Agriculture, Ecosystems and Environment 345 (2023) 108320

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

The combination of crop diversification and no tillage enhances key soil quality parameters related to soil functioning without compromising crop yields in a low-input rainfed almond orchard under semiarid Mediterranean conditions

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ARTICLE INFO

Keywords:
Inter-cropping
Low-input woody crops
Winter thyme
Soil management
Semiarid conditions
Soil ecosystem services
Climate change mitigation
Land equivalent ratio

ABSTRACT

Soils provide key ecosystem services and are crucial to combat climate change. Agriculture provides important ecosystem services but also causes negative environmental effects depending on agricultural management. In this regard, crop diversification is a promising sustainable land management strategy to combat soil erosion and degradation, mitigate climate change and ensure food security. Here, we assess the combined short-term effects of crop diversification and no tillage on several key soil physico-chemical parameters related to soil functioning as well as on crop yields in a rainfed almond (*Prunus dulcis* Mill.) orchard under semiarid Mediterranean conditions. Almond trees were inter-cropped with *Capparis spinosa* L. (caper) or *Thymus hyemalis* Lange (winter thyme) and compared with the almond monocrop system. The experimental design consisted of three plots in a randomized-block design, with three replicates for each crop management treatment (almond monocrop, almond inter-cropped with caper, and almond inter-cropped with winter thyme). Along with crop yields, the combined effects of crop diversification and no tillage on a range of soil quality and health indicators including soil physical (bulk density, aggregate stability, water retention and availability) and chemical (total and particulate organic carbon and nitrogen, ammonium and nitrate content, available macro- and micro-nutrients) properties were monitored in the topsoil and subsoil (at 0–10 and 10–30 cm depth, respectively) one and three years from establishment.

Results: from this study indicate that soil water retention capacity and water availability for plants were enhanced in both crop diversification systems after three years from their implementation at 0–30 cm depth. Likewise, improvements in particulate organic carbon and available N were observed in the subsoil of both crop diversifications. Crop diversification did not significantly affect the main crop yields, highlighting that crop diversification can be a promising sustainable management practice for improving soil health without compromising food security under semiarid Mediterranean conditions. Indeed, land equivalent ratios (LER) of almond trees inter-cropped with winter thyme were higher than those of their respective monocrop systems for two consecutive years, indicating that inter-cropping with aromatics can improve the productivity of rainfed woody monocrop systems under semiarid conditions. Our results emphasize the importance of selecting an appropriate secondary crop that ensures a permanent soil cover while contributes to enhance the agroecosystem productivity from the first year of establishment onwards to off-set plausible lower yields from the main crop. In this regard, preliminary assessments on soil condition and crop nutrient requirements are encouraged before designing and implementing a crop diversification in these low-input cropping systems.

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https://doi.org/10.1016/j.agee.2022.108320
Received 20 May 2022; Received in revised form 13 September 2022; Accepted 12 December 2022

Likewise, long-term studies are needed to provide evidence on the stability of the production of diversified crop management, particularly in these low-input cropping systems under harsh environmental conditions.

1. Introduction

Agriculture is a dominant form of land management globally and its expansion and intensification are considered major threats to biodiversity, natural habitat fragmentation, soil and fresh water preservation, and global warming through greenhouse gas emissions worldwide (Power, 2010; Montanarella et al., 2016; Paustian et al., 2016; Campbell et al., 2017; IPCC, 2019). However, if wise managed, agricultural soils can also provide a broad range of supporting (e.g., waste decomposition and nutrient cycling), regulation (e.g., climate change mitigation, water supply and erosion control) and provisioning (e.g., food, fibre and raw materials) ecosystem services, contributing to climate change mitigation and adaptation goals (IPCC, 2019; 2022). Whether any particular agroecosystem provides services or disservices depends on management, and management is influenced by the balance between short-term and long-term benefits (Power, 2010).

A new crop production paradigm based on the concepts of ecological intensification and sustainable soil management is needed to face both local and global challenges of providing food and material in a growing demand scenario while minimizing negative environmental impacts (Bommarco et al., 2013; Ramankutty et al., 2018; García-Palacios et al., 2019). In this regard, crop management based on diversification practices that enhance biodiversity in cropping systems can increase resource use efficiency and the stability of the agroecosystem production over time (Cardinale et al., 2012; Wagg et al., 2014; Renard and Tilman, 2019). In other words, diversified cropping systems are expected to promote ecosystem functions and services, thereby reducing dependency on agronomic inputs as well as on a single crop while maintaining high crop yields and contributing to climate change mitigation and adaptation (i.e., protecting bare soils against erosion and increasing the capture of atmospheric CO_2). However, we are still very far from a comprehensive knowledge of diversified crop management potential to cope with perturbations while maintaining yield stability of the main crop in the long-term (Newbold et al., 2015; Tamburino et al., 2020; Beillouin et al., 2021).

Although contradictory results have been previously reported in the literature in relation to crop diversification practices, spanning from positive to negative impacts on main crop yields, a recent meta-analysis (Tamburini et al., 2020) has demonstrated that increasing agroecosystem functional biodiversity (through different diversified practices such as inter-cropping, diversifying habitats, reducing tillage or inoculating beneficial microorganisms into the soil) promotes the provision of multiple ecosystem services such as pollination and pest control, water regulation, carbon sequestration, regulation of soil fertility and nutrient cycling, without compromising crop yields. However, in the same meta-analyses referred above, negative impacts on crop yields and climate regulation were also found in a proportion of the diversified cropping systems included in the study. Noteworthy, this new crop production model can be quite a challenge under rainfed semiarid conditions, as it is the case of Mediterranean agricultural systems, where an accurate and locally-adapted management will be necessary in order to avoid competence for water and nutrients between the main and the new-diversified crop (Palese et al., 2014; Daryanto et al., 2018; Morugán-Coronado et al., 2020). In this regard, the selection of species adapted to the local pedoclimatic conditions, whose management is compatible with available machinery, and that have a competitive market price, is crucial to ensure the success of inter-cropping under semiarid conditions (Hinsinger et al., 2011; Isbell et al., 2015). Furthermore, we have to be aware of the fact that the transition to more sustainable and diversified cropping systems is a long pathway and continuously evolving process that entails up-to-date and integrated assessments adapted to each particular socio-environmental context (Beillouin et al., 2021).

Understanding and predicting agroecosystem functioning (e.g., food provision, climate change mitigation through carbon sequestration, soil retention, regulation of soil fertility and nutrient cycling) and the role of soil management in regulating carbon, water, and nutrient storage requires an integrated assessment of a suite of soil ecological indicators. Those indicators should encompass different dimensions of the soil system (soil physics, soil chemistry, soil biodiversity and soil ecosystem functions) that directly link to targeted goals under the European Soil Strategy, the Green Deal, the Sustainable Development Goals and the Paris Agreement. On this regard, soil variables such as soil aggregation, water retention capacity, organic carbon content and nutrient availability, have been proposed as excellent indicators of soil functional biodiversity (Guerra et al., 2021).

Most of the scientific literature on crop diversification has, to date, focused either on ecological outcomes or on production (Hufnagel et al., 2020). However, to our knowledge, there is a lack of studies assessing the agronomic and environmental impacts of crop diversification, and particularly in low-input rainfed cropping systems. Here, we conducted an experiment to demonstrate the environmental and agronomic benefits of inter-cropping conventionally managed almond monocrops under semiarid rainfed conditions in order to scale up agricultural landscape restoration in dryland regions facing serious land degradation problems. This extensive cropping system was selected because it is very representative of the South-eastern Spain agricultural landscape and has a significant potential to provide a wide range of ecosystem services if sustainable land management practices are adopted (Almagro et al., 2016; IPCC, 2019). However, it is nowadays endangered due to its low profitability and lack of national policies support (i.e., promotion of more-profitable irrigated and intensively-managed cropping systems). Consequently, large scale rural abandonment or the conversion of traditional rainfed farming systems to intensively irrigated ones is becoming more frequent nowadays, resulting in over-exploitation and land degradation problems since the 1950s, a situation that will be aggravated by ongoing climate change (IPCC et al., 2022).

The objective of this study was to assess the combined short-term effects of crop diversification and no tillage on the agroecosystem functioning in a rainfed woody cropping system under semiarid Mediterranean conditions. To do so, a range of soil physico-chemical quality properties related to soil health, functioning and services, as well as crop yields, were monitored one and three years after two crop diversifications were implemented in a conventionally managed almond monocrop under semiarid rainfed conditions. The specific objectives were to assess the impacts of inter-cropping under rainfed semiarid conditions on: 1) the main crop yield and the land equivalent ratio as indicators of the agroecosystem productivity and sustainability; 2) a suite of soil physical properties related to ecosystem services such as water regulation and soil retention (bulk density, aggregate stability and available water for plants); and 3) a set of soil chemical properties related to ecosystem services such as climate regulation through soil carbon sequestration and soil fertility maintenance (carbon content and available nutrients for plants). We hypothesize that crop diversification improves soil condition due to the combined effect of increased plant biomass inputs from the secondary crop and tillage cessation. However, and due to the short-lived experiment, major improvements are expected in the topsoil rather than in the subsoil. We also expect that combining inter-cropping and no tillage management will not negatively affect the main crop yields compared to the almond monocrop system.

2. Material and methods

2.1. Study site description and experimental design

The study was conducted in a rainfed organic almond (*Prunus dulcis* Mill.) orchard with an extension of 2.63 ha cultivated on terraces with a 7 m x 7 m spacing located in the Region of Murcia (Spain, Los Ramos, 37° 57′ 31″ N, 0° 56′ 17″ W; 167 m a.s.l.; Figure 1). The climate of the study site is semiarid Mediterranean, with warm dry summers and relatively cold wet winters. The mean annual precipitation and air temperature is 231 mm and 17.5 °C, respectively. The mean potential evapotranspiration reaches 1300 mm yr^{-1} (calculated by the Thornthwaite method) and the mean annual water deficit is around 1000 mm. The soils in the study site, developed on marl, are classified as Calcaric Eutric Regosols (IUSS Working Group WRB, 2015) and have a silt-loam texture with high contents of $CaCO_3$ (~ 54%), a pH (H2O, 1:5) of 8.9, and an electrical conductivity of 0.20 dS m^{-1}. The total soil organic carbon and nitrogen contents are relatively low (4.5 g kg^{-1} and 0.7 g kg^{-1}, respectively).

In 1950, almond trees were planted in rows with a 7 m × 7 m spacing, since when no fertilizers have been applied. This almond orchard is ploughed twice or three times a year after important rainfall events to control weeds, so the soil is uncovered almost all year round and biomass inputs from spontaneous vegetation are negligible. To increase the soil cover, profitability and resilience of this almond monocrop, two crop diversification practices were implemented in November 2018. These consisted of intercropping a proportion of the rainfed almond trees with *Capparis spinosa* (hereafter caper) at a spacing of 3.5 m × 3.5 m, or with *Thymus hyemalis* (hereafter winter thyme) at a spacing of 0.5 m (between rows) × 1 m (between individuals within the same row), leaving the remaining part of the almond crop as a monocrop. These native species were selected as secondary crops because they are well adapted to the local pedoclimatic conditions and can increase farmeŕs profitability since they can be sold as food (caper) or spices and essential oils (aromatics) used in pharmacy, cosmetics and biotechnology industries (De Martino et al., 2015). The selection of the species for inter-cropping was based on a combination of approaches, including data mining from previous published studies and reports on potential crop associations and low-input management practices (Morugán-Coronado et al., 2020), surveys to farmers, researchers, and technicians, and the analysis of the gathered information using a multicriteria decision methodology (Gómez-López et al., 2019).

The experimental design consisted of nine plots (7 m x 30 m), each enclosing five almond trees, in a randomized-block design, with three replicate plots for each of the three crop management treatments (almond monocrop, almond inter-cropped with caper, and almond inter-cropped with winter thyme; Fig. 1). In the rainfed almond monocrop, tillage was performed by chisel ploughing to 15–20 cm depth twice or three times a year after important rainfall events to control weeds. In the diversified rainfed plots, no tillage operations were performed due to the presence of the secondary crops in the inter-tree rows (Fig. S1). Moreover, to monitor the performance of winter thyme and caper without associated almond orchards (that is, as monocrop systems), two additional plots (7 m x 20 m) were implemented in a nearby field under the same pedoclimatic conditions than the crop diversification systems.

2.2. Crop production

The annual almond yield in each crop management practice was estimated by harvesting the almond kernels from four or five trees per block (a total of twelve-fifteen trees per crop management practice) and weighing them, after removal of the pericarp, in August 2019, 2020 and 2021. In the crop diversification treatments, moreover, the annual production of the secondary crop (i.e., caper and winter thyme) was estimated. Winter thyme production was estimated by cutting off the top ten-fifteen cm of above-ground biomass of each individual (in 4th March 2020 and 23rd April 2021), leaving around 5 cm of remnant biomass above the woody parts for subsequent resprout. The essential oil extracted from the harvested material was weighted and expressed as crop yield. The annual production of caper could not be estimated during the experimental period because between four and five years are needed to obtain its first harvest (Barbera and Di Lorenzo, 1983).

To characterize land use efficiency of crop diversifications the land equivalent ratio (LER) was estimated as the sum of the relative yields in

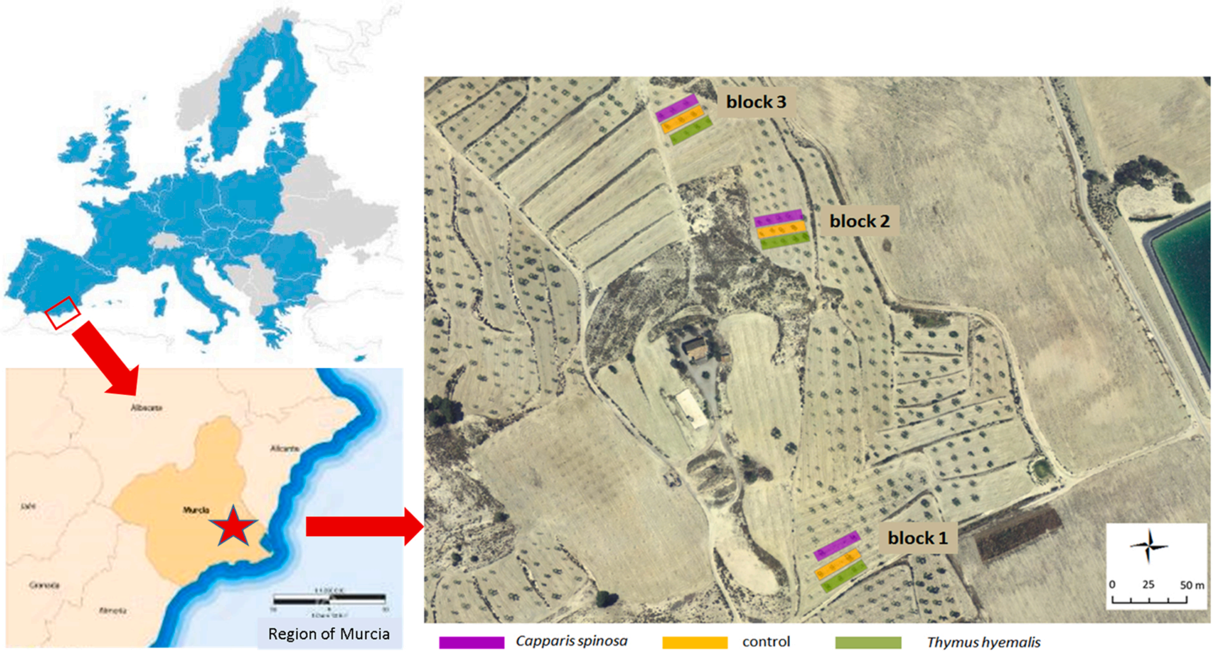

Fig. 1. Location of the study site and experimental block design regarding the different crop management treatments under rainfed conditions: almond monocrop (orange), almond inter-cropped with caper (pink), and almond inter-cropped with winter thyme (green).

the intercropped system divided by the sole-crop yields in the monocrop systems. According to Mead and Willey (1980), a LER > 1 means that the intercropping system results advantageous since it produces more yields with the same land requirements.

2.3. Soil sampling and analysis

Soil samples were collected at 0–10 cm and 10–30 cm depth on 8th April 2019 and 24th March 2021, one and three years after the diversification practices started to be implemented. The soils were sampled in the alleys between the trees, 2 m from the tree trunks. Three disturbed composite soil samples (each one from five randomly collected subsamples) were taken per crop management practice and block in each cropping system for physical and chemical analyses. Undisturbed samples were also collected at the same spots using steel cylinders (100 cm^3 core volume) for bulk density determinations. Gravimetric soil moisture was determined by weighing before and after drying at 105 °C for 24 h. The disturbed soil samples were air-dried and sieved to < 2 mm for physical (texture, water retention capacity) and chemical (C, N, P, etc.) analyses. The remaining non-sieved soil samples were stored for aggregate stability analysis.

2.4. Soil physical analysis

Soil texture 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 bulk density (BD, in g cm^{-3}) was calculated from the oven-dried mass (105 °C, 24 h) following the method described by Burke et al. (1986). Water-stable aggregates were separated from soil composite samples of each crop management practice and soil depth following the wet-sieving method proposed by Elliott (1986). Briefly, a 100-g subsample of air dried soil was placed on top of a 2000-μm sieve and gently moistened by sprinkling to minimise aggregate slaking before immersed in water at room temperature. The sieving was performed manually by moving the sieve up and down 3 cm, 50 times in 2 min, to achieve aggregate separation. A series of three sieves (2000, 250, and 53 μm) was used to obtain four aggregate-size classes: i) large macro-aggregates (LM; > 2000 μm); ii) small macro-aggregates (SM; 250–2000 μm); iii) micro-aggregates (m; 53–250 μm); and iv) silt plus clay-sized particles (s + c; < 53 μm). The aggregate size classes were oven-dried at 50 °C, weighed, and stored in glass jars at room temperature (21 °C). The macroaggregate-to-microaggregate ratio was used as an indicator of aggregate stability.

Soil water retention, at matric potentials of − 50 kPa (water content at field capacity) and − 1500 kPa (water content at permanent wilting point) was measured using disturbed samples sieved at 2 mm (Keller et al., 2007). The water contents were measured gravimetrically using a Soil Moisture Equipment (Corp., Santa Barbara, CA), as described by Dirksen (1999). Volumetric values were then calculated by multiplying the gravimetric measurements by the BD values obtained previously. The available water content (AWC), the maximum soil capacity to store available water for plants, was estimated as the difference between the water content at field capacity and the water content at permanent wilting point.

2.5. Soil chemical analysis

Soil pH and electrical conductivity (EC) were measured in deionized water (1:2.5 and 1:5 w/v, respectively). Total organic carbon (SOC, in g kg^{-1}) and nitrogen (total N, in g kg^{-1}) were analyzed using an N/C Analyzer (Flash 1112 EA, Thermo-153 Finnigan, Bremen, Germany) after elimination of the soil carbonates with 1 M HCl. Soil NH_4^+-N was extracted with 2 M KCl in a 1:10 soil:extractant ratio and measured (Keeney and Nelson, 1983; Kandeler and Gerber, 1988). Soil NO_3^--N was extracted with deionized water in a 1:10 soil:extractant ratio and measured by ion chromatography (Metrohm 861). Available phosphorus was extracted using the Burriel-Hernando method (Díez, 1982), with 0.2 g $CaCO_3$, 0.17 g $MgCO_3$, 5 mL glacial acetic acid and 0.2 mL H_2SO_4 in 2 L deionized water in a 1:25 soil:extractant ratio and measured by ICP-MS (Agilent 5977 A).

Particulate organic carbon (POC) and nitrogen (PON) were determined following the method described by Cambardella and Elliott (1992). Briefly, 20 g of air-dried soil sample sieved to 2 mm was dispersed by shaking overnight in a 100 mL solution of sodium hexametaphosphate (5 g L^{-1}). The mixture was then sieved through a 53 μm sieve by rinsing gently with deionized water to remove reagent remnants and filtrated. The material retained on the filter was dried in an oven at 60 ∘C for 48 h, weighed and finely ground using a ball mixer mill. The C and N concentrations of the POM fraction (≥ 53 μm) were analyzed using an Elemental Analyzer (LECO TRUSPEC CN, Michigan, USA). The particulate organic carbon (POC; g kg^{-1}) and nitrogen (PON; g kg^{-1}) contents were then calculated by multiplying the weight percentage of dried retained material by the respective percentages of organic carbon and nitrogen.

Cation exchange capacity (CEC) was determined using $BaCl_2$ as exchangeable salt; and exchangeable Na, Ca, K and Mg were measured in the $BaCl_2$ extract from CEC (Álvaro Fuentes et al., 2019). Bioavailable oligoelements (Fe, Mn, Cu and Zn) were extracted using the chelating agent DTPA (1:2 w/v) (Álvaro Fuentes et al., 2019). Macro- and micro-nutrient (Ca, Mg, Na, K, B, Zn, Cu, Mn and Fe) concentrations were determined using ICP-MS (Agilent 7900).

2.6. Statistical analyses

Annual differences in soil physical (bulk density, aggregation index, and available water for plants) and chemical (pH, total and particulate organic carbon and nitrogen contents, cation exchange capacity, plant-available nutrients for plants) properties within each crop management practice (almond monocrop, almond inter-cropped with caper, and almond inter-cropped with winter thyme) were analyzed using a two-way ANOVA, in which "year" and "soil depth" were considered as the main fixed factors and "block" as a random variable. When significant time and/or soil depth effects were found, pairwise comparison tests with Bonferroni adjustment were performed to detect differences among years and soil depths. Differences in the main crop yields were analysed using a two-way ANOVA, in which "crop management practice" and "year" were considered as the main fixed factors and "block" as a random variable. When significant crop management practice effects were found, pairwise comparison tests with Bonferroni adjustment were performed to detect differences among crop management practices within each year. Prior to these analyses, the data were tested for ANOVA assumptions, and were log- (LM, Nt, POC, PON, NO_3^--N, NH_4^+-N: NO_3^--N, P_{av}), root-square (e.g., main crop yields) or arcsine-transformed (SM, available water content and phosphorous) when necessary. All the statistical analyses were performed using SPSS 22.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Main crop yields and land productivity

Average almond crop yields ranged from 49.5 to 187.2 kg ha^{-1} yr^{-1} depending on the crop management practice and year. The crop management practice did not significantly affect the main crop yields when pooled across years ($F = 3.86$; $P = 0.11$; Table S1). However, there was a significant crop management x year interaction ($F = 4.60$; $P = 0.02$). In the third year of implementation, almonds inter-cropped with winter thyme resulted in significantly lower yields than those in the other crop management treatments (Fig. 2).

While caper production was negligible during the experimental

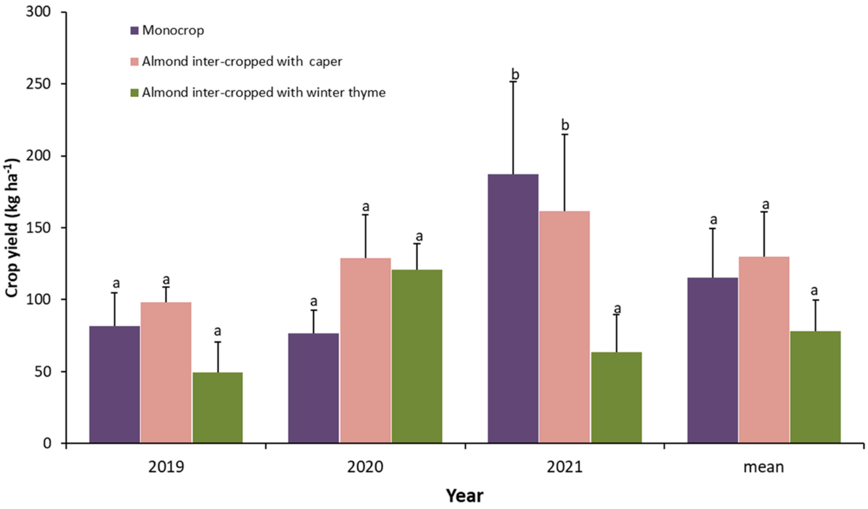

Fig. 2. Average annual almond yields (in kg ha^{-1}) for each crop management practice (almond monocrop, almond inter-cropped with caper, and almond inter-cropped with winter thyme) in 2019, 2020 and 2021. Average almond yield for each crop management practice over the 3-year period is also shown. For each year, different letters denote significant differences among crop management treatments according to Bonferroni test ($P < 0.05$).

period, the production of the winter thyme essential oil started fifteen months after its implementation. In 2020, about 8.1 and 6.4 L ha^{-1} of essential oil from winter thyme were obtained in the winter thyme monocrop and the almond inter-cropped with winter thyme systems, respectively. In 2021, however, the production of essential oil was slightly higher in the diversified (9.9 L ha^{-1}) than in the monoculture (9.1 L ha^{-1}) system.

Based on our results, the land equivalent ratio of the almond inter-cropped with winter thyme was 2.22 and 1.56 in 2020 and 2021, respectively, which means that a total of 2.22 and 1.56 ha of sole cropping area would be required to produce the same yields as those of the inter-cropped system in 2020 and 2021, respectively.

3.2. Soil physical properties

3.2.1. Soil bulk density

Soil bulk density values, ranging from 1.10 to 1.33 g cm^{-3} depending on the crop management practice and soil depth, did not significantly change with time at any soil depth within each crop management practice (Table 1).

3.2.2. Soil aggregation and stability

Soil aggregate stability improved with time in both crop diversification treatments. After three years, the percentage of large macroaggregates significantly increased in the topsoil (0–10 cm depth) of

Table 1
Soil physical properties of the almond monocrop, almond inter-cropped with caper, and almond inter-cropped with winter thyme in the topsoil and subsoil one and three years after implementation (values on dry weight basis). Standard errors are given in parentheses. Asterisks indicate significant differences between sampling times at each soil depth within each crop management treatment.

Soil variables	Sampling time	Almond monocrop		Almond inter-cropped with caper		Almond inter-cropped with winter thyme	
		Topsoil (0–10 cm)	Subsoil (10–30 cm)	Topsoil (0–10 cm)	Subsoil (10–30 cm)	Topsoil (0–10 cm)	Subsoil (10–30 cm)
BD (g cm^{-3})	Year 1	1.1 (0.01)	1.3 (0.02)	1.2 (0.03)	1.3 (0.04)	1.2 (0.03)	1.3 (0.02)
	Year 3	1.1 (0.06)	1.2 (0.07)	1.2 (0.04)	1.3 (0.05)	1.1 (0.07)	1.3 (0.04)
fPOM (%)	Year 1	0.2 (0.09)	0.1 (0.1)	0.2 (0.06)	0.2 (0.1)	0.1 (0.03)	0.0 (0.03)
	Year 3	0.1 (0.01)	0.1 (0.02)	0.1 (0.04)	0.2 (0.07)	0.1 (0.02)	0.3 (0.2)
LM (%)	Year 1	2.0 (0.3)	2.8 (0.7)	1.3 (0.4)	3.2 (0.8)	1.5 (0.4)	4.1 (1.2)
	Year 3	2.7 (0.8)	2.9 (0.9)	2.8 (0.9)*	2.7 (1.9)	5.7 (1.8)*	6.6 (2.8)*
SM (%)	Year 1	17.0 (1.2)	17.2 (1.6)	16.8 (1.6)	25.1 (1.4)	14.1 (0.5)	21.3 (1.3)
	Year 3	21.5 (0.9)*	29.7 (1.7)*	18.3 (1.3)	27.6 (2.6)	20.6 (1.5)*	26.7 (1.9)
m (%)	Year 1	17.4 (0.4)	33.4 (3.2)	28.7 (3.8)	20.5 (0.9)	40.6 (0.3)	18.0 (0.7)
	Year 3	17.4 (0.4)	19.2 (0.9)	17.4 (0.4)	19.1 (0.9)	16.7 (1.0)	19.2 (1.2)
s + c (%)	Year 1	63.2 (1.6)	46.5 (1.8)	53.3 (2.4)	51.2 (1.8)	43.7 (0.6)	56.5 (2.1)
	Year 3	58.3 (0.9)	47.7 (1.8)	60.5 (1.3)*	50.5 (3.1)	57.6 (1.1)*	48.3 (2.6)*
LM:m	Year 1	0.12 (0.02)	0.10 (0.04)	0.06 (0.02)	0.16 (0.03)	0.04 (0.01)	0.24 (0.08)
	Year 3	0.16 (0.05)	0.17 (0.06)	0.17 (0.06)	0.26 (0.13)	0.40 (0.14)*	0.54 (0.2)*
AWC (m3 $m^{-3)}$	Year 1	0.1 (0.03)	0.09 (0.03)	0.09 (0.03)	0.10 (0.03)	0.08 (0.03)	0.08 (0.03)
	Year 3	0.1 (0.04)	0.09 (0.03)	0.11 (0.04)*	0.12 (0.04)*	0.10 (0.03)*	0.12 (0.04)*

BD: bulk density; fPOM: floating particulate organic matter; LM: large macroaggregates; SM: small macroaggregates; m: microagrgregates; s + c: silt plus clay; LM:m: large macroaggregate-to-microaggregate ratio; AWC: available water content

*For each treatment and soil depth, differences between the first and third year after crop diversifications were implemented were found after Bonferroni test (P < 0.05) both crop diversification systems (by 123% and 274% in the almond inter-cropped with caper and with winter thyme, respectively) as well as in the subsoil (10–30 cm depth) in the almond inter-cropped with winter thyme (by 58%; Table 1). In the almond monocrop system, however, no temporal changes were observed in the percentage of large macro-aggregates. Likewise, the macroagregate-to-microagregate ratio, an index of soil aggregation and stability, significantly increased with time in the topsoil and subsoil of the almond inter-cropped with winter thyme, while no significant increments were detected at any soil depth in the almond monocrop or the almond inter-cropped with caper.

3.2.3. *Soil available water content*

Soil-available water content (AWC) ranged between 0.8 and 0.12 m^3 m^{-3} depending on the crop management treatment and soil depth (Table 1) and there were significant interactions between crop management treatment, soil depth and year. At the end of the experiment, available water content for plants increased in the topsoil and subsoil of both crop diversifications.

Table 2

Soil chemical properties of the almond monocrop, almond inter-cropped with caper, and almond inter-cropped with winter thyme in the topsoil and subsoil one and three years after implementation (values on dry weight basis). Standard errors are given in parentheses. Asterisks indicate significant differences between sampling times at each soil depth within each crop management treatment.

Soil variables	Sampling time	Almond monocrop		Almond inter-cropped with caper		Almond inter-cropped with winter thyme	
		Topsoil (0–10 cm)	Subsoil (10–30 cm)	Topsoil (0–10 cm)	Subsoil (10–30 cm)	Topsoil (0–10 cm)	Subsoil (10–30 cm)
pH	Year 1	8.4 (0.03)	8.4 (0.03)	8.4 (0.04)	8.4 (0.03)	8.3 (0.04)	8.3 (0.06)
	Year 3	8.5 (0.02)*	8.5 (0.02)	8.5 (0.07)	8.5 (0.07)	8.6 (0.05)*	8.5 (0.06)*
EC (dS m^{-1})	Year 1	0.2 (0.01)	0.2 (0.01)	0.23 (0.02)	0.18 (0.01)	0.26 (0.04)	0.21 (0.01)
	Year 3	0.2 (0.02)	0.17 (0.01)	0.19 (0.01)	0.17 (0.01)	0.24 (0.03)	0.22 (0.03)
CEC (cmol kg^{-1})	Year 1	11.4 (0.4)	11.1 (0.4)	9.9 (0.7)	11.1 (0.7)	10.3 (0.5)	10.2 (0.4)
	Year 3	13.8 (0.3)*	14.6 (0.3)*	13.7 (0.4)*	14.6 (0.5)*	13.6 (0.4)*	14.0 (0.5)*
TOC (g kg^{-1})	Year 1	4.5 (0.2)	3.8 (0.3)	4.5 (0.3)	3.7 (0.4)	3.7 (0.3)	3.2 (0.2)
	Year 3	4.6 (0.3)	4.1 (0.3)	4.7 (0.3)	3.7 (0.2)	4.6 (0.3)*	3.3 (0.3)
Nt (g kg^{-1})	Year 1	0.7 (0.02)	0.6 (0.03)	0.7 (0.04)	0.6 (0.05)	0.5 (0.03)	0.5 (0.02)
	Year 3	0.9 (0.03)*	0.8 (0.1)*	0.8 (0.05)	0.7 (0.02)	0.6 (0.08)	0.6 (0.02)*
POC (g kg^{-1})	Year 1	1.2 (0.1)	0.8 (0.1)	1.2 (0.1)	0.5 (0.05)	0.9 (0.2)	0.5 (0.07)
	Year 3	1.2 (0.1)	0.6 (0.07)	1.3 (0.1)	0.7 (0.07)*	1.2 (0.2)	0.7 (0.1)*
PON (g kg^{-1})	Year 1	0.09 (0.01)	0.06 (0.01)	0.1 (0.01)	0.06 (0.01)	0.08 (0.01)	0.07 (0.01)
	Year 3	0.1 (0.01)	0.08 (0.01)	0.1 (0.01)	0.07 (0.01)	0.1 (0.01)*	0.06 (0.00)
NH_4^+ (mg kg^{-1})	Year 1	2.7 (0.1)	2.1 (0.4)	2.2 (0.1)	1.5 (0.4)	1.5 (0.3)	0.9 (0.5)
	Year 3	1.5 (0.2)*	2.0 (0.2)	1.4 (0.2)	2.7 (0.2)*	1.7 (0.2)	3.4 (0.6)*
NO_3^- (mg kg^{-1})	Year 1	26.4 (6.7)	16.2 (4.0)	27.1 (7.4)	4.4 (1.0)	14.2 (2.7)	5.6 (0.6)
	Year 3	11.3 (2.6)*	15.0 (3.3)	9.3 (1.7)*	7.3 (1.0)	8.5 (2.5)	12.3 (1.4)
P (mg kg^{-1})	Year 1	0.4 (0.2)	0.3 (0.04)	0.5 (0.2)	0.3 (0.1)	0.3 (0.06)	0.2 (0.04)
	Year 3	4.0 (1.1)*	2.0 (0.5)*	3.6 (0.9)*	2.2 (0.7)*	1.7 (0.5)*	1.0 (0.3)
K (g kg^{-1})	Year 1	213.3 (6.9)	145.5 (7.9)	184.2 (13.2)	129.0 (8.0)	177.7 (10.3)	129.0 (8.9)
	Year 3	215.9 (13.2)	151.3 (8.4)	217.5 (9.5)*	145.5 (9.2)	221.7 (18.1)*	146.9 (15.2)
Na (g kg^{-1})	Year 1	BDL	0.03 (0.02)	0.04 (0.02)	0.03 (0.01)	0.03 (0.02)	0.03 (0.02)
	Year 3	0.02 (0.01)	0.02 (0.01)	0.04 (0.01)	0.04 (0.01)	0.06 (0.01)	0.09 (0.01)*
Ca (g kg^{-1})	Year 1	1.8 (0.1)	1.7 (0.1)	1.6 (0.1)	1.8 (0.1)	1.6 (0.1)	1.6 (0.1)
	Year 3	2.3 (0.1)*	2.4 (0.1)*	2.2 (0.1)*	2.4 (0.1)*	2.1 (0.1)*	2.1 (0.1)*
Mg (g kg^{-1})	Year 1	0.2 (0.04)	0.2 (0.06)	0.2 (0.05)	0.2 (0.04)	0.2 (0.03)	0.2 (0.05)
	Year 3	0.2 (0.03)	0.2 (0.04)	0.2 (0.02)*	0.2 (0.02)	0.3 (0.05)*	0.3 (0.07)*
Mn (mg kg^{-1})	Year 1	9.9 (1.2)*	12.3 (2.0)*	13.0 (1.3)*	13.9 (0.9)*	12.7 (0.8)*	13.9 (1.3)*
	Year 3	2.7 (0.2)*	2.9 (0.3)*	2.2 (0.1)*	2.5 (0.2)*	2.4 (0.04)*	2.7 (0.2)*
Zn (mg kg^{-1})	Year 1	0.1 (0.02)*	0.1 (0.02)*	0.2 (0.03)	0.1 (0.01)	0.2 (0.02)	0.1 (0.02)*
	Year 3	0.2 (0.01)*	0.1 (0.02)*	0.2 (0.01)	0.1 (0.02)	0.2 (0.08)	0.2 (0.05)*
Fe (mg kg^{-1})	Year 1	1.4 (0.1)	1.8 (0.2)	1.8 (0.1)*	2.1 (0.1)*	2.1 (0.2)*	2.2 (0.2)*
	Year 3	1.5 (0.07)	1.4 (0.07)	1.3 (0.07)*	1.3 (0.1)*	1.5 (0.1)*	1.5 (0.1)*
Cu (mg kg^{-1})	Year 1	0.6 (0.05)	0.6 (0.06)	0.9 (0.08)	0.8 (0.06)	0.9 (0.09)	0.8 (0.1)
	Year 3	0.7 (0.04)*	0.7 (0.05)	0.8 (0.04)	0.7 (0.04)	0.7 (0.05)	0.6 (0.05)*

EC: electrical conductivity; CEC: cation exchange capacity; TOC: total organic carbon; POC: particulate organic carbon; PON: particulate organic nitrogen.

*For each treatment and soil depth, differences between the first and third year after crop diversifications were implemented were found after Bonferroni test ($P < 0.05$)

BLD: Below detection limits

3.3. Soil chemical properties

3.3.1. Soil organic carbon, nitrogen and phosphorous

Total organic carbon (TOC) content ranged from 3.2 to 4.7 g kg^{-1} depending on the crop management practice and soil depth and it increased with time only in the topsoil of the almond inter-cropped with winter thyme ($F = 7.55$; $P = 0.008$). Particulate organic carbon (POC) content significantly increased with time in the subsoil of both crop diversification systems (by 43% and 46% in the almond inter-cropped with caper and with winter thyme, respectively) while no annual changes were observed in the almond monocrop (Table 2).

Total nitrogen (Nt) content increased in all crop management treatments and soil depths, although significant differences were only detected in the whole soil profile of the almond monocrop and in the subsoil of the almond inter-cropped with winter thyme. Particulate nitrogen (PON) content significantly increased with time in the topsoil of the almond inter-cropped with winter thyme ($F = 6.95$; $P = 0.01$) while no changes were found in the almond monocrop or the almond inter-cropped with caper (Table 2).

Soil ammonium (NH_4-N) content ranged from 0.9 to 3.4 g kg^{-1} and no consistent temporal trends were observed between crop management treatments and soil depths. Soil NH_4-N content decreased with time in the topsoil of the almond monocrop while the opposite was observed in the subsoil of both crop diversification treatments.

Soil nitrate (NO_3^--N) content decreased with time in the topsoil of all crop management treatments, although statistical significant differences were only detected in the case of the almond monocrop and of the almond inter-cropped with caper. In the subsoil, however, no consistent patterns were observed among crop management treatments. The NO_3^--N content increased in the subsoil of both crop diversification treatments while no changes were observed in the almond monocrop at this soil depth. Plant-available phosphorous (P) increased with time in all crop management treatments and soil depths.

3.3.2. Cation exchange capacity and plant-available nutrients

The cation exchange capacity (CEC) increased with time in all crop management treatments and soil depths (Table 2). Plant-available nutrients for plants did not show consistent temporal trends among crop management practices and soil depths. Plant-available potassium (K) increased with time in the topsoil of both crop diversifications while no changes were observed in the almond monocrop system. Plant-available calcium (Ca) uniformly increased with time in the topsoil and subsoil of all crop management treatments. Plant-available magnesium (Mg) increased with time in the topsoil of both crop diversification systems, as well as in the subsoil of the almond inter-cropped with winter thyme, but not in the almond monocrop. Plant-available sodium (Na) increased with time only in the subsoil of the almond inter-cropped with winter thyme.

No consistent temporal trends were observed in micro-nutrients among crop management practices. The content of Mn available for plants uniformly diminished with time in all treatments and soil depths while the opposite was observed in the case of Zn. Soil Fe content was reduced in the topsoil and subsoil of both crop diversifications while it did not change at any soil depth in the almond monocrop. The Cu content increased with time in the topsoil of the almond monocrop while the opposite occurred in the subsoil of the almond inter-cropped with winter thyme.

4. Discussion

Results from this study demonstrate that the combination of inter-cropping permanent crops with perennials and no tillage under rainfed semiarid conditions might have beneficial effects on key soil physico-chemical properties as indicators of soil structure recovery and of improvements in water and nutrient availability for plants, which ultimately have effects on the functioning (i.e., erosion control, water regulation, soil carbon sequestration, fertility maintenance and crop productivity) of the whole agroecosystem.

4.1. Combined effects of crop diversification and no tillage on land productivity

Crop diversification did not significantly affect the main crop yields over the 3-year study period. Expectedly, our almond yields resulted much lower than those reported in previous studies in which rainfed almond monocrops were inter-cropped with different perennials such as sage, rosemary and thyme, under sub-humid Mediterranean conditions with a mean annual precipitation of 540 mm (Durán Zuazo et al., 2008). Noteworthy, climate conditions are particularly dry and warm in our experimental site. Specifically, our mean annual precipitation (~ 220 mm) and temperature (~ 17.5 ºC) are well below and above the thresholds (470 mm and 15.5 ºC, respectively) identified in a recent meta-analysis to detect increments in the main crop yields of crop diversification systems compared to their monocrop counterparts (Morugán-Coronado et al., 2020). In this regard, several authors have stated that inter-cropping with annual crops in semiarid regions under rainfed conditions can be a more suitable management option since those can be easily removed to avoid excessive competition for water and nutrients before critical periods take place, such as severe water scarcity in summer or when nutrients requirements increase for the main crop fruit production and development, and so prevent from negative effects on yields (Palese et al., 2014; Daryanto et al., 2018). Several pros and cons have been reported in the literature when diversifying with annuals or perennials. On the one hand, inter-cropping with annual species entails more agricultural practices (i.e., annual seeding) and increases the probability of leaving the soil uncovered if crop failure occurs because adverse weather conditions, but it also guarantees crop harvest in the first year from implementation. On the other hand, inter-cropping with perennials requires much less maintenance and management practices after crop establishment, provides a permanent habitat for pollinators and other beneficial soil organisms, protects the soil against erosion all year round since fallow periods are avoided, and improves soil structure and carbon sequestration in deeper layers due to deeper root systems (Ferrarini et al., 2017; Ledo et al., 2020).

The essential oil production of the winter thyme, which was about 7 and 10 L ha^{-1} in the second and third year, respectively, was very similar to that reported for the same diversified almond system referred above (Durán Zuazo et al., 2008), and thereby could off-set the lower almond yields observed in this crop diversification system in the third year. This statement is supported by the higher land equivalent ratios obtained for this crop diversification system (2.22 and 1.56 in 2020 and 2021, respectively) compared to their respective monocrop systems. Our land equivalent ratios are somewhat higher than those reported elsewhere for other crop diversification systems under similar semiarid conditions (Bai et al., 2016; Arenas-Corraliza et al., 2018), indicating that inter-cropping with aromatics can improve the productivity of rainfed monocrop systems. However, caper production was negligible during the study period because between four and five years are needed to obtain its first harvest (Barbera and Di Lorenzo, 1983), and therefore it did not contribute to increase land productivity in the almond inter-cropped with caper treatment in the short-term.

4.2. Combined effects of crop diversification and no tillage on soil physical properties

After three years, both soil aggregate stability and water availability for plants were significantly improved in the topsoil of both crop diversifications while the soil bulk density remained very similar in all crop management treatments. Our results indicate that tillage suppression in rainfed woody cropping systems can enhance soil structure and water availability for plants without causing topsoil compaction in the short-term. This statement is supported by the similar patterns observed in the topsoil of both crop diversification systems regardless phenological differences between secondary crops and distinct plantation densities. Previous research has reported both beneficial (i.e, enhancement of soil structure and water availability for plants) and detrimental (i.e., soil compaction) effects of tillage suppression in woody cropping systems under semiarid conditions (Peregrina et al., 2010; Martínez-Mena et al., 2013; Almagro et al., 2017; Martínez-Mena et al., 2021b). In the subsoil, however, soil aggregate stability and water availability for plants only improved in the diversification with winter thyme, highlighting the importance of selecting species that provides carbon inputs and a permanent plant cover all year round as secondary crops while allowing higher plantation densities, as it is the case of winter thyme, for improving more effectively key physical properties related to water regulation and soil formation in the subsoil. Nevertheless, the available water content values observed in our study site are below the threshold identified for fine-texture soils (between 0.10 and 0.15 m^3 m^{-3}) to allow root growth and development (Verdonck et al., 1984), which may explain the very low almond yields observed over the course of the experiment as well as the potential to increase them if soil structure and water availability for plants are improved in the long-term.

4.3. *Combined effects of crop diversification and no tillage on soil organic carbon and inorganic nitrogen pools*

The total N content was at the lower limit reported for agricultural soils (0.8–4 g kg^{-1}; Bremner, 1965), consistent with the low level of TOC, highlighting that soils have been subjected to erosion and degradation for years due to conventional soil management in this area (i.e., lack of plant cover since tillage is performed two or three times per year to control weeds). Indeed, according to the much higher TOC and N contents reported for a native shrubland adjacent to our experimental plots (11.7 and 1.4 g kg^{-1}, respectively; Martínez-Mena et al., 2021a), the TOC and N contents have been reduced by 65% and 48%, respectively, after 20 years of land-use change and intensive management.

After three years, the topsoil organic carbon content only enhanced in the almond inter-cropped with winter thyme, while a significant increment in the POC content was observed in the subsoil of both crop diversification systems. The fact that topsoil organic carbon only increased in the almond inter-cropped with winter thyme could be explained by the higher plantation density of winter thyme compared to that of caper but also by phenological differences between both secondary crops. While winter thyme provides a permanent plant cover in the inter-tree rows and continuous leaf-litter C inputs to the soil from its establishment, caper shoots are lost annually from November to April, when it re-sprouts, and therefore leaf-litter inputs from this crop can be assumed to be negligible during half of the year. It is well known that leaf-litter inputs contribute to increase the organic carbon content in the topsoil while roots contribute more to increase the organic carbon content in the subsoil (Rasse et al., 2005 and references therein). Nevertheless, and noteworthy, the extremely harsh environmental conditions (i.e., low mean annual precipitation and high evapotranspiration rates) of the study site together with the recalcitrant nature of the plant residues derived from the inter-cropped perennial species (winter thyme and caper) slow down soil organic carbon dynamics and sequestration (Ogle et al., 2005; Almagro et al., 2017, 2021). Our results also highlight the important role of roots, rather than leaf-litter inputs, in increasing the particulate organic carbon (Puget and Drinkwater, 2001; Kemp et al., 2003; Austin et al., 2009) since improvements of this labile organic carbon pool were only observed in the subsoil.

Expectedly, given that the N content was at the lower limit reported for agricultural soils and that no fertilizers are applied in our treatments, the ammonium and nitrate values of our crop management treatments were very low. Our figures are in the range of those reported for other rainfed low-input perennial cropping systems (Martínez-Mena et al., 2021b; Sánchez-García et al., 2016) and are in agreement with the almost negligible soil N_2O emissions monitored in the site over two years (Sánchez-Navarro et al., 2022). It is well known that the disruption of soil aggregates by tillage induces nitrate release and thereby previous research has reported significant reductions in mineral N (NO_3^--N) caused by tillage suppression in other semiarid rainfed organic cropping systems (Bergh et al., 1995; Silgram and Shepherd, 1999; Malhi et al., 2001; Martínez-Mena et al., 2013, 2021b). However, our results do not support this pattern, as reductions in the topsoil NO_3^--N content were observed with time in all crop management treatments regardless tillage frequency. The fact that reductions in the topsoil NO_3^--N content were observed with time in all crop management treatments could be explained by the relatively higher soil moisture content detected in the field at that sampling date in the third year compared to that in the first year, presumably causing N leaching episodes, consistent with what reported in other studies (Kopáček et al., 2013; Liu et al., 2022). Other authors reporting a similar pattern than that observed in our study have related it to increases in the abundance of functional genes involved in the denitrification process under increased soil moisture (Liu et al., 2022) that consume NO_3^--N as it is the main substrate for denitrification (Dobbie and Smith, 2003). However, we do not have data to confirm this interpretation. On the other hand, the fact that both NO_3^--N and NH_4^+-N contents increased in the subsoil of both crop diversification systems, while no changes (in the case of NO_3^--N) or even the opposite (in the case of NH_4^+-N) occurred in the almond monocrop system at this soil depth, indicates that inter-cropping has improved the availability of N for plants in the subsoil. This has probably been boosted by vegetation recovery in the alleys of these crop management treatments that has activated the soil microbiota (Wagg et al. (2014); Wachendorf et al. (2020); Beule and Karlovsky (2021); D'hervilly et al. (2021). On the other hand, our results seem to contradict those by Dittrich et al. (2021), who reported lower NH_4^+-N levels in a vineyard inter-cropped with two different species of aromatic plants compared to the monocrop system, indicating their higher affinity and demand toward NH4$^+$-N.

4.4. *Combined effects of crop diversification and no tillage on plant-available macro- and micro-nutrients*

Plant-available soil nutrient levels in our study site were relatively low compared to those reported in other agricultural soils under similar semiarid and management conditions (Gómez et al., 2009; Ramos et al., 2010; Martínez-Mena et al., 2021b; Soto et al., 2021). After three years of inter-cropping, plant-available macro- and micro-nutrients did not show consistent temporal patterns among crop management practices and soil depths, and in most cases no significant changes were found. The fact that exchangeable-K levels increased with time in the topsoil of both crop diversification systems while no changes were observed in the almond monocrop system is explained by changes in soil management and the new crop inducing exchangeable K stratification under those treatments, as it has been reported elsewhere (Jobbágy and Jackson, 2001; Mallarino and Borges, 2006; López-Garrido et al., 2011). Stratification normally occurs when roots uptake K from deeper soil layers and above-ground plant residues are deposited in the soil surface, particularly in no tillage systems, as it is our case. Our results are in line with those by López-Garrido et al. (2011), who also reported an increase of available K in the topsoil under no tillage cropping systems, suggesting that K could be a good indicator of early changes caused by soil management. However, others authors have reported reductions in soil exchangeable-K contents when aromatic plants were inter-cropped with other perennial crops, highlighting a potential competition for this nutrient between the main and the secondary crop (Dittrich et al., 2021). Nevertheless, soil nutrient availability for plants varies seasonally and with management (e.g., before/after harvest), so comparisons among studies should be made with caution and considering the season when the soil was sampled.

Likewise, the fact that exchangeable Mg and Na increased with time in the subsoil of the almond inter-cropped with winter thyme indicates that the presence of winter thyme in the inter-rows has contributed to improve the availability of such as crucial nutrients for plants. On the other hand, the fact that soil Fe and Cu levels diminished with time in the whole soil profile of both crop diversifications, while it did not change at any soil depth in the monocrop system, indicates competence for these micro-nutrients between the almond tree and the inter-cropped crops (Ballester-Costa et al., 2017).

In conclusion, the results from this study demonstrate that intercropping permanent crops with perennials under no-tillage management can be a promising sustainable management practice for improving soil health without compromising food security under semiarid Mediterranean conditions. The new crop under no tillage improved the soil structure as well as the availability of water and some nutrients for plants, which ultimately enhances the functioning (i.e., soil, water, carbon and nutrient retention, fertility and land productivity) of the whole agroecosystem, even in the short-term. Our results also emphasize the importance of selecting an appropriate secondary crop that ensures a permanent soil cover while contributing to enhance the agroecosystem productivity from the first year of establishment onwards to off-set plausible lower yields from the main crop, like rosemary, sage, safflower or lavender. In this regard, preliminary assessments on soil condition and crop nutrient requirements are encouraged before intercropping with perennials in low-input cropping systems under semiarid conditions. Likewise, long-term studies are need to provide evidence on the stability of the productivity of diversified cropping systems, particularly in these low-input cropping systems under harsh environmental conditions.

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.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the European Commission Horizon 2020 project Diverfarming [grant agreement 728003]. María Almagro acknowledges the financial support from the Spanish Ministry of Science, Innovation and Universities through the “Ramón y Cajal” Program [RYC2020–029181-I]. Paula Re acknowledges the financial support from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) through their CLIFF-GRADS programme, as well as to the Government of New Zealand for providing financial support.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108320.

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