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Effect of the implementation of alley crops on the soil physical properties of a mandarin crop with regulated irrigation deficit, in the Mediterranean region

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ABSTRACT

In the Mediterranean region, orchard aisles usually remain bare throughout the year, which causes soil degradation and erosion. Alley cropping could be a suitable strategy to improve soil physical quality while increasing land productivity. The aim of this study was to assess if alley cropping in a mandarin orchard can affect water content at field capacity, wilting point, available water, aggregates stability, bulk density, and saturated hydraulic conductivity and if there is a relationship between these and crop production and quality. For this, three different treatments were applied: i) a mandarin monoculture (MM); ii) a mandarin crop diversified with a multiple cropping of vetch/barley and fava bean (AC1), with regulated deficit irrigation (RDI); and iii) a mandarin crop diversified with a rotation of fava bean, purslane and cowpea, with RDI (AC2). After three crop cycles, we found an increase in the amount of available water in all treatments, being slightly higher in AC2. The mean weight diameter of soil aggregates was reduced in all treatments, especially in AC1 (> 45 %). Saturated hydraulic conductivity increased in all treatments, especially in MM. In addition, we observed an increase in moisture at field capacity and available water results in larger mandarins, with a lower proportion of soluble solids. Thus, the establishment of alley crops did not lead to a better evolution of the soil physical properties in the short-term. However, the effect of diversification systems on the soil physical properties would be appreciated with the establishment of the mandarin crop diversified with cover crops or perennial crops in a long-term period.

1. Introduction

Soil management can change soil properties, altering properties such as aggregate size distribution, water holding capacity and bulk density (Soto-Gómez et al., 2018). The conventional production model, which emerged because of the food shortages that occurred in the 1940s (Morgan and Murdoch, 2000), is based on the use of herbicides and intensive tillage to reduce weed incidence, improve soil water holding capacity and increase aeration, although conditioned by the geographical area and the type of crop (Coolman and Hoyt, 1993; Womach, 2005; Simmons and Nafziger, 2014). However, in recent years, it has been reported that this type of management is not sustainable in the long term since it overloads the soil with chemicals and toxins that can be harmful for soil microbiota and fauna (Panhwar et al., 2018). In addition, this conventional production system is associated with a loss in soil organic matter (SOM) content (by increasing its oxidation with tillage), the reduction of earthworm activity and the decrease in soil aggregate stability (Pulleman et al., 2003). Thus, conventional management, with many hours of heavy traffic, results in soils with poorly developed structures, in which rooting problems appear, and which are more susceptible to erosion or waterlogging phenomena (Raper, 2005). This is particularly worrisome in Mediterranean areas, with woody crops that

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are subject to frequent tillage to keep soil bare all year to avoid competition for water and nutrients with weeds or other crops (García-Ruiz, 2010). Moreover, there is a social belief that keeping vegetation cover in orchards is associated to abandonment and dirt (Cerdà et al., 2018). This together with the shortage of rainfall under Mediterranean climate and its torrential character in autumn makes these areas even more sensitive to soil physical degradation.

There are some sustainable production methods that can be used in conventional farming in order to help in the preservation of soil quality. For example, management practices focused on specific rotations, taking into account the local crops, trying to include species adapted to soil and climatic conditions, in combination with pasture periods (Wachter and Reganold, 2014). Rotations are also used for adventitious control, since this type of systems are usually designed to compete with these plants. Maintaining cover crops in olive fields, for example, not only improves soil structure and reduces erosion, but also favours the development of biodiversity (Moreno et al., 2009; Berg et al., 2018). Cover crops, intercropping with cereals (Niemsdorff and Kristiansen, 2017) or heavy mulching systems are also used to slow the weed emergence (Wachter and Reganold, 2014). In contrast to cover crops, intercropping involves several crops being grown simultaneously in the same area (van Alfen, 2014). A specific type of intercropping is alley cropping: in this case, one of the intercropped crops is a tree species, and between the rows of trees, annual crops are usually cultivated (Grebner et al., 2021). However, perennial crops can also be used, as in the experiment carried out by Almagro et al. (2023), where caper and thyme are used as alley crops in almond orchards. This type of management has the following advantages: tree crops improve microclimatic conditions and allow sensitive crops to be planted in the alleys; increase the economic value of the land by providing a higher production in the same area; increase biodiversity; and enhance carbon sequestration (Quinkenstein et al., 2009). In addition, if alley cropping is combined with the incorporation of organic amendments, it is possible to positively affect the development of the structure, improving water retention and nutrient availability (Morugán-Coronado et al., 2020).

Thus, agricultural management practices, climatic conditions and crop type can have a specific effect on soil physical properties. With this specificity in mind, it is essential to perform experiments to analyse the effects of specific alley crops on soil properties from specific orchards. Therefore, the objectives of this work were to: i) assess how alley crops by using annual crops can affect soil structure, specifically bulk density, aggregate size distribution and stability, hydraulic conductivity, and water content at field capacity and wilting point; and ii) to elucidate if there is a relationship between soil physical properties and crop production and quality. We hypothesized that root development and activity of alley crops, related to crop residues incorporated as green manure, would improve aggregate formation and stabilization, and so aeration, water availability and infiltration rate, compared to bare soils managed with herbicides and tillage.

2. Material and methods

2.1. Study area

This study was conducted in a commercial mandarin orchard (*Citrus reticulata Blanco* var. Clemenvilla) from Murcia, SE Spain (37° 57’ 31’’N; 0° 56’ 17’’ W). Climate is semiarid Mediterranean, with a mean annual rainfall of 280 mm and a mean annual temperature of 18 ºC. Mandarin crop was established in 2000 and occupies an area of 2.3 ha, with 970 trees, at a spacing of 6 m between rows and 4 m between trees within the same row. A drip irrigation system was installed with one line per tree row and 3 pressure-compensated emitters, and applied at night or early morning (4 L h^{-1}). Irrigation frequency depended on the season and varied from 1 or 2 times per week in winter to 7–14 times in summer. The soil is a Calcaric Regosol (IUSS Working Group WRB, 2022) derived from marls, silt loam textured (16 % sand, 70 % silt and 14 % clay), pH of 7.56, bulk density of 1.20 g cm^{-3}, 55 % of $CaCO_3$ content and total organic carbon of 7.6 g kg^{-1}.

2.2. Crop diversification practices description and experimental design

This study started in September 2018, and three different treatments were applied: i) a mandarin monoculture with no alley cropping (MM); ii) a mandarin crop diversified, every year, with fava bean (*Vicia faba* L.) between September and December/January, and barley/vetch (*Hordeum vulgare* L. /*Vicia sativa* L.), between February and June (AC1); and iii) a mandarin crop diversified with fava bean, purslane (*Portulaca oleracea*) and cowpea (*Vigna unguiculata*), as alley crop rotations (AC2). The schedule of the different alley crops is shown in Fig. 1. Three plots per treatment were setup as split-plot design, with dimensions of 12 m x 24 m, with the long side of each plot following the direction of the maximum slope, including three rows of 6 trees. The average plot slope was 12 %.

Fava bean cultivation in the AC treatments was always carried out in early September, manually, in three rows in each of the aisles, separated 1 m, leaving a plant spacing of 0.4 m in each row to achieve a density of 2.5 plants m^{-2}. Barley/vetch seeds (1:3 ratio) were manually sown in AC1 throughout the aisle at 150 kg ha^{-1} in February. Purslane seedlings were manually planted in AC2 in May 2019, in three rows in each of the aisles, separated 1 m, leaving a plant spacing of 1 m in each row to achieve a density of 1 plant m^{-2}. Cowpea was manually sown in July 2020 in three rows in each of the aisles, separated 1 m, leaving a plant spacing of 0.2 m in each row to achieve a density of 5 plants m^{-2} (Supplementary Figure S1).

Tillage was carried out up to 30 cm before sowing/planting to prepare soil for cultivation, and after harvest to incorporate plant residues as green manure. Due to climatic conditions, the alley crops were irrigated using a drip irrigation system consisting of three lines of 4 L h^{-1} dripper every 0.4 m per alley. This irrigation system was semi-independent from that of the mandarin trees for each AC plot, i.e. only when the trees were irrigated was it possible to schedule the opening or closing of the alley irrigation sector, so that fertilisation of secondary crops only occurred when the mandarin trees were fertigated. The ETc of each crop was estimated according to the FAO balance (Allen et al., 1998) and were irrigated according to water availability and effective rainfall, although at sowing or transplanting a 1.5 h irrigation was applied to overlapping of the wetting bulb of the drippers. For AC1 and AC2, the crop coefficients ranged between 0.25 and 0.55 proposed by the Agricultural Information System of Murcia (http://siam.imida.es) for this area. No irrigation was performed in the alleys of MM.

Consumption of water in MM during the period of the experiment was 8246.7 m^3 ha^{-1} for mandarin. While, in AC1 the water consumption was 6433 m^3 ha^{-1} for mandarin (a 78 % of the control, RDI), 1526 m^3 ha^{-1} for fava bean and 1771 m^3 ha^{-1} for barley/vetch (a total of 9625 m^3 ha^{-1} for the study period). Water consumption in mandarin trees in AC2 was the same as in AC1 (6433 m^3 ha^{-1}, RDI), but we need to add the water needed for the alley crops (59 m^3 ha^{-1} for fava bean, 524 m^3 ha^{-1} for purslane, and 1005 m^3 ha^{-1} for cowpea), giving a total of 7963 m^3 ha^{-1} for the study period.

Usual cultural practices (e.g., fertilization, pruning, fruit thinning and banding) were carried out by the technical department of the commercial orchard. In the MM treatment, weed control was carried out through chisel ploughing two times a year, to a depth of 20 cm. Weeds were not controlled in AC plots. Mandarin pruning was carried out in February in all cycles, chopped in situ using a rotary tiller and incorporated as mulch only in MM and AC2, since in AC1 the aisles were covered with barley/vetch. In MM, an average amount of 12.20 kg of mandarin pruning was incorporated into the soil (11.35 kg in 2019; 12.83 kg in 2020 and 12.40 in 2021). In AC2, an average amount of 20.66 kg of mandarin pruning was incorporated into the soil (15.20 kg in 2019; 19.57 kg in 2020 and 27.21 in 2021). For MM and AC2, Mandarin pruning was in the soil as mulch for a month, until the next

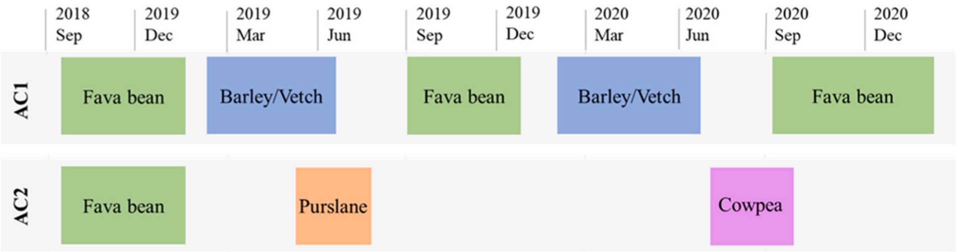

Fig. 1. Schedule of the alley crops grown in the two AC treatments.

crop was planted (AC2). Fertilizers were applied by fertigation, by use of the commercial products Neptuno PK 28, Neptuno Triton and Neptuno Pandora (Medifer, Constantino Gutiérrez, SA), as a mixture of soluble N, P, K, Ca, Mg and chelated micronutrients. Table S1 shows the quantity of N, P and K added with fertilizers per treatment and crop in five months periods.

2.3. Soil sampling and analyses

Soil samplings were carried out on 21/02/2019 and 17/02/2021. Samples were taken with an Edelman auger at two depths (0–10 cm and 10–30 cm). Three composite soil replicates were taken in each plot, each consisting of five random sampling points. Samples were air-dried and then divided into two aliquots: one not sieved to perform soil aggregate analysis, and another one sieved < 2 mm for the rest of the properties. Bulk density was also determined at two depths (0–10 cm and 10–30 cm) using the cylinder method (Campbell and Hensall, 1991). In each plot, saturated hydraulic conductivity (K_s) was measured during the soil sampling using the ring method proposed by Bagarello et al. (2012). The procedure to determine K_s is as follows: a 0.15 m diameter and 0.10 cm high ring (0.007 m^3 of volume) is inserted about 1 cm into the soil, 0.15 L of water are poured into the cylinder, and the time it takes for the volume of water to infiltrate is measured. Water infiltration times range from 10 s to about 15 min. The same volume (0.15 L) continues to be added, recording the time until the steady-state of infiltration I is reached, i.e., the infiltration time remains constant. When plotting the cumulative I $\sqrt{t}^{-1}$ versus $\sqrt{t}^{-1}$, the slope of the obtained regression corresponds to the infiltration rate, IR (mm s^{-1}). Then, K_s (mm s^{-1}) can be determined by using the following Eq. 1:

$$K_s = \frac{IR}{0.467\left(1 + \frac{2.92}{r \quad \alpha^*}\right)} \tag{1}$$

Where r (m) is the radius of the ring used, and α* (mm^{-1}) is a parameter calculated with the infiltration rate: 0.0262 + 0.0035 ln (IR).

Moisture at field capacity (FC) and wilting point (WP) were determined as follows: the soil sample was placed on a porous ceramic plate, a pressure of - 33 kPa (for FC) and - 1500 kPa (for WP) was applied, and the water content was measured gravimetrically using a Soil Moisture Equipment (Corp., Santa Barbara, CA), as described by Dirksen (1999). Volumetric values were calculated by multiplying the gravimetric measurements by the bulk density values obtained previously. These two parameters were used to calculate the amount of water available to the plants (AW) according to Eq. 2:

$$AW = FC - WP \tag{2}$$

Aggregate size distribution and mean weight diameter were determined using the wet sieving method proposed by Elliot (1986) and modified by Six et al. (2000). This method is based on the wet sieving of a determined quantity of soil aggregates (between 50 and 100 g), using sieves of decreasing diameter (2000, 250 and 53 µm), the soil is sieved for two minutes by moving the sieve up and down (3 cm amplitude, approximately) 50 times. After that, the sieve is left stand for 30 s and the soil sample is collected from the sieve using water and then drying each fraction at 105 ºC. Proportions of aggregates of sizes between 8000 and 2000 µm, 2000 and 250 µm, 250 and 53 µm, and those smaller than 53 µm were determined. The mean weight diameter (MWD) (Klute et al., 1986) was determined from these proportions according to Eq. 3:

$$MWD = \sum_{i=1}^{4} x_i w_i \tag{3}$$

Where x_i is the average diameter of each of the separated aggregate fractions (5000, 1125, 101.5 and 26.5 µm, respectively), and w_i is the proportion of each fraction.

In addition, other properties related to soil chemistry were measured in these soils. Properties related to organic matter (total organic carbon (TOC), total particulate carbon (POC), and total nitrogen (T_N)) were determined, and bioavailable manganese (Mn_{ba}) and copper (Cu_{ba}), and the amount of calcium carbonate have also been measured. The results obtained for these properties are summarised in Table S2. TOC was determined using an elemental analyser, with sieved (2 mm) and ground samples from which $CaCO_3$ was removed by 2 N HCl (Álvaro-Fuentes et al., 2019). T_N was determined using the same method but omitting the carbonate removal step. POC was determined according to the (Cambardella and Elliott, 1992) method. Mn_{ba} and Cu_{ba} were extracted with 0.05 M DTPA (pH 7.3) (Lindsay and Norvell, 1978). In all extracts obtained, the elements were measured using an ICP-MS (Agilent 7900).

2.4. Crop production and quality

Crop productions were measured directly by harvesting the production of each plot and determining the weight of each crop. Mandarins were harvested on 24/01/2019, 07/01/2020 and 03/02/2021; barley/vetch on 13/06/2019 and 22/06/2020; fava bean on 09/01/2019, 23/12/2020 and 12/02/2021; purslane on 06/07/2019; and cowpea on 22/09/2020. Barley/vetch and purslane productions were determined by weighing the aerial biomass, since the final use for barley/vetch was fodder and purslane fresh food. Fava bean was harvested by collecting all the pods in each plot when the seeds were fresh, while cowpea when the seeds were dry.

We determined the overall land production (kg ha^{-1}) as the sum of all crops in each treatment per year. In addition, in mandarins, average weight per fruit (g), soluble solids amount (° Brix), juice pH, titratable acidity (g L^{-1}), juice percentage (%), acidity degree (%) and sugar content (° Brix) were determined. In fava bean and cowpea seeds we measured thousand kernel weight (g), moisture (%) and protein content (%). Table S3 summarizes the data related to crop production and quality.

2.5. Statistical analysis

The normality of the distribution of the data obtained for each property was tested by means of a Kolmogorov-Smirnov test ($p < 0.05$). To analyse the temporal evolution of the measured properties, we subtracted the initial average value of each property (21/02/2019 sampling) from the final value (17/02/2021 sampling), divided it by the initial value and multiplied the result by 100, as shown in the following equation:

$$\text{Property evolution with time } (\Delta) = [(\text{Final value - Initial value}) / \text{Initial value}] \times 100 \quad (4)$$

A two-way ANOVA test was used to determine if there were significant differences between the evolution of the soil properties considering the different treatments and the two depths. For variables where depth is not considered, one-way ANOVA was used. To determine the normality of the ANOVA residuals, histograms were analysed. Correlations between crop properties and soil physical properties were established by using Pearson's coefficient.

A principal component analysis (PCA) was also carried out considering the Δ values of both, soil properties and those related to the crop and its nutritional quality. Previously, all variables were standardized using their mean and standard deviation: Standard $\Delta = (\Delta - \text{Average } \Delta)/\text{sd}(\Delta)$. For the statistical analysis, the IBM SPSS software for Windows, Version 20 was used.

3. Results

3.1. Soil properties

Table 1 shows the average results of the soil properties for the different treatments, at the two depths sampled on the two sampling dates. Table 2 shows the evolution in two years (Δ) of the moisture-related properties field capacity (FC); moisture proportion at wilting point (WP); available water proportion (AW), as well as aggregate mean weight diameter (MWD), bulk density (ρ_D), and saturated hydraulic conductivity (K_s).

As can be seen in Table 2, ΔFC decreases in most cases, and there is only a small increase in AC1 surface samples (increases 3.17 %), and in MM subsurface samples (increases 1.22 %). If we perform a two-way ANOVA considering treatment and depth, we see that ΔFC depends on treatment (F = 5.84; sig. = 0.01), but not on depth (F = 0.19; sig. = 0.66) (Table 3). In the case of treatment, it is the AC2 treatment the one that differs, FC loss in this treatment is significantly higher than in the other two. On the other hand, the interaction treatment/depth also showed significant differences (F = 6.26; sig. = 0.00).

In the case of ΔWP, the trend is the same in all treatments: there is a decrease in the values of this property. This decrease is more pronounced in the AC2 soils at both depths, especially when compared with the results obtained for AC1. However, there is no significant effect of the depth or the interaction between the two factors (treatment and depth).

ΔAW increases in the types of treatments and at the two depths, but no significant differences are observed with respect to this parameter. The increase is slightly higher in AC1 samples (16.87 %), and more discrete in AC2 samples (9.61 %). In absolute values, the AC2 samples already started from significantly higher AW values than AC1 (F = 13.28, sig. = 0.00) and MM (F = 4.39, sig. = 0.04) (Table 1). It was also observed that the increase in ΔAW is slightly higher at subsurface level (15.80 %) than at surface level (12.46 %).

Regarding the ΔMWD, the trend in AC1 is clear: aggregate size decreases in surface (-45.53 %) and subsurface samples (-33.53 %). In the other two treatments this decrease is not so evident or does not occur, so there are significant differences in the evolution of MWD with respect to treatment (F = 7.045, sig. = 0.001). Neither depth nor treatment/depth interaction produced significant differences in the evolution of MWD.

In general, the ρ_D has decreased in all treatments and at both depths, except in AC1 surface samples ($\Delta\rho_D$). In this case there is a considerable increase in the $\Delta\rho_D$ (32.78 %). If we consider the subsurface sampling, there is a discrete decrease in $\Delta\rho_D$ (-4.62 %). Therefore, on average, in this treatment there was a compaction. Moreover, if we analyse the significant differences, with the raw data (Table 1), we can observe that during the first year we cannot find significant differences between the treatments, while in the second year, AC1 presents a significantly higher ρ_D, both at surface level (F = 54.884, sig. = 0.00) and subsurface level (F = 11.356, sig. = 0.00).

K_s increased in all treatments, but this increase was greater in the MM soils. In this treatment, K_s values were very similar in 2019 (between 4.03 and 4.54 mm h^{-1}) and reached values around 16 mm h^{-1} in 2021 ($\Delta K_s = 307.49$ %) (Table 2). In the other two treatments, the ΔK_s was lower, in AC1 the increase was 77.83 %, while in AC2 K_s increased by 134.48 %. Despite these differences, no significant differences were found with regard to treatment.

The properties mentioned in previous paragraphs showed good correlations with other properties related to soil chemistry. For example, the amount of $CaCO_3$ was directly related to AW ($R^2 = 0.22$, N = 108), while was inversely related to WP ($R^2 = -0.16$, N = 108). On the other hand, MWD was directly correlated with bioavailable manganese and copper ($R^2 = 0.21$, N = 108 and $R^2 = 0.22$, N = 108, respectively) and with properties such as total nitrogen ($R^2 = 0.21$, N = 108), total organic carbon ($R^2 = 0.36$, N = 108) and POC ($R^2 = 0.17$, N = 108).

3.2. Relationships between soil properties and crop production and quality-related parameters

If we consider the first year (2019), no clear trends were observed when comparing raw soil data (not Δ) with production results. However, by 2021, certain trends were already beginning to emerge. For example, those plots with higher available water (MM and AC1) produced fruits

Table 1
Average results (with standard errors) of the properties considered for the different treatments, at the two depths sampled on the two sampling dates.

Sampling date: 21/02/2019							
Depth	Treatment	FC	WP	AW	MWD	ρ_D	K_s
0–10 cm	MM	0.278 ± 0.003	0.146 ± 0.007	0.132 ± 0.007	0.981 ± 0.097	1.24 ± 0.03	4.24 ± 0.15
	AC1	0.253 ± 0.004	0.133 ± 0.007	0.120 ± 0.006	0.853 ± 0.077	1.16 ± 0.04	5.54 ± 1.38
	AC2	0.278 ± 0.002	0.134 ± 0.004	0.144 ± 0.003	0.473 ± 0.059	1.32 ± 0.06	2.72 ± 0.35
10–30 cm	MM	0.265 ± 0.002	0.142 ± 0.006	0.123 ± 0.004	0.522 ± 0.057	1.55 ± 0.09	
	AC1	0.271 ± 0.004	0.156 ± 0.008	0.115 ± 0.007	0.857 ± 0.090	1.47 ± 0.04	
	AC2	0.274 ± 0.004	0.140 ± 0.005	0.135 ± 0.007	0.569 ± 0.047	1.65 ± 0.06	
Sampling date: 17/02/2021							
Depth	Treatment	FC	WP	AW	MWD	ρ_D	K_s
0–10 cm	MM	0.267 ± 0.003	0.122 ± 0.004	0.145 ± 0.004	0.827 ± 0.075	1.19 ± 0.03	16.64 ± 1.15
	AC1	0.261 ± 0.003	0.122 ± 0.004	0.139 ± 0.003	0.466 ± 0.064	1.52 ± 0.02	8.45 ± 1.75
	AC2	0.265 ± 0.003	0.113 ± 0.002	0.153 ± 0.002	0.503 ± 0.066	1.22 ± 0.02	5.94 ± 0.82
10–30 cm	MM	0.268 ± 0.002	0.133 ± 0.002	0.146 ± 0.002	0.530 ± 0.054	1.20 ± 0.03	
	AC1	0.262 ± 0.005	0.133 ± 0.006	0.129 ± 0.005	0.513 ± 0.061	1.40 ± 0.04	
	AC2	0.259 ± 0.002	0.109 ± 0.002	0.149 ± 0.003	0.470 ± 0.058	1.23 ± 0.02	

MM, mandarin monocrop; AC1, alley cropping system 1; AC2, alley cropping system 2; FC, field capacity; WP, wilting point; AW, available water; MWD, aggregate mean weight diameter (mm); ρ_D, bulk density (g cm^{-3}); and Ks, saturated hydraulic conductivity (mm h^{-1}).

Table 2

Average evolution with time of the properties considered (Δ, in %) for the different treatments, at the two depths sampled, with standard errors.

Depth	Treatment	ΔFC	ΔWP	ΔAW	ΔMWD	$\Delta\rho_D$	ΔK_s
0–10 cm	MM	−3.98 ± 0.98	−14.96 ± 3.94	11.85 ± 6.79	−6.38 ± 14.71	−3.48 ± 0.46	307.49 ± 33.58
	AC1	3.17 ± 1.50	−6.75 ± 4.20	19.16 ± 9.81	−45.53 ± 5.31	32.78 ± 5.12	76.83 ± 54.31
	AC2	−4.55 ± 1.12	−15.48 ± 2.29	6.38 ± 3.16	11.63 ± 14.64	−6.21 ± 5.33	134.48 ± 66.47
10–30 cm	MM	1.22 ± 1.49	−12.74 ± 4.32	19.96 ± 4.85	10.67 ± 14.16	−20.74 ± 2.54	
	AC1	−2.75 ± 2.49	−12.70 ± 5.63	14.59 ± 6.10	−33.53 ± 11.98	−4.62 ± 6.08	
	AC2	−5.52 ± 1.42	−20.81 ± 2.85	12.85 ± 5.31	−15.24 ± 9.93	−24.36 ± 4.47	

MM, mandarin monocrop; AC1, alley cropping system 1; AC2, alley cropping system 2; FC, field capacity; WP, wilting point; AW, available water; MWD, aggregate mean weight diameter; ρ_D, bulk density; and K_s, saturated hydraulic conductivity.

Table 3

Significance values of the two-way ANOVAs performed for the different properties considering treatment, depth and the interaction between both (Treatment * Depth).

	ΔFC	ΔWP	ΔAW	ΔMWD	$\Delta\rho_D$
Treatment	0.005*	0.122	0.467	0.002*	0.000*
Depth	0.665	0.362	0.522	0.942	0.000*
Treatment * Depth	0.004*	0.531	0.557	0.157	0.034*

with a higher sugar content ($R = 0.73$, $p < 0.05$).

On the other hand, considering the Δ values (both for soil and crop properties), we can observe some significant correlations. For example, ΔFC at surface (0–10 cm) is correlated with ΔMandarin average weight ($R = 0.84$, $p < 0.05$), with the ΔTotal soluble solids ($R = -0.76$, $p < 0.05$), and with the Juice pH ($R = 0.78$, $p < 0.05$). Furthermore, the ΔAW, also offers a significant correlation with the Δ of fruit production ($R = 0.74$, $p < 0.05$). Finally, we also found significant correlations including the ΔMWD: with the ΔTotal soluble solids ($R = 0.68$, $p < 0.05$) and with the ΔJuice pH ($R = -0.84$, $p < 0.05$).

3.3. *Principal component analysis results*

Regarding the PCA, using the standardized Δ variables of soil and crop properties, the first two components explained more than 77 % of the variance (Fig. 2). The first factor (PCA 1), which explains 56.79 % of the variance, can separate the three treatments, giving negative values to AC1, values close to zero to AC2 and positive values to MM. In AC1 there are greater increases in ρ_D, and fruit weight, while sugar content, K_s and MWD decrease a lot (Table 4). At the other extreme we have the data from MM, samples in which the opposite occurs, ρ_D decreases slightly, and the increase in average fruit weight is more discrete, while MWD remains the same or even increases a little. In component 2 (PCA 2, 20.64 %) it is not possible to differentiate treatments, but it informs us that the lost in fruit production in the three systems is not so important when the AW levels are higher (Table 4).

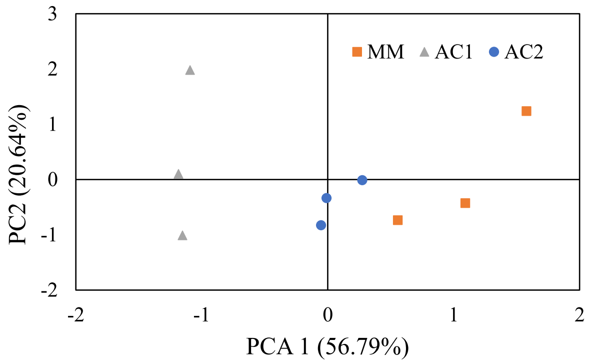

Fig. 2. Representation of the two main components of the PCA, which explain 77.43 % of the variance. Different colours represent different treatments.

Table 4

Loading matrix of the PCA for the two mains principal components (with the percentage of variance explained).

	Component	
	First Component (56.79 %)	Second Component (20.64 %)
ΔMandarin production	−0.331	0.862
ΔAverage fruit weight	−0.890	0.297
ΔTitrable acidity of the juice	0.958	0.152
Δ% of juice per fruit	−0.660	0.331
ΔTotal soluble solids	0.941	−0.067
ΔK_s	0.631	−0.272
ΔAW	0.116	0.969
ΔMWD	0.843	0.158
$\Delta\rho_D$	−0.783	0.298

4. Discussion

In all treatments, the amount of available water increases since the loss of WP moisture is always much higher than the FC loss. This is also noticeable in Δ values (Table 2). This gain in AW may be caused, in many cases, by differences in the amount of organic carbon. The MM treatment is a soil that possesses a slightly higher amount of TOC than AC1 and AC2, which would allow MM to store more AW (Fig. 3C). One of the parameters that offer a good correlation with AW content is the amount of calcium carbonate in the soil ($R^2 = 0.22$, $N = 108$), a relationship maintained regardless of depth. This has already been observed in previous studies (Duniway et al., 2010; Abrol et al., 1968), and the origin is not so clear, but may be caused by a reduction in moisture at WP. In this respect, Duniway et al. (2007) observed that AW was significantly negatively correlated with calcium carbonate, which disagree with our results, where the relationship between WP and calcium carbonate is also negative ($R^2 = -0.16$, $N = 108$). Our results could be explained by the formation of calcium carbonate precipitates on the the surface area of the small pores, blocking these pores and reducing the WP.

MWD was significantly reduced in the AC1 samples at both depths (Table 2), while in MM and AC2 this property remained constant (Fig. 4). In fact, a slight increased was observed in AC2 surface samples (ΔMWD = 11.63), and in MM subsurface samples (ΔMWD = 10.67). MWD was found to be significantly (and positively) correlated with soil organic matter related parameters: total organic carbon ($R^2 = 0.36$, $N = 108$), POC ($R^2 = 0.17$, $N = 108$), and T_N ($R^2 = 0.21$, $N = 108$). This makes sense since soil aggregation plays an important role in the retention of soil organic carbon as well as it protects against the decomposition (Six et al., 2000). The effect of organic matter on soil stabilization and in the development of a more complex structure has been known for years (Chaney and Swift, 1984). These results suggest that the loss of organic matter that has taken place in AC1 soils was caused by an increase in the frequency of tillage, since tillage disturbs the aggregate formation and thus it affects the soil organic associated with the aggregates (Six et al., 2002). In contrast, Li et al. (2024a, b) observed that different crop diversification strategies (cover cropping,

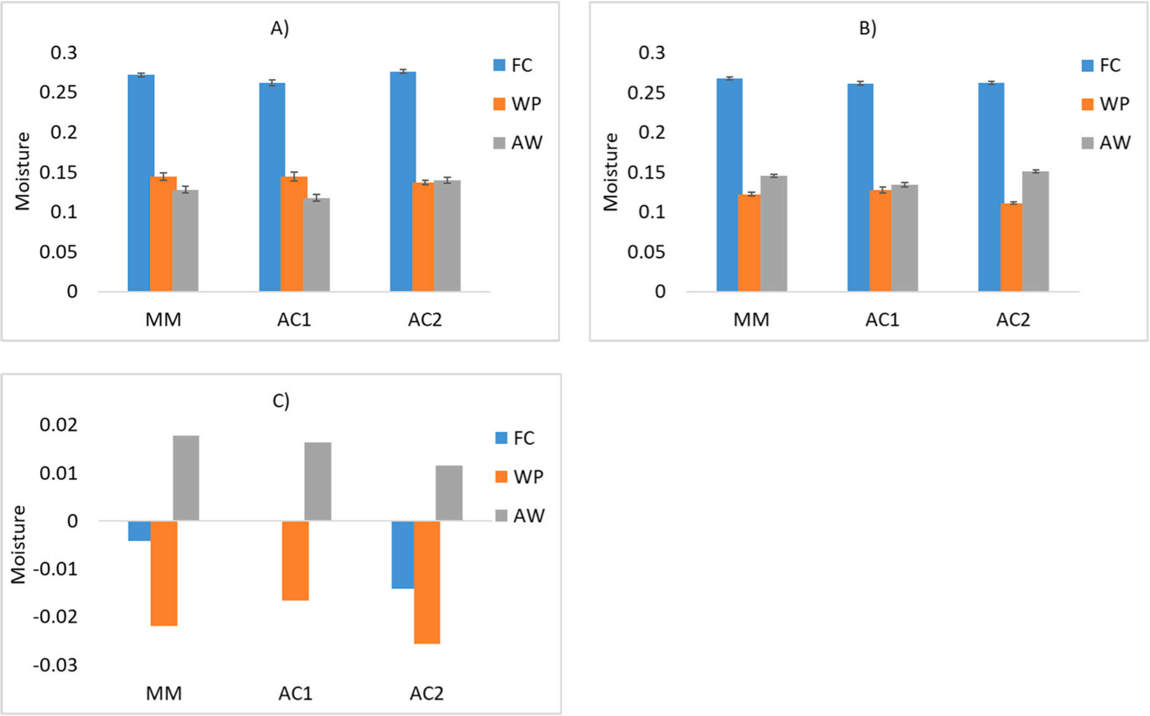

Fig. 3. Moisture at field capacity (FC), moisture at wilting point (WP), and available water (AW), in the three treatments (monocrop, MM; alley cropping 1, AC1; and alley cropping 2, AC2) in the A) 2019 and B) 2021 samplings. C) Shows the differences between the data obtained in both years (2021–2019). In these graphs, the mean raw value (not Δ) of the two depths was considered.

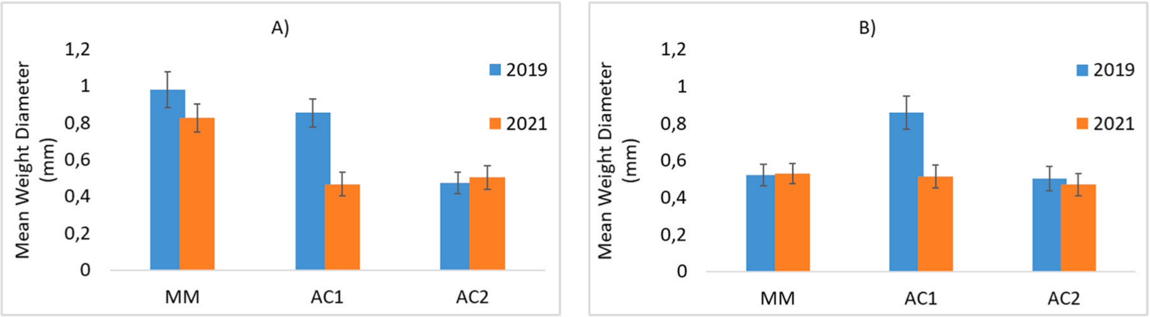

Fig. 4. Variation of the aggregate mean weight diameter (mm) between the two samplings (2019 and 2021) in A) superficial (between 0 and 10 cm depth); and B) subsurface (between 10 and 30 cm depth) samples. In these graphs, the raw values (not Δ) were considered.

crop rotation, and intercropping) significantly increased both the MWD and total organic carbon of the soil. This is consistent with the fact that diversified agricultural systems contribute greater amounts of organic residues and root biomass, which enhance the labile organic carbon pools in the soil. Labile carbon serves as a binding agent that promotes aggregate formation and stability. In this context, tillage in the short term, when compared to organic inputs, may disrupt soil aggregates and accelerate the mineralization of organic matter, leading to carbon losses and reduced aggregate stability (Huang et al., 2016). These negative effects can be mitigated by the incorporation of organic residues, which stimulate microbial activity and contribute to the stabilization of soil aggregates (Björsell et al., 2017). Likewise, the implementation of a drip irrigation system in AC1 and AC2, compared to MM, promotes the improvement of soil aggregate structural stability, particularly in clay-textured soils. This is because localized irrigation helps maintain optimal moisture levels, which in turn enhance microbial activity and the accumulation of organic matter, both key factors in aggregate formation and stabilization (Alshami et al., 2024). However, the full benefits of organic inputs in a crop diversification system typically manifest over the long term, as organic matter accumulates, microbial communities stabilize, and aggregate stabilization processes mature (Wang et al., 2022). On the other hand, although crop rotation can provide C inputs in the belowground, since it mitigates the soil carbon losses (Tiemann et al., 2015), the lower values of organic carbon in AC1 regarding AC2 soils could be caused by the fact that pruning residues were not incorporated into the soil. Finally, the removal of part of that organic matter with the harvest of the crops in this diversification could be linked to these losses of organic matter. It is important to note that, in the case of AC2, despite presenting a lower MWD during the first year and suffering the same tillage frequency as AC1, it is a soil that, at the surface, experiences an increase in aggregate size. Aliba et al. (2020) observed that, under a system in which conventional tillage is carried out, cowpea produces slightly larger soil aggregates than those generated in a control soil without tillage. In addition, it has been observed that higher MWD values contribute to an increase in intra-aggregate porosity (Zhang, 1994), which improves the soil's capacity to store substances (Bedel et al., 2018). For this reason, MWD offers significant correlations with bioavailable elements such as manganese ($R^2 = 0.21$, N = 108) or copper ($R^2 = 0.22$, N = 108). Regarding K_s, this parameter increased in all treatments, but the increase is more noticeable in MM soils ($\Delta K_s = 307.49 \pm 33.58$ %), compared to AC1 ($\Delta K_s = 76.83 \pm 54.31$ %) and AC2 ($\Delta K_s = 134.48 \pm 66.47$ %). On the one hand, the frequency of tillage in MM soil was lower than in the other two, which translates into less soil compaction and less rupture of the natural soil porosity. The effect of the machinery on the soil produces soil compaction, a factor that limits the flow through the soil (Nakano and Miyazaki, 2005). In addition, soil preparation works break the continuity of the naturally created pores, altering the movement of water and dissolved substances through them (Soto-Gómez et al., 2020). In this respect, Kreiselmeiera et al., (2020) observed stronger increases of K_s on a reduced tillage treatment. This fact was explained by a higher availability of organic material in the topsoil of the reduced tillage compared to the conventional tillage treatment. This makes sense in this study, since MM soil showed higher organic carbon content (10.5 g kg^{-1} in 2019 and 10.4 g kg^{-1} in 2021) compared to soils under diversification systems (8.9 g kg^{-1} in 2019 and 8.5 g kg^{-1} in 2021) (Sánchez-Navarro et al., 2023). On the other hand, the effect of the machinery is easily visible when comparing the results of bulk density: the greatest decrease in this parameter occurs in the subsurface samples of AC2 (where it decreases by about 24 %), and the greatest increase occurs in the surface samples of AC1 (where it increases by more than 30 %). Moreover, in AC soils, the plants caused an increase in sedimentation and a reduction of erosion (Fig. 5), which also translates into the mobilization of finer particles towards the alley and clogging of the smaller pores, with a consequent increase ρ_D and reduction in K_s (Jennings et al., 1988). Despite this, it is important to note that in all cases there is an increase in K_s, even in AC soils, this may be caused by the porous system of the crops used in the alley. Soto-Gómez et al. (2019) demonstrated that the root system has a crucial role in the transport of fluids and particles. Also, the huge increase in K_s in MM soils can be caused by the effect of temperature changes in unprotected soils (Rayhani et al., 2007), during long drought cycles, the plastic behaviour of clays can lead to the appearance of cracks that favour the movement of water through the soil, increasing its K_s.

It is difficult to establish correlations between physical properties and those related to crop production and quality, since there are certain non-soil factors that have strongly conditioned production. For example, during the last year there was a significant drop in mandarin production caused by a plague of *Alternaria spp*. However, we found some significant relations considering the Δ values. For example, Δ in FC is correlated with the Δ Mandarin average weight, with the Δ Juice pH, and with the decrease of Δ Total soluble solids. The relationship between mandarin size and the ΔFC is very similar to the relation found between ΔAW and mandarin production, and has been previously described in mandarin fields (Kirda et al., 2007), the more the available water, the more the trees are going to absorb, and the bigger the fruits. On the other hand, the increase in the amount of water at field capacity reduces the hydric stress and avoids the need for the production of secondary metabolites (such as sugars, vitamins and acids), so the amount of total soluble solids is reduced and the pH of the juice is not as acidic (Ripoll et al., 2014). Yakushiji et al. (1996) found that the accumulation of acids and sugars in the fruit is an osmoregulation method that the mandarin tree uses as protection against water stress, and not a result of dehydration of the fruit. This is very interesting, considering that the irrigation of AC1 and AC2 had been reduced (RDI), but still the mandarin trees did not suffer from water stress.

The importance of MWD on production is not so clear, but we observed that ΔMWD is directly related to ΔTotal soluble solids and inversely related to ΔJuice pH. Stine, Weil.. (2002) pointed out that macro-aggregate stability is related to crop productivity, since the formation of more stable aggregates may be related to better water storage and higher nutrient availability. This last point, nutrient availability, can be responsible for the increase of soluble solids and the accumulation of acids in the fruits (decreasing the pH).

Considering the lack of improvements in terms of soil available water and structure after the establishment of these diversification systems, other agricultural management practices are needed. The best choice could be the introduction of diversification systems with cover crops or perennial crops, which would reduce or eliminate the tillage, maintain soil moisture conditions and provide organic matter. Meanwhile, reduced tillage or no-tillage practices have a key role of maintaining soil structure (Bhattacharyya et al., 2022) and improving water infiltration and retention (Canet-Martí et al.,2023; Wuest et al., 2023). This approach would improve soil available water and structure and thus, the mandarin crop quality parameters and yield linked to these soil physical properties.

5. Conclusions

In several plots within a mandarin monoculture (MM), two types of alley crop rotations were tested: AC1, which consisted of a multiple cropping of fava beans with a barley/vetch mixture; and AC2 plots, in whose alleys, fava beans, purslane and cowpea were rotated. In both alley crop rotations, mandarin irrigation was reduced by 78 % regarding

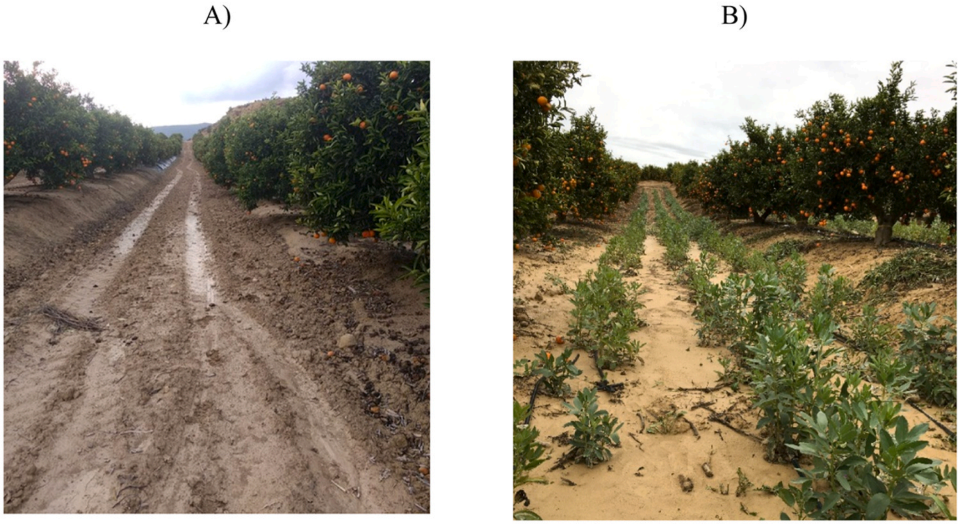

Fig. 5. Photographs of two of the plots, A) control (MM), with the alley uncultivated, and B) diversification 1 (AC1), with fava beans in the alley, after a heavy rainfall event.

the control (MM). A series of analyses of the soils physical and crop properties were carried out on two dates, separated by about two years (21/02/2019 and 17/02/2021), and the evolution (Δ) of the soil in the alley crop systems was analysed and compared with the control.

In general, we could not find huge differences between the evolution of soil physical properties when comparing the three treatments. It was observed that there was an increase in available water in all treatments, at the two depths studied, even though irrigation was reduced by 78 % in AC1 and AC2. On the other hand, the MWD decreased in all three treatments, if we consider the average of the first 30 cm of the soil, but this value increased in surface samples from AC2 (11.63 %) and in subsurface samples from MM (10.67 %). The K_s increased in all treatments. This increase was much higher in MM, where the mean in 2021 was three times higher than in 2019. Finally, we found that some physical properties seem to be related to the mandarin production and crop quality: plots with more moisture at field capacity and available water produce bigger mandarins, with pH more neutral and less proportion of soluble solids; and in the treatments that favour the formation of stable aggregates, the fruits have a higher concentration of acids and soluble solids. In order to appreciate the effect of diversified crops on the soil physical properties, it would be necessary to establish the mandarin crop diversifies with cover crops or perennial crops in a long-term period. Moreover, focusing exclusively on physical parameters limits the understanding of overall soil health, which also depends on chemical and biological factors. Therefore, this study should comprehensively assess the concurrent evolution of the soil's physical, chemical, and biological parameters alongside the indicators of fruit quality and yield. This approach will enable the establishment of clear causal relationships and the development of management strategies that enhance both soil sustainability and crop quality

CRediT authorship contribution statement

Virginia Sánchez-Navarro: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Diego Soto-Gómez:** Writing – original draft, Methodology, Investigation, Conceptualization. **Alejandro Pérez-Pastor:** Writing – review & editing, Methodology. **Fernández Juan A Antonio:** Writing – review & editing, Investigation, Conceptualization. **Silvia Martínez-Martínez:** Writing – review & editing, Methodology, Investigation. **Jose A. Acosta:** Writing – review & editing, Methodology, Data curation. **Josefina Contreras:** Writing – review & editing, Methodology, Investigation. **María Martínez-Mena:** Writing – review & editing, Investigation, Conceptualization. **Almagro Maria:** Writing – review & editing, Methodology, Investigation. **Elvira Díaz-Pereira:** Writing – review & editing, Methodology, Conceptualization. **Carolina Boix-Fayos:** Writing – review & editing, Investigation, Conceptualization. **Pablo Berrios:** Writing – original draft, Methodology, Data curation. **Abdelmalek Temnani:** Writing – original draft, Methodology, Investigation, Data curation.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109982.

Data availability

Data will be made available on request.

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