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Root production and root mortality of winter wheat grown on sandy and loamy soils in different farming systems

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Abstract Winter wheat was grown over 2 years (1995, 1996) in an organic and integrated cropping system on sandy and loamy soils. Root growth was measured on five to six occasions each year with an auger sampling procedure and the ingrowth core method. The first resulted in an estimate of net root development, while the latter revealed gross root growth (GG) or root production. Total root production was about 80–150 km m^{-2} (0- to 30-cm soil layer) between April and July and exceeded the net size of the root system at harvest by a factor of between 2 and 4. The C input into the soil could be estimated as 1.4–2.6 t ha^{-1} by this root production. The cropping systems had nearly no influence on root production. The largest differences occurred between the years. The net root length tended to be lower on sandy soils compared to the loam, but total root production was higher. Root mortality, which is the difference between GG and net root growth, was also higher on sandy soils. The turnover index, which is the mean of the relative root production rates and relative root mortality rates, was positively related to the soil sand content in both years.

Keywords Cropping system · Root mortality · Root production · Soil texture · Winter wheat

Introduction

The Agroecosystems Research Network Munich (Forschungsverbund Agrarökosysteme München, FAM) was established to investigate the effect of different farming systems on the environment (refer to http://fam.weihenstephan.de). Under investigation was a integrated cropping system which utilized a fertilization regime linked to the removal of nutrients, reduced soil tillage and a reduced use of pesticides. This was compared to an organic cropping system without chemical pesticides or mineral fertilization. Part of FAM's objective was to model C and nutrient flows in the various agroecosystems.

The C input into the soil mainly originates from organic fertilizers, crop residues and rhizodeposition, which consists of root exudates and dead root tissue. It is difficult to assess the total amount of root production because of complications during plant growth associated with root turnover, which is the simultaneous dying and decay of roots while new roots are growing. This turnover can be substantial. Sauerbeck and Johnen (1976), Van Noordwijk et al. (1994), Swinnen (1994) and Swinnen et al. (1995) determined a 2- to 5-fold higher total root production during the growth of winter wheat than present in living roots at harvest.

It is known that nutrient supply, soil texture, soil density, soil moisture and other factors may influence the size of root systems (Brouwer 1983; Drew 1990). But these investigations are usually done on living roots. Little is known about the influences on total root production or root mortality. Merckx et al. (1987) measured a slightly reduced root production of maize at a reduced level of fertilization. No remarkable effect of drought on root production and root mortality of potato was determined by Smit and Vamerali (1998), but relative mortality (mortality in relation to the standing root system) was increased. Indications of a higher root turnover of wheat on sandy soils compared to a silty clay loam were found by Merckx et al. (1985). Swinnen (1994) Swinnen et al. (1995) and Van Noordwijk et al. (1994) investigated root production of cereals and sugar beet in a conventional and an integrated cropping system by using C isotopes or minirhizotrons, respectively. The influence of the cropping system was low and the results were not clear. Swinnen (1994) determined a slightly higher root pro-

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Table 1 Texture of the upper soil layer (0–30 cm) and available water capacity (0–90 cm) of the soils on the experimental sites

Year	Soil type	Cropping system	Available water capacity (mm)	Fine fraction (<2 mm)			Coarse fraction >2 mm (%)
				Clay (%)	Silt content (%)	Sand (%)	
1995	Loam	Integrated	160	20	60	20	2
	Sand	Integrated	139	15	30	55	8
	Loam	Organic	174	15	55	30	7
	Sand	Organic	61	5	15	80	32
1996	Loam	Integrated	169	22	50	28	7
	Sand	Integrated	153	15	46	39	25
	Loam	Organic	135	17	47	36	6
	Sand	Organic	57	9	20	71	35

duction of winter wheat under the conventional cropping system, whereas Van Noordwijk et al. (1994) measured higher production under the integrated farming system.

The differences in crop management between organic and integrated cropping systems are larger than between integrated and conventional ones. If there is a substantial influence of cropping systems on root production it must be more obvious in a comparison between organic and integrated farming systems than in the comparison done by Swinnen (1994) and Van Noordwijk et al. (1994). Therefore, root growth patterns of winter wheat were investigated on sandy and loamy soils in the organic and integrated farming compartments of the FAM, located in Bavaria, south Germany. Root production was determined by the ingrowth core method (Persson 1983; Steen 1991; Steingrobe et al., 2001a, 2001b). Mesh bags filled with root-free soil were buried into the rooting zone. After 2–3 weeks root length inside the bags was measured. These roots reflect root production under the assumption that no root mortality occurs during the short time the bags are open for ingrowth. Adding data from several subsequent periods results in total root production which can be compared to the size of the standing root system measured by the more usual auger sampling method. The difference between root production and the change in size of the standing root system is assumed to represent root mortality. In contrast to other methods for measuring root production like the use of isotopes or minirhizotrons, the ingrowth core method is easy to handle and is able to quantify root production on a field scale (Steingrobe et al., 2001a, 2001b). The objective was to find differences in root growth pattern caused by the cropping system and different soil textures.

Materials and methods

Winter wheat was grown in 1995 and 1996 on the research farm of the FAM in Scheyern, Bavaria, Germany. The experimental site is divided into an integrated and an organic farming compartment. The different cropping systems were established 2 years before the root investigations started. In the integrated system nutrients were given as mineral fertilizer and liquid manure (from 1.5 animal units ha^{-1}) in an amount according to the nutrient removal by crop yield (average 170 kg N ha^{-1}). Soil tillage was reduced and ploughing was not used. Plant protection was also reduced and only performed when a critical level of damage was reached. The cropping sequence was maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.) followed by winter wheat.

The organic cropping system used no mineral fertilizer or chemical pesticides. Nutrients were applied as solid and liquid manure (from 0.8 animal units ha^{-1}). The amount of total N (organic and mineral) supplied with the manure was 0 and 140 kg N ha^{-1} depending on the preceding crop which was lupin (*Lupinus luteus* L.) in 1995 and potato (*S. tuberosum*) in 1996. The amount of mineral N in the manure was <25 kg N ha^{-1}. This resulted in a N shortage for the winter wheat crops. Soil tillage was also reduced in the organic system but ploughing took place. The rotation included seven crops with 30% legumes [potato (S. *tuberosum*, winter wheat (*T. aestivum*), sunflower (*Helianthus annuus* L.), fallow, winter wheat, oilseed rape (*Brassica napus* L.), and lucerne (*Medicago sativa* L.) mixed with clover (*Trifolium repens* L.)]. More details are given by Hantschel and Lentz (1993), Filser (1998) and the FAM homepage (http://fam.weihenstephan.de). Because of the hilly landscape different soil types are located on the experimental site, which allows studies to be undertaken on sandy and loamy soils close together (Table 1). In 1995 the different soil types were on different plots, whereas in 1996 high-yielding and low-yielding areas of the same plot were chosen, which appeared to be also low and high in sand content, respectively. The P and K concentrations in the soils were 70–110 and 100–250 mg kg^{-1}, respectively, as determined with the calcium-acetate-lactate extraction method (Schüller 1969). These are high up to very high supply levels according to German recommendations.

Root and shoot production was measured at time intervals of 2–3 weeks on six occasions in 1995 and 5 times in 1996. At each sampling date 1 m^2 of shoots was harvested, dried at 70°C and weighed after separation into grain and shoot. The size of the standing root system (net size) was investigated by taking soil samples with a hand auger. Each sample had a diameter of 8 cm and a length of 15 cm. Roots were sampled down to 90 cm depth, but in this paper only the two upper soil layers (0–15 and 15–30 cm) are considered. Roots were washed out of the soil carefully over a 200-µm sieve and root length was determined with a line intersection method using a binocular according to Newman (1966). The division into dead and living roots was done visually according to colour and condition of the roots. From the root counts the root length in the soil 0- to 30 cm soil layer was calculated per unit soil surface resulting in the unit kilometre per metre square.

Root production was measured by the ingrowth core method (Persson 1983; Steen 1991; Steingrobe et al., 2001a, 2001b). Mesh bags with a diameter of 4 cm and a length of 42 cm were buried into the rooting zone at an angle of 45°. In this manner a soil depth of 30 cm was covered. The bags were pulled over a plastic tube with the same diameter to insert them into the soil. For opening the mesh bags for root ingrowth, the tube was carefully pulled out a few centimetres and soil was filled through the tube into the bag. The soil was collected from the same site and roots were sieved out before filling into the bags. The soil inside the bags was brought to a density comparable to the bulk soil by a wooden stick. This procedure was repeated until the whole mesh bag was filled. After 2–3 weeks the bags were pulled out and root length was determined as described above. Under the assumption that no root mortality or decay occurs inside the bags in this short period, the root length inside the ingrowth cores reflects root production (gross root growth; GG). At harvest of a set of cores the subsequent set was opened for root ingrowth. By accumulating the root length inside the cores over the five (1995) or four (1996) periods of 2–3 weeks the total root production in this time could be calculated. The differences between this root production (GG) and the development of the standing root system (net growth) was assumed to represent root mortality.

To compare the root growth pattern of single treatments, the daily root production (daily GG) of a treatment should be related to the size of the standing root system (net size), yielding the relative root production rate (RPR). The equation is similar to that for the calculation of relative growth rates in shoot growth analysis:

$$\mathrm{RPR} = \frac{\Delta \mathrm{GG}_{i \to i+1}}{\Delta t_{i \to i+1} \frac{\mathrm{RL}_i + \mathrm{RL}_{i+1}}{2}} \quad (1)$$

with ΔGG in the time period between harvests (i) and (i+1). ΔGG is given by the root length in the ingrowth cores opened in this time interval. The number of days between harvest (i) and (i+1) is given by Δt and RL is the root length of the standing root system (net size) at harvests (i) and (i+1).

According to this, relative root mortality rate (RMR) can be calculated as:

$$\mathrm{RMR} = \frac{\Delta \mathrm{M}_{i \to i+1}}{\Delta t_{i \to i+1} \frac{\mathrm{RL}_i + \mathrm{RL}_{i+1}}{2}} \quad (2)$$

ΔM is the root mortality in the time period (i) to (i+1), which is the difference between GG and the net development of the root length (RL) in this period:

$$\Delta \mathrm{M}_{i \to i+1} = \Delta \mathrm{GG}_{i \to i+1} - (\mathrm{RL}_{i+1} - \mathrm{RL}_i) \quad (3)$$

To describe the turnover of the root system, Cheng et al. (1990) introduced the turnover index (TI), which is the mean of the RPR and the RMR":

$$\mathrm{TI} = \frac{\mathrm{RPR} + \mathrm{RMR}}{2} \quad (4)$$

The shoot and root measurements were replicated 3–4 times. Each root sample of a replicate consisted of two or three soil cores of ingrowth cores. One-way ANOVAS were performed and the treatment means were compared by the Tukey test if significant differences occurred.

Results

Shoot growth

Shoot development in 1995 and 1996 was very similar (Fig. 1). On the loamy soils shoots reached a dry matter yield of about 14–16 t ha^{-1} without differences between the cropping systems. Shoot production on sandy soils tended to be lower in the integrated system and was significantly reduced in the organic cropping system. The growing period in 1996 started later than in 1995 because of a long winter period, but growth was faster because of higher mean temperatures in early summer. Grain yield corresponded to total shoot production with 9.4, 6.8, 8.9, and 4.8 t ha^{-1} (at 85.5% dry matter content) in 1995 and 8.6, 8.4, 7.0, and 4.4 t ha^{-1} in 1996 on the integrated and organically managed loamy soils and the integrated and organic sandy soils, respectively.

Net root production

The root net length in the 0- to 30-cm soil layer increased in 1995 from about 20 km m^{-2} in April to about 45 km m^{-2} at anthesis in June (Fig. 2), which corresponds to a root length density of 6.7 and 13.3 cm cm^{-3}, respectively. After anthesis there was a slight decrease in root length until harvest. The root length at flowering in the upper 30-cm soil layer was about 70–80% of the total root length down to 90 cm soil depth (data not shown). There were no significant differences between the treatments, but it appears that roots in the integrated cropping system (circles in Fig. 2) were always slightly longer and that in both cropping systems root length in sandy soils (open symbols) was a bit lower. In 1996 the overall development of the root systems was similar with an increase in root length until anthesis and a slight decrease

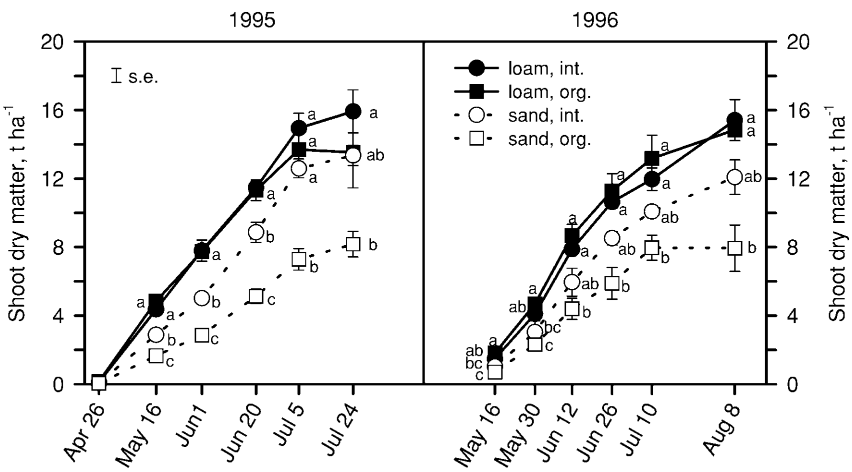


Fig. 1 Total shoot dry matter production of winter wheat grown on loamy and sandy soils in an integrated (*int.*) and organic (*org.*) cropping system in the years 1995 and 1996. *No error bar* is reported when the value is within the limits of the symbol. ANOVA was performed for each sampling date, *different letters* indicate significant differences between treatment means; *n.s.* not significant

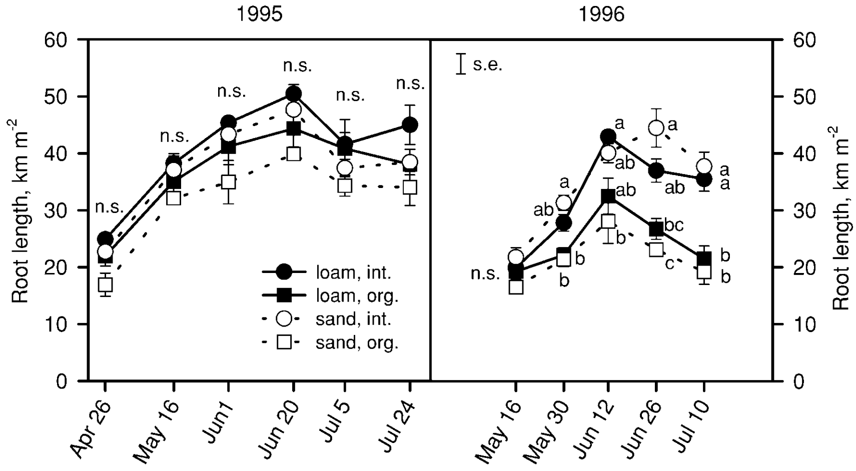


Fig. 2 Development of the root net length of winter wheat grown on loamy and sandy soils in an integrated and organic cropping system in the years 1995 and 1996 (0–30 cm soil layer). *No error bar* is reported when the value is within the limits of the symbol. ANOVA was performed for each sampling date, *different letters* indicate significant differences between treatment means

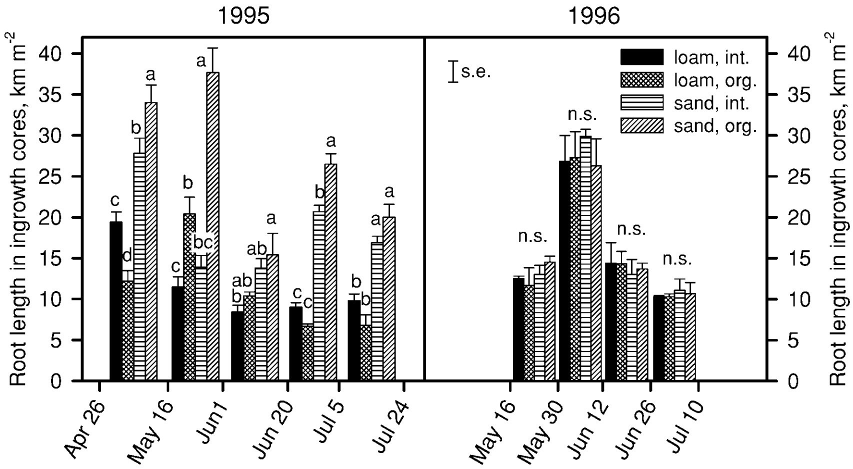


Fig. 3 Root length of winter wheat in the ingrowth cores. Wheat was grown on loamy and sandy soils in an integrated and organic cropping system in the years 1995 and 1996. Root length in the cores is assumed as root production. ANOVA was performed for each sampling date, *different letters* indicate significant differences between treatment means

afterwards. But in 1996 the differences between the cropping systems were more pronounced with double the root length in the integrated treatments (circles) at harvest compared to the organic systems (squares). Again the lowest root length was on the sandy soil in the organic cropping system.

Summing up, it can be said that no consistent differences in the root net length between the treatments occurred. However, root length tended to be longer in the integrated system and on loamy soils than in the organic systems or on sandy soils.

Total root production and dynamics of root growth

Root length inside the ingrowth cores, which is assumed to represent GG or root production, is shown in Fig. 3 for the respective time periods. The data suggest that root production was higher before anthesis than afterwards. This is most obvious in the peak between 30 May and 12 June in 1996. The high root production corresponds with the increase in the standing root system before anthesis in 1995 and 1996 shown in Fig. 2. After flowering root production decreased, perhaps because grain development was a strong sink competitor to root development. But root growth continued at a lower level until harvest. In 1995 root production on the sandy soils was generally significantly higher than on loamy soils. Especially after flowering when the reduction in root growth was less pronounced on sand. Furthermore, root production on sandy soils was slightly increased in the organic cropping system compared to the integrated one. These differences were not clear on loamy soils. In 1996 no differences between the treatments occurred.

It is striking that root production during the 2–3 weeks the bags were open for ingrowth was in a similar order to the size of the standing root system. This resulted in a much higher total root production than can be assumed from a single measurement of root length at harvest or anthesis. Total root production, as the sum of root length inside the cores between April/May and harvest in July, is shown by the upper curves of Fig. 4a, b for each treatment and year. Subtracting the size of the standing root system (dotted area) from the production curves results in the root mortality (lower curves in Fig. 4a, b). Total root production was about 80–90 km m^{-2} in the 0- to 30-cm soil layer for nearly all treatments except on the sandy soils in 1995 which ended at 120

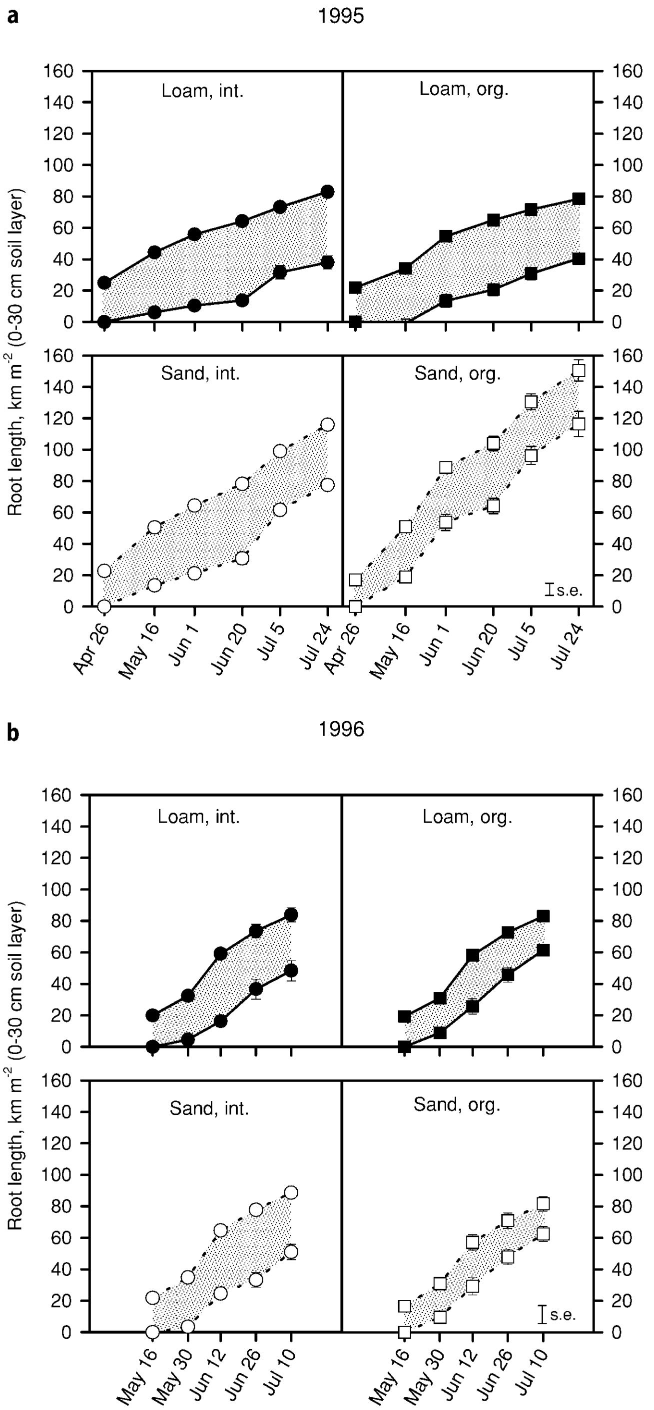


Fig. 4a, b Total root production (*upper curve*) and total root mortality (*lower curve*) of winter wheat in the soil layer 0–30 cm summarized over the whole measurement period. Mortality is calculated by subtracting the root net length (*dotted area*) from the production curve. Wheat was grown on loamy and sandy soils in an integrated and organic cropping system in the years **a** 1995 and **b** 1996. *No error bar* is reported when the value is within the limits of the symbol

and 150 km m^{-2} in the integrated and organic cropping system, respectively. Root mortality was about 40–60 km m^{-2} in the measured period and even 80–120 km m^{-2} on the sandy soils in 1995. Thus, the total root production in the considered time period ranged from between twice (1995, loam, integrated and organic; 1996, integrated, both soils) up to 4 times (1995, sand, organic; 1996, organic, both soils) the size of the standing root system at harvest.

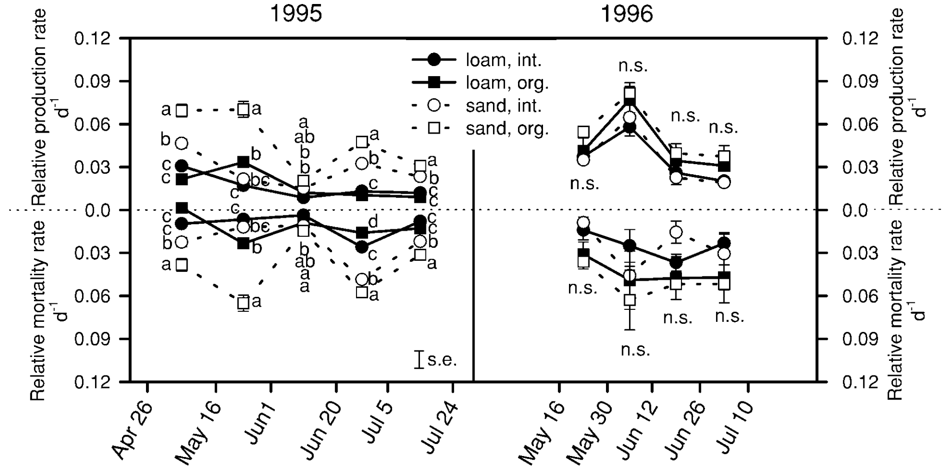
The presented results indicate that root growth pattern are poorly described by the development of the standing root system. In 1995 root net length did not differ between the treatments with a tendency to smaller root systems on sandy soils. Root production, however, was much higher on sandy than on loamy soils in this year. In 1996 the standing root systems in the integrated cropping system were larger than in the organic system, but root production was nearly the same. The differences were due to a higher root mortality in the organic system.

A higher root production is not necessarily the result of a better root growth performance but can also be caused by a greater standing root system already established at the beginning of the measurements (in this study in April/May). For a better comparison of root growth performance it can be useful to look at the RPR and the RMR. These rates describe the daily root production or root mortality in relation to the size of the standing root system (Eqs. 1, 2). In all years RPR was higher before anthesis than afterwards (Fig.5). Furthermore RPR was also higher than RMR before anthesis which resulted in the observed increase in root net length in this time. After anthesis RPR and RMR were more or less similar, or sometimes RMR was a bit higher. The high root production on the sandy soils in 1995 was due to higher relative production rates, i.e. a better growth performance over the whole measurement period. Root mortality was also increased. Differences in 1996 were not significant, but it seems that there was also a tendency to higher RPR and RMR on sandy soils. An influence of the cropping system was not observed in both years. However, in 1996 there seemed to be a slight trend to higher RPR and RMR in the organic system.

Due to the dying of roots and the replacement by growth of new roots, root systems are subject to a continuous turnover. To describe this root turnover, Cheng et al. (1990) introduced the TI which is the mean of relative production rate and relative mortality rate (Eq. 4). This index describes the velocity of growth and/or death of roots, but it gives no information about the predominating process. For example, a constantly growing root system without dying of roots may have the same TI as a constantly dying system without growth. Therefore, a comparison of TIs should only be done, if the overall development of root systems is alike, as it was for the wheat root systems of both years.

It seemed from the presented results that the sand content had a larger influence on root growth pattern than the cropping system. To determine this influence

Fig. 5 Relative root production rate (*RPR*) and relative root mortality rate (*RMR*) of winter wheat grown on loamy and sandy soils in an integrated and organic cropping system in the years 1995 and 1996. *No error bar* is reported when the value is within the limits of the symbol. ANOVA was performed for each sampling date, *different letters* indicate significant differences between treatment means. *d* Day



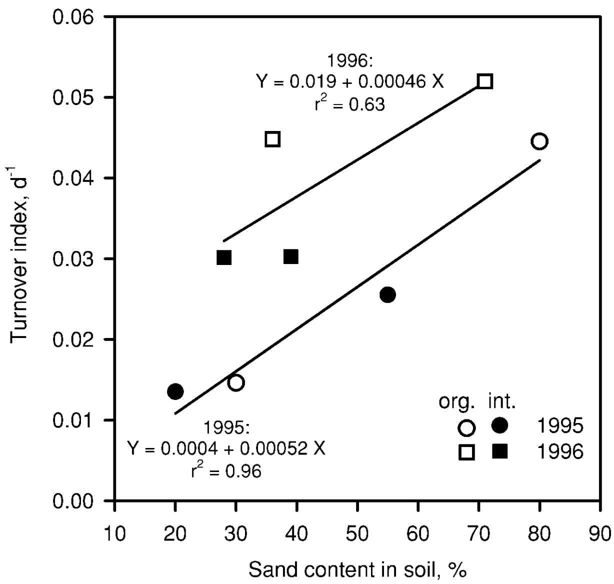


Fig. 6 Influence of the soil sand content on the root turnover index of winter wheat grown on loamy and sandy soils in an integrated and organic cropping system in the years 1995 and 1996. Turnover indices are averaged over the whole measurement periods. Regression lines were calculated for each year separately

the average TI of each treatment is related to the sand content of the soils (Fig.6). There was a strong relation between sand and TI in 1995. In 1996 the regression line had a similar slope, but was on a higher level and the correlation coefficient was less but still considerable. In Fig. 6 the integrated and organic cropping systems are marked by filled and open symbols, respectively. This shows that the deviations of the measured TIs from the regression lines were not related to the cropping systems. Thus, the observed differences in root growth pattern were predominantly caused by the soil characteristics rather than the cropping system.

Discussion

Comparison of different methods to determine root C input into soil

For modelling the nutrient and C cycle in an agroecosystem, knowledge about root growth characteristics and root production is essential. There have been few attempts made to measure the input of organic matter into the soil by wheat roots. In most of these investigations the distribution of C isotopes in the soil-plant system is determined after labelling the plants. In pot experiments with a constant labelling of spring wheat, the total rhizodeposition was equal to 2.3 t C ha^{-1} (Sauerbeck and Johnen 1976). This was about 4 times the amount of C detected in the standing root system at harvest. Measurements of rhizodeposition in the field are usually done using pulse labelling of single plants. The extrapolation of these data to the field scale is, therefore, as problematic as in pot experiments. The measurements for winter wheat ranged from 1.2 to 2.9 t C ha^{-1} depending on the age of the plants and the growing conditions (Jenkinson and Rayner 1977; Martin and Puckridge 1982; Buyanavsky and Wagner 1987; Keith et al. 1986; Whipps 1990). In these experimental set-ups the loss of labelled CO_2 from the soil was attributed to the decomposition of root-derived organic matter. However, it was not possible to distinguish between CO_2 losses from soil respiration and root respiration and soil respiration originating from only root-derived compounds. Furthermore, no distinction was possible between root tissue and root exudation as sources of soil organic matter. Swinnen (1994) tried to separate root from microbial respiration by using a model rhizodeposition technique. He measured a total organic input into the soil by winter wheat roots of 1.1 t C ha^{-1}, of which about 600 kg was due to root tissue. Van Noordwijk et al. (1994) used minirhizotrons for measuring root growth dynamics and quantified this on a field scale by the use of auger samples. They resulted in a total root production of 600–760 kg C ha^{-1}, when a C concentration in root dry matter of 40% was assumed.

Table 2 Total root production (dry matter) of winter wheat grown in a organic and integrated cropping system on sandy and loamy soils and the estimated C input into the soil

		Cropping system			
		Integrated		Organic	
		Loam (t ha^{-1})	Sand	Loam (t ha^{-1})	Sand
Total root production[a]	1995	4.3	5.5	3.8	6.3
	1996	3.9	4.0	3.6	3.5
C input[b]	1995	1.7	2.2	1.5	2.6
	1996	1.6	1.6	1.5	1.4

[a] Calculated from root length, root radius and an estimated dry matter content of 0.1
[b] Based on a C content in dry matter of 0.405

In this work the ingrowth core method was used to estimate total root production. Like the minirhizotron technique, this method only measures root growth. Root exudates are not included when C fluxes are determined. The ingrowth core approach (Persson 1983) has been used for root investigations in forest, grassland and agricultural research (Steen et al. 1984; Larsson and Steen 1984; Steen 1985; Steen and Håkansson 1987; Hansson et al. 1992; Makkonen and Helmisaari 1999). The technique has been modified by reducing the time of root ingrowth to 2–3 weeks to avoid root mortality inside the bags. Steingrobe et al. (2001b) demonstrated that the root injury caused by inserting the ingrowth cores had no influence on subsequent patterns of root growth. Another objection to this method could be the difficulties in establishing the same soil conditions inside the bags as outside (Vogt et al. 1998). But by changing soil density, soil moisture, and N and P contents inside the bags, Steingrobe et al. (2001a) indicated that only a very high soil density and to a minor extent a very high soil N content influences root growth inside the cores. Soil density and mineral N contents at the experimental site were measured and the soil used for the ingrowth cores was adjusted as far as possible in the presented experiments to simulate the surrounding soil environment.

C contents were not quantified in the present experiment. But average root diameter was determined at each sampling date for a representative number of roots. Root volume can be calculated by considering root diameter. By the assumption of a specific weight of 1 g cm^{-3} root the fresh weight can be estimated. The dry matter content of wheat roots is about 10% (Van Noordwijk and Floris 1979) whereas the C content of dry matter was measured as 40.5% in another wheat experiment on the same site (unpublished data). Therefore, it was possible to calculate the C input into the soil by total root production (Table 2). The C input differed between the years, ranging from 1.4 to 1.6 t ha^{-1} in 1996 and from 1.5 to 2.6 t ha^{-1} in 1995, and corresponded with those of 1.2–2.9 t ha^{-1} reviewed by Whipps (1990), but were higher than root production reported by Swinnen (1994) and Van Noordwijk et al. (1994), respectively. However, the sizes of the standing root systems reported by Swinnen (1994) and Van Noordwijk et al. (1994) were also smaller. The relationship between total root production and the net size of the standing root system they found was similar to our results, as they differed by a factor of about 2 (Fig. 4a, b).

All three methods commonly used to measure root production or C flow (i.e. labelling with isotopes, use of minirhizotrons and the ingrowth core method) lead to comparable results. This provides circumstantial evidence of the reliability of each method. The preferred use of one method over another can therefore be based on practical or logistical reasons.

Root growth pattern

The results presented here reveal the plasticity of root growth. Neither the size of the standing root system nor root production was consistent in both years of the investigation. The influence of the sand content in the soils or the cropping system on root production was relatively less important than the impact of the "year" (i.e. weather conditions, microclimate, soil conditions besides texture, etc.). A great variation in root growth on the research farm of the FAM has already been reported by Stoffel et al. (1995), who measured the root length distribution of winter wheat and spring barley on the whole farm before it was divided into the different farming systems. This great variation in root length presumably reflects the heterogeneity of soils and microclimate effects caused by the hilly landscape.

In 1995 and even more so in 1996, the size of the standing root system was smaller in the organic cropping system than in the integrated one. These results are in contrast to those of Bachinger et al. (1992) who found higher root densities of winter rye with organic than mineral fertilization in a long-term experiment.

Despite the observed differences in the root net length, root production was not different between the cropping systems. A minor influence of cropping systems on root production was also reported by Swinnen (1994) and Van Noordwijk et al. (1994), who compared a conventional and an integrated system. Thus, the input of organic matter by root growth into the soil appears not to be greatly influenced by the farming system, and the assumption that an organic cropping system with low nutrient input may enhance root growth could not be confirmed.

Despite similarities in root production, the cropping systems had an influence on C partitioning by the plants. The C used for root production was about 20% of the total plant C (C in shoot and root production). There were no great differences between the cropping systems on the loamy soils, but for the organic treatments on sand, root C increased by up to 42% total plant C in 1995 (Table 3). Perhaps of more interest is the amount of C the plants invested in root production in relation to the C partitioned

Table 3 C partitioning of winter wheat grown on sandy and loamy soils in an organic and integrated farming system. C_{root} C input (see Table 2), C_{total} sum of C_{root} and C content of the aboveground plant parts at harvest, C_{grain} C content in grain yield

		Cropping system			
		Integrated		Organic	
		Loam	Sand	Loam	Sand
C_{root}/C_{total}	1995	0.20	0.28	0.21	0.42
	1996	0.20	0.23	0.19	0.29
C_{root}/C_{grain}	1995	0.49	0.69	0.61	1.50
	1996	0.51	0.59	0.49	0.87

in the grain. This might be explained by the sink competitiveness of root and grain development. This "investment in roots" was much higher in the organic than in the integrated treatments on sandy soils and in 1995 on loam also (Table 3). The N limitation of organic farming seems to reduce shoot and grain development more than root production with the result of producing a relatively larger root system. However, under agricultural conditions a larger root system, at least in the upper soil layer (0–30 cm), might have no specific advantage for N acquisition (Wiesler and Horst 1994). Such an advantage might have been conferred under the selection conditions during plant phylogenesis. In the natural environment, N input into the soil is sporadic and a larger root system might enable a plant to "find" and exploit these N spots more rapidly than a competitor.

The influence of the soil texture on root growth was more pronounced than the effect of the cropping system. The size of the standing root system tended to be a bit lower on the sandy soils, whereas root production was higher. This was more pronounced in 1995 than in 1996. A combination of higher root production and the smaller net size led to higher RPRs and relative mortality rates and consequently to higher TIs on sandy soils. A smaller standing root system of white mustard plants (*Sinapis alba*) on a loamy sand compared to a sandy loam was also determined by Sauerbeck and Johnen (1976). But they also reported a lower total root production on sand, in contrast to our findings. The relationship between root production and the net size at harvest, however, was higher on the sand (3.2) than on the loam (2.4). This indicates a higher root production rate on the sand. Merckx et al. (1985) reported also that spring wheat had a smaller standing root system on a sandy soil compared to a silty clay loam. Soil-root respiration, however, was higher on the sand, which again indicates greater decay of root material and due to this, probably, higher root turnover.

The reason for the increased root production and the higher relative production and mortality rates on sandy soils remained unclear. A lower supply of nutrients seems unlikely since the effect of different nutritional levels on root production is limited (Merckx et al. 1987). Only at a severe P shortage for barley (*Hordeum vulgare* L., Steingrobe et al. 1999) and sugar beet (*Beta vulgaris* L.) and at a K shortage for *Vicia faba* L. could higher root production be observed (unpublished data). However, the P and K availability in all treatments was high and, therefore, the differences in root production between the soil types could not be due to a different P or K supply. Furthermore, neither did N deficiency occur in the integrated farming system. Water supply, which may become limited earlier on sandy than on loamy soils because of the lower water-holding capacity (Table 1), was not a major problem in either year. Furthermore, Smit and Vamerali (1998) found no great effect of water shortage on production and mortality of potato roots.

The possibility of dividing the net development of root systems into the gross processes of root production and root mortality gives the opportunity to investigate factors which influence the gross process. This may well lead to a better understanding of root growth in the field.

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