, most of the CO_2 derived from heterotopic respiration could be exhaled by soil microorganisms (Li et al., 2013), producing the above-mentioned priming effect (Kuzyakov, 2006). This could also explain the high mineralization rate found by Soria et al. (2021) in a previous study in the same experimental plots amendment with sludge. On the other hand, traditionally, it has been observed that organic amendments from sewage sludge enrich the soil in nitrogen compounds, especially when thermally dried sludge is used (Smith and Durham, 2002; Tarrasón et al., 2008). This could explain that the soils restored initially with sludge (SS, Mix1 and Mix2) in the quarry had also higher TN content than the other restored, natural and control soils (Table 1). Nitrogen has a strong influence on the soil carbon cycle and has been described as a priming effect modulator that also contributes to activating the microbiota in decomposing organic matter (Chen et al., 2014) and favouring CO_2 emission to the atmosphere. Given that much of TOC in sewage sludge consists of labile organic compounds such as carbohydrates and fatty acids, the high rates of mineralization previously found in the experimental plots with sludge (Soria et al., 2021) could rapidly release CO_2 into the atmosphere (Fig. 4; Table 2) and, with the concomitant effect of climate change, could rapidly reduce the carbon stock applied by this amendment in restored soils.

However, interestingly, monitoring CO_2 emissions for a year and a half showed that these emissions decreased extraordinarily sharply since the first field measurement campaign (FieldC1), especially from soils amended with sludge (Table 3). Furthermore, CO_2 emissions from all amended soils continued to decline sharply in successive field campaigns; and, curiously, at the end of the studied period, all restored soils reached generally similar CO_2 emission rates that were lower than those in the natural soils (NAT) (Fig. 4). These conclusions are supported by the absence of significant differences in TOC content between all restored soils, ranging the TOC from 3.08 ± 0.20 in SS soils to 2.65 ± 0.03 in CG and 3.37 ± 0.17 in CC soils, one year and a half after the amendments were applied. These results suggest a very efficient biomineralization of organic matter in the functioning of the carbon cycle in arid and semiarid Mediterranean ecosystems and a short-term stabilization of resilient organic matter provided by organic amendments in all restored soils.

Nevertheless, CO_2 emission from soils restored just after the application of both compost types (CG and CC) presented a different behaviour from that in the soils restored with sludge (SS) or their mixtures (Mix1 and Mix2). Curiously, the CG-restored soils showed the lowest rate of CO_2 emissions just after the amendment applications, comparable to that of the CO_2 emission from unamended control soils (CON), although CG soils had a slight upturn in CO_2 emission after rainfall over the last monitored month (Fig. 4, Table 3). This result was very striking because the low CO_2 emission rates from CON soils could be explained by the extremely low content of TOC and TN (Table 1), but the CG-restored soils presented a high TOC that did not differ significantly from that of the SS-restored soils, although there were significant differences throughout the sampling period in the TN content (Table 1). The small peak of CO_2 emission from CON soils could be due to the high content of carbonates and bicarbonates typical of arid and semiarid carbonate soils, which, when dissolved, could cause some CO_2 emission (Shrestha and Lal, 2006). Nevertheless, the extremely low priming effect in CG restored soils could be due to the composition of the composts applied to the soils. CG compost was made from the remains of pruning waste and plant remains, so it could be rich in lignin compounds, which are hardly biodegradable, and the microorganisms would need a period of adaptation by the bacteria to proceed with their decomposition (Kuzyakov et al., 2000). The contribution of these recalcitrant organic compounds provided by this fertilizer could limit the access of microorganisms to decomposition to organic inputs (Shrestha and Lal, 2006) and favour slow-growing organisms over fast-growing bacteria because of competition or succession processes (Leon et al., 2006); thus, the microbial activity would be lower and consequently their respiration rates, generating lower CO_2 emissions. These results corroborate the lower mineralization and enzymatic activities involved in the C cycle in CG restored soils (Soria et al., 2021). Therefore, the low CO_2 emission pattern in CG soils throughout the sampled period suggests that in these restored soils, organic matter mineralizes very slowly, gradually providing nutrients for plants (Soria et al., 2021) but guaranteeing at the same time a carbon reserve in the medium or long term.

A similar pattern was observed in CC restored soils with the other type of compost from plant debris from greenhouses. Although these soils presented a high content of TOC and TN in FieldS1, like the soils with sludge (Table 1), the CO_2 emission rates were significantly lower than in the SS, Mix1 and Mix2 soils (Fig. 4; Table 3). However, they presented higher emission rates than CG and CON soils. This behaviour could also be explained by the contribution made by the organic amendment's molecular composition to the soil. Compost made from greenhouse remains could provide compounds derived from lignin such as leaves and stems, which are difficult for soil microorganisms to biodegrade but could provide more complex carbon compounds such as lignin, cellulose and hemicellulose (Cooperband, 2002). However, it could also provide other easily biodegradable organic compounds such as simple carbohydrates (polysaccharides and starches) from fruits (Cooperband, 2002). A balanced composition with labile and resilient organic compounds could explain a mineralization rate and concomitant CO_2 emission intermediate between the SS and CG treatments. Curiously, surrounding natural soils (NAT) showed CO_2 emission rates similar to those of CC restored soils, although their TOC and NT content was significantly lower (Table 1). This results could suggest that the CO_2 emissions from NAT soils could be attributed in part to the positive priming effect of plant inputs to substrate and root respiration (Crow and Wieder, 2005; Kuzyakov, 2006; Li et al., 2013) and the rhizosphere of readily available C supplies, known as the "rhizosphere priming effect" (Kuzyakov, 2002, 2006), which could change rhizosphere microbial activity.

Our results showed that, during a year and a half of monitoring CO_2 fluxes between soil-atmosphere, all soil types produced peaks of carbon dioxide emissions after rain events (Fig. 3). Our statistical analyses corroborated the importance of soil moisture (M) in the CO_2 fluxes in the quarry, in addition to the soil properties, as mentioned above (Table 5). Soil moisture and temperature have been described as important modulators of CO_2 emissions (Kuzyakov, 2006; Miralles et al., 2018; Oyonarte et al., 2012; Ray et al., 2020). The rainfall was not constant in the study area (Fig. 3) but responded to the pulses characteristic of arid and semiarid zones (Huxman et al., 2004; López-Ballesteros et al., 2016; Oyonarte et al., 2012; Unger et al., 2010). Then, the CO_2 emissions increased in relation to these observed rainfall pulses and increases in soil moisture, consequently, during the wet season compared with dry periods (Supplementary Figure 1). Moreover, these CO_2 emission peaks were more pronounced in soils with higher TOC and TN contents (restored soils and NAT) and especially in soils with higher contents of labile organic matter (SS, Mix1 and Mix2) and higher soil. In the contrary, the restored soils hardly showed differences in the CO_2 emission rates in dry periods, highlighting the important role that soil moisture plays in the CO_2 emission patterns in soils restored with organic amendments, as well as it was also confirmed by the significantly high positive correlation between soil moisture and CO_2 emission ($r = 0.74$). Nevertheless, curiously, as time elapses and the organic matter content decreased in the experimental plots, possibly as a result of the initial mineralization of labile organic compounds, it is also observed that the abovementioned pattern dissipated and the peaks CO_2 emission become milder, even in wet periods (Fig. 4 and Supplementary Figure 1). This trend was clearly observed in the experimental plots with sludge and their mixtures (SS, Mix1 and Mix2), followed by compost CC. The influence of the wetting-drying pattern was difficult to observe in the soils restored with CG, although it is worthy to note that the soil moisture was lower in CG compared to previous amendments (Supplementary Figure 1). However, throughout the entire sampled period, CO_2 emission was practically non-existent in CON soils with low organic matter content even in rainy periods. The synergistic effect of easily biodegradable organic matter, nitrogen content, and soil moisture activate soil microbial communities, thus beginning to mineralize efficiently organic compounds and emitting CO_2, which is released from soil microbial respiration as mentioned above. Application of organic amendments guarantees the immediate increase of the soil water retention capacity (Zancada et al., 2004), as was supported by our statistical analysis (Table 1; Fig. 3), since the increase of TOC improves the formation of soil structure and stable aggregates and increases the soil porosity favouring water infiltration (Miralles et al., 2009). This contributes to increasing the moisture content (M) in restored soils with respect to control soils (CON), especially after rain events (Table 1; Fig. 3). In dry periods, CO_2 emissions decreased considerably (Supplementary Table 1; Table 4) suggesting that soil moisture could be considered as an essential limiting factor in CO_2 fluxes, although it depended also on the type of restoration treatment and the organic matter composition. Soil moisture plays a key role in microbial communities (Moyano et al., 2013) because microorganisms depend on water to support their normal cell activity (Angel and Conrad, 2013). Nevertheless, curiously, although temperature is also considered an important factor time-variant soil respiration and CO_2 emission (Buchmann, 2000; Conant et al., 2004; Li et al., 2013), our statistical results did not show that this parameter exerted a significant role in CO_2 emission from the analysed soils (Table 5), as even the negative correlation between T and CO_2 emission suggested (Table 4). This could be because the temperatures were similar in all rainy periods with a range of mild temperatures during rain events (Fig. 3). Others authors have also described that there may be thermal acclimatization of soil microorganisms in arid and semiarid areas (Bradford et al., 2019; Dacal et al., 2019 -; Luo et al., 2001). Dacal et al. (2019) found this adaptation to temperature fluctuation in drylands around the world, and Zogg et al. (1997) reported that bacterial communities could change their function or composition by adapting to seasonal variations in temperature.

5. Conclusions

Compost from plant residues could be more suitable for application in the restoration of soils degraded by open-cast mining in limestone quarries, at least in terms of improving the physical and chemical soil properties in the short-term, with the consequent positive feedback in the recovery of soil quality and in turn, the soils restored with compost from gardening and from horticultural greenhouse crop, presented the lowest CO_2 emission rates, similar to unamended soils and to natural soils respectively. On contrast, the sludge amendments showed higher initial CO_2 emissions rates than in the rest restoration treatments, suggesting rapid mineralization of labile organic matter and the consequent feedback for global warming. Restoration treatments with mixtures from sludge and compost, could also be a good solution, since the CO_2 emission rates are higher at the beginning but their stabilization is faster and therefore, this could mean that the contribution of sludge could give a first boost by providing organic matter that would stimulate the proliferation of soil microorganisms, while the plant remains would provide more stable organic matter over time.

Environmental factors and physical and chemical soil properties influencing the soil biological activity played a key role in the CO_2 emission from all restored soils and natural soils, with the soil moisture as the factor with the greatest weight in CO_2 emission rates followed by TOC, pH and TN. Nevertheless, the type of organic amendment and its chemical composition with labile or resilient organic compounds facilitating or hindering soil mineralization processes also played an important role in CO_2 emission from soils restored with organic amendments from residues recycled. These results could suggest a very efficient biomineralization of organic matter and stabilization of organic matter provided by organic amendments in the short term in a quarry from arid and semiarid Mediterranean ecosystems.

Overall, addressing this recovery through the application of organic amendments is appropriate, because increased the organic matter content, improve the water retention and stimulate the soil microorganisms compared with unamended soils. Long-term studies are necessary to obtain information on the dynamics of carbon cycle in highly degraded ecosystems from arid and semiarid zones, restored with organic residues recycled with different chemical composition.

Credit author statement

All authors contributed to the intellectual input of this study and discussed different aspects of analysis and interpretation of data. Isabel Miralles: Conceptualization, Methodology, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. Rocío Soria: Conceptualization, Resources, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing; Raúl Ortega: Conceptualization, Formal analysis, Supervision. Manuel Esteban Lucas Borja: Conceptualization; Formal analysis, Writing - Original Draft, Writing - Review & Editing. Natalia Rodríguez-Berbel: Conceptualization, Recourses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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