Agriculture, Ecosystems and Environment 361 (2024) 108826

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Intercropping in rainfed Mediterranean olive groves contributes to improving soil quality and soil organic carbon storage

Jesús Aguilera-Huertas [a], Luis Parras-Alcántara [a], Manuel González-Rosado [a,b], Beatriz Lozano-García [a,*]

[a] SUMAS Research Group, Department of Agricultural Chemistry, Soil Science and Microbiology. Faculty of Science, Agrifood Campus of International Excellence - ceiA3, University of Cordoba, Cordoba 14071, Spain
[b] Department of Agricultural Science, Universidad Politécnica de Cartagena, Paseo Alfonso XIII 48, Cartagena 30203, Spain

ARTICLE INFO

Keywords:
Crop diversification
Carbon sink
Soil depth
Stratification index
Soil management
Soil quality

ABSTRACT

Given the current degradation problems that Mediterranean soils endure, the implementation of alley cropping in olive orchards has been suggested as a sustainable strategy to increase agricultural productivity and improve carbon storage and soil fertility. Therefore, the objective of this study was to evaluate in the short term (3 years) the effect of alley cropping with minimum tillage versus conventional tillage in a traditional rainfed olive grove on soil organic carbon, total nitrogen concentrations, and stocks. Changes in soil quality through a stratification index, and the success of the 4‰ strategy in these soils with this type of management were also evaluated. Three intercropping strategies were tested: *Crocus sativus* (D-S), *Vicia sativa* and *Avena sativa* in rotation (D-O), and *Lavandula x intermedia* (D-L), all with minimum tillage versus olive with conventional tillage without intercropping, which was used as a control. Intercropping increased soil organic carbon in topsoil (0–10 cm) by 41.1, 28.5, and 30.5% for D-S, D-O, and D-L, respectively, compared to conventional tillage. At a depth of 10–30 cm, the soil organic carbon and the soil organic carbon stock increased slightly, although significant differences were found only in D-L. In the diversified plots, total nitrogen did not vary. However, total nitrogen increased in olive with conventional tillage due to fertilisation. Concerning soil quality, no significant differences were observed when evaluating the soil carbon and nitrogen stratification index in any of the treatments. However, the implementation of intercropping reached the objectives set by the 4‰ initiative in these soils with an increase in soil carbon per hectare and per year of 80, 87.4, and 86.4% for D-S, D-O, and D-L, respectively. Therefore, based on these results, in the short term, intercropping treatment enhances carbon storage in these soils, effectively achieving the objectives of the 4‰ initiative.

1. Introduction

In Europe, to remedy the soil degradation problem and ensure that all European soils are in healthy conditions by 2050, the European Union launched the soil strategy by 2030 (EU soil strategy for, 2030) at the end of 2021. To this end, this strategy proposes specific actions to achieve sustainable soil management concerning climate change mitigation, biodiversity, restoration, and soil monitoring, ultimately obtaining soils that can provide as many ecosystem services as possible (Janzen et al., 2021; Panagos et al., 2022).

Therefore, in this context, there is growing emphasis on the application of sustainable soil conservation measures to maintain or improve soil quality and productivity and to contribute to the long-term sustainability of agroecosystems and climate change mitigation (de Torres et al., 2021). Two such measures are the elimination of tillage practices and the promotion of crop diversification, i.e., the planting of intercropping (Yang et al., 2019; Lal, 2020), as these management changes provide great environmental and agronomic benefits, such as reduced soil erosion, increased productivity of both the main crop and intercrop, improved biodiversity, soil fertility and structural stability, and increased soil capacity to store carbon (Rodríguez-Lizana et al., 2020; Tripathi and Gaur, 2021), in addition to be able to offer a multitude of ecosystem services (Lee et al., 2019).

The olive tree (*Olea europaea*) is one of Spain's most widespread perennial crops, with more than 2.7 Mha (MAPA, 2019). In the Mediterranean basin, this crop has dramatically increased its area in recent

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* Corresponding author.
E-mail address: beatriz.lozano@uco.es (B. Lozano-García).

https://doi.org/10.1016/j.agee.2023.108826
Received 19 June 2023; Received in revised form 16 November 2023; Accepted 19 November 2023

years, accounting for 95% of the global site devoted to olive groves (FAO, 2019), which gives it great importance both ecologically and socioeconomically (Ortega et al., 2020).

The Mediterranean climate is characterised by hot and dry summers and winters with intense and short rains (Morugán-Coronado et al., 2020; González-Rosado et al., 2022), which causes scarcity of water and therefore low vegetation cover, causing intense soil erosion (Espejo-Pérez et al., 2013). In addition, both monocrop and conventional management in most olive groves (heavily ploughed, usually twice a year and 20–25 cm in depth, together with fertiliser and herbicide application) (Sastre et al., 2017) can intensify these problems by promoting the removal of vegetation cover in olive grove alleys, soil compaction, and favouring the depletion of soil organic matter and soil carbon (Linares et al., 2014; Aguilera-Huertas et al., 2022).

Specifically, in rainfed olive orchards, the intercropping implementation can contribute to improving the soil quality, reducing soil erosion, and promoting the pollinator's presence (Durán et al., 2020), coming to intervene significantly in overcoming the challenges of developing agricultural system production, with an increase in the harvest and yield of both the main crop and intercrop (Raza et al., 2019; Cuartero et al., 2022).

However, the selection of the type of crop to use as an intercrop is essential to avoid water competition with the main crop, improve soil structure and fertility, enhance carbon storage, and increase farmer incomes though the secondary crop (Beillouin et al., 2021; Chen et al., 2023). *Crocus sativus, Vicia sativa/Avena sativa* in annual rotation and *Lavandula x intermedia* as an intercrop were chosen in this study because of the multiple benefits they generate. From an economic point of view, saffron cultivation can be a source of income for the farmer during its life cycle, given the yield of its flowers and corms, additionally generating more employment for its maintenance (Khorramdel et al., 2022). From an environmental point of view, rotational sowing of oats and vetch and lavender can improve both plant and soil properties. This type of legume (oats and vetch) can fix not only CO_2 but also N_2 in the soil, which is incorporated through root exudates and plant residues, thereby improving the nitrogen content (Özbolat et al., 2023). In addition, lavandin causes an increase in pollinators, increases biodiversity, and can produce a greater amount of essential oil given the effect of these pollinators, which can be marketed, also increasing the farmer's income (Radev, 2023). In this way, a more sustainable olive grove can be achieved by maintaining agricultural landscapes and the quality of their soils.

In addition, the choice of intercropping and the study area was part of the experimental design of the H2020 DIVERFARMING project (Crop diversification and low-input farming across Europe: from practitioners' engagement and ecosystems services to increasing revenues and chain organization). The choice of the study area of rainfed Mediterranean olive groves was motivated by the need to evaluate how the implementation of intercropping affects and improves the soils and the main crop in rainfed olive groves located in the Mediterranean area of southern Spain.

Rodríguez-Lizana et al. (2020) highlighted the potential of intercropping to provide the soil with a relevant benefit, producing specific effects, such as increased soil fertility, water availability, reduced greenhouse gas emissions, erosion prevention, and increased soil diversity and soil organic carbon (SOC) stocks (Kavvadias and Koubouris, 2019; Wang et al., 2020). In this context, it is important to examine the role of soil C management since an increase in SOC can actively affect the generation and fixation of greenhouse gases, altering soil biogeochemical processes and affecting soil properties (Caviglia et al., 2016).

Thus, the 4‰ storage initiative "4 per thousand Soils for Food Security and Climate" takes on special relevance. This voluntary action plan aims to improve the global SOC content at 40 cm depth with an incremental rate of 4‰ as it depends on the total stock and the depth studied (Minasny et al., 2017; Rumpel et al., 2020). Therefore, being aware that, through this type of management (intercropping), an increase in soil carbon is favoured, this storage initiative can be reached. Thus, through this initiative, an innovative model is promoted to help mitigate climate change by increasing SOC with good agricultural soil management practices and contributing to climate change adaptation and food security (Soussana et al., 2019). In this way, recarbonisation of these soils can be achieved, turning them into large C sinks. Moreover, SOC is a good indicator of soil quality, which is defined as the measurement of the combined effects on the physicochemical properties of the soil over a period of time and offering comparability between soils due to the change in management so that it can reflect the short-, medium-, and long-term changes in their properties (Fernández-Romero et al., 2016a). Therefore, due to the increase in SOC due to the sustainable management carried out on the soil, and depending on its degree of distribution in depth and its degree of stabilisation in the different soil aggregate fractions, an improvement in its quality can be produced (Mazzoncini et al., 2016).

Therefore, this research is novel because it evaluates the short-term effects of intercropping on soil physicochemical properties, especially on C storage in Mediterranean rainfed olive grove soils that are heavily degraded and under semi-arid climatic conditions. From this study, the response of this type of soil can be observed mainly from the point of view of recarbonisation in the face of the implementation of sustainable management and the abandonment of conventional tillage, with the aim of highlighting their role as carbon sinks. The results obtained in this study can serve as a reference from the governmental sphere to begin to reverse the current situation, promoting the establishment of new strategies for sustainable soil management and its long-term maintenance based on the trends obtained in the short term to achieve a final improvement in the health and quality of soils and enhance their role in the contribution of olive grove agriculture to climate change mitigation. As a starting hypothesis, it was proposed that the implantation of intercropping crops, such as saffron, oats, and vetch in rotation, and lavender in olive grove soils, associated with a strategy of minimum tillage, would lead to an improvement in soil chemical properties (carbon and nitrogen storage), in the SR soil quality index, and in the achievement of the objective set by the 4‰ initiative, compared to olive monocultures with bare soil. Therefore, the objective of this study was to quantify how intercropping in olive orchard soils can affect carbon and nitrogen in the soil in the short term with respect to olive with conventional tillage. The effects of three intercrops (*Crocus sativus, Vicia sativa* and *Avena sativa* in rotation, and *Lavandula x intermedia*) on concentrations and stocks of SOC and total N (TN), the degree of soil carbon and nitrogen stratification, and the achievement of the 4‰ strategy were evaluated over three years.

2. Materials and methods

2.1. Description of the study site

This study was conducted over 3 years (between seasons 2018/2019 and 2020/2021). It was carried out on an experimental centenary olive farm in the south of Spain (37°50'20''N - 3°52'32''W) (Fig. 1). The farm has an area of 10 ha, and the experimental plot (200 olive trees, *Olea europea* picual variety) corresponds to case study number 4 of the H2020 project DIVERFARMING (Crop diversification and low-input farming across Europe: from practitioners' engagement and ecosystems services to increasing revenues and chain organization). This project has been relevant at the European level because it aims, in part, to explore how diversified cropping systems can, with low input practices, increase soil fertility, water availability, and above- and belowground diversity, reduce greenhouse gas emissions, favour carbon storage, and prevent erosion in different crops throughout Europe (Diverfarming.eu).

The landscape of this area is formed by small hills with an average slope <6% whose parent material is Miocene loams and marl limestones. It presents a denudation morphogenesis (Fernández-Romero et al., 2016), where a conventional rainfed permanent olive monocrop system

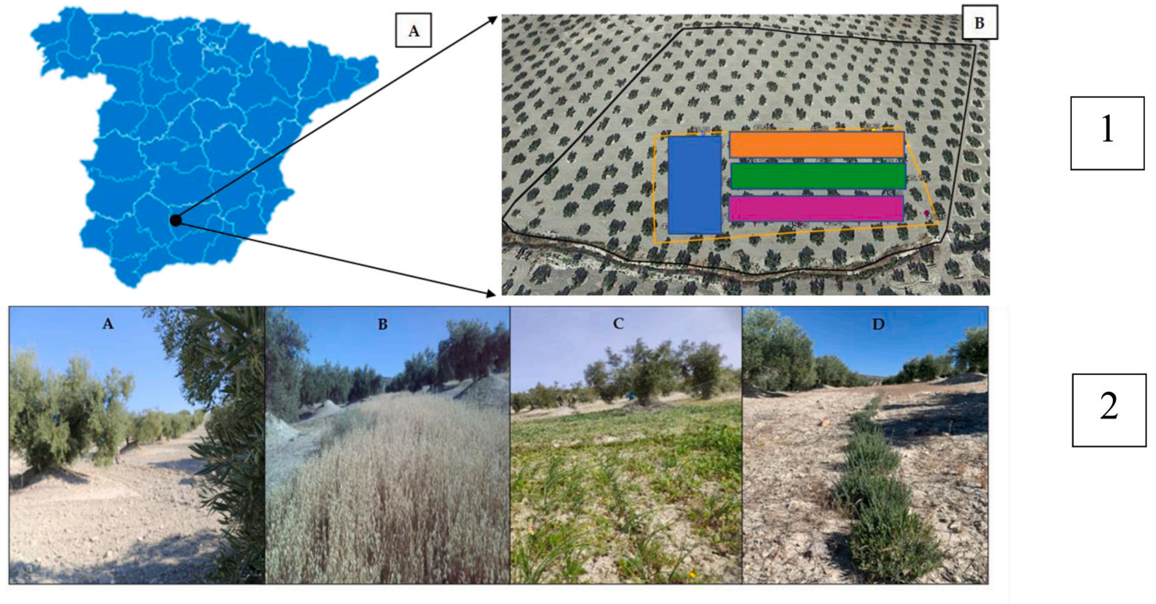

Fig. 1. Location map of the study area (Garcíez-Torredelcampo (Jaén-Spain)) (1): (A) and aerial view of experimental treatments (B). Conventional tillage (blue), saffron cultivation (orange), oats cultivation (green) and lavender cultivation (purple) and (2) management systems implemented in the study area: (A) Olive monocrop under conventional tillage, and (B) Olive intercropped with *Vicia sativa* and *Avena sativa* in rotation, (C) Olive intercropped with *Crocus sativus* and (D) Olive intercropped with *Lavandula x Intermedia*.

(12 m × 12 m pattern) has been established. The climate is typically Mediterranean, with significant seasonal contrasts and the following climatic characteristics (AEMET, 2023): mean annual precipitation, 493.2 mm; average annual temperature, 17.1°C (maximum, 46.2°C (August); minimum, −7.8°C (January)); relative humidity, 59%; insolation, 237 h month^{-1}; wind speed, 6 km h^{-1}; humidity, 0.50; rainfall erosivity, very variable (2.1–75); and 5 months with risk of frost. The soils of this study were classified as Calcareous Cambisols (FAO-ISRI-C-ISSS, 2015) and characterised by a low gravel content (12.6–15.7%), clayey texture (69–73.7%), basic pH (7.63–8.19), high erosion rates, and low soil organic matter levels (0.88–1.29%) (González-Rosado et al., 2021; Aguilera-Huertas et al., 2022).

The carbon in these soils is composed of SOC and soil inorganic carbon (SIC). In semi-arid areas, such as those under study, SIC storage can be affected by climatic factors (Raheb et al., 2017), land use and soil management (Kim et al., 2020), soil acidification by fertilisers (Guo et al., 2010), and soil depth (Harrison et al., 2011), among others. Considering these factors, the evaluation of the SIC has not been considered since rainfall in this area is very low, and the effect of management is short term (3 years), requiring a longer period to observe the changes produced in the SIC.

2.2. *Experimental details, soil sampling, and laboratory analysis*

The experimental farm was a centenary olive grove cultivated under conventional tillage since the 1950 s. However, there is no information on the plant community due to fertilisation and intensive tillage carried out in the study area. Farmers use this type of management to eliminate the plant community and avoid competition for water with the main crop (Aguilera-Huertas et al., 2021). This management was characterised by tilling the soil (to 25 cm depth) with a cultivator in spring, followed by a tine harrow and disc in summer. In addition, fertiliser (100 kg ha^{-1} of urea, 46% N-rich) was applied in February of alternate years after harvesting olives and herbicides (1 L of 36% glyphosate ha^{-1}) in autumn to control weeds. In 2018, four experimental plots formed by three rows of olive trees and an area of 2000 m^2 were considered. The first was a control plot (CP) managed under conventional tillage. The other three experimental plots were established by introducing three intercrops into the olive alleys: *Crocus sativus* (D-S), an annual rotation of *Vicia sativa* and *Avena sativa* (D-O), and *Lavandula x intermedia* (D-L). These intercropping plots were established without irrigation, and no herbicides or fertilisers were used (Fig. 1). In these three plots, minimum tillage was carried out for the crop, which was performed with a flexible tine coulter (10 cm) for the planting bed of each cover crop (in D-O, tillage was performed annually) and mechanical weeding with a hand-operated star cone weeder.

In addition, olive pruning (6 Mg ha^{-1}) was carried out once every two years, and pruning residues were chopped in the olive grove alleys to be reused as mulch in the 4 study plots, as this type of management practice is assumed by farmers in the area.

The diversified crops tested were sown as follows: first, D-O as an annual crop with a seed dose of 120 and 140 kg ha^{-1}; secondly, D-S, which was sown only once with a seed dose of 2000 kg ha^{-1}; and thirdly, D-L with a plant rate of 12,000 plants ha^{-1}, which required replanting in the second year after the failure of the first planting because of adverse weather conditions. These intercrops were established in the middle of the olive grove alleys, in the cases of oat, vetch, and saffron, at a distance of 4.5 m from the olive tree trunk. However, in the case of lavandin, the distance to the trunk was higher (5.5 m) because lavandin is a perennial intercrop, and the passage of machinery during olive harvesting had to be allowed. In addition, as shown in Fig. 6, these intercrops coexisted with spontaneous cover that proliferated due to the elimination of herbicides and fertilisers, creating mixed vegetation cover.

Soil samples were collected in the month of September, both in 2018 and 2021, in all research plots simultaneously. A randomised block design considering 3 subplots within each main plot was established to compare intercropping (D-S, D-O, and D-L) with monocropping (CP) management. Therefore, under each main plot, nine sampling points were randomly selected (3 sampling points × 3 subplots), and soil samples were collected in the olive alleys at 0–10 and 10–30 cm depth from a manually dug pit. Therefore, 18 samples were obtained for each main plot (9 samples of 0–10 cm + 9 samples of 10–30 cm), obtaining a total of 72 samples per year (18 samples per plot × 4 main plots) that will be the subject of the present investigation. Once the samples were collected and coded in the field, they were transported to the laboratory, where they were left to dry at room temperature to remove moisture from the sample. When the samples were dry, they were sieved at 2 mm to perform the different physicochemical analyses.

The laboratory analyses, analytical methods, and other calculated parameters used to determine the different soil properties followed the "Handbook of Plant and Soil Analysis for Agricultural Systems" (Álvaro-Fuentes et al., 2019). From an analytical point of view, the methods used in this work were as follows:

Bulk density (Mg m^{-3}) was measured using the cylinder method (Blake and Hartge, 1986), with a cylinder of 10 cm depth, 3 cm diameter, and a total volume of 70.65 cm^3. In the 10–30 cm layer, the cylinder sample was taken from hand-dug pits. The particle size distribution (soil texture) was analysed using the Bouyoucos hydrometer method (Nelson and Sommers, 1982). Soil samples were ground with a mortar to determine SOC and TN. Both determinations were performed using a CN elemental analyser (CN 802, VELP Scientifica, Italy) (Díaz Pereira et al., 2019). For the determination of TN, the dry combustion method was used. To determine the SOC, the ground samples were previously acid attacked with 2 N HCl to eliminate inorganic carbon, dried in an oven at 105°C to bring them to absolute dryness, and analysed using the dry combustion method. The determination of the calculated parameters was performed as follows:

SOC stock (SOC-S) in Mg ha^{-1} was calculated as the product of SOC concentration, bulk density, depth, and gravels and was obtained by Eq. (1) (Chiti et al., 2012; Li et al., 2019).

$$\text{SOC-S} = \text{SOC concentration} \times \text{BD} \times \text{d} \times (1 - \delta 2\ \text{mm}) \times 10^{-1} \quad (1)$$

.

where SOC is the organic carbon content in g C kg^{-1}, d is the horizon thickness (cm), BD is the bulk density in Mg m^{-3}, and δ2 mm is the ratio of gravel larger than 2 mm in size in the soil. The same equation obtained the total N stock (TN-S) using the N concentration in g kg^{-1} instead of the SOC concentration.

The evaluation of the 4‰ initiative was carried out by calculating the C storage rate (CSR) in Mg C ha^{-1} $year^{-1}$ (Francaviglia et al., 2019), thus observing the extent to which the study soils have achieved the storage objectives set by this initiative, among which are improving land and soil quality and combating climate change and its impacts, providing C storage, greenhouse gases regulation (Lal, 2016), and soil functioning as a C buffer (European Commission, 2006). This rate was obtained from Eq. (2) for the soil depth indicated in the experiment.

$$\text{CSR} = (\text{SOCf} - \text{SOCi}) \,/\, \text{years} \quad (2)$$

.

and CSR in Mg C ha^{-1} $year^{-1}$ × 1000 was calculated with the following equation:

$$\text{CSR (per 1000)} = [(\text{SOCf–SOCi}) \,/\, \text{years})] \,/\, \text{SOCi} \times 1000 \quad (3)$$

where SOCf and SOCi are the final and initial SOC-S (Mg C ha^{-1}), and "years" is the duration of the experiment expressed in years.

The stratification ratio (SR) is defined as a soil property at the soil surface divided by the same property at a shallower depth (Franzluebbers et al., 2002). In this study, we defined a single SR for SOC (Eq. 4) and another SR for TN (Eq. 5) using the following formula:

$$\text{SR-SOC}=\text{SOCS1/SOCS2} \quad (4)$$

$$\text{SR-TN} = \text{TNS1/TNS2} \quad (5)$$

where S1 and S2 are the different depths taken for the calculation of SR, 0–10 cm is S1, and 10–30 cm is S2.

Olive grove harvesting data were determined as the total weight of olives harvested (Kg) from the whole plot and extrapolated to hectares (kg ha^{-1}).

2.3. Statistical analysis

As for the statistical analysis, the effect of the treatment that included both minimum tillage and the implantation of different intercrops + spontaneous covers and the effect of the olive monoculture treatment with conventional management on the yield of the main crop (olive harvest), SOC, TN, SOC-S, TN-S, and SR of both carbon and nitrogen was evaluated. For this purpose, prior to data analysis, the data were subjected to normality assessment using the Kolmogorov–Smirnov test. As the data did not meet the normality test, nonparametric tests (Kruskal–Wallis ANOVA) were used to test this normality. The interaction between the two time periods and the different treatments was determined using a one-way analysis of variance. Tukey's post hoc analysis was then applied to detect significant differences at $p < 0.05$. All calculations were performed with Sigma Plot v14.0 (San Jose, CA, USA). Graphs were produced using SPSS Statistics 21.

3. Results and discussion

3.1. Effect of intercropping on olive orchard productivity

The studied soils were poor and heavily degraded due to intensive and continued conventional management together with climate action in this area and low external organic inputs (Aguilera-Huertas et al., 2021). This situation, extended in the Andalusia region (López-Pintor et al., 2018), together with the progressive reduction of public subsidies of the European Union, is making rainfed Mediterranean olive groves face an economically unsustainable situation.

This has led farmers to look for alternatives (Orlandi et al., 2016). One option is intercropping to increase soil properties, such as biodiversity and soil quality, in addition to achieving extra income derived from intercrop yields. However, in our case study, extra income could not be obtained from intercropping yields, as these did not reach the expected success in terms of harvest, being necessary for the replanting of lavender and with very scarce growth of saffron and oats and vetch in rotation due to the semi-arid climatic conditions of the area and the presence of rabbits during the period studied, which used these crops as food.

However, the change in management towards minimum tillage and the absence of herbicides and fertilisers in the intercropping plots allowed the growth of a spontaneous plant cover that accompanied the intercropping and grew to a greater extent in plot D-S, with percentages of cover reaching over 80% during the period studied, followed by D-O (reaching up to 50%) and D-L (reaching up to 20%). This finally resulted in mixed vegetation cover (intercropping + spontaneous cover), which significantly influenced the evolution of the different physicochemical properties of the soil (Fig. 6).

Moreover, related to the main crop yield, as shown in Fig. 2, intercropping did not have a positive effect during the three years studied in comparison with CP, obtaining values in the three intercropped plots that did not exceed 4000 kg ha^{-1}, while the CP plot yielded over 5000 kg ha^{-1}. These results coincide with those obtained by Martínez-Mena et al. (2021) and Almagro et al. (2023).

The main causes of this decrease in terms of harvest, production, and income for the farmer are the changes produced both in management, with the elimination of tillage, and in the elimination of fertilisation in the plots where intercropping was implemented, requiring a longer period of time for the soil to assimilate these changes and produce an improvement in production. This statement is supported by Daryanto et al. (2018), who showed that this type of crop intercropped with perennial crops needed a longer period to improve the production and fruit development of the main crop so in a longer period an increase in the yield of the main crop could be observed.

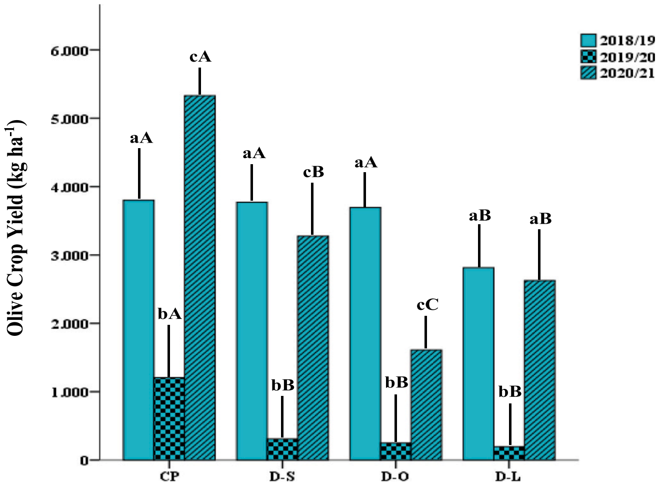

Fig. 2. Mean olive crop yield (average ± SD) under conventional tillage (CP); saffron (D-S); oats (D-O) and lavender (D-L) diversifications over time (2018/19 (blue bars), 2019/20 (blue bars with plot one) and 2020/2021 (blue bars with plot two)). Different lowercase letters above error bars indicate significant differences for the same management among the three time periods at $p < 0.05$. Different capital letters above the error bars indicate significant differences between the different managements over the same time period at $p < 0.05$. ($n = 3$).

3.2. *Effect of intercropping on soil C and N in the short term (2018–2021)*

Traditionally, woody crop farmers in the Mediterranean area have considered the minimum tillage application and the implementation of intercropping, such as green manure, an unsustainable practice due to the competition for water and nutrients between intercropping and the main crop and the high risk of soil compaction, affecting soil carbon and nitrogen storage (Morugán-Coronado et al., 2020, 2022).

Our results showed significant SOC increases ($p < 0.05$) in the three intercropping plots of 41.1, 28.5, and 30.5% for D-S, D-O, and D-L, respectively, in the surface layer (0–10 cm) in the short term (2018–2021). However, the SOC-S showed no significant differences. In the deepest soil layer (10–30 cm), the results showed a generalised increase in C in the three diversified plots. This increase in SOC and SOC-S concentrations was only significant in plot D-L, with SOC values increasing from 2.3 (2018) to 4.3 g kg^{-1} (2021) and SOC-S increasing from 6.1 (2018) to 9.4 Mg ha^{-1} (2021) (Fig. 3). In addition, as shown in Table 1, in the 3 years of experimentation (2018–2021), in the first 30 cm of soil, an average SOC-S increase of 4.08 Mg ha^{-1} was found. These results agree with those of Jaziri et al. (2022). In contrast, Ben Moussa-Machraoui et al. (2010) did not observe a significant increase in SOC in their study after the application of no-tillage with intercrop diversification, pointing to the short time of use of minimum tillage or changes in soil structure when subjected to conventional tillage for a long time. Chen et al. (2020) found that more sustainable management, such as crop rotation, which were also used in this study as one of the types of intercropping, was able to significantly increase cumulative aboveground biomass production by 23% compared to monoculture, although, according to their results, it did not cause effects on topsoil carbon and nitrogen stocks compared to monoculture, even when examined in terms of soil equivalent mass.

However, the main cause of this generalised increase in C in the intercropped plots in our case study was the maintenance of alley cropping because of intercropping + spontaneous cover and plant stubble contributed by the cover crop. This mixed vegetative cover that

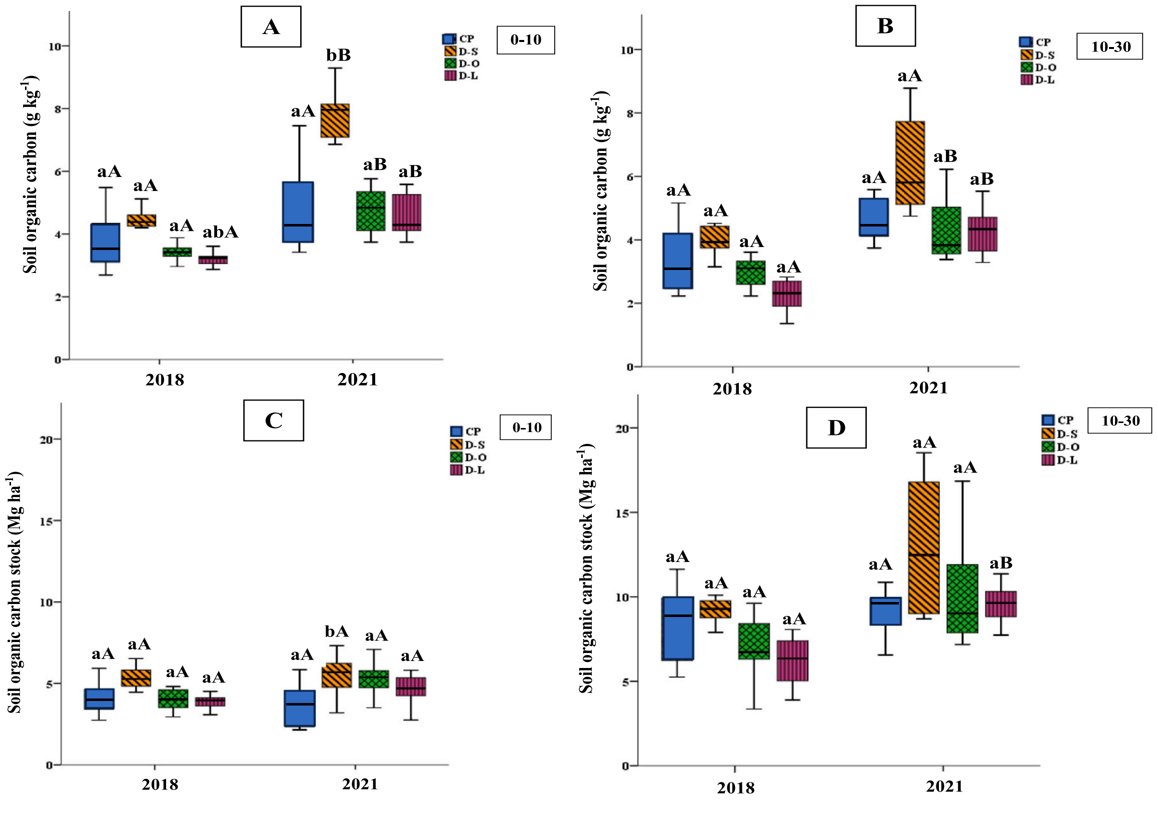

Fig. 3. SOC (g kg^{-1}) (A and B) and SOC-S (Mg ha^{-1}) (C and D) (average ± SD) under different treatments at 0–10 cm and 10–30 cm depth over time (2018–2021). Different lowercase letters above the error bars for the same soil layer indicate significant differences between the different managements over the same time period at $p < 0.05$. Different capital letters above the error bars for the same soil layer indicate significant differences for the same management between the two time periods at $p < 0.05$. ($n = 3 \times 3$).

Table 1
SOC-S variation according to management (conventional tillage (CP); saffron (D-S); oats (D-O) and lavender (D-L) diversifications plus spontaneous cover) and CO_2-eq relationships in Mediterranean rainfed olive grove in the study area. Data are means ± SD ($n = 9$).

Year	Management	Soil depth	T-SOC-S (Mg ha^{-1})	ΔT-SOC-S (Mg ha^{-1}) (2018/2021)	ΔCO_2-eq (Mg ha^{-1}) (2018/2021)	CO_2-eq y^{-1} (Mg ha^{-1})
2018	CP	0–10 cm	11.87 ±1.05a			
		10–30 cm				
2021	CP	0–10 cm	12.69 ±1.72a	0.82 ±1.38a	3.01a	1.00a
		10–30 cm				
	D-S	0–10 cm	18.38 ±2.66b	6.51 ±1.86b	23.89b	7.96b
		10–30 cm				
	D-O	0–10 cm	15.53 ±2.16c	3.66 ±1.61c	13.43c	4.48c
		10–30 cm				
	D-L	0–10 cm	13.93 ±1.12c	2.06 ±1.09c	7.56c	2.52c
		10–30 cm				
Average (D-S, D-O, D-L) 2021			15.95 ±1.98	4.08 ±1.63	14.96	4.99

SD: Standard deviation; T-SOC-S: Total soil organic C stock (0–10 cm + 10–30 cm); ΔT-SOC-S: Increasing in the T-SOC-S period 2018–2021; ΔCO2-eq: CO2-eq is a term for describing different GHGs in a standard unit. For any GHG quantity and type of GHGs, CO2-eq signifies the amount of CO2 that would have the equivalent global warming impact. The atomic weight of a carbon atom is 12, and the atomic weight of oxygen is 16, so the total atomic weight of CO2 is 44 (12 + (16 × 2) = 44) (44/12 = 3.67) (IPCC, 2014 and FAO, 2018). Numbers followed by different lowercase letters within the same column present significant differences (p < 0.05) between the different soil managements during the same time period.

was created provided a great benefit in olive grove soil by producing an increase in diverse root biomass, which contains a greater supply of chemically complex rhizomes that promote the establishment and increase of soil C (Alletto et al., 2022). The root activity from this cover crop in the soil was enhanced; thus, a higher extracellular enzyme activity in enzymes, such as dehydrogenase, β−1,4-glucosidase, leucine aminopeptidase, β−1,4-N-acetylglucosaminidase, and phosphatase, and a change in the soil bacterial community and its structure could be verified in a study conducted in the same experimental farm (Aguilera-Huertas et al., 2023), leading to an increase in soil C and an improvement in soil quality (Curtright and Tiemann, 2021).

Regarding TN, the results showed no significant variations between intercropped plots in either soil layer (0–10 cm and 10–30 cm) over time. However, an increase in TN concentration of 34.1% in the surface layer (0–10 cm) and 41.4% in the deep layer (10–30 cm) was observed in CP after 3 years. Similarly, TN-S in the CP plot showed a significant increase of 29.7% in depth (10–30 cm) (Fig. 4). In contrast, in the diversified plots, a significant ($p < 0.05$) decrease in TN-S at the surface (0–10 cm) was observed in D-S and D-O (38.3% and 27.6%, respectively), although no changes were observed in the deepest soil layer (10–30 cm) in any of the intercropped plots.

These results could be due to several factors. First, they could be due to the fact that although diversified plots should begin to have a greater potential to promote an increase in nitrogen and improve soil fertility. The long history of unsustainable management of these soils, high erosion rates, TN alteration influenced by urea leaching, and lack of vegetative cover have made them extremely sensitive to management disturbances and degradation (González-Rosado et al., 2020a).

Second, another determining factor was the fertilisation of the plots. In the intercropped plots, when fertilisation was eliminated, there was a stagnation in the TN concentration in the CP plot; when fertilisation continued to be applied (100 kg ha^{-1} of urea, 46% rich in N), there was an increase in TN concentration in these plots. This statement has been corroborated by Mazzoncini et al. (2011), who obtained similar results.

However, although spontaneous cover developed accompanying the main intercrops, creating a mixed vegetation cover, the climatic conditions (high temperatures and low rainfall) would not have contributed to a high biomass or abundance of N-fixing bacteria (Francaviglia et al., 2018). As corroborated in another study conducted in the same experimental plots (Aguilera-Huertas et al., 2023), atmospheric nitrogen fixation rates could have been low due to the presence of bacterial genera, such as *Ramlibacter* and *Haliangium*, involved in denitrification processes (Zhang et al., 2021). In addition, a higher abundance of bacteria belonging to the Nitrosomonadaceae family was also observed, which are usually present in conventional tillage before starting reduced tillage, causing a decrease in soil nitrogen content due to their involvement in nitrification processes (Özbolat et al., 2023).

Therefore, based on the above, although the success in the development of intercropping was not ideal, a mixed vegetation cover derived from the combination of intercropping + spontaneous cover + minimum tillage was created, which has contributed to the results obtained and is part of this sustainable management. It is expected that in the long term, the effect of this mixed cover crop will not only improve the nutrients and physical–chemical properties of the soil but will also maintain the yield of the main crop at the same level as in the traditional system with intensive tillage (Martínez-Mena et al., 2021).

3.3. Effects of sustainable soil management on SR-SOC and SR-TN

The SR of SOC and TN are among the most researched soil quality indicators (Franzluebbers, 2002).

As shown in Fig. 5, the SR-SOC and SR-TN values showed no significant differences between the intercropped plots and CP during the study period. Based on the SR-SOC values, soil quality was poor in all managements since SR-SOC values were <2 in absolute values (McDaniel et al., 2022; Zhang et al., 2022). Although there were no significant differences, some trends were observed regarding the SR values obtained. The diversified plots followed a disparate trend. D-O and D-L showed a decreasing trend for both the SR of SOC and the SR of TN, and D-S showed a decreasing trend for the SR of TN but increased for the SR of SOC (Fig. 5).

These results are in contrast with other studies, such as those of Sastre et al. (2018), who observed an improvement in SR-SOC and SR-TN on the surface with vegetative cover in olive groves during three years of study due to the high production of residues of this type of management, which maintained greater amounts of aerial biomass. The fact that our results did not show significant variations could be due to the fact that although the success in intercropping development was low, there was a low production and contribution of plant residues. Mixed vegetation cover was created as a result of the combination of intercropping + spontaneous cover. However, the previous degree of degradation of these soils indicated that this mixed vegetation cover could contribute low amounts of aerial biomass. Although there was an increase in enzymatic activity and in the soil bacterial community, affecting the improvements in carbon and nitrogen, the short term of the study had a great influence on these stratification indexes, requiring a longer period to observe well-established trends.

Moreover, this downward trend and the absence of significant variations are also closely related to soil texture, possibly due to the high proportions of clay in these soils (between 69% and 73.3%) (Aguilera-Huertas et al., 2022), which caused deep leaching of soluble organic compounds, reducing carbon and nitrogen (Yu et al., 2020). Therefore, this can also explain the lack of significant changes in SOC concentrations at a depth of 10–30 cm, and these results agree with those previously mentioned.

Therefore, it would be convenient to carry out future research on

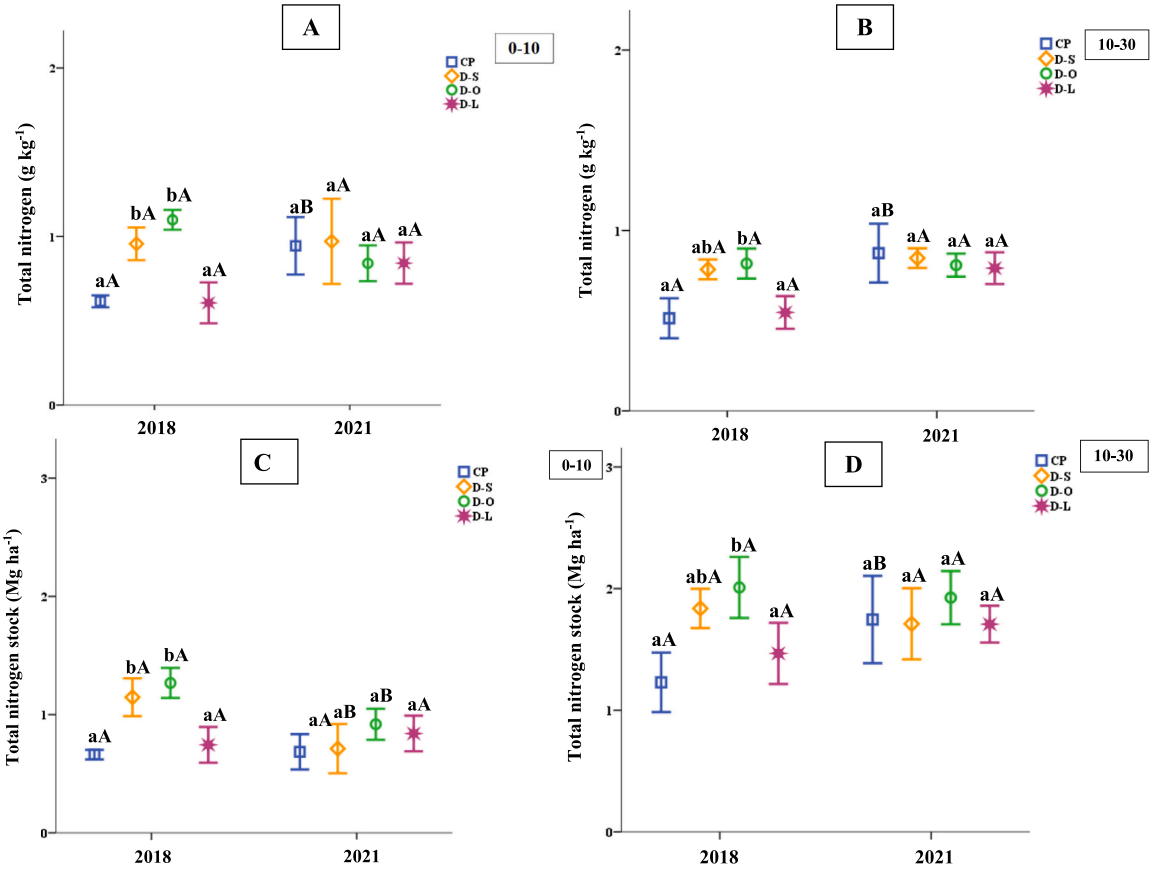

Fig. 4. TN (g kg^{-1}) (A and B) and TN-S (Mg ha^{-1}) (C and D) (average ± SD) under different treatments at 0–10 cm and 10–30 cm depth over time (2018–2021). Different lowercase letters above the error bars for the same soil layer indicate significant differences between the different managements over the same time period at $p < 0.05$. Different capital letters above the error bars for the same soil layer indicate significant differences for the same management between the two time periods at $p < 0.05$. ($n = 3 \times 3$).

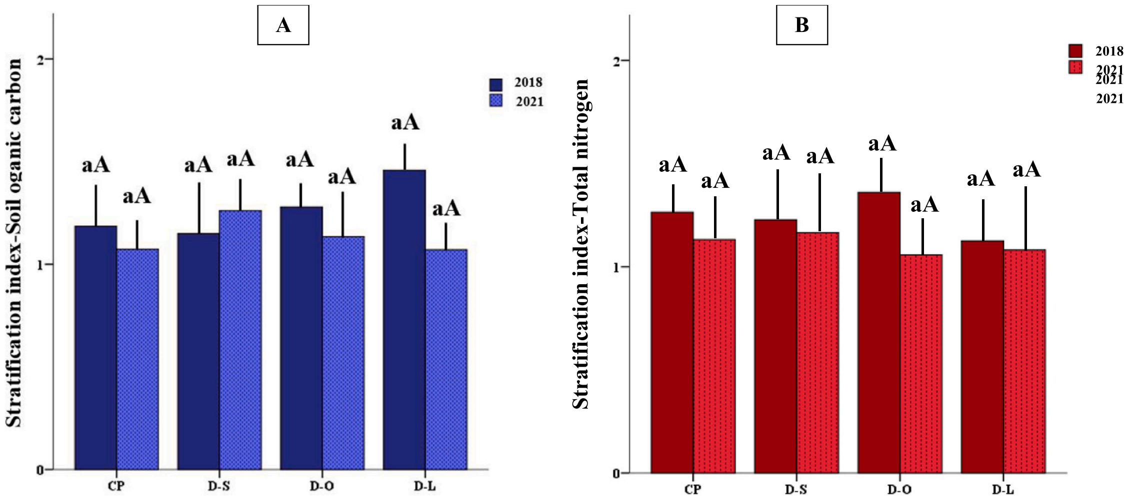

Fig. 5. SR-SOC (A) and SR-TN (B) (average ± SD) under conventional tillage (CP); saffron (D-S); oats (D-O) and lavender (D-L) diversifications over time. Different lowercase letters above the error bars indicate significant differences between the different managements over the same time period at $p < 0.05$. Different capital letters above the error bars indicate significant differences for the same management between the two time periods at $p < 0.05$. ($n = 3 \times 3$).

these soils, for example, an analysis of carbon and nitrogen at depth (from 30 cm) to effectively determine whether this change in management leads to an accumulation of carbon and nitrogen in the subsoil despite surface leaching, thus affecting the SR and producing increases in soil quality at depth. A long-term evaluation of these indices after 3 years and with the change in management, it has been possible to verify how the results obtained could be contradictory with respect to carbon and nitrogen concentrations, especially in semi-arid areas, such as our case study. This is mainly due to the climatic conditions of these areas, which limit the content of carbon and nutrients, such as nitrogen, causing alterations in these values between the surface layer of the soil and the subsoil (Francaviglia et al., 2019; Aguilera-Huertas et al., 2021;

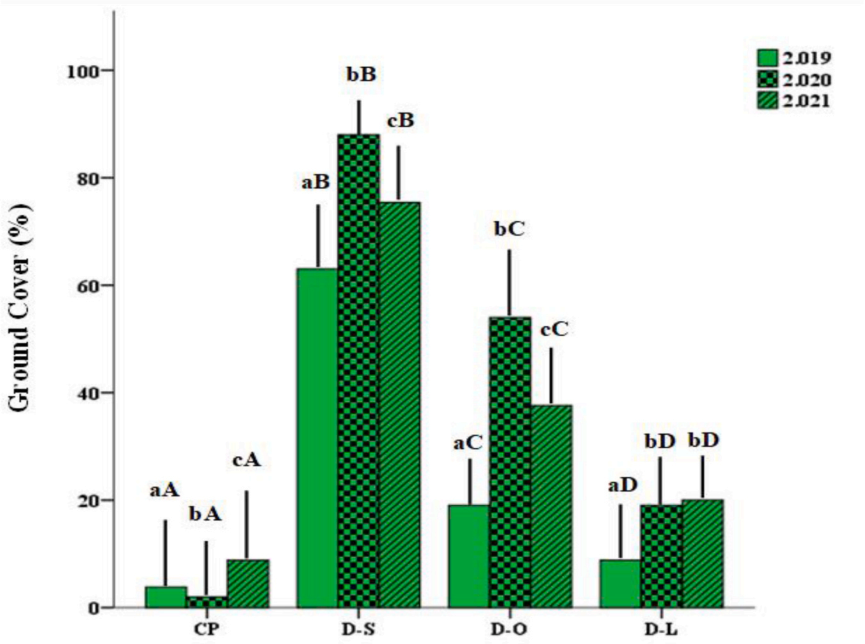

Fig. 6. Percentage of vegetation cover (average ± SD) under conventional tillage (CP); saffron (D-S); oats (D-O) and lavender (D-L) diversifications over time. Different lowercase letters above error bars indicate significant differences for the same management among the three time periods at $p < 0.05$. Different capital letters above the error bars indicate significant differences between the different managements over the same time period at $p < 0.05$.

Lessmann et al., 2022). Thus, the beneficial effect of this management (intercropping + spontaneous cover + minimum tillage) on soil quality can be observed in the SR.

3.4. 4‰ initiative: intercropping contribution to soil recarbonisation

Agricultural soils can contribute to climate change mitigation through carbon storage. However, despite carbon storage being one of the most important sustainability factors in agroecosystems, the pathways of SOC storage and stabilisation, especially in intercropping systems, are poorly understood (Angst et al., 2018; Dijkstra et al., 2021).

In our case study, implementing vegetation cover (intercropping + spontaneous cover) for three years contributed to achieving the target set by the 4‰ initiative. The three diversified plots exponentially increased their storage rates concerning CP (Fig. 7). D-O increased its storage the most, with a gain of 140.7 Mg C ha^{-1} yr^{-1} × 1000, followed by D-L with a growth of 130.1 Mg C ha^{-1} yr^{-1} × 1000 and D-S with a gain of 88.6 Mg C ha^{-1} yr^{-1} × 1000. This represents an increase with respect to the CP plot of 80, 87.4, and 86.4% for D-S, D-O, and D-L, respectively (Fig. 7).

These results are in line with those obtained by Francaviglia et al. (2019), who showed how the application of organic amendments

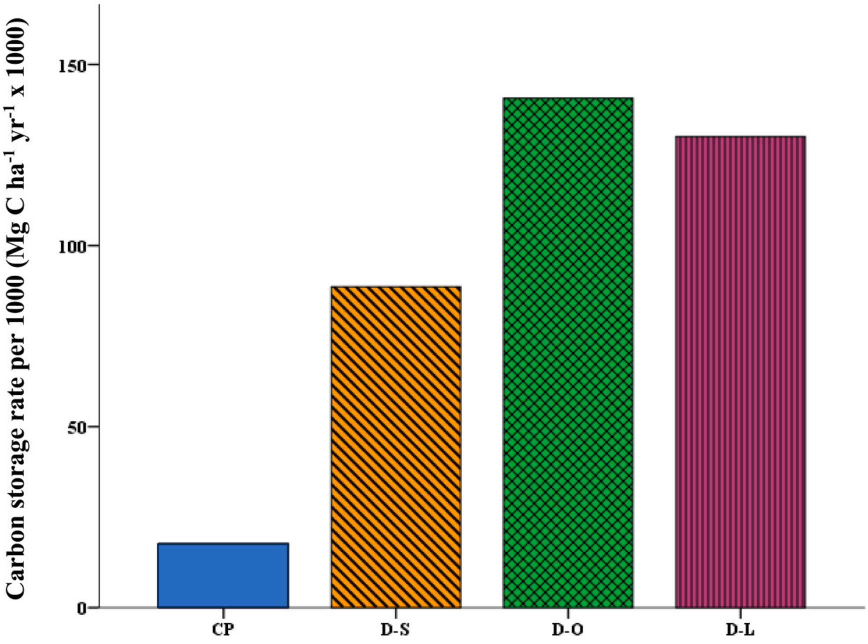

Fig. 7. Carbon storage rate per 1000 (CSR per 1000) (Mg C ha^{-1} yr^{-1} ×1000) under different treatments, based on the duration of the experiment in years (2018–2021) and corresponding to the first 30 cm of soil.

contributed to an increase in CSR × 1000 in Mediterranean woody crops of up to 80 Mg C ha^{-1} yr^{-1} × 1000, being up to 1.5 times higher (76% higher) compared to CP and even exceeding this target with ranges up to 540 Mg C ha^{-1} yr^{-1} × 1000.

However, one factor to consider is the effect of the duration of the experiment on CSR × 1000. In our case study, it is believed that this CSR per 1000 could decrease in the coming years due to the stabilisation and adaptation of the soil to the change in management and the implementation of intercropping, although it would continue to meet the objectives set by the initiative. This hypothesis is supported by Vicente-Vicente et al. (2016), who demonstrated that the C storage rate with sustainable management practices was higher in the first years than in the following years due to the effect of the management carried out.

Therefore, based on these results, management with minimum tillage + intercropping + spontaneous cover was determined to be optimal to increase the carbon storage of the Mediterranean soils studied dedicated to olive cultivation. Thus, properly managed soils can contribute greatly to such storage. It is considered that this type of research can serve as a basis for policymakers when developing European Union strategies, such as the 2030 and 2050 soil strategies (Panagos et al., 2022).

3.5. *Effect of management on the SOC-S and its influence on the CO_2-eq stored in the soil*

One of the objectives of the European Union Soil Strategy for 2030 (E.U., 2021) is to achieve a net greenhouse gas removal of 310 million Mg CO_2-eq per year for the agricultural sector, especially mineral soils. In this sense, the Mediterranean olive grove can play an essential role due to its capacity to store SOC (Galán-Martín et al., 2022).

Therefore, based on the results obtained in Table 1, this type of management causes an average increase in the CO_2-eq y^{-1} of 4.99 Mg ha^{-1}, varying between 7.96, 4.48, and 2.52 Mg ha^{-1} for D-S, D-O, and D-L, respectively (Table 1). These results showed that the change in management (minimum tillage versus conventional tillage), together with intercropping + spontaneous cover crops, contributed to adding plant debris to the soil and could increase the capacity of the soil to act as a CO_2 sink. Because conventional tillage accelerates decomposition rates of soil organic matter (Balesdent et al., 2000), minimum tillage reduces this decomposition. Moreover, these results are in line with those obtained by González-Sánchez et al. (2012) and Vicente-Vicente et al. (2016) for different meta-analyses, finding SOC-S increases of 1.6 Mg ha^{-1} y^{-1} (5.9 Mg ha^{-1} y^{-1} of CO_2-eq y^{-1}), on average, in olive groves with plant cover management (spontaneous natural vegetation) with minimum tillage compared to conventional tillage (tillage with herbicides).

These results indicate that land management change in the Mediterranean olive groves can constitute great potential to contribute to the European Union climate-neutrality goal committed in the Green Deal and the transition towards sustainable circular economies.

3.6. *Future research perspectives*

With respect to future projections and research priorities, it should be noted that the results obtained in this work are intended to serve as a basis for the evaluation of the real effect of the implementation of plant cover in the alleys of a traditional olive grove under rainfed conditions, although a longer period of time is necessary to achieve more significant improvements. In this way, it can be observed whether the variations produced in soil carbon and nitrogen are real and maintain the same trend over time once the covers are well established since the changes in the soil are long term. Sánchez-Navarro et al. (2023) also supported this assertion, highlighting the need for long-term monitoring programmes to check the real effect of the implementation of intercropping on the soil.

Therefore, it is intended that, taking this type of study as a scientific basis, sustainable practices such as these are encouraged to address the current climate problem to promote the role of soils in achieving climate neutrality.

4. Conclusions

This research focused on quantifying how, in the short term, the implementation in olive groves of alley cropping, such as *Crocus sativus, Vicia sativa* and *Avena sativa* in rotation, and *Lavandula x intermedia* together with spontaneous cover and managed under minimum tillage versus conventional tillage, can affect soil carbon and nitrogen storage, soil quality, and the viability of this type of treatment for the achievement by these soils of the 4‰ initiative.

During the period studied, alley cropping did not contribute to increasing the productivity of the main crop, as it did not increase the yield of the olive grove.

However, after 3 years with this cropping system strategy, carbon content generally increased, highlighting an increase in SOC in the soil surface in the intercropping versus CP. In contrast, TN only increased in CP due to the maintenance of fertilisation.

As for soil quality, the SR-SOC and SR-TN indices did not show an improvement in soil quality with intercropping; it is believed that it would be necessary to study the evolution of this index in soil depth over a longer period of time.

However, the positive effect of intercropping + spontaneous cover was observed in the three diversified plots for the fulfilment of the objectives set in the 4‰ carbon storage initiative.

In addition, this change in soil management highlighted the readiness of olive soils to become large carbon sinks due to the soil's capacity to store a large amount of CO_2-eq.

However, based on the results obtained in the short term, although they showed generally positive trends, mainly in terms of carbon storage and achievement of the 4‰ initiative, it is believed that more time is needed to demonstrate whether these practices have a potential positive impact for nitrogen storage and for improving soil quality in olive groves in the Mediterranean basin. Therefore, long-term monitoring programmes are needed to provide reliable data on these improvements, as soil changes are a long process.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Beatriz Lozano Garcia reports financial support, administrative support, equipment, drugs, or supplies, and travel were provided by The European Commission Horizon 2020 project Diverfarming. Jesus Aguilera Huertas reports financial support, administrative support, equipment, drugs, or supplies, and travel were provided by The European Commission Horizon 2020 project Diverfarming. Luis Parras Alcantara reports financial support, administrative support, equipment, drugs, or supplies, and travel were provided by The European Commission Horizon 2020 project Diverfarming. Manuel Gonzalez Rosado reports financial support, administrative support, equipment, drugs, or supplies, and travel were provided by The European Commission Horizon 2020 project Diverfarming.

Data availability

The authors do not have permission to share data.

Acknowledgements

This research was funded by The European Commission Horizon 2020 project Diverfarming (Crop diversification and low-input farming across Europe: from practitioners' engagement and eco-systems services to increased revenues and value chain organisation), grant agreement

728003.

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