Effect of tillage system on the root growth of spring wheat

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Abstract

Little research has examined the influence of tillage system on root growth in wheat grown on rainfed Vertisols. A 3-yr field study (2003, 2004 and 2005) was carried out on a typical Vertisol (southern Spain), to determine the effects of tillage system on root growth in spring wheat (*Triticum aestivum L*) grown in continuous rotation with faba bean (*Vicia faba L*), within the framework of the long-term "Malagón" experiment started in 1986. Tillage treatments were no-tillage (NT) and conventional tillage (CT), and the experiment was designed as a randomized complete block with three replications. The following parameters were measured: above-ground biomass, grain yield, root length density (RLD), root biomass (RB) and root N content. In the topmost 10 cm of soil, higher values were found under CT than under NT for RLD in the rainiest year (20.2 vs. 9.6 km m^{-3} respectively) and for RB (512 vs. 261 kg ha^{-1} respectively) in all study years. In deeper layers, no difference was recorded between the two tillage systems. Greater wheat root development in the upper soil layer under CT may reflect the greater soil penetration resistance found in the topmost 10 cm under NT. Root separation using a sieve with a 0.5 mm mesh screen led to a marked underestimation of RLD and RB, with values up to three times higher when using a 0.2 mm mesh screen. Mean wheat root N content in the topmost 30 cm of soil accounted for over 80% of total root N content. The highest grain yield was observed under NT, since this system provided greater water storage in the soil profile in the mostly dry study years.

Introduction

Root growth is determined both by plant genetic characters and by soil physical and chemical properties. Clark et al. (2003) suggest that the ability of roots to grow and explore the soil for water and nutrients is a key determinant of plant growth rates. The major factors influencing root growth are: an appropriate pore system into which roots can grow, root impedance, soil water content, soil temperature, oxygen (O_2) and nutrient supply (Johnson et al. 2006). However, as reported by Asady and Smucker (1989), these factors tend to be synergic and difficult to separate.

Tillage system may modify certain soil properties, such as bulk density, penetration resistance and aggregate stability. Huwe (2003) reports that tillage influences both biotic and abiotic processes, modifying structural properties such as cracks, aggregates and pore continuity, as well as affecting soil aeration, temperature and moisture levels. Tillage may have a significant impact on root growth, as well as give rise to differences in soil nutrient status. Relatively little is available on root growth response to different tillage systems in cool temperate regions, particularly for small-grain cereals. Gregory (1994) found that NT was associated with higher RLD in the topmost layer. However, other studies in temperate climates found no difference in root growth for winter wheat under NT and CT (Ellis and Barnes 1980; Qin et al. 2004). Pearson et al. (1991) reported that the impact of tillage on root growth may depend on the length of time since the implementation of NT. Rasmussen (1991) has observed that the influence of tillage on RLD is evident in the layer affected by plowing, noting that root accumulation is greater in the 0 - 5 cm layer under NT than under CT. Similar findings were reported for temperate climates and loamy silt and sandy loam soils by Qin et al. (2004). By contrast, RLD is found to be lower at greater depths under NT (Chan and Mead 1992; Rasmussen 1991).

Vertisols occur in many areas of the world, particularly in dry regions, where they allow a subsistence agriculture which 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. The effect of CT on Vertisol degradation has been documented and analysed in depth by Coulombe et al. (1996). Conventional and continuous cultivation lead to, among other things, an increase in bulk density and soil strength, and degradation of the macropore space and pedality. The tillage pan may also pose serious problems in Vertisols under intensive tillage. Conservation tillage systems, such as NT, were developed as an alternative to CT practices, to help reduce the risk of soil erosion and alleviate soil degradation. Greater soil water content and similar grain yields in the NT system compared to the CT system have been reported (Halvorson and Reule 1994; López-Bellido et al. 2000). Therefore NT has thus come to be seen as an attractive management alternative for Vertisols. However, Coulombe et al. (1996) have also drawn attention to certain negative effects of NT management on physical properties. According to Probert et al. (1987) and Blevins and Frye (1993), the use of NT in fine-textured (clayey) soils may, over time, lead to adverse physical conditions for the root system, increasing impedance and apparent density in the topmost 30 cm, and, as a result, hinder root penetration.

Opinions differ regarding the influence of water deficit on root growth rates. Although plant water deficit reportedly leads to restrictions in root growth (Gajri et al. 1991 and Ruiz-Canales et al. 2006), soil water deficit has been shown to stimulate root development (McCully 1999). Deficit irrigation has also been applied in order to stimulate root growth (Romero et al. 2004) especially in the deeper soil layers (Burkart et al. 2004). López-Bellido et al. (2007) reported that, in many rainfed areas, root growth restrictions limit utilization of all the water available in the soil profile. As a result, cropping practices designed to reduce physical impedance to root growth may benefit dryland crop yields in areas with a limited water supply (Turner 2004). Changes in the topsoil as a result of tillage system and residue management may increase soil water retention capacity, enhancing the ability of roots to extract more water from the soil profile, or reducing losses through infiltration.

Little research has focused on the influence of tillage system on wheat root growth in Vertisols. This study aimed to determine the response of spring wheat root growth (root length density and root biomass) to tillage system in a Vertisol under rainfed Mediterranean conditions.

Materials and methods

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-yr period (2003, 2004 and 2005), within the framework of a long-term experiment named ''Malagón'', started in 1986. Treatments were NT and CT. The experimental design was as a randomized complete block with three replications. The area of each experimental plot was 10 x 5 m (50 m^2).

Crop management

No-till plots were seeded with a no-till seed drill, being weeds controlled with glyphosate [N-(phosphomethyl)glycine] + MCPA [(4-chloro-2-methylphenoxy)acetic acid] at a rate of 0.5 + 0.5 L a.i. ha^{-1} prior to planting. The CT treatment included moldboard plowing and disk harrowing and/or vibrating tine cultivation to prepare a proper seedbed. In both tillage systems, within the growing season, weeds were controlled with specific herbicides, namely: diclofop methyl + tribenuron at 0.9 and 15 g a.i. ha^{-1} respectively.

Hard red spring wheat (*Triticum aestivum* L cv. Gazul) was planted in 18-cm-wide rows between 1 to 10 December in 3-yr at a seeding rate of 150 kg ha^{-1}. Nitrogen fertilizer (100 kg N ha^{-1}) was applied to the wheat plots as ammonium nitrate; half was applied before sowing (incorporated by disk harrowing in CT plots and surface-broadcast in no-till plots); the remaining N was applied as a top dressing at the beginning of wheat tillering (GS31) (Zadoks et al. 1974). Each year, the wheat plots were also supplied with phosphorus (P) fertilizer at a rate of 65 kg ha^{-1}; the fertilizer was incorporated into CT soil and banded with a drill in the no-till plots. Soil-available potassium (K) was adequate (530 mg kg^{-1}).

Soil water content (Table 2) was measured twice on each plot, at planting and at harvest, to a depth of 0.9 in 0.3 m increments, using a ThetaProbe mL2x soil moisture sensor (AT Delta-T Devices, UK).

At harvest, a 0.5 m² portion at the center of each wheat plot was sampled. From this sample, biomass was measured by drying the plants at 80ºC to a constant weight. In each year, wheat was harvested in June from a 30 m^2 area using a 1.5 m wide Nursemaster elite plot combine. N content in the above-ground biomass was measured at maturity by the Dumas Combustion Method (EA 3000 Eurovector SpA, Milan, Italy).

Root sampling and analysis

Cylindrical soil cores were sampled randomly and in triplicate at the centre of each plot and on rows, using an 8 cm-diameter bi-partite root auger (Eijkelkamp, NL). Each core was taken at 7 different depths (0-10, 10-20, 20-30, 30-40, 40-55, 55-70 and 70-85 cm). Sampling was carried out during wheat anthesis (GS65) (Zadoks et al. 1974), when root development is at its maximum (Gregory et al. 1978; Barraclough and Leigh, 1984). Soon after sampling, soils were frozen at -30ºC to avoid root decomposition.

The roots were washed using calgon (a 10% sodium hexametaphosphate and sodium bicarbonate solution) as a dispersant. This method did not have effect on root N content in comparison with water washing. After 12 hr in this solution, the roots were rinsed in water and collected on a sieve with a 0.5 mm mesh screen, according to Amato and Pardo (1994) and Gregory et al. (1978). Debris and dead roots were manually separated from vital 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). In 2005, a 0.2 mm sieve was also used to measure root biomass only, since the roots recovered with this sieve were too small to allow RLD measurement.

The roots were scanned and the images were processed to determine length, using the specific image-processing software package CIAS version 2.0 (CID 2002). They were

then dried at 40ºC for 24 hr and weighed; N content was measured by the Dumas Combustion Method.

The following indices were calculated: root length density (RLD), i.e. length of roots per unit volume of soil (km m^{-3}); root biomass (RB), i.e. root weight per unit area (kg ha^{-1}); and root N content, i.e. the amount of N in the roots per unit area (kg ha^{-1}).

Statistical analysis

Annual data for each parameter over the whole 3-yr period were subjected to analysis of variance (ANOVA), using a year-combined randomized complete block design as described by McIntosh (1983). Treatment means were compared using Fisher's protected least significant difference (LSD) test at P ≤ 0.05. Different correlations were also calculated. Analyses of variance were performed using Statistix 8.0 Analytical Software (Analytical Software 2005) to determine the treatment effects.

Results

Weather conditions and yield

Mean annual rainfall recorded a maximum interannual variation of 441 mm: 2003 was the wettest year (704 mm), followed by 2005 (402 mm) and 2004 (263 mm) (Fig. 1). A 30-yr annual average rainfall in the area was 584 mm; 2003 was therefore a wet year; 2005 was a dry year and 2004 was a very dry year (Fig. 1). Rainfall in the pre-anthesis period represented 81%, 69% and 72% of the total rainfall in 2003, 2004 and 2005 respectively.

Mean winter temperatures ranged between 9 and 11ºC over the 3 yr. Minimum winter temperature ranged between 5 and 6ºC in 2003; between -0.5 and 3ºC in 2004 and between 3 and 4ºC in 2005. During the grain filling period (April-May) the mean temperature was 17.5ºC in 2003, 19ºC in 2004 and 20ºC in 2005 (Fig. 1). The mean maximum temperature during this period was 25ºC in 2003 and 27ºC in both 2004 and 2005 (Fig. 1).

Heavier rainfall in 2003, together with good distribution over the wheat growing season, gave rise to higher biomass, grain yield and N content in above-ground biomass values (Table 3). The reverse was true of 2004, an extremely dry year, which recorded values five times lower for biomass, grain yield and N content in the above-ground biomass (Table 3). In 2005, a moderately dry year, intermediate values were recorded, with yields just under half of those of the first year (Table 3). Over the 3-yr period, the tillage method exerted a significant influence, with a greater yield and N content obtained under NT (Table 3).

Root length density (RLD)

The RLD values varied significantly between years and also between soil depths (Table 4). By contrast, for the experiment as a whole, tillage system had no significant impact on RLD (Table 4). The year exerted a highly significant influence on RLD across the profile as a whole, and showed a strong positive correlation with rainfall. In the wettest year (2003), the mean RLD value was 7.6 km m^{-3} with a wider range of variation in the top 0-85 cm of the profile (from 20.2 in the 0-10 cm layer to 1.0 km m^{-3} in the 70-85 cm layer) (Fig. 2). In 2005, which was a dry year throughout most of the study area (Fig. 1), the mean RLD was 5.7 km m^{-3}. Significant differences were also recorded between soil depths, especially in the first 30-40 cm of the profile (Fig. 2). The values in that year ranged from 12.6 km m^{-3} in the 0-10 cm layer to 0.13 km m^{-3} in the 70-85 cm layer. Finally, in 2004, an extremely dry year (Fig. 1), there was no significant differences in RLD as a function of depth, with a mean value of 2.5 km m^{-3} (Fig. 2).

The influence of tillage system on RLD was significant only in the rainiest year (2003) and only in the topmost soil layer (0-10 cm), where RLD was considerably greater under CT than under NT (20.2 km m^{-3} vs. 9.6 km m^{-3}, respectively) (Fig. 2).

The strong positive relation between RLD values and wheat grain yield (Fig. 3) indicated a significant linear response of yield to increasing RLD, with higher values for grain yield under NT than under CT, as is evident also in Table 3.

Root biomass (RB)

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Like RLD, RB varied significantly from year to year, both throughout the soil profile as a whole and at individual depths (Table 4). Over the 3-yr study period, the tillage system had no influence on RB over the whole profile studied, and the year x tillage interaction was not significant (Table 4). By contrast, the year x soil depth interaction was significant (Table 4); differences were only apparent down to 30 cm, with root biomass values – like those for RLD – evening out at lower depths (Fig. 4). In the topmost 10 cm, year-to-year differences in RB were very marked: the highest values were recorded in the rainiest year (2003), when the mean RB was 619 kg ha^{-1}. In 2005, a drier year, the mean value was 402 kg ha^{-1}, while in 2004, an extremely dry year, the mean RB in the topmost 10 cm of soil was only 138 kg ha^{-1} (Fig. 4). The decline in RB values as a function of soil depth was significant and very marked in 2003 and 2005 down to a depth of 30 cm. By contrast, in 2004, an extremely dry year, there were no significant differences in RB as a function of soil depth (Fig. 4). From 40 cm downwards, RB showed no influence of year; mean values over the 3-yr ranged between 57 for the 40-55 cm layer and 14 kg ha^{-1} for the 70-85 cm layer. However, a significant difference in RB was found as a function of tillage system in the topmost soil layer (0-10 cm), with values considerably higher under CT than under NT (512 vs. 261 kg ha^{-1}, respectively, in the first 10 cm) (Fig. 5). These differences disappeared from 20 cm downwards (Fig. 5), with values evening out in a similar manner to those for RLD.

The shoot/root biomass ratio varied from year to year, with values increasing as the shoot biomass yield and grain yield increased: 7 in 2003 (wet); 4.7 in 2004 (very dry) and 6.3 in 2005 (dry). This ratio also differed as a function of tillage system: 7.5 under NT and 5.3 under CT.

In order to ascertain the extent of that influence in the third year of the study, RB was also measured using a 0.2-mm mesh in addition to the 0.5 mm mesh used in the 3 study years. A marked linear relationship was observed (Fig. 6) between the two RB measurements and the notable increase in RB recorded using the 0.2 mm mesh. Regression analysis for the experiment as a whole showed that the 0.5 mm mesh recovered only 29% of the RB recovered with the 0.2 mm mesh (1140 kg ha^{-1} vs. 3922 kg ha^{-1}). That percentage was higher in rainier year than in dry years (ranging from 32 to 23%), and was also higher under NT than under CT (33% vs. 27%, respectively). The percentage recovery of RB with the 0.5 mm mesh as a proportion of that recovered with

the 0.2 mm mesh decreased at greater soil depths (from 29% in the 0-10 cm layer to only 14% in the 70-85 cm layer). Also a highly-significant linear correlation was noted between RLD and RB (Fig. 7).

Root N content

Mean wheat root N content was 12.5 kg ha^{-1}, with a significant difference between study years and also between soil depths (Table 4). However, tillage system had no overall significant effect. In the rainier years, there were no significant differences in wheat root N content (16 and 15 kg ha^{-1} respectively). By contrast, in the driest year (2004), root N content values were significantly lower than in the other 2- yr (6 kg ha^{-1}) (Fig. 8). Wheat root N content decreased at lower sampling depths; the top 30 cm of soil contributed over 80% of total root N content in the profile studied (0-85 cm) (Fig. 8).

The year x tillage system x soil depth interaction (Fig. 8) confirmed marked year-on-year differences in root N content as well as differences between tillage systems in the two uppermost layers (0-10 and 10-20 cm) in 2003 and 2005.

With regard to the RB obtained using the 0.2 mm mesh, the shoot/root nitrogen ratio varied from year to year: 2.6 in 2003; 1.3 in 2004 and 2.1 in 2005. This ratio also differed as a function of tillage system: 2.6 under NT and 1.3 under CT.

Discussion

The tillage system had no influence on root length density for the experiment as a whole, a finding also reported by Wulfsohn et al (1996) and Qin et al (2004) in winter wheat. By contrast, Merrill et al. (1996) found that root development in winter wheat was better under NT than under CT, with an increase in RLD values of up to 40%. These conflicting results may be due to soil type; Probert et al. (1987) suggest that the influence of tillage system on root growth and proliferation is negligible in Vertisols, owing to their strongly clayey texture and small pore size.

The RLD was higher under CT than under NT in the top 10 cm of soil in the rainiest year. By contrast, Qin et al. (2004), in a study of loamy silt and sandy loam soils in

Central Europe, reported that NT was associated with an increase in RLD in the uppermost soil layer (0-5 cm), values from 5 to 10 cm downwards, similar to those recorded under CT. Benítez-Vega (2006), in the same long-term experiment, found greater penetration resistance in the topmost 10 cm under NT than under CT, due to the existence of a compacted layer as a result of not using tillage equipment. Similar results are reported by Potter and Chichester (1993) and Cassel et al. (1995). Moreover, increased topsoil compaction under NT systems may decrease water infiltration; as a result, the soil may become waterlogged following heavy rainfall, giving rise to impaired soil aeration and restricting the length and function of plant roots (Asady and Smucker, 1989). By contrast, the values for penetration resistance between 10 cm and 50 cm were higher under CT, but had no effect on RLD values. Qin et al. (2004) also noted that tillage effects disappeared below 30 cm.

Root distribution over the soil profile determines the crop's ability to extract nutrients and water from the soil. Here, 75% of the total root length is found in the topmost 30 cm of soil; values dropped sharply from 40 cm downwards, and only 1.9% of total root length was found in the deepest layer. Barraclough et al. (1989) reported a similar percentage in the topmost layers, but a less marked decrease in root density lower down in the profile. The overall mean RLD recorded in the 0-85 cm profile (5.3 km m^{-3}) was considerably lower than that noted by Barraclough et al. (1991) and Merrill et al. (2002) for spring wheat and barley in Central Europe (over 15 km m^{-3}). The mean RLD recorded here in the topmost 10 cm of soil (10.4 km m^{-3}) was lower than that found in wheat by Amato and Pardo (1994), who observed values ranging from 5 to 320 km m^{-3}.

A strong correlation was noted between RLD and yield, as also reported by Thangaraj et al. (1990) on rice. Thus, any differences in grain yield as a function of tillage system cannot be attributed to the influence of RLD, but must be attributed instead to other factors and particularly to differences in soil water retention capacity under the two tillage systems, especially – as shown here – during dry periods. Similar results have been reported by López-Bellido et al. (2000) for the same long-term experiment.

The distribution of RB may be associated with the strongly clayey texture of Vertisols and their resulting hydraulic behaviour. Sufficient soil moisture tends to be retained in the deepest soil layers, which are not immediately affected by yearly rainfall due to the

slow water infiltration characteristic of Vertisols. Hydromorphic conditions at greater soil depths may be one reason for the small amount of RB.

Measurement of the amount of nitrogen supplied by the roots to the soil is particularly important in rainfed systems, where organic matter is very scarce. Root N content in the topmost soil layer was greater under CT, perhaps because tillage creates better soil-structure conditions (aeration, macropores, etc.) in the top 20 cm of Vertisols, leading to better root development in that layer, as is evident in higher values for RLD, RB and root N content.

The higher shoot/root biomass and shoot/root nitrogen ratios under NT in rainier years would suggest that the shoot growth system is more sensitive to weather conditions, and particularly to rainfall, while the influence of rainfall on the root system is lessened by the high water retention capacity typical of Vertisols. The RB thus appears to be fairly stable, and to display greater capacity and flexibility in the supply of water and nutrients to respond to increases in shoot biomass. Klepper (1992) has also reported that under limited soil moisture conditions, root growth is reduced less than shoot growth. Similarly, Hamblin et al. (1990) found that under unfavorable rainfall and nutrient conditions, the contribution of RB to total biomass tends to increase. However, the values reported by these authors for shoot/root biomass ratio were considerably lower than those recorded here (ranging from 1.1 to 5.2), most likely because their studies were carried out in less-fertile sandy loam soils.

Conclusions

Under dryland Vertisol conditions, rainfall had a marked influence on RLD and RB down to a soil depth of 30-40 cm, values for both parameters being considerably higher in rainier years. Seventy-five percent of the total root length was found in the topmost 30 cm of soil.

The CT was associated with significantly higher values for RLD and RB, though only in the upper 10 cm of soil. This may be due to greater soil penetration resistance in the topmost 10 cm under NT, as a result of soil compaction. At lower depths, no differences were recorded between the two tillage systems.

The top 30 cm of soil contributed over 80% of total wheat root N content. Use of the 0.5 mm mesh prompted a considerable underestimation of RLD, RB and root N content values compared to the 0.2 mm mesh. The close linear relationship between RLD and RB may be of value for estimating RB using non-destructive measuring methods such as the minirhizotron. Greater root development in the upper soil layer under CT was not associated with increased grain yield, which was recorded under NT. This may be due to the greater soil water reserve under NT in dry years.

Acknowledgments

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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	143	187
Silt (g kg^{-1})	179	152	26
Clay (g kg^{-1})	694	705	787
pH (water)	7.7	7.6	7.6
Organic matter (g kg^{-1})	10.2	7.4	5.3
Calcium carbonate equivalent (g kg^{-1})	75	93	71
CEC (cmol kg^{-1})	46.5	36.6	30

Table 2

Soil water content at sowing and harvest of wheat as influenced by year, tillage system (NT, no tillage; CT, conventional tillage) and soil depth in a rotation with faba bean at Córdoba (Spain)[a]

Year	Tillage system	Water content (m^3 m^{-3})					
		Depths at sowing (cm)			Depths at harvest (cm)		
		0-30	30-60	60-90	0-30	30-60	60-90
2003-2004	NT	0.45a	0.43a	0.45a	0.14a	0.34a	0.38a
	CT	0.45a	0.45a	0.45a	0.20a	0.30a	0.43a
2004-2005	NT	0.17a	0.38a	0.40a	0.06a	0.12b	0.18b
	CT	0.18a	0.37a	0.39a	0.06a	0.28a	0.31a
2005-2006	NT	0.34a	0.17a	0.34a	0.12a	0.05a	0.15a
	CT	0.27b	0.09b	0.26b	0.10a	0.07a	0.20a
LSD		0.03	0.07	0.02	0.08	0.10	0.08

[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

Wheat biomass above-ground, grain yield and N content in the above-ground biomass at maturity as affected by year and tillage system in a continuous rotation with faba bean at Córdoba (Spain)[a]

Treatment	Biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	N content (kg ha^{-1})
Year:			
2003-2004	12611a	4811a	143a
2004-2005	2430c	921c	35b
2005-2006	7077b	2736b	106c
Tillage System:			
No tillage	8369a	3199a	109a
Convencional tillage	6376b	2447b	80b
MEAN	7373	2823	95

[a] Within treatment (years or tillage) means followed by the same letter are not significantly different at *P*<0.05 according to LSD

Table 4

Level of significance for year, tillage system and soil depth on root-length density (RLD), root biomass (RB) and N root at anthesis in a wheat crop in a continuous rotation with faba bean at Córdoba (Spain)

Source	RLD (km m^{-3})	RB (kg ha^{-1})	N root (kg ha^{-1})
Year (Y)	**	**	**
Tillage (T)	NS	NS	NS
Y x T	NS	NS	NS
Soil depth (D)	***	***	***
Y x D	***	***	***
T x D	NS	***	**
Y x T x D	*	NS	*

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability level

NS, not significant

Fig. 1   Monthly and annual rainfall, mean maximum and minimum temperatures over the 3-year study period at Córdoba (Spain).
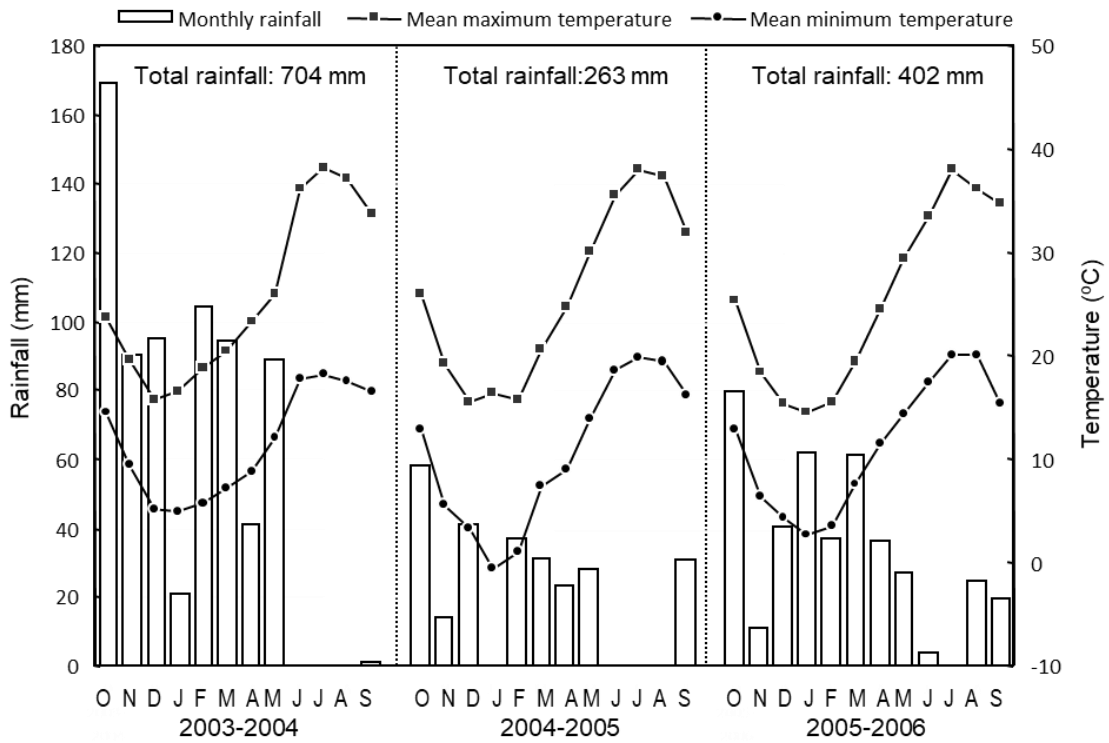
Fig. 2   Root-length density (RLD) at wheat anthesis as influenced of year, tillage system (NT, no tillage; CT, conventional tillage) and soil depth in a continuous rotation with faba bean at Córdoba (Spain). Vertical bars represent LSD (P<0.05) for significant year x tillage system x soil depth interaction: a) for the same levels of year and tillage; b) for the same levels of year; c) for different levels of year.
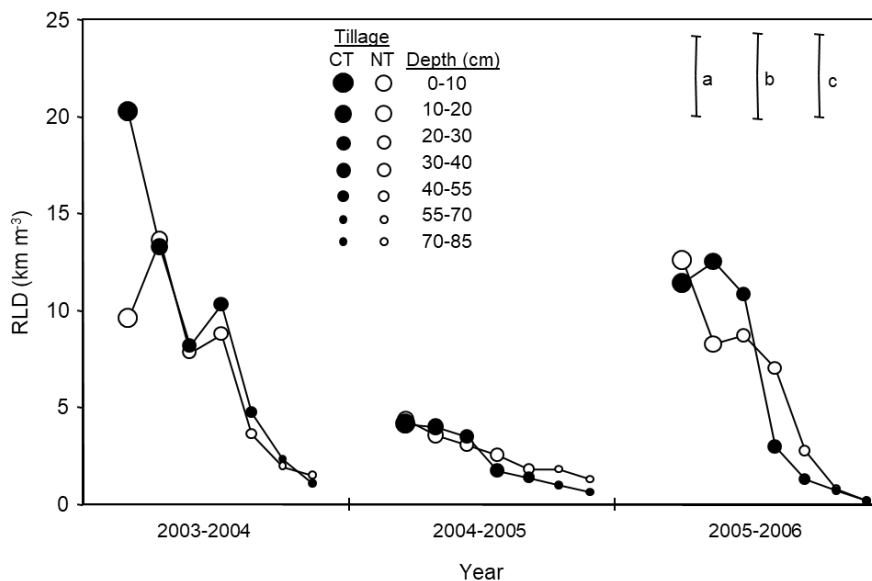
Fig. 3   Relationship between wheat grain yield and root-length density (RLD) at anthesis as affected by tillage system (NT, no tillage; CT, conventional tillage) in a continuous rotation with faba bean at Córdoba (Spain).
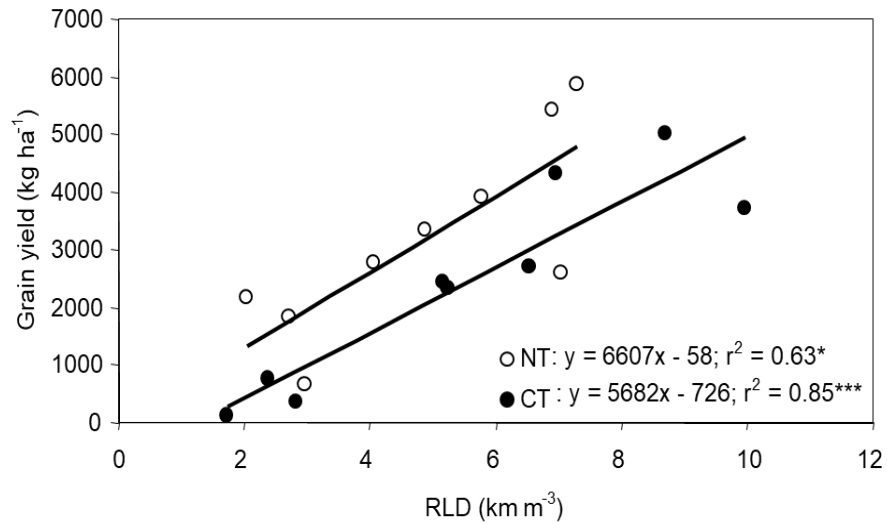

NT: y = 6607x - 58; r^2 = 0.63*
CT : y = 5682x - 726; r^2 = 0.85***

Fig. 4   Root biomass (RB) at wheat anthesis as influenced by year and soil depth in a continuous rotation with faba bean at Córdoba (Spain). Horizontal bars represent LSD (P<0.05) for significant year x soil depth interaction: a) for the same level of year; b) for different levels of year.
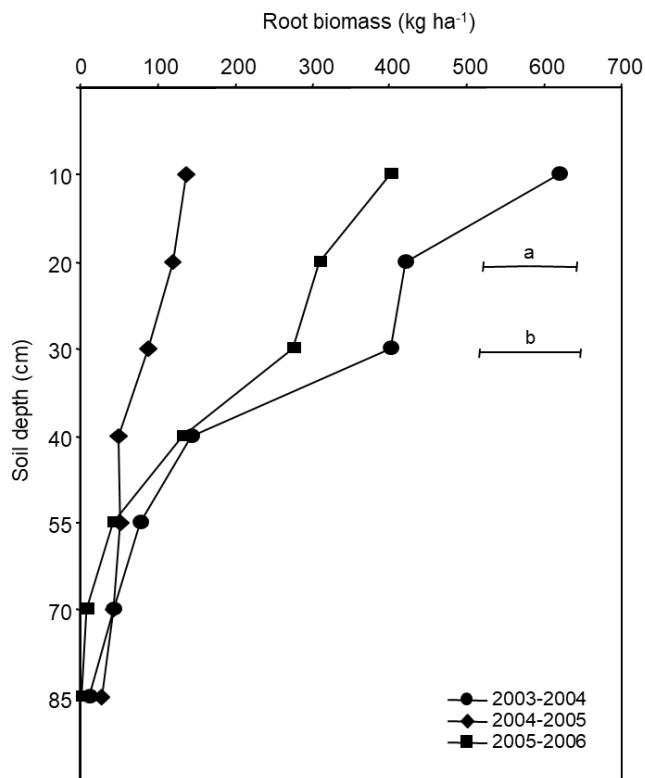
Fig. 5   Root biomass (RB) at wheat anthesis as influenced by tillage system (NT, no tillage; CT, conventional tillage) and soil depth in a continuous rotation with faba bean at Córdoba (Spain). Horizontal bars represent LSD (P<0.05) for significant tillage system x soil depth interaction: a) for the same level of tillage system; b) for different levels of tillage system.
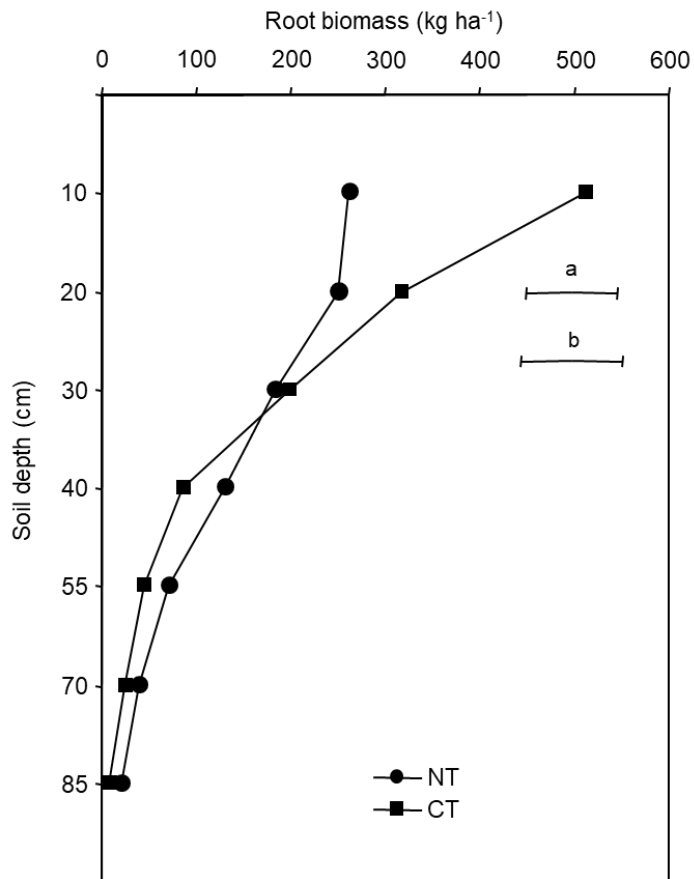
Fig. 6 Relationship between root biomass (RB) as collected with a 0.5 mm and a 0.2 mm mesh sieve, at wheat anthesis, in a continuous rotation with faba bean at Córdoba (Spain).
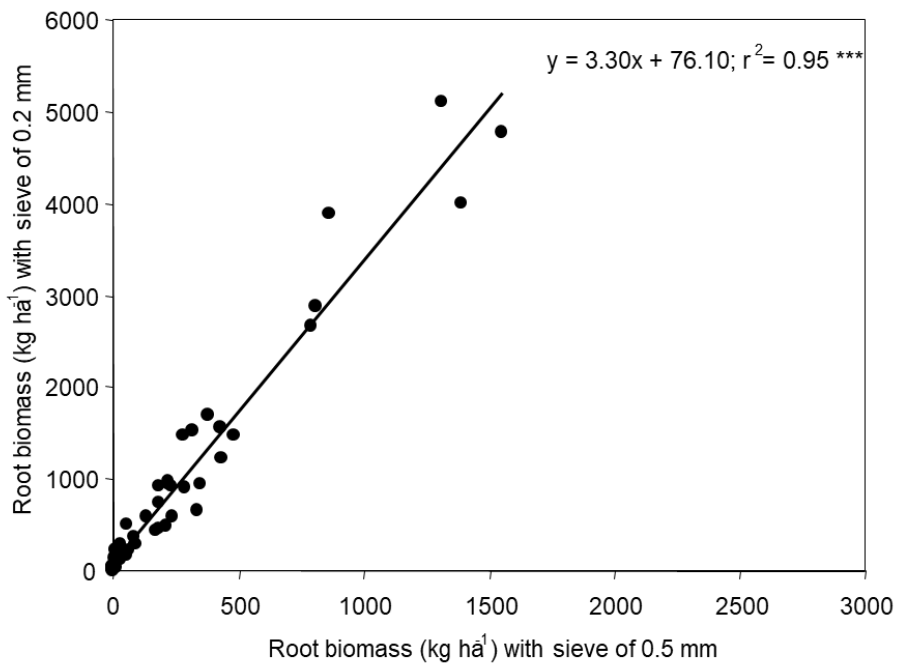

$y = 3.30x + 76.10; r^2 = 0.95$ ***

Fig. 7 Relationship between root-length density (RLD) and root biomass (RB) at wheat anthesis in a continuous rotation with faba bean at Córdoba (Spain).
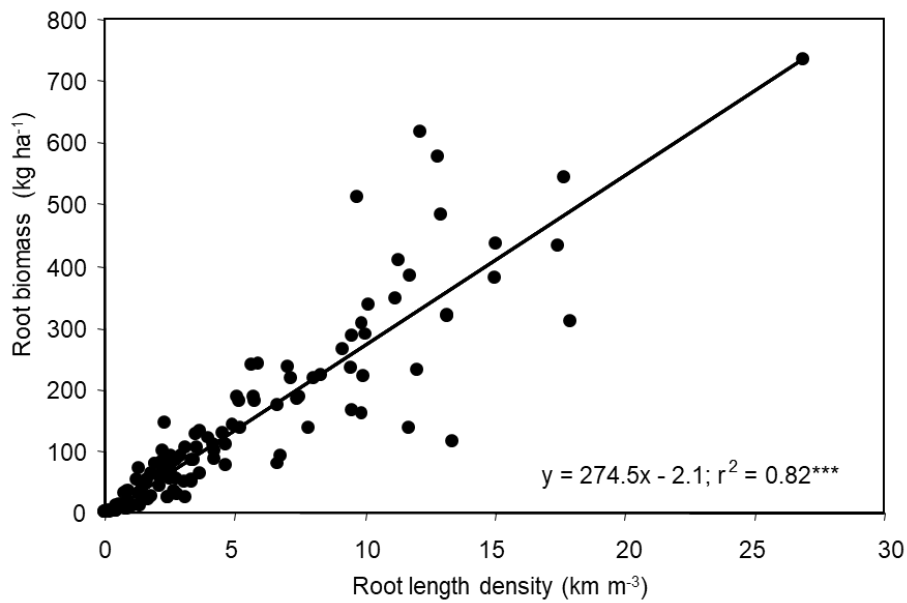

$y = 274.5x - 2.1; r^2 = 0.82$***

Fig. 8   Root N content at wheat anthesis as influenced by year, tillage system (NT, no tillage; CT, conventional tillage) and soil depth in a continuous rotation with faba bean at Córdoba (Spain). Vertical bars represent LSD (P<0.05) for significant year x tillage system x soil depth interaction: a) for the same levels of year and tillage; b) for the same levels of year; c) for different levels of year.