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Perennial alley cropping contributes to decrease soil CO_2 and N_2O emissions and increase soil carbon sequestration in a Mediterranean almond orchard

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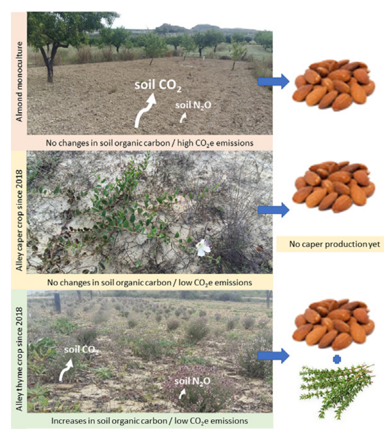
HIGHLIGHTS

- Almond orchard diversified with caper (D1) and thyme (D2) as perennial alley crops
- D1 and D2 significantly decreased soil CO_2 emissions, related to no-till practice.
- Higher CO_2 emissions in monoculture after tillage events in warm days
- D2 significantly increased soil organic carbon owing to its evergreen nature.
- No effect on N_2O emissions likely due to lack of external fertilizers and low SOM

GRAPHICAL ABSTRACT



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ABSTRACT

The implementation of alley cropping in orchards can be a sustainable strategy to increase farm productivity by crop diversification and contribute to climate change mitigation. In this research, we evaluated the short-term effect of alley cropping with reduced tillage on soil CO_2 and N_2O emissions and soil total organic carbon (TOC) in an almond orchard under Mediterranean rainfed conditions. We compared an almond monoculture with tillage in all plot surface (MC) with almond crop with reduced tillage and growth of *Capparis spinosa* (D1) and almond crop with reduced tillage and growth of *Thymus hyemalis* (D2). For two years, soil CO_2 and N_2O were measured, with soil sampling at the start and end of the experimental period. Results showed that CO_2 emission rates followed the soil temperature pattern, while N_2O emissions were not correlated with temperature nor moisture. Soil CO_2 emissions were significantly higher in MC (87 mg m^{-2} h^{-1}), with no significant differences between D1 and D2 (69 mg m^{-2} h^{-1}). Some peaks in CO_2 effluxes were observed after tillage operations during warm days. Soil N_2O emission rates were not significantly different among treatments. Cumulative CO_2 and CO_2 equivalent (CO_2e) emissions were significantly highest in MC. When CO_2e emissions were expressed on a crop production basis, D2 showed the significantly lowest values (5080 g kg^{-1}) compared to D1 (50,419 g kg^{-1}) and MC (87,836 g kg^{-1}), owing to the high thyme yield, additional to the almond yield. No production was obtained for *C. spinosa*, since at least two more years are required. TOC did not change with time in MC neither D1, but it significantly increased in D2 from 3.85 g kg^{-1} in 2019 to 4.62 g kg^{-1} in 2021. Thus, alley cropping can contribute to increase the agroecosystem productivity and reduce CO_2 emissions. However, it is necessary to grow

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evergreen alley crops such as thyme to obtain short-term increases in soil organic matter. Thus, to estimate increases in TOC with alley cropping, the plantation density and the period required by the crop to cover most of the surface are essential factors at planning the cropping strategy.

1. Introduction

The third agricultural revolution was a milestone in agriculture in the last century, since it allowed the increase of crop yields, associated with the introduction of chemical fertilizers, pesticides and mechanization (Pingali, 2012). However, this phenomenon led to the overall adoption of the current agri-business models based on monocultures and intense mechanization, with many associated environmental impacts (Morugán-Coronado et al., 2020). It has been proved that current systems lead to increases in greenhouse gas (GHG) emissions and decrease of soil organic matter (SOM) because of low residue turnover and absence of soil cover during the entire year and the use of frequent tillage, that favour the rapid SOM mineralization (Bot and Benites, 2005; FAO, 2017; Zornoza et al., 2018). Loss of SOM also occurs owing to erosion processes due to bare soil surface with poor soil structure (Almagro et al., 2016; Boix-Fayos et al., 2017). As a consequence, GHG emissions by crop production has increased from 7 to 34 mill tons of CO_2e per year in the period 1900–2018 (Aguilera et al., 2020). In the end, agriculture has become a source of GHG emissions when it has an enormous potential to be a C sink by both soil and biomass (Albaladejo et al., 2013). In this sense agricultural soils present a unique opportunity for C sequestration and compensating emissions by sustainable cropping systems (Chabbi et al., 2017).

Crop diversification can decrease the use of pesticides, fertilizers and water by management of biodiversity, while can decrease GHG emissions and foster C sequestration in soil and biomass (Morugán-Coronado et al., 2020). Although perennial croplands represent 10 % of total cropland in Europe, they are highly important in the Mediterranean region, with 67 % global production of olive oil and 25 % global production of almonds, only exceeded by the USA (Eurostat, 2019). In fruit tree orchards, alley cropping with perennial crops can be a suitable strategy to both increase land productivity and decrease the C footprint of the cropping systems by decreases in GHG emissions and increases in C storage in soil and perennial biomass (Kay et al., 2019; Xu et al., 2019). This can be achieved by decreases in tillage or no-till practices and by the presence of a perennial vegetation cover in the alleys that protects soil against erosion and enriches it in SOM by root exudates and litter incorporation (Baggs et al., 2006; Sims et al., 2009; Zikeli and Gruber, 2017). This type of agroforestry system is currently not common mainly because of cultural and social barriers. There is a general agreement about keeping alleys free of vegetation, mostly associated to decreasing competition by water and nutrients of trees with alley plants (Gao et al., 2013). However, alley cropping properly selected and managed, can have positive effects, contributing to enhance a variety of ecosystem services such as lower GHG emissions, higher land productivity, improvement in soil quality, enhanced C sequestration and water holding capacity, attraction of pollinators and auxiliary fauna, etc. (Battie-Laclau et al., 2020; Rosa-Schleich et al., 2019). In fact, this strategy is aligned with the European Green Deal (European Commision, 2019) and the European Climate Law (European Commission, 2020), which aim to make a fair transition in the EU's economy to achieve climate neutral farms by 2050.

When selecting a crop to be grown as alley cropping, it is important to select species adapted to the soil and climatic conditions of the area, be compatible with the current agronomic machinery and have a competitive price in the market with identified supply chains (Hinsinger et al., 2011; Isbell et al., 2015). In this sense, the use of caper or aromatic species such as thyme, lavender, rosemary, salvia, etc., are a promising option to be used as alley cropping in Mediterranean orchards (i.e. fruits, olives, almonds), because: i) they are native of the area and so, adapted to climate and soils characteristics, and ii) they can be sold for food (caper) or spices and essential oils (aromatics) used in pharmacy, cosmetics and biotechnology industries (De Martino et al., 2015).

Hence, there is a need to provide scientific data about agronomic strategies that can foster climate neutrality in farms, by decreasing GHG emissions and increasing C storage. Thus, the objectives of this study were to: i) assess if alley cropping with perennial crops such as capper or thyme can contribute to decrease soil GHG emissions and increase C sequestration in soil in a Mediterranean rainfed almond orchard; and ii) evaluate if alley cropping can contribute to increase land productivity. Thus, we hypothesized that the growth of caper or thyme in the alleys of the almond orchard, associated to a no-till strategy, would reduce soil CO_2 and N_2O emissions and increase SOM content. The decrease in GHG emissions would be mostly related to the lack of tillage, since there is no breakage of soil aggregates and soil aeration is reduced, but the increases in SOM would be more related to the growth of the crop, owing to the incorporation of litter and an active root exudation. The growth of alley crops would increase land productivity by the harvest of a new product, with no negative effect on the main almond crop. This would be associated to lower soil CO_2 equivalent (CO_2e) emissions per unit of crop production. This research provides novelty at assessing the use of perennial alley crops in Mediterranean orchards. This strategy is not currently performed at great scale in the region, but could promote increases in land productivity in marginal lands while contributing to climate change mitigation by decreases in GHG emissions and increases in C sequestration and storage in soil and biomass. To efficiently reverse the current situation of soil loss by erosion and organic matter loss by intensive farming in orchards, this type of practices should be fostered by policy-makers and land planners to tackle current cultural and social barriers that hinder their adoption, but based on robust scientific evidence.

2. Materials and methods

2.1. Study site and experimental design

This experiment was performed from April 2019 to April 2021 in a commercial almond orchard (*Prunus dulcis* (Miller) D. A. Webb), located in Murcia, SE Spain (37° 57′ 31″N; 0° 56′ 17″W). The *P. dulcis* orchard had an extension of 2.63 ha, with 540 trees, at a spacing of 7 m × 7 m, planted in 1950. The climate is semiarid Mediterranean with mean annual temperature of 18 °C and mean annual rainfall of 280 mm. The potential evapotranspiration rate is 1300 mm year^{-1}. The soil is a Calcaric Eutric Regosol (IUSS Working Group WRB, 2014) developed on marl, with silt loam texture (9 %, 65 % and 26 % of sand, silt and clay, respectively), 59 % of $CaCO_3$ content, pH of 8.4, bulk density of 1.30 g cm^{-3}, total organic carbon of 3.86 g kg^{-1}, total nitrogen of 0.60 g kg^{-1} and a cation exchange capacity of 14.5 cmol^{+} kg^{-1} at 0–30 cm depth (Ap horizon).

Three different treatments were established as randomised block design with three replicates. Plots of 210 m^2 were established, with the long side of each one following the direction of the maximum slope, including rows of 5 trees. The average plot slope was 8 %. Treatments were: i) almond monoculture with tillage in all plot surface (chisel ploughing 2 times yr^{-1} at 20 cm depth) (MC); ii) almond plantation with reduced tillage (rototiller (Lander 180, Spain) 2 times yr^{-1} at 20 cm only 1.5 m around each tree trunk), with no till in the rest of the alley, and diversified with *Capparis spinosa* L. as alley crop (D1); and iii) almond plantation with reduced tillage as explained in D1 and diversified with the aromatic species *Thymus hyemalis* Lange as alley crop (D2). Seedlings of *C. spinosa* acquired from a local nursery were manually planted on 01/10/2018 at a spacing of 3.5 m × 3.5 m. Seedlings of *T. hyemalis* acquired from a local nursery were manually planted on 05/11/2018 at a spacing of 1 m × 0.5 m covering all the alley surface, except for the area tilled around each tree. These two species were selected as alley cropping because they are native of the area, spontaneously growing in the surroundings, and have commercial interest by sale of capers (*C. spinosa*) or herbs/essential oil (*T. hyemalis*) that can diversify crop production in the farm with complementary incomes for the farmer. *T. hyemalis* was also selected because it can successively resprout after harvest, and can produce high quantity of essential oil (Sáez, 1995). The orchard was kept at rainfed conditions. However, thyme and caper plants were irrigated in four occasions to ensure proper establishment, adding 12 L of water per plant, on 05/11/2018 (planting day), 15/01/2019, 04/03/2019 and 02/07/2019. No pesticides were applied during the experiment duration, and weeds were controlled by tillage in MC. No control of weeds was performed in the no-till area. As a consequence, D1 and D2 plots were colonized mainly by *Artemisia herba-alba* Asso, *Piptatherum miliaceum* (L.) Coss, *Dittrichia viscosa* (L.) Greuter, *Phagnalon saxatile* (L.) Cass. *Sonchus tenerrimus* L. and *Diplotaxis erucoides* DC, although no negative effect on alley crops growth was observed owing to their low density (proportion of caper-thyme: invasive species was 3:2 as average; see photos of the plots in the Fig. S1 of the Supplementary Material). Plots were only fertilized each September by adding the dry outer green shell cover of the almond rind after harvest in all plots regardless the treatment, at a rate of 290 kg ha^{-1} and 205 kg ha^{-1} in 2019 and 2020, respectively (differences due to differences in almond production).

2.2. Soil greenhouse gas measurements

Measurements of CO_2, N_2O and CH_4 were made every 7–20 days, depending on climate conditions in triplicate in all replicated treatments from 11/04/2019 to 08/04/2021, between 9:00 and 11:00. We performed three measures per plot, nine measures per treatment and 27 measures per day. We measured GHG emissions during 63 days in the indicated period, with a total of 1701 measures in all plots. The basic experimental procedure used in this study was the dynamic gas chamber technique. The chamber was made of non-oxidisable steel, with a diameter of 7.5 cm and a height of 20 cm, with one inlet and one outlet connected to a photoacoustic infrared spectroscopy multi-gas analyser with ultra-sensitive cantilever pressure sensor (Gasera One, Gasera Ltd). The dynamic system with inlet and outlet in the chamber permits a continuous flow and avoids pressure fluctuations. The chambers were inserted into the bare soil to a depth of 15 cm between two almond trees in CT, and between two caper or thyme plants in D1 and D2, equidistant to all specimens in all cases, and at least 2,5 m away from a tree. N_2O, CO_2 and CH_4 were quantified every 1 min for a period of 5 min to assess the linear trend. N_2O, CO_2 and CH_4 emissions rates were expressed as the difference between the quantification at the end and the beginning of the measure period divided by the time. However, no CH_4 emissions were detected in the entire experimental period. CO_2 and N_2O cumulative emissions for each treatment were estimated by numerical integration (Chen et al., 2013). GHG emissions were converted into CO_2equivalent (CO_2e), and then cumulative emission data (g m^{-2}) were also expressed on a production basis (g kg^{-1}) for the experimental period (sum up of yields of both crops) to assess the emissions per products of each system. For this, N_2O emissions were converted into CO_2e according to their global warming potential, which is 265 (Vasconcelos et al., 2022).

Meteorological data were measured using an automatic weather station located in a nearby orchard (4 km). Soil temperature (T) and soil moisture (M) were measured using a ProCheck and 5TM sensors (Decagon Devices, USA) introduced at 10 cm depth adjacent to the place where GHG measures were done.

2.3. Crop production, soil sampling and analytical methods

Almond crop yield was calculated by weighing all the almonds harvested directly from the trees in each plot on 29/07/2019 and 03/08/2020. Thyme was harvested by cutting the aerial part of all plants in the entire surface of each plot, which were at full blossom on 04/03/2020 and on 23/04/2021. Plants were steam distilled in a commercial company for 2 h. Thyme yield was expressed as the quantity of essential oil per surface. No production of caper was obtained in the experimental period, since 3–4 years are needed to have the first harvest (Aytaç et al., 2009).

Two soil sampling campaigns were yearly performed: 08/04/2019 and 24/03/2021 at two different depths (0–10 cm and 10–30 cm) with an auger. Three composite samples derived from 5 random subsamples were collected in each plot (9 composite soil samples per treatment). Soil cores using steel cylinders were taken to determine soil bulk density (BD). Soil was air-dried for one week and sieved at <2 mm.

Particle size distribution was determined using a Coulter LS200 ‘Laser particle sizer’ (Coulter Corporation, Miami, Florida). Previously, soil samples were treated with hydrogen peroxide to remove organic matter before being dispersed using sodium hexametaphosphate for 12 h. Soil pH and electrical conductivity (EC) were measured in deionized water (1:2.5 and 1:5 *w/v*, respectively). Total organic carbon (TOC) and total nitrogen (Nt) were determined by an elemental CHNS-O analyser (EA-1108, Carlo Erba). Soil NH_4^+ was extracted with 2 M KCl in a 1:10 soil:extractant ratio and calorimetrically measured (Kandeler et al., 1988; Keeny and Nelson, 1982). Soil NO_3^- was extracted with deionized water in a 1:10 soil:extractant ratio and measured by ion chromatography (Metrohm 861).

2.4. Statistical analysis

Data were checked to ensure normal distribution using the Kolmogorov-Smirnov test at $P < 0.05$. Homoscedasticity was checked by the Levene test, and data was log-transformed when needed. GHG data were submitted to two-way repeated measures ANOVA, with measurement date as within-subject factor, and treatment (MC, D1 and D2) as between-subject factor. GHG was also submitted, independently for each date, to one-way ANOVA and Tukey's post hoc test ($P < 0.05$) to compare significant differences between treatments. Cumulative crop yield data and cumulative GHG emission values for the experimental period were submitted to a one-way ANOVA and Tukey's post hoc test (P < 0.05) to compare significant differences among treatments. Soil data were submitted to two-way repeated measures ANOVA, with sampling date (2019 and 2021) as within-subject factor, and treatment (MC, D1 and D2) as between-subject factor. Histograms of the residuals from ANOVA were plotted for each variable to confirm the normality assumption. Relationships among properties were studied using Pearson correlations. Statistical analyses were performed with the software IBM SPSS for Windows, Version 20.

3. Results

3.1. Greenhouse gas emission rates

Soil CO_2 emission rates mostly followed the soil temperature trend, as shown in Fig. 1, with a positive significant correlation between both properties ($R = 0.39$; $P < 0.01$). In addition, highest CO_2 emissions were associated to highest soil moisture with high temperature values, with a positive correlation between CO_2 emission rates and soil moisture ($R = 0.36$; $P < 0.01$). Thyme crop contributed to significantly increase ($P < 0.05$) soil moisture compared to monoculture, mostly during the second year of experiment (Fig. 1). As an average, soil moisture was 10.2 % in MC and 11.1 % in D2 for the entire experimental period (24 months). Soil CO_2 emission rates were significantly affected by the treatment, with significantly higher emissions in MC, with no significant differences between D1 and D2 for the complete experimental period. Eight out of the 63 CO_2 emission rate measures were significantly highest in MC (Fig. 1). Some of the peaks observed in CO_2 emission rates were related to tillage events. As an average, CO_2 emission rates were 87 mg m^{-2} h^{-1} in MC, 69 mg m^{-2} h^{-1} in D1 and 70 mg m^{-2} h^{-1} in D2 for the entire experimental period. The highest rate of CO_2 emissions occurred simultaneously with tillage in the high temperature days.

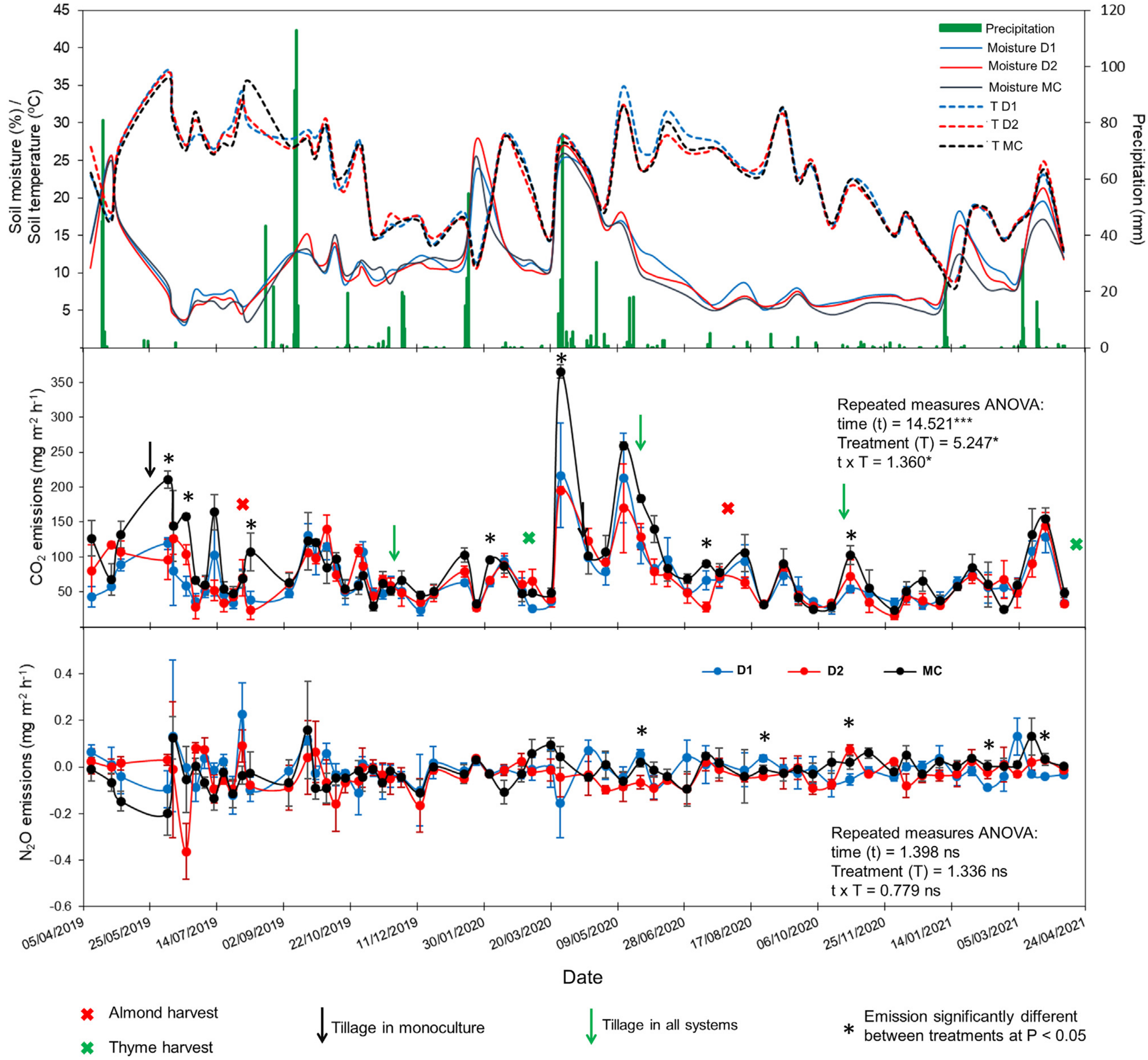

Fig. 1. Environmental conditions during the duration of the experiment (top), soil CO_2 emission rates (center) and soil N_2O emission rates (bottom) from the almond monoculture with tillage in all plot surface (MC, in black), diversified orchard with *C. spinosa* and reduced tillage (D1, in blue) and diversified orchard with *T. hyemalis* and reduced tillage (D2, in red). Values are mean ± standard error (n = 3). P: precipitation; T: soil temperature; For repeated measures ANOVA data: significant at ***$P < 0.001$; *$P < 0.05$; ns: not significant ($P > 0.05$).

Soil N_2O emission rates were not correlated to soil moisture nor temperature, with a flat trend with small oscillations up and down of 0 mg m^{-2} h^{-1} (Fig. 1). Soil N_2O emission rates were not significantly different between treatments for the complete experimental period. Indeed, only five out of the 63 N_2O emission rate measures showed significant differences among treatments, not following a general trend. As an average, N_2O emission rates were −0.018 mg m^{-2} h^{-1} in MC, −0.012 mg m^{-2} h^{-1} in D1 and −0.032 mg m^{-2} h^{-1} in D2 for the entire experimental period.

3.2. Overall cumulative emissions

The estimation of cumulative CO_2, N_2O and CO_2e released during the experimental period confirmed the significantly highest overall CO_2 and CO_2e emissions in MC, with no differences between the other two treatments (Table 1). There were not significant differences with regard to cumulative N_2O released during the experimental period among treatments. When GHG emissions were expressed on a crop production basis, owing to the high thyme yield in D2 (higher than the almond yield), D2 showed an average value of 5080 g kg^{-1}, significantly lower than D1 (50,419 g kg^{-1}) and mostly MC (87,836 g kg^{-1}) (Table 1).

Cumulative CO_2 emission was significantly positively correlated with Nt (R = 0.49; P < 0.001), with no correlation with TOC, POC or C/N ratio. Cumulative N_2O emissions was only negatively correlated with NO_3^- (R = −0.48; P < 0.001), with no correlation with Nt, C/N ratio or NH_4^+. The absolute values of these properties for the different treatments can be found in Almagro et al. (under review).

3.3. Soil carbon sequestration

TOC was low in all treatments, with values ranging from 3.70 to 4.75 g kg^{-1} in the superficial layer, and from 3.24 to 4.14 g kg^{-1} at 10–30 cm depth (Fig. 2). TOC did not change with time in MC neither D1 at any depth, but it significantly increased in D2 from 3.85 g kg^{-1} in 2019 to 4.62 g kg^{-1} in 2021 at 0–10 cm depth. Nt significantly increased

Table 1
Cumulative values of soil CO_2 and N_2O, total CO_2 equivalent emissions and cumulative CO_2 equivalent emission data expressed on a production basis released from alley soil in the almond monoculture with tillage in all plot surface (MC), orchard with reduced tillage and growth of *C. spinosa* (D1) and orchard with reduced tillage and growth of *T. hyemalis* (D2) during the entire experimental period (11/04/2019–08-04-2021).

	Cumulative CO_2	Cumulative N_2O	CO_2e	Cumulative almond yield	Cumulative thyme yield	CO_2e
	g m^{-2}			kg ha^{-1}	kg ha^{-1}	g kg^{-1} of crop production
MC	1613 ± 54 b	0.321 ± 0.191	1517 ± 21 b	173 ± 5	–	87,836 ± 3548 c
D1	1221 ± 112 a	0.243 ± 0.036	1149 ± 119 a	230 ± 27	–	50,419 ± 2980 b
D2	1247 ± 42 a	0.592 ± 0.131	1071 ± 42 a	177 ± 48	1935 ± 68	5080 ± 159 a
F-ANOVA	8.359*	1.835 ns	10.335*	1.005 ns	–	239***

Significant at *P < 0.05; ns: not significant (P > 0.05).

in MC at both depths and in D1 at 0–10 cm depth. This led to a decrease in the C/N ratio in MC from 6.2 in 2019 to 5.0 in 2020 and in RT from 6.1 in 2019 to 5.6 in 2021. D2 showed no significant effect on C/N ratio with time, with an average value of 6.7.

4. Discussion

The establishment of perennial alley crops associated to no-tillage has resulted in a suitable strategy to reduce soil CO_2 emissions, independently on the species selected. This finding seems related to the no-till strategy rather than to the development of the alley crop. As explained before, *C. spinosa* losses all its shoots in November, and resprouts in April. So, during 5 months of winter time, soil is not covered by caper biomass, with the only protection of spontaneous vegetation (see Supplementary Fig. S3). Thyme biomass is highest in winter owing to the highest water availability and reduced water stress. Nonetheless, despite so big differences in ground cover by the alley crop, soil CO_2 emissions were similar between both alley crops. In addition, the cessation of tillage has caused soil compaction and

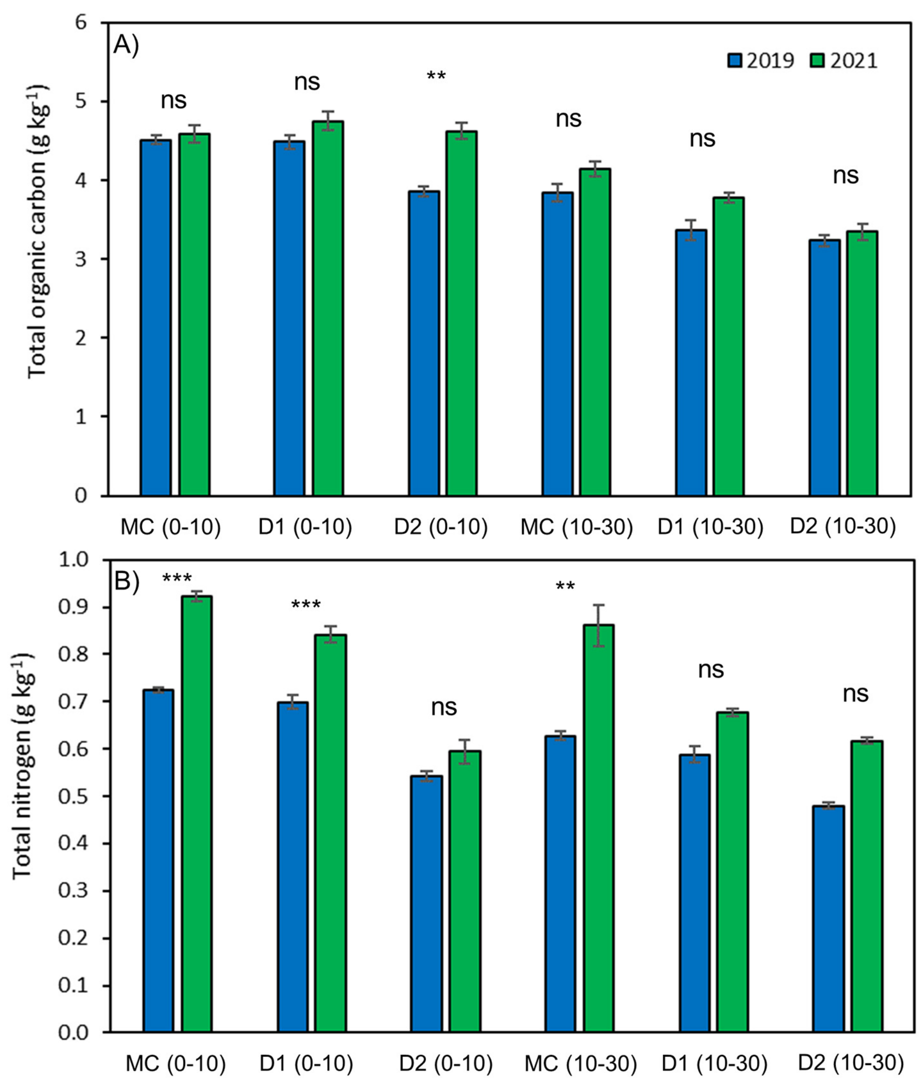

Fig. 2. Evolution of soil total organic carbon (A) and total nitrogen (B) from 2019 to 2021 in the three different systems at the two sampling depths (0–10 cm and 10–30 cm). Vertical bars indicate standard error. MC: almond monoculture with tillage in all plot surface; D1: almond orchard diversified with *C. spinosa* and reduced tillage; D2: almond orchard diversified orchard with *T. hyemalis* and reduced tillage. (0–10) and (10–30) after treatment denotes soil depth. Significant at ***P < 0.001; *P < 0.05; ns: not significant (P > 0.05) between sampling dates for each treatment and depth.

reduced porosity in the soil surface (see Supplementary Figs. S1, S3 and S4), compared to the monocrop with tillage in the entire plot surface, also supported by increases in bulk density. This is due to the high content of silt and low content of SOM, that causes the clogging of soil pores (de Lima et al., 2022). Thus, reduced porosity can be associated to reduced gas exchange, and so, lower GHG emissions. In this line, Pengthamkeerati et al. (2006) also reported increased soil compaction caused by reduced tillage under rainfed farming, which increased diffusive resistant to gas movement in soil. Moreover, besides higher gas exchange in MC owing to tillage, tillage events have been associated to peaks of CO_2 effluxes, mostly in days in warm temperatures. This is due to the breakage of aggregates and release of organic compounds that are rapidly and easily degraded by microorganisms at high temperatures (Conant et al., 2011; Wang et al., 2015a, 2015b). Similarly, previous research has recorded significantly higher soil CO_2 emissions under conventional tillage (tillage in all orchard surface with high machinery passages) compared to reduced tillage owing to tillage events, especially during the summer season (Almagro et al., 2017; Boeckx et al., 2011; La Scala et al., 2006; Lu et al., 2016). In this line, Zornoza et al. (2018) also reported the greater dominance of temperature on GHG emission control in semiarid orchards. CO_2 emissions have been correlated with Nt, indicating a deficit of soil N in the agroecosystem. So, microorganisms can mineralize more organic compounds in those areas where with more available N sources, as previously reported (Lu et al., 2016; Zornoza et al., 2018, 2016).

N_2O emissions were low in this agroecosystem, likely due to the lack of fertilization, and as a consequence, no effect of temperature, soil moisture, tillage or alley cropping was observed. Zornoza et al. (2018) neither observed a significant correlation between N_2O emission and soil moisture and temperature in a Mediterranean orchard. However, some other authors have reported higher N_2O emissions from no-tilled soils than conventionally tilled soils in the presence of inorganic N sources, likely due to restricted soil aeration (Grave et al., 2018; Gregorich et al., 2008; Liu et al., 2007). Thus, N_2O emissions are dependent on high availability of mineral N in soil, which may increase under no-till systems owing to lower aeration and so, higher anaerobic spots for denitrification (Thomson et al., 2012).

Besides reducing GHG emissions, the main goal of alley cropping is to enhance soil C sequestration and storage. This is a strategy to mitigate climate change, but also to improve soil structure and fertility, vital in soils from rainfed orchards under Mediterranean climate (Morugán-Coronado et al., 2020). After two years of alley crop development, only the establishment of *T. hyemalis* was associated to significant increases in TOC. Thus, it seems that the reduction in GHG emissions is related to the cessation of tillage, but soil C sequestration is related to a continuous vegetation cover provided by thyme, as an evergreen species. Root and leaf residues of the intercropped plants represent direct carbon inputs to the soil, especially in the soil surface, that can be decomposed and transformed into a stable source of organic matter (Mungai et al., 2006). Tamartash et al. (2014) also recorded a significant increase in TOC in the surface layer of a soil cultivated with thyme. The lack of ground cover during winter with the development of *C. spinosa*, and the lowest plantation density can be related to the lack of increases in TOC in two-year period. So, long-term monitoring is needed to assess the efficiency of these species to contribute to diversify crop production (no harvest obtained in this short experimental period) and enhance soil C sequestration and storage. Hence, the selection of evergreen aromatics for alley cropping can be suggested as a sustainable practice, since it can increase TOC even short-time under semiarid Mediterranean conditions, with positive potential effects to improve soil structure and reduce the compaction generated by the lack of tillage. This crop can also reduce GHG emissions and increase the overall production of the agroecosystem with the harvest of the thyme for spices or essential oil, highly demanded in cosmetics, pharmacy or biotechnology (De Martino et al., 2015) In addition, the vegetal residues of intercropped thyme, that are resistant to decomposition in short-term owing to high C/N ratio, can also explain the lower soil CO_2 emissions and higher stabilization and accumulation in soil (Martínez-Mena et al., 2021; Wang et al., 2015a, 2015b; Yang et al., 2020). Aka Sagliker et al. (2017) showed that thyme leaves addition to the soil reduced soil carbon mineralization, likely due to the high recalcitrance of thyme tissues. Xue and An (2018), investigating the effect of different land uses on soil organic matter, concluded that *Thymus* sp., as a natural shrubland, had the greatest effect in increasing the quantities of TOC, Nt and C/N compared to the other land cover types, highlighting the high capacity of thyme to increase soil carbon content.

It is important to highlight that associated to the increases in TOC with the cultivation of thyme, there has been a significant increase in soil water availability. This is of vital importance in rainfed crops under semiarid conditions, since water is the most limiting factor to maintain crop production. Thus, the development of thyme, contrary to the cultural/social belief (Cerdà et al., 2018), not only does not compete with the tree for water, but also increases water availability in soil to maintain two crops at the same land. In this line, several studies also pointed out that intercropping improves the conservation of soil water, enhances the water availability, decreases the run-off and thus increases the water use efficiency and crop yield (Chen et al., 2018; Hu et al., 2017; Sharma et al., 2017).

5. Conclusion

Alley cropping with perennial crops is an appropriate strategy to reduce soil CO_2 emissions with no negative effects on the almond yield, increasing the overall productivity of the agro-ecosystem. However, in soils with heavy textures and low organic matter content, cessation of tillage can lead to soil compaction. The transition to an improved soil structure with higher organic matter and decrease of initial soil compaction would take place in a medium term (>3 years) with some perennial species, such as *T. hyemalis*, likely due to its high ground cover during all year. Moreover, the growth of thyme also significantly increased soil moisture content compared to the monoculture. This increase in soil organic carbon and moisture was not observed with *C. spinosa* in two-years period, since this species losses its shoots in winter and resprouts in spring, leaving soil uncovered half of the year. Thus, short-term increases in soil organic C can be obtained in semiarid rainfed orchards by introduction of evergreen crops with higher density. Most of the CO_2 emission peaks were detected after tillage events during high temperature days. Consequently, in order to avoid high CO_2 emission rates, it is recommended not to plough during warm days. No effect of treatment was observed with regard to N_2O emissions, likely due to the lack of fertilization. Thus, alley cropping can be considered as a sustainable strategy to decrease soil GHG emissions and enhance soil C sequestration and storage, if properly selected and managed. These findings can encourage farmers, land managers and decision-makers to implement and foster the adoption of alley cropping to enhance land production and delivery of ecosystem services such as biodiversity, C sequestration and storage and decreased GHG emissions. Long-term studies are needed to assess the evolution of GHG emissions and soil organic matter increase with the development of *C. spinosa*, since it also may contribute to soil C sequestration with time.

CRediT authorship contribution statement

Virginia Sánchez-Navarro: Investigation, Formal analysis, Writing - original draft. **Vajihe Shahrokh:** Writing - original draft. **Silvia Martínez-Martínez:** Investigation, Writing - review & editing. **Jose A. Acosta:** Investigation, Writing - review & editing. **María Almagro:** Methodology, Investigation, Writing - review & editing. **María Martínez-Mena:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Carolina Boix-Fayos:** Conceptualization, Methodology, Investigation, Writing - review & editing. **lvira Díaz-Pereira:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Raúl Zornoza:** Conceptualization, Methodology, Investigation, Writing - original draft, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

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