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FULL-LENGTH RESEARCH ARTICLE

Response of Wheat and Faba Bean to Intercropping and Tillage System on a Mediterranean Rainfed Vertisol

Rafael J. Lopez-Bellido[1] · Veronica Muñoz-Romero[2] · Purificacion Fernandez-Garcia[1] · Luis Lopez-Bellido[1]

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Abstract The sustainability of agricultural systems can be improved by practices such as intercropping or no tillage. Such practices have not been evaluated for wheat–faba bean cropping systems on a Vertisol in the rainfed Mediterranean region. A 3-yr study (2014–2015, 2015–2016 and 2016–2017) was conducted to determine the effects of tillage systems (reduced tillage and no tillage) on wheat (*Triticum aestivum* L.)–faba bean (*Vicia faba* L.) intercrop and sole crop performance under a dryland rotation system with sunflower (*Helianthus annuus* L.) rotation. Wheat was intercropped with faba bean arranged 2:1 row. The field experiment was designed in a split plot randomized block with tillage system in main plot and cropping system in sub-plot with four replications. The land equivalent ratio of the grain yield was greater than 1, indicating a more efficient use of land by intercropping. No tillage improved the grain yield compared to reduced tillage by 65, 10 and 32% in the cultivation of wheat, faba beans and sunflower, respectively. The grain yield obtained with the intercropping system was higher than that with the sole cropping system only in the faba bean crop. The cropping system was not influenced by the tillage systems. The soil–plant analyses development (SPAD) values were lower for the intercropped wheat, suggesting a lower bioavailability of N in this cropping system. However, intercropping could be highly beneficial compared to planting wheat alone since higher grain yields are achieved even without the application of N fertilizer.

Keywords Broomrape · Land equivalent ratio · No till · SPAD · Yield components

Introduction

The excessive use of chemical inputs (mineral fertilizers, pesticides and insecticides) in intensive agriculture has a negative impact on the environment. Therefore, the development of sustainable agricultural practices aimed at reducing environmental costs is essential. One of these practices can be intercropping, which is defined as the concurrent cultivation of two or more crops in the same agricultural space for significant part of their growing periods.

Intercropping seems to be a good strategy for improving the efficient use of soil, light and water resources [14, 30]. Additionally, intercropping decreases the occurrence of weeds, pests and diseases [25]. Cereal–legume intercropping improves soil fertility due to increased nitrogen fixation [23]. Cereal is more competitive than legume for inorganic nitrogen in the soil due to a more efficient root system [11], forcing the legume to increase its reliance on symbiotic nitrogen fixation [2, 12, 14]. In general, intercropping cereal–legume crops improves the yield stability compared to the same crops grown alone [19]. Moreover, since high rates of mineral N fertilizers contribute to environmental damage through nitrate leaching, legume-

✉ Purificacion Fernandez-Garcia
g72fegap@uco.es

[1] Eco-Efficient Cropping Systems, Department of Agronomy, Campus de Rabanales, University of Cordoba, Edificio C4 “Celestino Mutis”, 14071 Córdoba, Spain

[2] SUMAS Research Group, Department of Agricultural Chemistry, Soil Science and Microbiology, Faculty of Science, Agrifood Campus of International Excellence—ceiA3, University of Cordoba, 14071 Córdoba, Spain

based intercrop systems are viewed as a viable method for introducing N into low-input agrosystems and reducing reliance on mineral forms of N [7]. In Europe, there has been growing interest in intercropping, especially with cereal–pea crops [19]. Other authors [15, 29] have also highlighted the role of faba bean as a legume in intercropping, as it ensures earlier canopy closure and thus better weed control than single crops.

On the contrary, not all intercropping systems provide benefits in terms of all possible metrics. For example, in temperate regions, grain legumes and cereals intercropped as forage yield variable gains depending on the cereal and legume species, the sowing ratio and the specific growing conditions [1]. When intercropping benefits do occur, they emerge from more complete exploitation of resources, such as solar radiation, water, soil and fertilizers [30]. Intercropping may be undesirable when a single standardized product is required and might lack economies of scale for labor and time management. Intercropping has not usually been seen as suitable for mechanization in an intensive farming system [6]. Consequently, and despite its potential benefits, intercropping faces huge competition from large-scale, intensive monocrop farming. Thus, to ensure their uptake and enable sustainable agricultural intensification, intercropping systems must be optimized to enhance resource-use efficiency and crop yield simultaneously [18].

Rainfed agrosystems in Mediterranean climates have unique characteristics. These soils often experience high temperatures, scarce or irregular rainfall, minimal cloud cover and low quantities of crop residues. These factors act as poor surface covers for minimizing the impact of radiation and the effects of water and wind erosion. Vertisols occur in many areas of the world, particularly in dry regions, where they enable a subsistence agriculture that would not be viable with other soil types. They pose specific tillage problems and have particular requirements, and their properties vary considerably both in space and time.

Numerous authors have studied cereal–legume intercropping systems. However, few studies have included the influence of tillage systems (no tillage and reduced tillage) and rotation with another crop (sunflower) on the intercropping system. The objective of this study was to evaluate the grain yield and the yield components of faba bean and wheat as a function of the tillage system, cropping system and the effect of intercropping systems when included with a rotation.

Materials and Methods

Site Characteristics and Experimental Design

The field experiment was conducted in Cordoba, southern Spain (37.755, − 4.536; 200 m a.s.l. for three crop cycles (2014–2015, 2015–2016 and 2016–2017). Research was conducted under rainfed conditions. Climate data for the experiment were collected from a weather station at the research site (Fig. 1). The mean annual temperature of the area ranges between 9.5 and 27.5 °C. The mean annual rainfall in this area is 584 mm (39% from October to December, 37% from January to March, 19% in June and 5% from July to September). The mean annual potential evapotranspiration is 1000 mm.

The soil was a Vertisol (Typic Haploxererts), typical of the Mediterranean region, where dryland cropping is the standard practice. The soil texture is strongly clayey, with a clay content of 73% in the 0–90 cm soil depth.

Experimental Details

Cultivars of hard red spring wheat (*Triticum aestivum* L., cv. Gazul) and faba bean *(Faba bean* L., cv. Alameda) were grown as sole crops and as mixed crops. Treatments consisted of two tillage systems (no tillage and reduced tillage) and three cropping systems (sole wheat, sole faba bean and wheat:faba bean intercrop) in rows of 2:1 (two rows of wheat intercropped with one rows of faba bean, with 18 cm inter-row spacing between wheat and faba bean).

The experimental design was a split plot in a randomized complete block with four replications. The two tillage systems were randomly assigned to the main plots while the three cropping systems were randomly allocated to the subplots. The gross main plot size was 30 m × 10 m (300 m^2), while the subplot size was 10 m × 5 m (50 m^2). The net plot size for data collection was 9 m × 1.5 m (13.5 m^2). Preceding crop was sunflower (*Helianthus annuus* L. cv. LG5485).

Crop Management

In monoculture, wheat and faba bean were sown in rows at the recommended plant densities targeting 500 and 42 plants m^{-2}, at a row spacing of 0.18 and 0.36 m, respectively. Row intercropping consisted of sowing wheat and faba bean in alternate rows of 2:1 row arrangement targeting 333 wheat and 12 faba bean plants m^{-2}. Wheat was sown in late November and faba bean in early December.

Sunflower was sown in rows at a density of 13 plants m^{-2} in February. All crops were sown in rows using

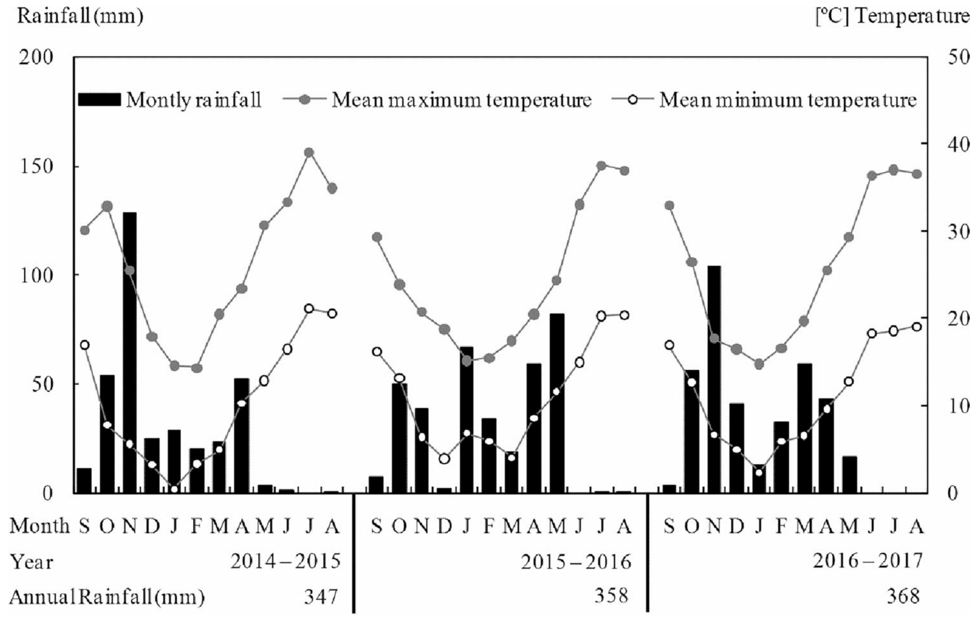

Fig. 1 Monthly and annual rainfall, mean maximum and minimum temperatures over the 3-year study period at Córdoba (Spain)

a specific seed drill in each tillage systems except faba bean in intercropping which were sown by hand. Weeds were controlled with glyphosate [N-(phosphonomethyl) glycine] + MCPA [(4-chloro-2-methylphenoxy) acetic acid] at a rate of 0.5 + 0.5 L active ingredient ha^{-1} prior to planting. Reduced tillage treatment included disk harrowing and field cultivation for final seedbed preparation. Glyphosate was applied to the faba bean plots at a rate of 0.065 L active ingredient ha^{-1} as a postemergence spray when the broomrape (*Orobanche crenata* Forsk) was approximately 0.5–1 cm high [8]. Nitrogen fertilizer (150 kg N ha^{-1}) was applied to the sole wheat plots as ammonium nitrate (34.5% N), and the intercropping wheat was not fertilized because cultivated intercropping legumes are known to transfer N to the associated cereals. Each year, the sole-cropped wheat and rows of wheat in the intercropped areas were also supplied with P fertilizer at a rate of 65 kg P ha^{-1}; the fertilizer was incorporated following the standard practice in the reduced tillage soil and was banded with drilling in the no tillage plots. The soil-available K was adequate (530 mg kg^{-1}).

Measurements and Calculations

Plants in the middle section of each plot, leaving two rows on either size, were harvested at maturity (early in June for wheat and faba bean and at the end of July for sunflower) using a 1.5-m-wide Nurserymaster Elite Plot Combine (Wintersteiger, Austria) for yield measurements. A subsample was collected from a 1-m^2 area at the center of each plot. From this sample, the straw yield and yield components [ear m^{-2} and grain ear^{-1} in wheat; pod m^{-2} and grain pod^{-1} in faba bean; head m^{-2} and grain $head^{-1}$ in sunflower; and 1000-grain weight for all crops] were measured. Dry matter was determined by drying the sampled plants at 80 °C to constant weight.

A Minolta SPAD 502 chlorophyll meter (Konica Minolta) was used to measure the leaf SPAD values at anthesis in wheat (growth stage 61) [33] and in faba bean (growth stage 65) [16] in both years. SPAD readings were measured at the midpoint of the topmost fully developed leaf, and 20 representative plants were randomly selected to be measured in each experimental plot; the results were averaged.

The number of *Sitona lineatus* (L.) larvae and nodules was assessed at the late flowering stage of the faba bean. Ten randomly selected plants from each plot were uprooted using a spade to excavate a circle with a radius of 15 cm around the plant to an approximate depth of 30 cm. Sitona larvae were counted on each of these plants. Soil that adhered to the root was removed by washing with tap water [28]. The nodules attached to each plant root were removed, and the dry weight was recorded (after drying to constant weight at 80 °C).

The relative performance of intercrops compared to sole crops is often characterized using the land equivalent ratio (LER). The LER was calculated by comparing the area under sole cropping to the area under intercropping required to yield equal amounts at the same level of management. The LER is a common approach used to assess the land use advantages of intercropping [31]:

$$\mathrm{LER} = \mathrm{LERw} + \mathrm{LERf} = \frac{Y_{\mathrm{int,W}}}{Y_{\mathrm{mono,W}}} + \frac{Y_{\mathrm{int,F}}}{Y_{\mathrm{mono,F}}}$$

where $Y_{\mathrm{int,W}}$ and $Y_{\mathrm{int,F}}$ are grain yields of intercropped wheat and faba bean and $Y_{\mathrm{mono,W}}$ and $Y_{\mathrm{mono,F}}$ are grain yields in monoculture wheat and faba bean in kg ha^{-1}.

LERw and LERf are the partial LER values for each species. A LER value higher than 1.0 indicates that there is a land use advantage for intercropping [17]. Partial land equivalent ratio values are used to assess the contribution of each crop to the total LER and are more detailed in terms of land use assessment. The LER of biomass was calculated as grain + shoot biomass.

Intercrop productivity was assessed according as wheat grain yield + faba bean grain yield.

In the study of competitive abilities in intercrop replacement series, expected yields of individual partners in mixture are those calculated using the sole crop (SC) yield multiplied by the seeding ratio used in IC. This calculation estimates how much the crop would have yielded in SC with the same seeding density imposed in IC. In the analysis of the results of the replacement series (where the density of each partner in IC is lower than in SC), the calculated expected yields are then compared with the observed yields to understand the effects of interspecific competition on yield alone. This expected yield was thus calculated under the null hypothesis that an individual wheat plant has the same yield in both intercropping and sole cropping [22].

Statistical Analysis

All data were analyzed by three-way analysis of variance (ANOVA) using statistix 9.0 software to determine the effect of year, tillage system and cropping system on aboveground grain and components yield on wheat, faba bean and sunflower except for LER, which was analyzed by two-way analysis of variance (ANOVA). The error term used followed the method outlined by McIntoch [24]. Year was considered a random factor in this work due to unpredictable weather conditions under rainfed Mediterranean conditions, and tillage system and cropping system were fixed factors [9]. When their effects were statistically significant, treatment means were separated and compared using Fisher's protected least significant difference (LSD) test with a significance threshold at $p \leq 0.05$.

Results

Land Equivalent Ratio

The total LER values of grain yield and biomass were greater than one (1.09 ± 0.03 and 1.22 ± 0.05, respectively). Regarding crop, the partial land equivalent ratio for faba bean was higher than that for wheat in two of the three years with insignificant differences between the two crops in the other. On the other hand, tillage system did not present significant influence in LER ($F = 3.15$; $p = 0.08$).

Yields in Sole and Intercropping Crops

Wheat

The wheat grain yield and biomass showed significant differences between tillage system and cropping system, significantly modulated by the influence of the year (Supplementary Material). On the other hand, biomass was not affected by interaction tillage × cropping system in any case ($F = 0.38$; $p = 0.55$ for grain, and $F = 0.23$; $p = 0.64$ for biomass).

The no tillage system achieved higher grain yields than reduced tillage in all years (Fig. 2). Regarding cropping system, wheat grain yield was higher in the sole wheat crop than in the intercropped areas in 2016 and 2017 (Fig. 2). ($F = 27.39$; $p < 0.001$).

The wheat biomass, as the wheat yield, was higher in no tillage system than in reduced tillage subplots and higher also in sole crop planting compared to intercropping in 2015 and 2017 (Table 1).

Faba Bean

The grain yield of faba bean showed significant differences regarding tillage system and cropping system, with significant influence of the year (Supplementary material) without interaction between tillage and cropping systems ($F = 0.22$; $p = 0.647$). The faba bean grain yield value was higher under no tillage only in 2015 (1389 ± 152 kg ha^{-1} in no tillage and 1049 ± 95 kg ha^{-1} in reduced tillage) (Fig. 3, Supplementary material). However, the faba bean grain yield was higher in intercropping subplots than planting as a sole crop for all years, with averages of 1323 ± 72 and 705 ± 50 kg ha^{-1}, respectively (Fig. 3).

Regarding faba bean biomass, only cropping system presented significant effect (Supplementary material) without significant interaction between tillage × cropping systems ($F = 0.11$; $p = 0.737$). The biomass of faba bean in intercropping was clearly higher than that of sole crop planting (Table 2).

Yield components in Sole and Intercropping Crops

Wheat

Tillage system and cropping system were statistically significant for the number of ears m^{-2} with significant influence depending on the year. The number of ears m^{-2} was higher in the no tillage system compared to reduced tillage only in 2015 (Table 1). Wheat planted as a sole crop

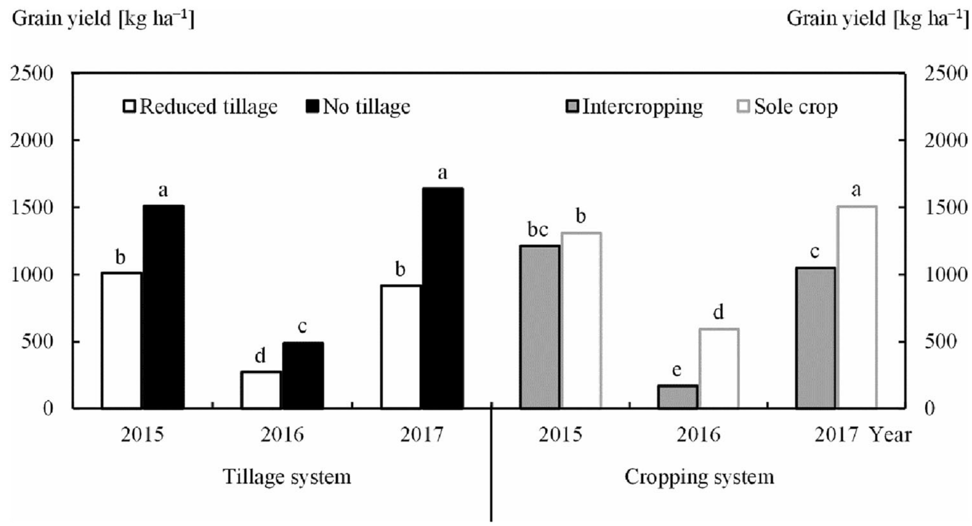

Fig. 2 Wheat yield as affected by year, tillage system (reduced tillage and no tillage) and cropping system (sole crop and intercropping). Different letters indicate significant differences at $p \leq 0.05$ according to LSD

Table 1 Biomass and yield components of wheat and faba bean as affected by year, tillage system (reduced tillage (RT) and no tillage (NT)) and cropping system (sole crop (SC) and intercrop (IC))

Treatment		Wheat				Faba bean			
		Biomass (kg ha^{-1})	Ears m^{-2}	Grain ear^{-1}	TGW† (g)	Biomass (kg ha^{-1})	Pods m^{-2}	Grain pod^{-1}	TGW† (g)
Year	2015	4002 a*	203 a	21 b	31 a	2423 a	94 a	2.2 b	508 a
	2016	1436 b	86 c	17 b	28 b	2113 a	107 a	2.2 b	414 b
	2017	4152 a	148 b	27 a	31 a	1968 a	77 b	2.6 a	401 b
Tillage system	RT	2777 b	127 b	19 b	30 a	2120 a	84 a	2.3 a	429 a
	NT	3616 a	164 a	24 a	30 a	2216 a	102 a	2.4 a	453 a
Cropping system	SC	3859 a	165 a	22 a	28 b	1364 b	77 b	2.4 a	461 a
	IC	2534 b	127 b	21 a	32 a	2973 a	108 a	2.2 b	422 b

Within treatments, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD

†Thousand grain weight (TGW)

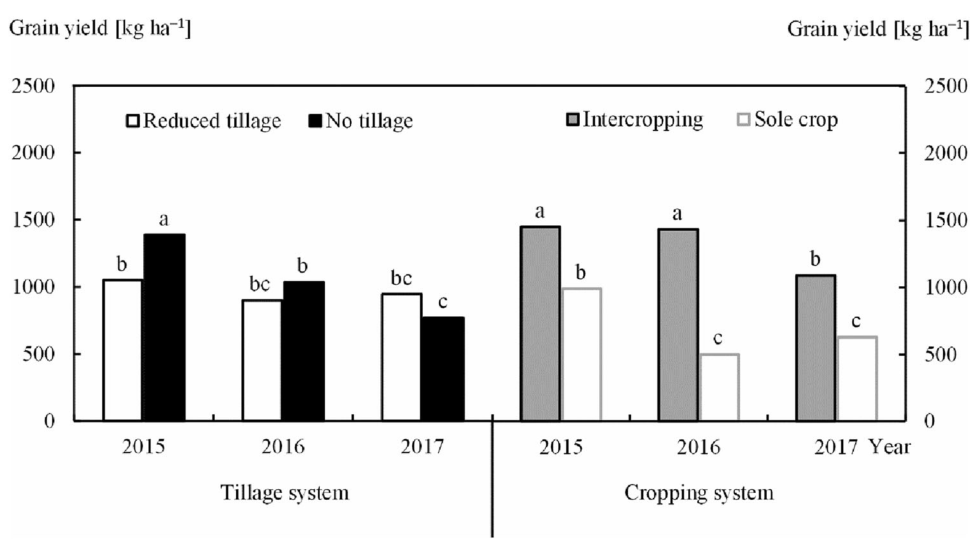

Fig. 3 Faba bean yield as affected by year, tillage system (reduced tillage and no tillage) and cropping system (sole crop and intercropping). Different letters indicate significant differences at $p \leq 0.05$ according to LSD

Table 2 Grain yield and yield components of sunflower as affected by year, tillage system (reduced tillage (RT) and no tillage (NT)) and crop rotation (faba bean and wheat sole crop and intercrop (IC))

Treatment		Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})	Heads m^{-2}	Grain head^{-1}	TGW† (g)
Year	2015	1178 a*	3871 a	8.3 a	526 b	38 a
	2016	925 a	3683 a	7.5 a	340 c	46 a
	2017	1301 a	4327 a	7.3 a	686 a	35 a
Tillage system	RT	979 b	3806 a	7.7 a	484 a	35 b
	NT	1290 a	4115 a	7.8 a	551 a	44 a
Crop rotation	Faba bean	1196 a	3735 a	7.7 a	563 a	44 a
	Wheat	1091 a	4092 a	7.9 a	488 a	37 a
	IC	1117 a	4054 a	7.7 a	501 a	38 a

*Within treatments, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD

†Thousand grain weight (TGW)

produced significantly more ears m^{-2} than intercrop wheat (Table 2).

There was statistically significant effect of tillage system on the number of grain ears^{-1} of wheat. The number of grain ears^{-1} was higher in the no tillage treatment compared to the reduced tillage (24 and 19 grain ears^{-1}, respectively) (Table 2).

The 1000-grain weight varied significantly depending on cropping system. The 1000-grain weight was higher for the intercropping treatment (32 g) than for the treatment of wheat planted alone (28 g) (Table 2).

Faba Bean

The number of pods m^{-2} in faba bean was significantly influenced by the tillage and the cropping system with significant influence depending on the year. The number of pods m^{-2} was higher in the no tillage system compared to reduced tillage (Table 2), and the highest number of pods m^{-2} was produced in the intercropping system in two of the three study years (2015 and 2016), with insignificant differences between the two cropping systems in 2017 (Table 1).

The effect of the cropping system on the number of grains pod^{-1} was statistically significant. The faba bean planted as a sole crop produced a higher number of grains pod^{-1} than intercropping (2.4 and 2.2, respectively) (Table 2).

The cropping system was statistically significant to 1000-grain weight of faba bean, being higher as a sole crop than in the intercropping treatment (461 and 422 g, respectively) (Table 2).

Yield and Biomass of Sunflower

The effect of the tillage and cropping system on sunflower grain yield was statistically significant greatly influenced by the year. The sunflower grain yield was higher in the no tillage system than in the reduced tillage system in 2015 and 2016 (Table 1). According to the cropping system, the sunflower grain yield was higher only in 2016 in the faba bean rotation than in the other two rotations (Table 1).

The sunflower biomass did not show significant differences in any of the treatments studied, with an average of 3960 kg ha^{-1} (Table 2).

The tillage system was statistically significant to the number of grains heads^{-1} with influence depending on the year although the number of grains heads^{-1} was only higher in the no tillage in 2015 compared to the reduced tillage (Table 1).

The effect of the tillage system on the 1000-grain weight was statistically significant, with no tillage resulting in a greater weight than reduced tillage (44 and 35 g, respectively) (Table 3).

SPAD Meter, Nodules, Sitona Larvae and Broomrape

The SPAD meter measurements were significantly affected by the tillage system and cropping system in wheat and by the tillage system in faba beans with an influence of the year in both crops. The SPAD meter measurements in 2015 were affected by tillage system being higher in the no tillage than in the reduced tillage in wheat and the opposite in faba beans (Table 1). The SPAD measurements were higher in wheat planted as a sole crop than in wheat in the intercropping treatment in 2017 (Table 1).

Table 3 Sunflower grain yield and heads m^{-2} and faba bean pods m^{-2} influenced by tillage (reduced tillage (RT) and no tillage (NT)) and cropping system (faba bean (Fb) and wheat (Wh) sole crop and intercrop (IC)) within each year*

		Sunflower		Faba bean
		Grain yield (kg ha^{-1})	Heads m^{-2}	Pods m^{-2}
2015				
Tillage system	RT	881 b	8.5 a	82 a
	NT	1474 a	8.2 a	107 a
Cropping system	Fb	1169 a	8.0 a	79 b
	Wh	1105 a	8.5 a	–
	IC	1259 a	8.5 a	109 a
2016				
Tillage system	RT	741 b	7.3 a	100 a
	NT	1109 a	7.8 a	115 a
Cropping system	Fb	1210 a	8.0 a	79 b
	Wh	839 bc	7.3 b	–
	IC	726 c	7.5 ab	136 a
2017				
Tillage system	RT	1314 a	7.3 a	69 a
	NT	1288 a	7.4 a	84 a
Cropping system	Fb	1209 a	7.1 b	75 a
	Wh	1328 a	8.0 a	–
	IC	1365 a	7.0 a	79 a

*For each year and effect, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD

The nodule weight $plant^{-1}$ was influenced by tillage system. No tillage led to an increase in the nodule weight $plant^{-1}$ compared to reduced tillage (0.25 and 0.14 g, respectively) (Table 4).

The number of sitona larvae was influenced by the tillage × cropping system interaction depending on the year, with the highest number of sitona larvae observed in reduced tillage and in the sole crop in 2015 compared to the other treatments (Table 4). There was no occurrence of broomrape on faba bean in either of the two growing systems.

Discussion

To the best of our knowledge, this is the first work assessing yields and LER in intercropping systems within a crop rotation system with different intensity of soil

Table 4 Nodules dry weight $plant^{-1}$ (g) and number of sitona larvae $plant^{-1}$ in faba bean and SPAD value at anthesis in faba bean and wheat as affected by year, tillage system (reduced tillage (RT) and no tillage (NT)) and cropping system (sole crop (SC) and intercrop (IC))

Treatment		Nodules dry	Sitona	SPAD value	
		Weight $plant^{-1}$	Larvae $plant^{-1}$	Wheat	Faba bean
Year	2015	0.18 a*	6.8 a	39.9 b	39.7 b
	2017	0.22 a	8.0 a	43.9 a	42.3 a
Tillage system	RT	0.14 b	8.2 a	41.8 a	42.1 a
	NT	0.25 a	6.6 a	41.9 a	39.9 b
Cropping system	SC	0.23 a	9.4 a	43.4 a	41.0 a
	IC	0.16 a	5.4 a	41.0 b	41.1 a

*Within treatments, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD preparation. Here we demonstrated the increase in yields of faba bean–wheat intercropping integrated into crop rotation system with sunflower, and as well as the benefits of the long-term no tillage system compared to tillage in Mediterranean rainfed Vertisols.

First, LER results showed the benefit of intercropping. The LER of the grain yield was above one (1.1), indicating that 10% more land area is needed in monocropping to achieve the same yields as in intercropping. Haymes and Lee [13] reported similar results of LER values for autumn-sown wheat and faba beans. Sahota and Malhi [27] reported similar results, with intercropping requirements of 7–17% less land than monoculture crops to produce the same yield. However, other authors have found different results.

A competitive advantage of faba bean over wheat was found for the intercrop treatment since the partial LER value was lower than 0.5 for wheat and higher for faba bean. Similar results were reported by Haymes and Lee [13] in autumn-sown wheat and faba beans intercropping. If intercropping has no effect on yield, then we would expect partial LER values of 0.5. Therefore, intercropped faba bean produced higher yields on the same land area as sole crops and the opposite occurred in wheat. The low LER of wheat can be attributed to a significantly lower number of ears m^{-2} at intercropping compared to sole crop while the high LER of faba bean can be explained because of a significantly higher number of pods m^{-2} in intercropping. The wheat appeared to be negatively affected by the competition with faba bean.

Regarding tillage system, in our experiment, wheat and faba bean grain yields increased by 65% and 10%, respectively, for no tillage subplots. Specifically, the tillage system had a significant effect on the grain yield in intercropping, which was 36% better under no tillage than under reduced tillage. There are scarce studies exploring tillage and cropping system with wheat–faba bean. In agreement with our results, Yin et al. [32], when studying a wheat-corn system, found significant differences in grain yields regarding the tillage system. The increase in soil organic matter that exists in a no tillage system compared to conventional tillage [20], together with increased root growth in both crops [26], could be the cause of the improved yields under no tillage. Moreover, symbiotic N_2 fixation by faba bean is higher along with N availability with no tillage [21], which can be attributed mainly to the higher soil water availability in a no tillage system. These conditions under no tillage favored a higher number of ears m^{-2} and of grains $ears^{-1}$ in wheat and an increase in the number of pods m^{-2} in faba bean compared to reduced tillage. No tillage improves the soil water storage capacity due to the increased infiltration caused by improved soil structure [26].

When comparing the grain yield in the sole planting systems with intercropping systems, the intercropping systems registered greater values compared to the sole plots only in faba bean. In intercropping, the wheat yield was lower than in sole planted wheat. Among the measured yield components, only pods m^{-2} in faba beans were higher in the intercropping system, related to the better yields obtained for this crop, while in wheat, the ears m^{-2} and 1000-grain weight were improved in monoculture wheat. However, the sum of the yields of both crops in intercropping was higher in two of the three years compared to the sole wheat. Nevertheless, the decrease in grain yield of one species was compensated by the grain yield of the other. Numerous studies on annual intercropping have reported that intercropping is more productive than sole crop production. Moreover, Bulson et al. [3], when studying a wheat–faba bean intercropping system, attributed the higher yields observed in the intercropped plots to their more efficient use of the limited plant resources (i.e., water, light, and nutrients) compared to the sole crops plots. Our research identified changes in wheat SPAD values associated with cropping systems, while insignificant differences in SPAD values were observed for faba beans. When planted as a sole crop, wheat showed higher SPAD values than when it was intercropped only in 2017. Since the SPAD readings correlate well with the leaf N contents [5], lower SPAD values in the intercropped areas suggest that the apparently available N is not sufficient under these growing conditions. Interestingly, Hauggaard-Nielsen and Jensen [11] reported that intercropped grain legumes and cereals at various N levels resulted in the grain legumes having higher interspecific competitive abilities at lower soil N levels, while those of the cereals were lower. According to Bedoussas and Justes [2], in a study conducted with a winter wheat–pea intercrop showed that an application of N fertilizer in the intercrop after the end of flowering of the legume (to prevent an adverse effect on N fixation) resulted in a significant increase in the grain protein concentration in wheat when N fertilization occurred after the end of the wheat stem elongation phase.

Sunflower yields improved in the no tillage system compared to the reduced tillage in the first two years despite low rainfall during these two years due to the higher soil water contents in this system. Hatfield et al. [10] reported that no tillage treatment had a positive effect on soil water content. Additionally, the root system of sunflower is deeper than that of other crops (wheat and faba beans), allowing sunflower to extract water from deeper soil profiles. Dardanelli et al. [4] reported that rooting depths of sunflower beyond 2.0 m are deeper than those of many annual crops, such as corn, sorghum, soybean and wheat. In the last year, however, the sunflower yields showed no differences between the two tillage systems due to the low rainfall in the preceding years, preventing sufficient water from being stored deeper in the soil profile. Crop rotations in sunflower had little influence on grain yield. Only in one year, faba beans had a positive influence on the sunflower crop. The low rainfall probably played a greater role in this study than the crop rotation system did.

Conclusions

Intercropping improved grain yield and pods m^{-2} in faba bean. However, in wheat, only the 1000-grain weight was improved through intercropping. In general, intercropped faba bean and wheat used land more efficiently than their equivalent sole crops. Nevertheless, the lower SPAD values obtained for the intercropped wheat could indicate a lower bioavailable N in this cropping system. No tillage improved the grain yields of sole and intercropped wheat. According to our results, intercropping could be highly beneficial compared to planting wheat alone since higher grain yields are achieved even without the application of N fertilizer. Our study included a 2:1 intercropping design for three dry years. Future research that includes different intercropping designs in different environmental conditions could provide valuable information for establishing productivity and land-use efficiency thresholds.

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Author Contributions Rafael J. Lopez-Bellido: conceptualization, data curation, investigation, methodology, writing-original draft preparation and resources. Veronica Muñoz-Romero: investigation, supervision, writing—reviewing and editing. Purificación Fernandez-Garcia: visualization, investigation, validation, writing—original draft preparation, writing—original draft preparation. Luis López-Bellido: conceptualization, methodology, resources, writing—reviewing and editing.

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Declarations

Conflict of 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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