Faba bean root growth in a Vertisol: tillage effects

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ABSTRACT

Studies on the growth of faba bean (*Vicia faba* L) root systems in Vertisols under Mediterranean climates are practically nonexistent. A three-year field study (2003–2004, 2005–2006 and 2006–2007) was conducted on a typical Vertisol (in southern Spain) to determine, using a minirhizotron system, the effects of tillage on root growth in faba bean grown in continuous rotation with wheat (*Triticum aestivum* L) as part of the long-term "Malagón" experiment that started in 1986. Tillage treatments were no-tillage (NT) and conventional tillage (CT). The parameters measured were root length (RL), root diameter (RD), root biomass (RB), seed yield and aboveground biomass. Root growth measures with minirhizotron were carried out at six soil depths for five growth stages throughout the faba bean growing season. For the calculation of RB, soil cores were collected during flowering from the same six soil depths. NT was more favorable for the development of the faba bean root system when compared with CT. This can be attributed to improved physical properties of the soil under NT, which improves the water conditions of the soil.

Keywords: *Vicia faba*; no tillage; conventional tillage; root length; root diameter; root biomass; minirhizotron

1. INTRODUCTION

Root function is very important to plant health and yield. Quantifications of root growth and root distributions are necessary to understand plant-soil interactions. The depth and distribution of roots are important parameters governing water and nutrient uptake by faba bean plants (Manschadi et al., 1998), especially in semiarid climates. Dardanelli et al. (1997) argue that during drought periods, a crop's capacity to extract soil water depends on the uniformity and depth of its root system. Smit and Groenwold (2005) suggest that rooting depth can be considered an inherent crop characteristic even though it can be influenced strongly by local conditions, for example, soil compaction or bulk density.

Faba bean (*Vicia faba* L) is a crop with a shallow root system with little osmoregulation and is very sensitive to high temperatures and water stress, particularly during anthesis and pod filling (Bond et al., 1994; Xia, 1994). When under water stress, faba beans have coping mechanisms that allow them to mitigate potential negative effects on the crop. According to Husain et al. (1990), these mechanisms consist of reducing its rate of height increase, decreasing its rate of leaf-area expansion slightly, greatly increasing root growth, producing leaves of smaller specific area and shedding leaves. Reid (1990) states that the increase in root growth of faba bean under limited water supply is the most effective of the above-mentioned adaptations to drought stress.

The effects of tillage systems on faba bean crops have been studied by López-Bellido et al. (2003) for rainfed Mediterranean conditions. However, these authors mainly refer to the effects on crop yield and the aboveground part of the plant. It is known that tillage systems influence soil properties such as bulk density, aggregation and pore continuity, temperature, aeration and moisture levels, which can affect root growth (Probert et al., 1987; Coulombe et al., 1996). On the other hand, roots also modify the structure and chemistry of the soil around them. Roots physically displace soil particles as they make their way through soil layers, and they alter the concentration gradients of water and nutrients within the soil as they take these up (Pierret et al., 2007). Roots can also perforate compact soil layers and create easily accessible pathways for the roots of succeeding crops (Henderson, 1989), which can also increase water movement and gaseous diffusion. Legume crops having the most extensive root development generally produce the greatest improvement in soil aggregation and stability (Stone and Buttery, 1989). Rochester et al. (2001) observed soil structural improvements as reduced soil strength where legume crops were grown, compared with non-legume crops. Haynes and Beare (1997) suggest that some legume roots deposit material of higher N content which enhance aggregate stability through greater exploration of those aggregates by fungal hyphae.

Vertisols are fine-textured soils that contain swelling clay minerals and develop wide and deep cracks during prolonged dry seasons. When dry, these soils have a hard consistency. They are plastic and sticky when wet, however (Lal, 1989). This soil has a large water holding capacity that allows crops to survive mid-season drought periods and grow long after rains have ended (Probert et al., 1987); however, they are also characterized by low infiltration rates and impeded internal drainage (Lal, 1989). Vertisols have particular management requirements, as well as specific problems due to tillage. Coulombe et al. (1996) extensively studied the degradation suffered by Vertisols by the effect of CT. In contrast, minimum or zero tillage systems and the retention of stubble can improve soil structure, increase organic matter content (Blair and Crocker, 2000) and soil water storage capacity (O´Leary and Connor, 1997), improve chemical fertility (Chan et al., 1999) and conserve water (Carroll et al., 1997). Mouldboard ploughing was and continues to be a common practice among farmers in our region. However, in recent years conservation tillage is gaining importance, as minimum tillage or no tillage.

The minirhizotron technique is becoming increasingly appreciated as a non-destructive method for studying the root dynamics of cultivated plants. However, the use of this technique has certain shortcomings, as pointed out by Johnson et al. (2001) and Hendricks et al. (2006), that should be investigated for each crop and each type of soil by contrasting it with traditional destructive methods.

The objective of this study is to determine the response of faba bean root growth to tillage when grown in a Vertisol under rainfed Mediterranean conditions, using minirhizotrons to estimate root length, root diameter and root biomass during the period of legume growth.

2. MATERIALS AND METHODS

2.1. Site and experimental design

Field experiments were conducted in Córdoba, southern Spain (37º46’ N, 4º31’ W, 280 m a.s.l.), on a Vertisol (Typic Haploxererts) typical of the Mediterranean region, where rainfed cropping is the standard practice (Table 1). The study took place over a 3-year period (2003–2004, 2004-2005 and 2005–2006), within the framework of a long-term experiment named ‘‘Malagón’’, started in 1986, and designed as a randomized complete block with a split–split plot arrangement and four blocks. Main plots were tillage system [no-tillage (NT) and conventional tillage (CT)]; subplots were crop rotation, with four 2-year rotations (wheat–sunflower, wheat–chickpea, wheat–faba bean and wheat–fallow) and continuous wheat; sub-subplots were N fertilizer rate (0, 50, 100, and 150 kg N ha^{-1}) applied to wheat. Each rotation was duplicated in reverse crop sequence in order to obtain data for all crops on a yearly basis. The area of each sub-subplot was 50 m^2 (10 by 5 m).

Since this study was conducted to independently evaluate the influence of tillage system on faba bean root growth in continuous rotation with wheat, using only the 100 kg N ha^{-1} rate applied to wheat, the design was a randomized complete block with three replications.

2.2. Crop management

No-till plots were seeded with a no-till seed drill. Weeds were controlled with glyphosate + 2-methyl-4-chlorophenoxyacetic acid (MCPA) at a rate of 0.5 + 0.5 L active ingredient ha^{-1} prior to planting. The conventional till treatment included moldboard ploughing (25–30 cm depth) and disk harrowing and/or vibrating tine cultivation (10–15 cm depth) several times to grind clods. The crop residues were not removed by either tillage treatment; residues remained as mulch on NT treatments and were incorporated in CT treatments.

Faba bean (cv. Alameda) was planted in 50 cm-wide rows in November at a seeding rate of 278,000 seed ha^{-1} with an average thousand seeds weight of 612 g. Nitrogen fertiliser (100 kg N ha^{-1}) was applied to the preceding wheat (*Triticum aestivum* L) plots as ammonium nitrate. Half of the N was applied before sowing (incorporated by disk harrowing in conventional till plots and surface broadcast in no-till plots). The remaining N was applied as a top dressing at the beginning of wheat tillering. Each year, the preceding wheat plots were also supplied with P fertiliser as calcium superphosphate at a rate of 65 kg ha^{-1}; the fertiliser was incorporated in conventional till soil and banded with a drill in the no-till plots. Soil-available K was adequate (530 mg kg^{-1}).

At harvest, a 1-m^2 area at the centre of each faba bean plot was sampled. From this sample, aboveground biomass was measured by drying plants at 80 ºC to a constant weight. The faba bean was harvested in early June each year by using a 1.5-m wide Nursemaster elite plot combine (30 m^2 per plot).

2.3. Measurements

Soil water content was determined with two measurements per faba-bean plot at planting and at harvesting to a depth of 0.9 m in 0.3-m increments using a ThetaProbe mL2x soil moisture sensor (AT Delta-T Devices, Cambridge, UK).

The pedestrian traffic was the normal amount for this type of experiment and we understand that no special perturbations or compaction occurred as a result.

2.3.1. Soil coring

Cylindrical soil cores were randomly sampled and in triplicate at the centre of each plot and on planting rows, using an 8 cm-diameter bi-partite root auger (Eijkelkamp, NL). The first sample was taken on a line from the center of the plot and the other two were taken on lines separated by 2-3 meters in the opposite direction. Manschadi et al. (1998) found differences between soil core taken on the row and between rows only in the first 15 cm. We adopted the criterion of taking soil core samples from the sowing line, since this is where the minirhizotron tubes were installed and one of our objectives was to perform a comparative study of the root system using both methods. Each location was sampled at six depths (0–15, 15–30, 30–50, 50–65, 65–80 and 80–100 cm). Sampling was carried out during full flowering of the faba bean (65 days) (Lancashire et al., 1991). Prior to processing, soil samples were immediately frozen at -30 ºC to avoid root decomposition.

Roots were washed using Calgon (a 10% sodium hexametaphosphate and sodium bicarbonate solution) as a dispersant. After 12 hours in this solution, the roots were rinsed in water and collected on a sieve with a 0.2-mm mesh screen. Debris and dead roots were manually removed from live roots. Distinguishing live from dead roots can be difficult and, no universal standard is applied. The criteria are typically based on colour (separating white or pale brown roots from darker materials) and physical appearance (e.g. branched, able to bend, some elasticity) according to Gregory (1994). The roots were always separated by a same experienced operator, which established a colour and flexibility criterion that followed along the all experiment. They were dried at 40 ºC for 24 hours and weighed to obtain root biomass (kg ha^{-1}).

2.3.2. Minirhizotron

Measurements of root length and diameter were made with the CI-600 root growth monitoring system (CID, Inc. Camas, WA 98607 USA) fitted with a scanner head for collecting images, a laptop computer with the CI-400 Computer Image Analysis Software

(CIAS) and standard clear 1.8-m soil tubes (50.8 mm internal diameter) with end caps. After faba bean emergence, tubes were installed permanently at the centre of each plot on the sowing line, 45º from vertical as recommended by Johnson et al. (2001). An auger of the same external diameter as the tube was used to facilitate close tube/soil contact. In turn, the scanner was inserted into each tube to a depth of 100 cm. Images were captured at six depths with the aid of an automatic indexing handle, equivalent to 0–15, 15–30, 30–50, 50–65, 65–80 and 80–100 cm (given the angle of the tube at 45º off vertical). Images were captured at the following stages of development (Lancashire et al., 1991): when 6–7 leaves unfolded (16) (10 weeks after sowing, WAS), the beginning of flowering (60) (14 WAS), full flowering (65) (18 WAS), the beginning of ripening (80) (21 WAS) and seed drying (96) (24 WAS). Measurements were made between February and mid-May in each of the three study years.

The images were processed with the WinRhizotron® software (Regent Instruments Inc.), which provided values for root length (mm cm^{-2}) and diameter (mm) for each plot and each faba bean growth stage under the two tillage systems tested.

2.4. Statistical analysis

The annual data for each variable over the total 3-yr period were subjected to analysis of variance (ANOVA), using a randomised block design combined over years and an error term according to McIntosh (1983). Tillage system and year were considered fixed effects. Growth stage and soil depth were considered as repeated measure variables. Means were compared using Fisher's protected least significant difference (LSD) test at $P < 0.05$. The LSDs for comparisons of the different main effects and interaction terms were calculated using the appropriate standard error terms. The Statistix v. 8.1 (Analytical Software, 2005) package was used for this purpose.

3. RESULTS

3.1. Weather conditions

Rainfall varied considerably between years, which is typical for a Mediterranean climate. The year 2003–2004 was the wettest (704 mm), followed by two dry years recording very similar low rainfalls (2005–2006: 402 mm; 2006–2007: 414 mm). The average annual rainfall in the area over 30 years is 584 mm. The amounts of rainfall before planting for each year were 403, 120 and 137 mm. The soil water contents at planting were 0.36, 0.25 and 0.28 m^3 m^{-3} for the years 2003–2004, 2005–2006 and 2006–2007, respectively, and at harvest, they were 0.41, 0.26 and 0.28 m^3 m^{-3}. The soil water content was significantly higher in 2003–2004 at both planting and harvest. There were significant differences between tillage systems in the soil water content at planting, especially in the dry years (Table 2).

The highest rainfall over the crop’s growing season occurred in the year 2003–2004, except the period between when 6–7 leaves unfolded and the beginning of flowering occurred had its highest rainfall in 2005–2006, and the period between the beginning of ripening and seed drying had its highest rainfall in 2006–2007 (Fig. 1).

3.2. Root length

Root length (RL) significantly differed depending on the year, tillage system, soil depth and growth stage of faba bean (Table 3). The year had a highly significant influence on the values of RL across the entire soil profile studied. The mean values of RL were 0.8, 0.09 and 0.4 mm cm^{-2} in 2003–2004, 2005–2006 and 2006–2007, respectively, with significant differences among them. The year × tillage system × soil depth × growth stage interaction was also significant for RL (Table 3, Fig. 2). In 2003–2004, RL decreased with increasing soil depth, although at the greater depths of soil in some stages of growth an increase in RL was observed (Fig. 2). In the other years, from the beginning of flowering of the faba beans, RL increased to a soil depth of 10–20 cm and decreased after that (Fig. 2). In the 2005–2006 and 2006–2007 growing seasons, virtually no roots were found at depths exceeding 30 cm; whereas the root depth exceeded 80 cm in the wet year almost until seed dry stage, specially in NT (Fig. 2).

The RL was higher under NT than under CT for most of the growth stages and depths in 2003–2004 (Fig. 2). In 2005–2006, the RL in NT was also higher than CT in most stages of growth, especially at the soil depth of 10–20 cm. In 2006–2007, however, the RL was higher in the CT at the beginning of flowering, although it was greater in NT at the full flowering phase (Fig. 2).

For both tillage systems, the maximum RL occurred at full flowering in 2003–2004 and 2005–2006 and in beginning of ripening in 2006–2007 (Fig. 2). In 2003–2004, the wettest growing season, the RL in the top 30 cm accounted for 46% of the total RL, whereas in the years 2005–2006 and 2006–2007, it constituted 77 and 96%, respectively.

3.3. Root diameter (RD)

The average RDs were 0.78, 0.48 and 0.66 mm in 2003–2004, 2005–2006 and 2006–2007, respectively, differing significantly (Table 3). A direct relationship between the values of RD and the rainfall and its distribution in the growing season was observed throughout the soil profile in different years, although the RD showed a slight tendency to decrease with increasing depth soil (Fig. 3). In the years 2003–2004 and 2005–2006, NT had higher RD than CT for most soil depths (Fig. 3).

3.4. Root biomass (RB)

A significant linear regression [RB(kg ha^{-1}) = 5024.5 RL(mm cm^{-2}) + 2,037] (r^2= 0.60, n=12, $p<0.01$) was obtained between RL measurements obtained by minirhizotrons and root biomass (RB) values obtained from soil cores in 2003–2004 and 2005–2006. Root biomass was estimated from the regression equation throughout the soil profile, taking into account the values of minirhizotron RL for each of the years and tillage systems (Fig. 4). The wettest year (2003–2004) had greater root biomass (3,192 kg ha^{-1}) than the other two years (640 and 1,865 kg ha^{-1} in 2005–2006 and 2006–2007, respectively); the values are significantly different (Fig. 4). The root biomass was higher in NT than in CT in 2003–2004 and 2005–2006 (Fig. 4).

3.5. Seed yield and aboveground biomass

Seed yield was significantly higher under NT than under CT for the growing seasons in 2003–2004 (1,875 versus 1,077 kg ha^{-1}) and 2005–2006 (779 versus 77 kg ha^{-1}) (Table 4, Fig. 4). The NT was higher than CT for the yield components during these years except for seed pod^{-1} in 2003–2004 (Table 4). These results match with the increased root biomass in NT compared with CT (Fig. 4). The straw yield was significantly higher under NT than under CT for the years 2005–2006 and 2006–2007 (Fig. 4). Seed yield, straw yield and aboveground biomass were directly related with root biomass (Fig. 5).

In 2003–2004 the root:shoot biomass ratio (0.87) was significantly higher than in other years (0.40 and 0.54 in 2005–2006 and 2006–2007, respectively). This ratio was not significantly different in relation to the tillage system.

4. DISCUSSION

4.1. Root length

There was a greater depth of root development in the wet year compared to dry ones (Fig. 2), which has also been confirmed by Schenk and Jackson for herbaceous crops. These authors maintain, for a given canopy size, that herbaceous plants have deeper maximum rooting depths in drier environments; however, because canopy size increases along the rainfall gradient, mean rooting depth also increases. In dry years, it is more economical for the plant to grow its roots closer to the soil surface where they can exploit most of the available nutrients and water from natural rainfall (Mickovski and Beek, 2009). Manschadi et al. (1998) have indicated that an increase in rooting depth under drought stress conditions can only occur when the deeper layers of the soil profile are wet enough to allow downward penetration of the rooting front. The restricted infiltration depth of the Vertisols may have prevented, in the dry years, soil deeper than 30 cm from having sufficient moisture for the roots to grow to greater depths. In addition, there is clearly a positive correlation between the amount of rainfall recorded in the growing season and the values of RL in faba bean, as clearly seen in the wet year compared to the other two drier years. It is more difficult to interpret differences in RL between years that record similar amounts of rain but have different distributions of rainfall throughout the growing season. Such variations could be attributed to a broomrape attack (*Orobanche crenata* Forsk) in 2005-2006, which produced differences in seedling emergence and crop establishment, which is also closely related to the state of soil moisture at this critical stage. In this sense, the rains in 2006–2007 were closer to the date of crop planting than those in 2005–2006. This led to increased plant density and numbers of pods m^{-2} in 2006–2007 (28 plants m^{-2} and 170 pods m^{-2}) compared to 2005–2006 (21 plants m^{-2} and 98 pods m^{-2}) (Table 4). The root length results of this study are similar to those obtained by Heeraman and Juma (1993) in faba bean crop, if the transformation is performed in equivalent units. If we express our root length results (cm cm^{-2}) in root length density (cm cm^{-3}), a measurement of 1.4 cm cm^{-3} is obtained for the 3 years throughout the entire soil profile. Wheat root length in the same experiment and in the framework of the wheat-faba bean rotation was 4.04 cm cm^{-3} (Muñoz-Romero et al., 2010). Maize root lengths of between 5-20 cm cm^{-3} were obtained under similar conditions to our current study (Grimes et al., 1975; Bonhomme, 1984). This suggests that cereals may have a root length that is 3 to 14 times greater than that of faba bean.

The maximum RLs were registered at full flowering in 2003–2004 and 2005–2006 and at the beginning of ripening in 2006–2007. The variation between the two dry years can be attributed to the different rainfall amounts recorded in April and May, corresponding to the period of filling and maturation of faba bean pods. During these months, the amount of rain in 2006–2007 was double that of 2005–2006 (Fig. 1). Manschadi et al. (1998) also observed that root growth continues in faba bean during the periods of flowering and pod filling, when soil moisture is adequate during the latter stage. Brown et al. (1989) indicated that indeterminate legume crops continue to allocate photosynthate to the root system during early pod filling so that the total size of the root system continues to increase, but often at a lower rate than before flowering.

Overall, RL was significantly higher under the NT system compared with CT, which could be attributed to an increase in water use under NT with respect to CT, which has been reported by López-Bellido et al. (2007) for rainfed Vertisols under Mediterranean conditions. Furthermore, the NT can improve soil structure, increase water infiltration and aeration. This can be attributed, in part, to the greater biotic activity, especially that of earthworms, under NT, and which increases the number of macropores and biochannels as their continuity and stability (Ehlers, 1975). In contrast, tillage can degrade soil structure. In addition, continuous and intensive tillage can lead to the formation of a massive structure in Vertisols, which would result in the absence of pedality, continuity and connectivity of macropores (Coulombe et al., 1996) causing the consequent deterioration of soil physical properties and a decrease in root growth (Probert et al., 1987).

4.2. Root diameter

The values of RD were also higher in NT compared with CT in two of the three years of study and for most soil depths, coinciding with the highest values of RL, which also were in NT. Gregory (2006) also indicated that there is a significant positive correlation between root diameter and elongation in many crop plants. However, for most legumes in general, and for faba bean in particular, no studies have established this relationship. In contrast, Qin et al. (2006), Pereira de Mello Ivo and Mielniczuk (1999) and Holanda et al. (1998) found higher values of RD in NT compared with CT for corn (*Zea mays* L). Chassot and Richner (2002) have suggested that greater soil strength under NT may be one of the main reasons for this. Veen and Boone (1981) also have stressed the importance of mechanical resistance in RD. According to Shein and Pachepsky (1995), the RD of plants grown in compacted soil is thicker than those from uncompacted soil in response to the higher mechanical impedance. In addition, Chassot et al. (2001) have suggested that lower soil temperature under NT may have resulted in higher mean root diameters during early stages of growth, which may have persisted until anthesis.

Our results are consistent with those of Ruggiero et al. (1999), who demonstrated the existence of a trend for the mean RD of faba bean to be higher in the top soil layer than in the deepest soil layer. According to Himmelbauer et al. (2004), the root diameter is one of the most important parameters for rhizosphere modelling. At the plant level, large-diameter roots account for most of the root system biomass. Small-diameter roots account for most of the root system surface area and are the site of the soil-plant exchanges responsible for water and nutrient uptake (Eissenstat and Yanai, 2002).

4.3. Root biomass

In 2005–2006 seed yield was very low due to broomrape attack. This attack was especially intense in CT, since NT reduced the broomrape infestation and increases seed yield (López-Bellido et al., 2009). Besides, the soil water content at planting was higher in NT (Table 2), so that faba bean crop could develop better in this tillage system.

In agreement with earlier root parameters, RB was also higher in NT compared with CT. Again, this behaviour can be attributed either to increased water retention capacity of soil under NT, which would induce more root growth, or an increase in water use under NT with respect to CT during dry years, as reported López-Bellido et al. (2007) for the same experiment. The mulching associated with NT also plays an important role in soil water conservation, slowing the evaporation of water from the soil surface and acting as an insulator against the conduction of heat toward the soil interior.

The greater root:shoot ratio recorded in the wettest years with higher water content in soil compared to dry years, shows that RB is more affected by water stress than aboveground biomass. Manschadi et al. (1998) reported that, under semiarid conditions, root growth is significantly reduced when compared with well-watered treatments. Husain et al. (1990) also reported that faba beans have a potentially advantageous adaptation to water deficit that makes it change its root and aboveground biomass according to the soil moisture conditions.

5. CONCLUSIONS

The minirhizotron has proved to be a useful tool in our field conditions to study the root system of faba bean during the season of crop growth in Vertisols. Root development of faba bean is closely related to good crop establishment (especially in dry years), the distribution of rainfall during the growing season and the seed yield. The root:shoot ratio of faba bean was lower in the driest years, indicating more reduced root growth and root penetration compared to shoot growth.

The NT system had significantly higher values of the root parameters studied (RD, RL and RB) than conventional tillage. The values of RD in the NT were 1.2 times higher than in CT. The values of RL and RB were 1.8 and 1.6 times higher in NT than in CT, respectively. The greater root development under NT could be attributed to the higher infiltration and water storage capacity of the soil, caused by the improvement in soil structure (stability and aggregate size).

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Table 1
The properties of the Vertisol used in field experiments. Córdoba (Spain)

		Depth[a] (cm) 0-30	30-60	60-90
Fine sand (g kg^{-1})		127 (17)	143 (19)	187 (21)
Silt (g kg^{-1})		179 (20)	152 (20)	26 (5)
Clay (g kg^{-1})		694 (35)	705 (37)	787 (39)
pH (1:2.5 soil-water)		7.7 (0.15)	7.6 (0.15)	7.6 (0.1)
Organic matter (g kg^{-1})		10.2 (0.11)	7.4 (0.17)	5.3 (0.2)
Calcium carbonate equivalent (g kg^{-1})		75 (13)	93 (41)	71 (5)
CEC (cmol kg^{-1})		46.5 (3.7)	36.6 (5.4)	30 (6.9)
Bulk density (t m^{-3}):	No tillage	0.95(0.06)	1.06(0.06)	1.10(0.08)
	Conventional tillage	0.90(0.01)	1.05(0.04)	1.04(0.04)

[a] Standard errors of the means are given in parentheses

Table 2. Soil water content at planting and harvest of faba bean as influenced of year, tillage system (NT, no tillage; CT, conventional tillage) and soil depth at Córdoba (Spain)[a]

		Water content at planting (m^3 m^{-3})			Water content at harvest (m^3 m^{-3})		
Year	Tillage system	0-30	30-60	60-90	0-30	30-60	60-90
2003-2004	NT	0.41a	0.35a	0.38a	0.41a	0.43a	0.40a
	CT	0.41a	0.35a	0.35b	0.41a	0.40b	0.37a
2005-2006	NT	0.35a	0.16a	0.37a	0.18a	0.32a	0.29a
	CT	0.25b	0.09b	0.28b	0.18a	0.27b	0.26a
2006-2007	NT	0.35a	0.24a	0.27b	0.23a	0.31a	0.33a
	CT	0.36a	0.21b	0.31a	0.23a	0.23b	0.31a

[a] For each year and depth, means followed by the same letter are not significantly different at P<0.05 according to LSD.

Table 3. Significant effects of year, tillage system, soil depth, and growth stage on root length and root diameter measured by minirhizotron; and of year and tillage system on grain yield in faba bean crop over 3 yr period.

Source	Root length ($mm\ cm^{-2}$)	Root diameter (mm)	Grain yield ($kg\ ha^{-1}$)
Year (Y)	***	***	***
Tillage system (T)	***	***	***
Y × T	***	ns	*
Soil depth (D)	***	***	–
Y × D	***	***	–
T × D	**	***	–
Y × T × D	ns	**	–
Growth stage (G)	***	***	–
Y × G	***	***	–
T × G	***	***	–
D × G	***	***	–
Y × T × G	***	***	–
Y × D × G	***	***	–
T × D × G	***	***	–
Y × T × D × G	**	***	–

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† ns, not significant.

Table 4. Yield and yield components of faba bean as affected by year and tillage system in a continuous rotation with wheat at Córdoba (Spain)[a].

Year	Tillage system	Yield (kg ha^{-1})	Pods m^{-2}	Seeds pod^{-1}	1000 seed weight	HI
2003-2004	NT	1875a	195a	2.5a	531a	50a
	CT	1077b	101b	2.3a	353b	32b
2005-2006	NT	779a	164a	1.4a	539a	38a
	CT	77b	31b	0.8b	293b	19b
2006-2007	NT	1854a	185a	1.7b	1089a	48a
	CT	1444a	172a	1.9a	941a	43a

[a] For each year, means followed by the same letter are not significantly different at P<0.05 according to LSD.

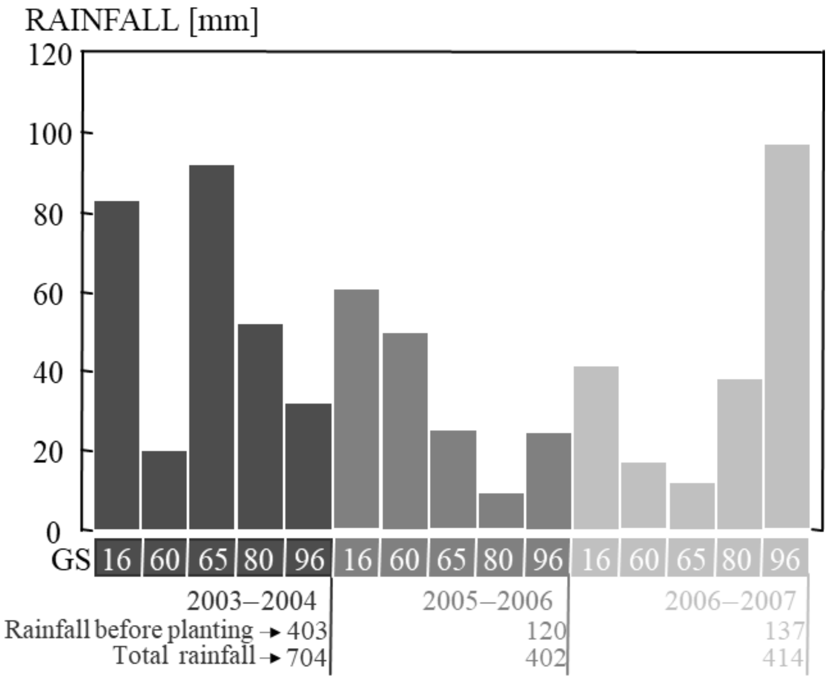

Fig. 1 Accumulated rainfall between the growth stage (GS)(Lancashire et al., 1991) indicated and the preceding one. Growth stage 16 represents the amount between planting and this GS.

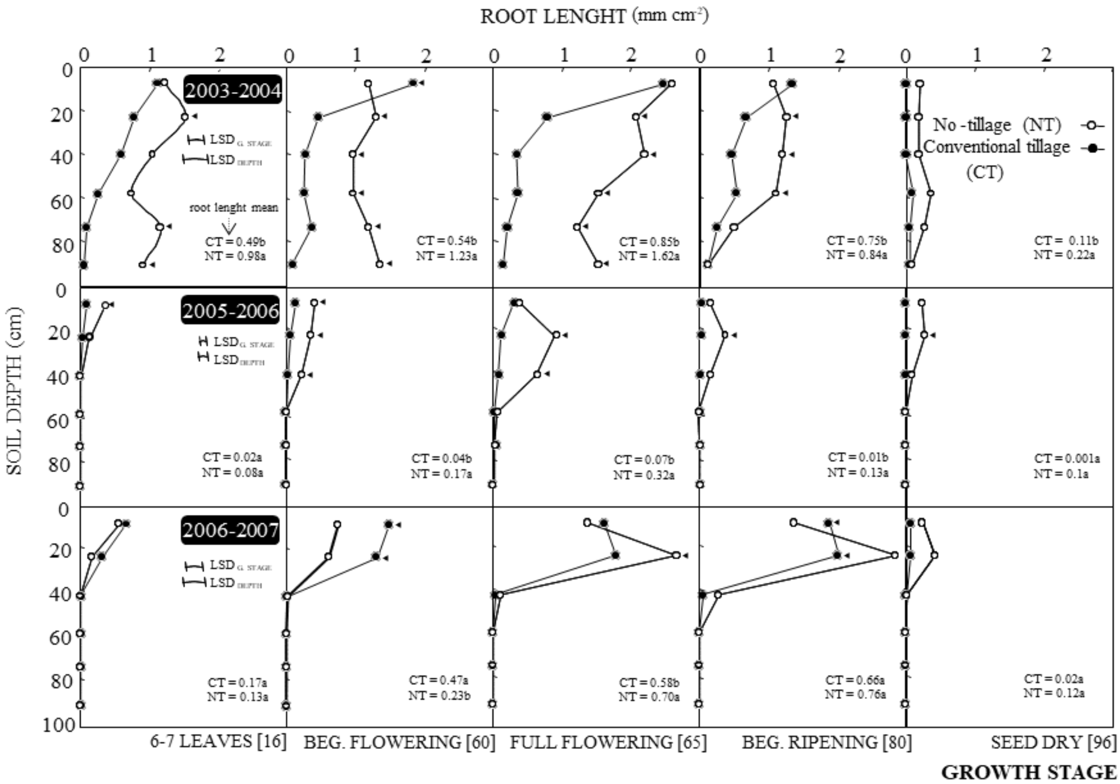

Fig. 2 Faba bean root length as influenced by year and tillage system for different soil depths and growth stages (Lancashire et al., 1991). The triangle (◂) represents significant difference between tillage systems. Horizontal bars represent LSD for comparison: $LSD_{G.\ STAGE}$, the same levels of year and tillage system; LSD_{DEPTH}, different levels of year.

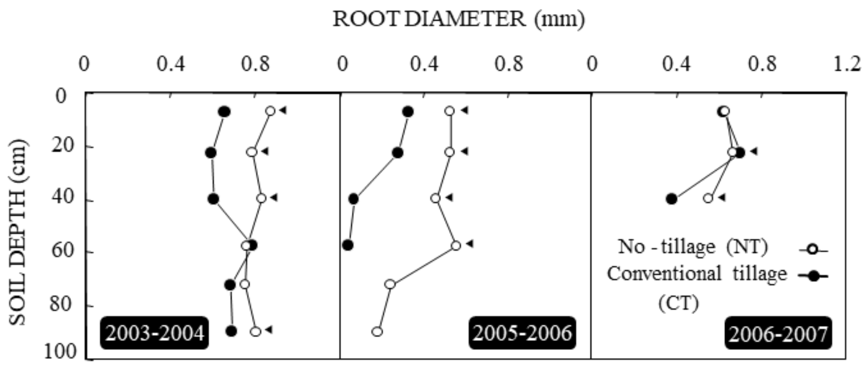

Fig. 3 Faba bean root diameter as influenced by year and tillage system for different soil depths. The triangle (◂) represents significant difference between tillage systems.

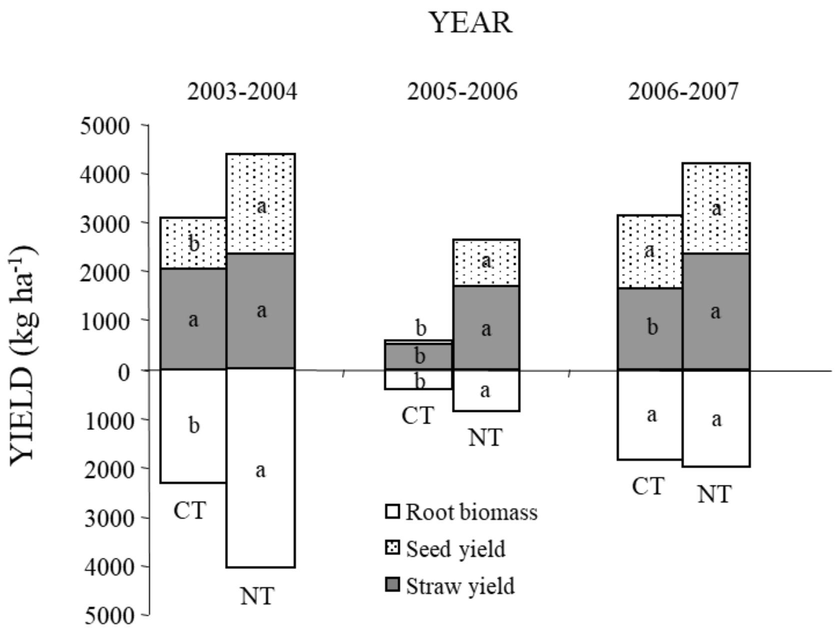

Fig. 4 Seed yield, straw yield and root biomass of faba bean as influenced by year and tillage system (CT: conventional tillage; NT: no-tillage). For each year and parameter, means followed by the same letter are not significantly different at P < 0.05 according to LSD

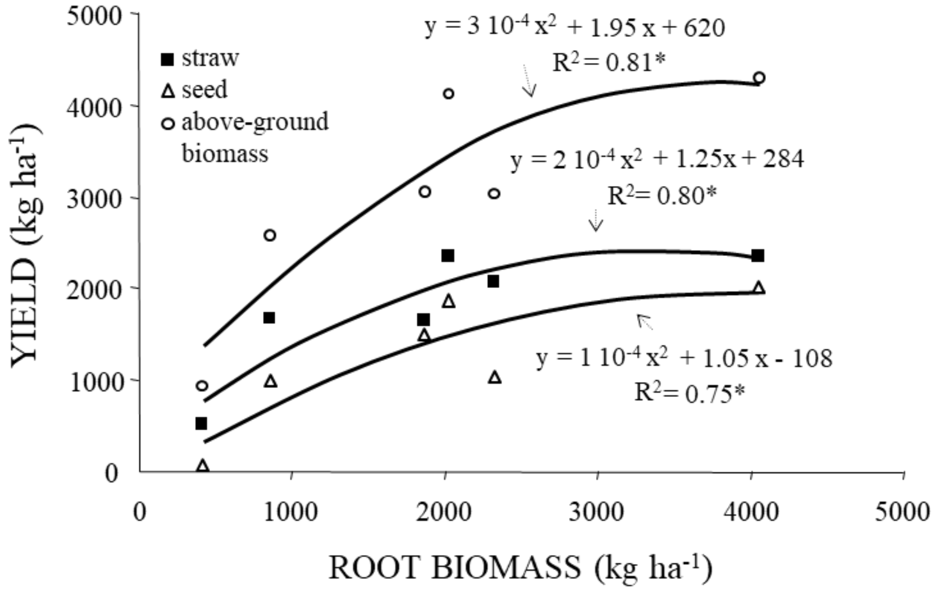

Fig. 5 Relationship between faba bean root biomass and seed yield, straw yield and aboveground biomass. * Significant at 0.05 probability level.