1 Long-term effects of sustainable management practices on soil properties and
2 crop yields in rainfed Mediterranean almond agroecosystems

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12 Abstract

13 The long-term effects of conservation agriculture on soil physical and chemical properties
14 and their relationship with crop yields are still relatively poorly understood. In addition,
15 the effects of those practices ranged widely depending on climatic and edaphic conditions
16 and so they cannot be generalized for all agro-ecological regions and crop types. This
17 study evaluates the effects of three conservation agriculture practices - reduced tillage
18 (RT), reduced tillage plus incorporation of green manure (RTG), and no-tillage (NT) - in
19 the soil quality on almond orchards under semiarid conditions and the soil factors
20 explaining crop yield under these management practices. The soil physical indicators used
21 were bulk density, resistance to penetration, total porosity, air capacity, relative field
22 capacity, available water content, infiltration rate and field plant-available water content.
23 The chemical parameters evaluated were soil organic carbon, total nitrogen, nitrate, and
24 available phosphorus. Changes in the soil physical properties with the incorporation of
25 green manure and with no-tillage, relative to RT were, mainly detected in the 5-15 cm
26 soil layer, where improvements in soil water availability were observed. In addition, there

was a positive effect of both green manure and no-tillage on the infiltration rate relative to RT. The shift from RT to RTG led to an improvement in total soil organic carbon and nitrogen, resulting in a positive effect on crop yield after six years of implementation. No-tillage led to a decline of about 70% in crop yield with respect to the tillage treatments, despite the improvement in the soil available water content from the first year of its adoption. However, a strong decrease in the concentrations of available nitrogen was the factor mainly responsible for the crop yield reductions under NT.

Introduction

Rainfed agroecosystems in semiarid Mediterranean conditions are characterized by complex climatic particularities (rainfall is highly unreliable, with strong risks of dry spells during the crop growth season, even during good rainfall years) and high interannual and spatial fluctuations of rainfall (Oweis and Hachum, 2009), which lead to water scarcity for crop production (Fernández-Ugalde et al., 2009).

Hence, agriculture in these areas is focused on capturing the maximum amount of water through soil management practices that reduce transpiration, maximize water use efficiency (McVay et al., 2006; Su et al., 2007), and reduce water losses by runoff (Gregory et al., 2000). Minimum tillage and no-tillage are examples of such practices, grouped together in conservation agriculture. The success of conservation agriculture systems is based on diversification through crop rotation and cover crops and on continuous, permanent application of no-tillage or minimum mechanical soil disturbance (FAO 2008; Kassam et al., 2009; 2014). As a way to achieve sustainable food production with minimal impact on the soil and atmosphere, conservation agriculture is becoming more and more important (Busari et al., 2015).

51 Conservation agriculture improves the water availability to crops (Fernández-Ugalde,
52 2009; Mutonga et al., 2019), the use efficiency of inputs, in particular nitrogen (N)
53 (Kumar et al., 2014; Carranca et al., 2018), physical and chemical soil properties, such as
54 the soil organic carbon, and the soil biological status (Melero et al., 2009; Bottinelli et al.,
55 2010), thus enhancing the edaphic environment. In addition, these practices might
56 increase the water availability to crops enhancing N uptake, with positive effects on
57 productivity (Renwick et al. 2019). The effects of conservation agriculture on several
58 physical and chemical indicators of soil quality (bulk density, resistance to penetration,
59 soil organic carbon, etc.) and, consequently, on yields have been reported (Armenise et
60 al., 2013, Singh et al., 2016; Hondebrink et al., 2017; Saikia et al., 2019). The physical
61 indicators, for example, are related to soil structure and affect nutrient availability and
62 plant growth (Ramzan et al., 2019; Chandrasekhar et al., 2019), thus affecting crop yields.
63 Compared to conventional systems, conservation agriculture has been found to maintain
64 or increase yields, reduce operational costs and machinery requirements, improve soil
65 fertility, and reduce erosion (Kassam et al., 2012; Corbeels et al., 2018).

66 No-tillage has gained popularity over the last half-century. The fact that the soil is not
67 tilled and remains permanently covered with crop residues leads to a better nutrient use
68 efficiency, increased nutrient availability from biological activity, soil carbon
69 sequestration, better conservation of water, and improved energy efficiency (Lal et al.,
70 2007; Mangalassery et al., 2015). However, the benefits of no-tillage are highly site-
71 specific and therefore cannot be generalized for all agro-ecological regions due to the
72 large variability in soil and climatic conditions (German et al., 2016; Jat et al., 2017).

73 In this regard, contradictory results have been reported about the effects of no-tillage on
74 soil properties and crop yields. Martínez et al. (2008) found that in the upper soil layers
75 there was an increased root length density under no-tillage in comparison to conventional

76 systems because compaction of deeper soil layers under NT constrains root development.
 77 However, Malhi and Lemke (2007) reported the opposite trend, with increments in root
 78 mass under NT relative to conventional tillage (CT). This could be due to the development
 79 of cracks, worm channels, and biopores under this management practice, facilitating root
 80 growth (Hodgkinson et al., 2017; Li et al., 2019). Blanco-Canqui et al. (2017), for a fine
 81 textured soil, found no differences, after 35 years, in physical properties, particularly in
 82 the water retention curve, between NT and disk, chisel, and moldboard plowing systems.
 83 Castellini et al. (2019), for a typical Mediterranean cropping system, verified that,
 84 compared to tilled soil, NT had not worsened the physical and hydraulic properties of the
 85 soil (cumulative infiltration or infiltration rate, soil sorptivity, saturated hydraulic
 86 conductivity, conductive pores size, or hydraulic conductivity).

87 An important topic reported in the literature is the transition time from CT to NT after
 88 which soil properties and crop yields begin to improve (Castellini et al., 2019). According
 89 to different authors, the conversion from CT to NT leads to a worsening of some soil
 90 properties (i.e., an increase in BD, a decrease in soil porosity) in the first 4-5 years
 91 (Blanco-Canqui et al., 2018). After this time, a progressive improvement in soil structure,
 92 organic carbon stabilization, soil nutrients, and crop yield can occur (Strudley et al., 2008;
 93 Vogeler et al., 2009; Reichert et al., 2016). These effects are usually detectable after
 94 decades in semiarid environments (Shiwakoti et al., 2019).

95 The long-term effects of conservation agriculture on soil physical and chemical properties
 96 and their relationship with crop yields are still relatively poorly understood (Basche and
 97 De , 2019). Most of these studies have been carried out in cereals (Alvarez and Steinbach,
 98 2009; Cavalieri et al., 2009; Mitchell et al., 2017; Armenise et al., 2013; Celik et al., 2019)
 99 and only a few in woody crop systems under semiarid Mediterranean conditions (López-
 100 Garrido et al., 2012; Castellini et al., 2013; Di Prima et al., 2018).

In a previous study carried out in a rainfed almond (*Prunus dulcis* Mill.) orchard (Martínez-Mena et al., 2013), a reduction in crop yield was observed after three years of no-tillage, compared to tillage treatments (reduced tillage and incorporation of green manure). Basically, this result can be attributed to a decrease in soil N availability and/or impaired N uptake by roots due to the soil compaction. In the same study, the incorporation of green manure into the soil under reduced tillage did not enhance crop yield, but tended to improve some key soil quality properties. Based on those results, it was hypothesized that a long-term perspective might be necessary to achieve significant positive changes in soil quality that entail increases in crop yields. Thus, the objectives of this work were: i) to determine the long-term effect of different soil management practices on soil properties at different soil depths (0-5, 5-15, and 15-20 cm) in a rainfed almond orchard under semiarid conditions, and ii) to identify key soil parameters that explain crop yields under the different soil management practices. To this end, we measure changes in key soil physical (bulk density, resistance to penetration, total porosity, air capacity, relative field capacity, available water content, infiltration rate and field plant-available water content) and chemical (organic C, total N, nitrate, and soil available P) properties as indicators of soil quality after six years of reduced tillage (RT), reduced tillage plus incorporation of green manure (RTG), and no-tillage (NT) in a rainfed almond orchard.

2. Material and Methods

2.1. Study site

The experimental area is located in the Southeast of Spain (38° 3'15''N, 1° 46'12''W), in the Northwest of the province of Murcia (Cehegín) at 633 m a.s.l. The climate is semiarid Mediterranean. The rainfall is characterized by a great inter- and intra-annual variability

and the average annual precipitation is 370 mm, mainly concentrated in the spring and autumn. The mean annual temperature is 16.6 °C, the mean potential evapotranspiration is 800 mm per year, and the mean annual water deficit is 430 mm (Thornthwaite method), July and August being the driest months. The soil is a *Petric Calcisol* (IUSS-WRB, 2015) with a silt loam texture in the surface layer and a loam texture from 5 to 20 cm depth, with a similar pH (8.7 ± 0.02) and electrical conductivity ($0.017 \pm 0.0004 \text{ S m}^{-1}$) throughout the soil profile. The cultivated area consists of an organic, rainfed almond (var. *Ferragnes*) orchard without terraces and with a slope of 5 %, planted at a spacing of 7 m x 7 m. More information on the study area can be found in Martínez-Mena et al. (2013) and Almagro et al. (2017).

2.2. Experimental design

For 14 years (the plantation age), the habitual soil management practice in the cultivated area was reduced tillage (RT) to control weeds using a cultivator, without the addition of any kind of fertilizer. In 2008, two additional treatments were included: (i) reduced tillage plus green manure (RTG) and (ii) no-tillage (NT). The experimental design consisted of nine plots (49 m in length and 7 m wide) in a randomized-block design, with three replicates for each treatment. Each plot comprised five almond trees: the three central trees were used for soil measurements and the other two constituted guard rows (a buffer zone, to avoid edge effects).

The tillage affected the whole plot area, including the area around the trunk base of each tree. RT was performed using a cultivator till 15 cm depth, twice a year (autumn/spring) to control weeds. In this treatment, weeds were the only vegetation present between rows. The green manure consisted of a mixture of common vetch (*Vicia sativa* L.) and common oat (*Avena sativa* L.), in a proportion of 3:1, sown annually during early autumn at 150

kg seeds ha⁻¹ and mowed in early May. After manual mowing it was incorporated into the soil. In the NT treatment, the annual and perennial vegetation growing between rows were manually mowed each year, in early May, and left on the soil surface. Almond-tree pruning was annually carried out in early autumn and residues were burnt in the farm. No addition of manure or other organic matter was performed.

2.3. Soil sampling and analysis

The sampling was carried out in April 2015. Due to the temporal variability of the measured soil physical and chemical properties, the determinations were carried out as late as possible after the last tillage, in order to evaluate only the cumulative effect of the different management practices on the soil properties. Three undisturbed soil cores (~100 cm³) and three composite disturbed samples were taken per treatment and block at 3.5 m from the tree trunk, at three depths (0-5, 5-15, and 15-20 cm depth) (3 replicates x 3 treatments x 3 blocks x 3 depths=81 samples in total).

2.3.1. Soil physical properties

Bulk density, BD (g cm⁻³), was measured in undisturbed soil cores according to Burke et al. (1986). Soil penetration resistance, PR (MPa), was measured by using a hand-held penetrometer (Eijkelkamp Agrisearch Equipment, Netherlands) that measures the mean vertical strength required to introduce a steel cone of 5.0 cm² into the soil. There were five replicates per treatment and block, and the maximum value for each depth was recorded (to a maximum depth of 80 cm). Simultaneously, the soil moisture content was measured (data not presented here), the average value at 0-30 cm depth being 13 %.

Soil water retention, at matric potentials of 0, -10, -50, and -100 kPa, was measured in the same undisturbed soil cores mentioned previously. Additionally, the water content at h = -1000 and -1500 kPa 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 calculated by multiplying the gravimetric measurements by the BD values obtained previously. From the measured points of the retention curve, the following indicators were obtained:

- Total porosity (TP, $\text{m}^3 \text{ m}^{-3}$), the soil volumetric water content at saturation:

$$\text{TP} = \theta_s (\Psi^m = 0) \quad (\text{equation 1})$$

where θ_s is the volumetric water content at saturation ($\text{m}^3 \text{ m}^{-3}$) and Ψ^m is the matric potential.

- Air capacity (AC, $\text{m}^3 \text{ m}^{-3}$), the ability of the soil to store and transmit air (represents pores $>30 \mu\text{m}$):

$$\text{AC} = \theta_s (\Psi^m = 0) - \theta_{\text{FC}} (\Psi^m = -10 \text{ kPa}) \quad (\text{equation 2})$$

where θ_s is the volumetric water content at saturation ($\text{m}^3 \text{ m}^{-3}$); Ψ^m is the matric potential; and θ_{FC} is the volumetric water content corresponding to the field capacity at matric potential in kPa (Reynolds et al., 2002).

- Relative field capacity (RFC, dimensionless):

$$\text{RFC} = \frac{\theta_{\text{FC}} (\Psi^m = -10 \text{ kPa})}{\theta_s} \quad (\text{equation 3})$$

where θ_{FC} is the water content at field capacity ($\text{m}^3 \text{ m}^{-3}$) and θ_s is the soil volumetric water content at saturation or the soil porosity ($\text{m}^3 \text{ m}^{-3}$).

- Available water content (AWC, $\text{m}^3 \text{ m}^{-3}$), the maximum soil capacity to store available water for plants:

$$\text{AWC} = \theta_{\text{FC}} (\Psi^m = -10 \text{ kPa}) - \theta_{\text{PMP}} (\Psi^m = -1500 \text{ kPa}) \quad (\text{equation 4})$$

where θ_{FC} is the water content at field capacity ($\text{m}^3 \text{ m}^{-3}$), θ_{PMP} is the water content at the permanent wilting point ($\text{m}^3 \text{ m}^{-3}$), and Ψ^m is the matric potential.

The infiltration rate was (IR) determined in the field by the simple ring method (Beerkam method). Six PVC rings (diameter = 40 cm) per treatment (two per replication) were inserted in the soil to a depth of 1–2 cm to prevent water leakage at the surface. Ten liters of water were poured into the ring at the start of the measurement and the time needed for the water to infiltrate was recorded. Once the water had completely infiltrated, another ten liters were added and the time taken for their infiltration was logged. This procedure was repeated until an apparent steady state of infiltration was reached (5-8 times, depending on the treatment).

The difference between the soil water content in the field and the soil water content at permanent wilting point was determined to serve as an estimation of the field plant-available water content, FPAWC (Fernández-Ugalde et al., 2009), since in semiarid areas the soil water content is usually lower than the soil water content at field capacity. The FPAWC is an indicator of how much water the soil can store and provide to plant roots (White, 2006). In addition, its measurement shows the temporal dynamics of the soil water content according to the different soil management practices implemented. The soil water content, SWC, was monitored monthly from May 2009 to September 2014; it was measured in the 0–12 cm depth interval using an FDR soil moisture sensor (HOBO event, Massachusetts, USA). Ten measurements, spatially distributed within the rows, were made each time for each management practice.

2.3.2. Soil organic carbon and nutrients

Soil organic carbon (SOC) and total nitrogen (total N) were analyzed, using an N/C Analyzer (Flash 1112 EA, Thermo-153 Finnigan, Bremen, Germany), in disturbed samples that had been air-dried, sieved through a 2-mm sieve, and ground. Before the analysis, soil carbonates were eliminated using 1 M HCl.

Mineral nitrogen (NO_3^-) was measured in aqueous extracts (1:20, w/v) by ionic chromatography, using a conductivity detector. Ammonium (NH_4^+) and nitrite (NO_2^-) were considered negligible in these soils (Gelfand and Yakir, 2008). Soil available phosphorus (P_{Olsen}) was extracted with 0.5 N NaHCO_3 at pH 8.5, using the method of Olsen et al. (1954).

230

2.3.3. Sampling and analysis for the almond stem water isotopic composition

In May 2010 and 2014 twig sections ($c.$ 10 mm in diameter and 20 mm in length) were sampled from nine almond trees in each treatment (three per replicate plot), placed in capped vials, and stored in the freezer until water extraction was carried out using a cryogenic vacuum distillation line (Ehleringer et al., 2000). Isotopic analyses of the stem water samples were conducted at the Center for Stable Isotope Biogeochemistry, University of California-Berkeley (USA).

For $\delta^{18}\text{O}$ analyses, 0.2-ml water samples were equilibrated with an atmosphere of 0.2% CO_2 for 48 h at room temperature (21–23°C). The $\delta^{18}\text{O}$ of the equilibrated samples was measured using a continuous flow IRMS (Finnigan MAT Delta Plus XL; ThermoFinnigan, Bremen, Germany) connected to a GasBench II interface (GB, ThermoFinnigan). The $\delta^{18}\text{O}$ of the samples was analyzed using a chromium reduction system at 900°C (Finnigan MATH/Device) coupled to a Finnigan MAT Delta Plus XL mass spectrometer (ThermoFinnigan MAT, Bremen, Germany). The long-term external precision for the oxygen isotope analyses was 0.12 ‰. The $\delta^{18}\text{O}$ values were expressed in delta notation (‰) relative to the international standard V-SMOW (Moreno-Gutiérrez et al., 2012).

2.3.4. Biomass and crop yield

The spontaneous biomass of the RT and NT treatments and the introduced (green manure) plus spontaneous biomass for RTG were collected annually in early May, from randomly placed quadrats (1 m x 1 m; n=4 per treatment replicate). The plant material was clipped, dried at 60°C for 72 h and weighed. The above and belowground biomass were separated in the laboratory and the root length was manually measured with a measuring tape. Almond roots biomass were estimated by exploring a volume of 1000 cm³, in the depth range between 5 and 15 cm, and at a distance of 65 cm from the trunk, following the directions N, S, E, and W. All of the roots were obtained through sieves by washing and hand-picked. For roots <1mm it was used the flotation procedure by decanting into a 0.1 mm mesh sieve and separating only the roots. Roots were mixed with sodium hexametaphosphate for 24 h to disperse clay particles, rinsed with tap water, dried at 55°C for 4 days, and weighed according to Almagro et al., (2010).

The almond yield for each management practice was estimated by harvesting the almond kernels from nine trees per practice (three trees per replication) and weighing them, after removal of the pericarp. A period of 10 years, from 2009 to 2018, is reported in this study.

2.4. Statistical analysis

Differences in the soil properties measured with depth were assessed using repeated measures analysis of variance (ANOVA), to account for the interdependency of soil properties (depth = the repeated measure, and treatment = the main effect). To compare the effects of the treatments on crop yield, a General Linear Model (GLM) procedure - which considered treatment as a fixed factor, block as a random variable, and trunk diameter as a covariable - was used. When significant differences among treatments, depths, and their interactions were identified at the 0.05 probability level of significance, the mean values were compared using Tukey's test. Stepwise multiple regressions

analysis was used to identify the main factors responsible for the crop yield variation across treatments and depths and within depths (Ramsey and Schafer, 1997). Careful inspection of the plots of the regression residuals indicated normality and independence of the residuals, as well as homogeneity of variances among the management practices and soil layers. To select the best model for predicting crop yield, we used the coefficient of determination (R^2), root mean square error (RMSE), and Akaike information criterion (AIC) (Akaike, 1974):

$$AIC = 2K + N \ln (SSE/N) \dots \dots \dots (\text{equation 5})$$

where K is the total number of parameters in the model, N is the number of data points or measurements, and SSE is the sum squares of errors.

Because the number of our measurements (N) was small, a modified version of Equation 5 was used to calculate the corrected AIC (AICc).

$$AICc = AIC + 2K(K+1)/N-1 \dots \dots \dots (\text{equation 6})$$

Equation 5 should be used unless N/K is greater than about 40 (Burnham and Anderson 2004). In our case, this ratio is much lower than 40 (i.e. about 9/27). The best statistical model is the one that minimizes the value of AICc.

Prior to the analyses, the data were examined for normality, by the Kolmogorov–Smirnov test, and for homogeneity of variances, by the Levene test. Data that were not distributed normally (AWC, RFC and P_{Olsen}) were ln-transformed. All analyses were carried out using IBM SPSS statistics 23.0 software (SPSS Inc., Chicago, Illinois). Statistical significance was set at $p < 0.05$.

3. Results

3.1. Soil physical properties

300 For most of the soil properties studied, significant differences among treatments were
 301 detected in the plow layer of 0-15 cm (Table 1). The BD values varied between 1.24 and
 302 1.55 Mg m⁻³, depending on the soil management and depth. Neither differences across
 303 depths within a management regime nor management x depth interactions were observed
 304 (Table 1). Differences in BD among the management practices were significant at 5-15
 305 cm, the BD being about 12% and 21% higher for NT than for RT and RTG, respectively.
 306 The values of PR oscillated between 1.47 and 4.92 MPa and depended on the soil
 307 management and depth, with a significant increase with depth in all treatments (Table 1).
 308 Treatment NT showed significantly higher PR values (40% and 13% higher, respectively)
 309 than RT and RTG at 5-15 cm.
 310 A lack of significant differences in TP among the soil management practices was
 311 observed, at all depths considered, with values fluctuating between 0.44 and 0.54 m³ m⁻³
 312 (Table 1). The TP was higher at 15-20 cm depth than at 0-15 cm under NT, while under
 313 the tillage practices (RT and RTG) TP increased from 0-5 cm to 5-15 cm depth.
 314 The AC values ranged from 0.19 m³ m⁻³ to 0.26 m³ m⁻³, depending on the soil management
 315 and depth (Table 1). An increase in AC from 0-15 to 15-20 cm depth in NT and from 0-
 316 5 to 5-15 cm in RT was observed, consistent with the increase in TP at those depths.
 317 Averaged across the depths, significant differences at p<0.1 among the treatments were
 318 observed, with higher values in NT compared to the tillage treatments.
 319 The AWC values obtained ranged between 0.14 and 0.20 m³ m⁻³, according to the soil
 320 management and depth (Table 1). Differences across the depths within the management
 321 practices were observed with an increase in NT, from 0-5 to 5-15 cm, but no change with
 322 depth under RT. In addition, the AWC values of NT were about 30% higher than those
 323 of RT at 15-20 cm, while no significant differences among the practices were observed

below the plow layer. In general, the AWC values followed the order NT > RTG > RT, in all layers.

The values of RFC ranged between 0.51 and 0.63, depending on soil management and depth (Table 1). An increase was observed from 0-5 to 5-15 cm depth under NT while no change with depth was observed under the tillage treatments. In addition, while at 0-15 cm depth NT showed higher RFC values than the tillage treatments (although not significantly so), below the plow layer the values in the RT and RTG soils were higher than in the NT soil. An RFC value of 0.60 was recorded in the RTG soil at all depths.

The infiltration rate ranged between 14 and 22 cm h⁻¹ and followed the order: NT > RTG > RT, with significant differences at $p < 0.1$ among treatments (Figure 1).

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3.2. Field plant-available water content

The soil water content in the field and the monthly rainfall were monitored from May 2009 to September 2014, this period having a total rainfall of 1896.80 mm. The FPAWC values were, in general, very low for all the management practices, being negative in 31 and 14 of the 51 months analyzed for the tillage treatments (RT and RTG) and NT, respectively (Figure 2), corresponding, mostly, to the three driest years (2011, 2013, 2014) of the whole period. Treatment NT displayed higher FPAWC values than the tillage treatments throughout the study period, this being more evident after six months of the tillage suppression, and the differences were greatest in the driest months (Figure 2).

344

3.3. Soil organic carbon and nutrients

The SOC content ranged between 8.50 and 14.40 g kg⁻¹, as influenced by the tillage and soil depth, being higher at the surface (0-5 cm) than at depth (5-20 cm) for all the treatments (Table 2). No significant differences in the SOC content between NT and RT

were observed for any of the soil layers studied. However, the values for RTG were higher than for RT and NT in the plow layer. Specifically, the SOC content in RTG was about 20 and 25% greater at 0-5 and 5-15 cm depth, respectively, compared to RT. Averaged across the depths, RTG also had higher SOC values than RT and NT.

The total N values were low, consistent with the SOC content in these soils. They ranged between 0.99 and 1.33 g kg⁻¹, depending on the management and depth (Table 2). In addition, a significant increase in total N from 0-5 to 5-15 cm was observed in RTG while similar values at different depths were observed for RT and NT.,

A wide range of nitrate values was observed across management practices and depths: from 16.06 to 100.15 mg kg⁻¹ (Table 2). An increase from the top to the deeper layers was found under the tillage treatments while there were no changes with depth under NT. A great reduction in the nitrate content was observed for NT, compared to RT, at all depths, with a reduction of about 80% average across depths (Table 2).

The values of P_{Olsen} across the management practices and depths varied between 4.42 and 11.46 mg kg⁻¹. A general reduction in P_{Olsen} with depth was detected in all practices, but it was only significant between 0-5 and 5-15 cm depth under RT. Differences among treatments were not significant at any layer due to the high spatial variability of this nutrient.

3.4. Isotopic composition of stem water

The stem water $\delta^{18}\text{O}$ values oscillated between -5.46 ± 0.17 and -7.99 ± 0.27 according to the management and year considered. For all the treatments, the values were significantly higher during a warm, dry year (May 2014) than during a wet year (May 2010) (Figure 3). The tillage treatments gave significantly higher stem water $\delta^{18}\text{O}$ values than the NT treatment in the wet year.

3.5. Cover crops performance and main crop yield

Higher belowground biomass production was obtained in RTG and NT, compared to RT, for the monitored period while the aboveground biomass production was similar among the different management practices. The root length value for the spontaneous vegetation was two-fold higher in treatment NT than in reduced tillage treatments (RT and RTG) (Table 3).

The main crop yield over a 10-year period (2009-2018) was, in general, low and highly variable - varying between 0.24 and 3.25 kg tree⁻¹, depending on the management practice and year (Figure 4). The yield reflects the dry conditions of this area, where water was not available to the plants during most of the year, as shown in the temporal variation in FPAWC. As reported in previous work by Martínez-Mena et al. (2013), a strong effect of the tillage treatment on crop yield was detected from the first year of the study, with significantly lower yields under NT, compared to RT or RTG, in almost of the years. The cumulative crop yield, the result of pooling the 10 years of data, was also strongly affected by the management, with a reduction of about 70% and 15% in almond production in NT and RTG, respectively, compared to RT (mean values in kg tree⁻¹: 1.52 ± 0.14; 1.32 ± 0.19; and 0.42 ± 0.04 for RT, RTG, and NT, respectively). However, while crop yield differences between NT and RT tended to increase with time, differences between green manure (RTG) and RT treatment tended to decrease with time, being closer to those of the RT treatment after six years of RTG implementation, and even being higher in RTG than in RT in years 2016 and 2017 (Figure 4).

3.6. Relationships between soil quality parameters and crop yield

Multiple regression analyses were performed for the 0-20 cm depth and for each soil layer separately to identify the main determinants of crop yield variation among the management practices in our Mediterranean rainfed almond orchard. The models that best

explained crop yield variation in relation to the parameters measured in the different soil layers, according to the AICc criterion, are shown in Table 4. Overall, the nitrate content was the best predictor of crop yield, explaining a significant percentage of the variation, either when all soil layers were pooled (0-20 cm) or when they were separated by depth intervals (0-5 cm; 5-15 cm; and 15-20 cm). Indeed, at 0-20 cm and 0-5 cm, the nitrate content was the single best predictor of crop yield, explaining 50% and 70% of the variation, respectively. At 5-15 cm depth, the nitrate content and the PR together accounted for 59% of crop yield variability. At 15-20 cm, however, the nitrate content and the TP together explained 79% of the variation in crop yield (Table 4).

4. Discussion

4.1. Changes in soil physical properties

The changes in the soil physical properties with the incorporation of green manure (RTG) were more evident at 0-15 cm, with a reduction in BD and an increase in AWC, in line with an increase in the SOC content relative to RT. Other authors also reported that the main changes in soil physical properties occurred at intermediate depths (between 5 and 15 cm), which might be related to the effect of the belowground biomass derived from the green manure (Imaz et al., 2010; Castellini, 2014).

Moreover, the IR in the soil profile was about 30% higher for RTG than for RT (Figure 1). The positive impact of green manure on the soil physical conditions, decreasing BD and improving water retention and soil infiltration (besides other effects), has been widely reported (Ramos et al., 2010; Mitchell et al., 2017; Basche and De Longe, 2019). However, in most cases, the soil physical improvement was found when green manure was compared to conventional tillage and under humid climates. The fact that such benefits were also observed in our work, where green manure was compared to reduced

tillage under semiarid conditions with low biomass production of cover crops, reinforces the relevance of the use of this practice to improve the soil quality and confirm our hypothesis of the long term perspective needed to achieve significant positive changes in soil quality.

Changes in soil physical properties due to NT were observed at 5-15 cm depth - where increases in BD, PR, AWC and relative field capacity relative to RT, were observed (Table 1). These results are similar to those obtained by other authors (Imaz et al., 2010; Castellini et al., 2014). The trend towards higher BD and PR with NT, compared to RT, agrees with results from previous research (Mitchell et al., 2017). Although PR values higher than 2 MPa have been mentioned in the literature (Griffith et al., 1986, Locher and De Bakker, 1990) as a “limit” beyond which root growth might be affected, other authors (Lampurlanés et al., 2003; Fernández-Ugalde et al., 2009) have reported values higher than 3 MPa for carbonate-rich soils (as is the case of our soils) and/or well-structured soils in which root development was not limited. This suggests that plant roots can grow through the soil within biopores and cracks; a greater infiltration capacity may be due to the continuity of such pores (Atkinson et al., 2019) and/or the presence of perennial plants (which formed part of the ground cover under NT) because they are a key feature of continuous roots in the soil (Basche and De Longe, 2019). In fact, in our study site the root length from the spontaneous vegetation was greater under NT than under the reduced tillage treatments at 5-15 cm depth (Table 3). This together with a slightly higher root biomass from the almond trees under NT (on average, $1.31 \pm 0.5 \text{ g m}^{-2}$ and $0.92 \pm 0.2 \text{ g m}^{-2}$ for NT and reduced tillage treatments, respectively) indicate a better development of roots under NT despite the increased PR and BD observed in this treatment.

In addition, under NT an increase of about 40% in the infiltration rate was found, compared to RT (Figure 1), which also supports the idea of the formation of channels or

449 pores in the soil by the active soil fauna and plant roots as commented on above. Such
 450 channels might help to improve the pore continuity that is required for water and air
 451 circulation (Rücknagel et al., 2016) and may explain the apparent contradiction of
 452 improved infiltration rate with increased BD under NT. Different results have been
 453 reported regarding the effect of NT on soil infiltration. Atkinson et al., (2020) found that
 454 the infiltration rate in NT was up to 4-times higher in comparison with CT, while other
 455 authors have reported lower infiltration rates under NT relative to CT (Rasmussen, 1999;
 456 Ferreras et al., 2000), or even no differences in the infiltration rate between NT and RT
 457 (Starr, 1990; Ankeny et al., 1990; Castellini et al., 2019). These conflicting results can be
 458 attributed in some cases to temporal variability of the soil infiltration rate, which is very
 459 high immediately after tillage, but diminishes rapidly in the following weeks, when it
 460 becomes greater under no-till than in tilled soil (Strudley et al., 2008). In our case,
 461 although the management practices implemented are all conservative and no conventional
 462 practices were monitored, a higher infiltration rate was obtained under NT compared to
 463 the reduced tillage treatments.

464 Suppression of tillage did not affect the soil TP at any depth, but an increase in AWC (as
 465 the difference between FC and PMP) of about 30% at 5-15 cm depth was observed
 466 relative to RT in agreement with the higher (although not significantly so) percentage of
 467 pores smaller than 30 μm at this depth (estimated from the RFC values). For fine-textured
 468 soils, like ours, values of $0.15 < \text{AWC} < 0.20$ are good for maximum root growth and
 469 functioning while values $0.10 < \text{AWC} < 0.15$ may constrain root development (Verdonck
 470 et al., 1983). According to this criterion, the AWC values can be designated as “good” at
 471 all depths under NT while for RT the values are limiting for root growth which is
 472 consistent with the greater root development observed under NT (Table 3). Interestingly,

higher AWC with higher BD means that the pore size distribution has also changed under NT.

4.2. Changes in the soil nutrient content and availability

The benefits of green manure improving soil nutrients status were more evident at 5-15 cm depth, where total N was higher than under RT. The same pattern was observed for the SOC content, with a higher increase in RTG, relative to RT at 5-15 cm (25%) than at 0-5 cm (11%) (Table 2). These results are consistent with the significantly higher increase in the belowground (105%) than in the aboveground (45%) biomass (derived from the introduced vegetation) in RTG compared to that (of the spontaneous vegetation) in RT (Table 3). They are also in line with the idea of a greater contribution of root residues to SOC than that of aboveground residues suggested by several authors (Manns et al., 2007; Daryanto et al., 2018). Other authors have reported the positive influence of the increase in biomass production resulting from green manure application on soil chemical properties (increases in organic matter and cation exchange capacity) and on the retention of nutrients in the soil (Ciotta et al., 2003).

Tillage suppression led to important decreases, throughout the whole profile, in the concentrations of available nutrients, mainly mineral N (NO_3^-) (Table 2). Bergh et al. (1995) reported reductions of about 42% in mineral N under NT systems in comparison to conventional ones. According to several authors, C mineralization and nitrate release are stimulated by tillage due to disruption of soil aggregates (Silgram and Shepherd, 1999; Malhi et al., 2001). In our study, lower ratio of mineral to total N under NT compared to RT in the plow layer, might reveal that there is a lower mineralization rate under the former. However, declines in C and N mineralization could also be due to the higher recalcitrance of the spontaneous vegetation (mainly perennial) growing under NT, as

proven in previous work where the litter C:N ratios were higher under NT than under tillage (Almagro et al., 2017). In addition, the increased infiltration capacity under NT may increase nitrate losses, which might contributed to its decreased concentration in this treatment.

4.3. Crop performance and yields

The beneficial effects of green manure on several soil quality parameters described above were positively reflected in the crop yield after six years of RTG implementation. Thus, from 2016 to 2018, similar or even slightly higher crop yields were obtained under RTG, compared to RT, independently of the annual rainfall (Figure 4). By contrast, during most of the first five years of the study, the crop yield under RTG was lower than for RT, with an average reduction of about 30%. A previous study in this orchard (Martínez-Mena et al., 2013), carried out after three years of green manure incorporation, detected some competition between the green manure crop and the main crop (almond) for water and nutrients, which was responsible for lower crop yields, with respect to RT. The potential negative effects of cover crops (in more arid regions) - since they may use soil water that would otherwise be available to the main crop, as reported by several authors (Parihar et al., 2016; Krstić et al., 2018) - are the main reason why this practice is not usual under semiarid, rainfed conditions. However, and according to our results, this situation might be reversed in the medium-term (six years), when the improvement in soil conditions would counteract the adverse effects of this management practice on crop yield in rainfed areas.

Suppression of tillage led to a low availability of nutrients, mainly N, and to an important reduction in crop yield despite the greater availability of soil water in the soil profile, and the consistently higher FPAWC (Figure 2) throughout the study period, as commented on

before. This confirms the hypothesis that NT produces a limitation of N, as was detected three years after its implementation (Martínez-Mena et al., 2013) and that seems to have remained six years later. In this low-input agroecosystem under semiarid conditions the most relevant aspect affecting crop performance is not the effect of soil management on water availability but its effect on N availability to crop. This contrast with the generalized accepted idea than in these systems water availability is the most limiting factor for crop (Fernández-Ugalde et al., 2009; Sun et al., 2018).

The $\delta^{18}\text{O}$ isotope results (Figure 3) for the almond stem water in a wet year (2010) show differences among tillage and NT management practices regarding the depth at which almond roots extracted water. Thus, the more negative $\delta^{18}\text{O}$ isotope values under NT indicate extraction of water from deeper layers - where nutrient concentrations are even lower than in the shallower layers - than under the tillage treatments. These results are consistent with the higher infiltration rates under NT, so that water is conducted deeper than in the tillage treatments when the soil is wet (Figure 3). They also indicate that although the soil available water is higher under NT, this does not mean that this water is totally accessible for the almond roots. This is probably due to the size of the pores storing this water and the relatively high BD and PR values observed under NT at 5-15 cm depth, which could limit the water and nutrients uptake by roots (Sands and Mulligan, 1990). In fact, the nitrate content at 0-5 cm depth explained 70% of the variance in crop yield while nitrate and PR at 5-15 cm explained about 60% of the variance (Table 4).

In our study, crop yield was lower under NT than under tillage management in most of the years (independently of the annual rainfall) and the difference among them increased with time (Figure 4). This is contrary to other studies where the benefit of NT to crop yield in very dry conditions was reported, while in wet periods a positive effect or no effect of tillage on crop yield was observed (Gómez et al., 1999). The mechanisms

underpinning yield reductions under no-tillage vary according to the local conditions (Soane et al., 2012). On the other hand, and according to several reports in the literature, crop yields immediately after the adoption of no-tillage are often appreciably lower than after plowing but improve or match conventional tillage yields after about three-five years of no-tillage as soil structural conditions improve (Pittellkow et al., 2015; Reitchert et al., 2016; Castellini et al., 2019). In our study a clear decrease in crop yield with NT was observed, despite the improvement in AWC, from the first year of its adoption (Figure 4), with no change in this behavior in the long-term (10 years of implementation) due to the limited N availability under this low-input supply conditions. So, applying N and occasional tillage might be needed in such agroecosystems in order to decrease the compaction and activate the C and N mineralization, as has been reported by other authors (Quincke et al., 2007; Çelik et al., 2019).

Conclusions

Changes in soil physical properties with the incorporation of green manure and with the suppression of tillage were mainly detected in the 5-15 cm soil layer. In this layer, improvements in soil water availability and infiltration rate, with respect to reduced tillage, were observed.

The shift from RT to RTG led to an improvement in soil physical parameters and some soil nutrient parameters (mainly total N), resulting in a positive effect on crop yield after six years of implementation. In this sense, the improvement in the soil quality in the medium-term might counteract the possible adverse effects of this management practice (competition for water and nutrients) on crop yield in semiarid rainfed areas.

Suppression of tillage led to a reduction in crop yield of about 70% with respect to the tillage treatments. This was mainly due to the strong decrease in the concentrations of

available N (NO_3^-) - which, at 0-20 cm depth, explained 50% of the crop yield variance. For this type of soil, with high carbonate content and poor in soil organic carbon and nutrients, the hypothesis that a longer period of sustained no-tillage is necessary to achieve positive changes in soil quality, that might increase crop yield, is not confirmed. Furthermore, N fertilization and occasional tillage should be performed in these systems in order to stimulate C and N mineralization and improve crop productivity.

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