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GROWTH AND DEVELOPMENT OF ROOT SYSTEMS OF WINTER CEREALS GROWN AFTER DIFFERENT TILLAGE METHODS INCLUDING DIRECT DRILLING

by F. B. ELLIS and B. T. BARNES

Agricultural Research Council Letcombe Laboratory,
Wantage, Oxon. OX12 9JT, England

KEY WORDS

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SUMMARY

A method is described for rapidly estimating the depth of penetration and density of roots of cereal crops under field conditions. Counts of living roots, traversing horizontal faces of soil cores, were made for winter wheat growing on direct-drilled and ploughed land.

The rate of penetration of roots of winter wheat in a clay and a sandy loam soil averaged 5 mm per day throughout winters without extremes of cold or wet. Death of roots near the soil surface occurred whilst others continued downward penetration. The rate of root elongation was slower during prolonged periods when the soil was wet and faster, *i.e.* to greater depths, during dry conditions.

Damage sustained to roots during adverse winter conditions often varied between direct drilling and ploughing. More roots at depth were consistently recorded on direct-drilled than on ploughed land when measured in spring after a soil water deficit had developed during the preceding month. After prolonged wet soil conditions during the winter on a soil with a large clay fraction and low hydraulic conductivity, root growth and penetration in spring, before the development of a soil water deficit, was more restricted on direct-drilled than on ploughed land.

INTRODUCTION

The development of contact non-residual herbicides has made crop production possible without any cultivation beyond that necessary to place the seed into the ground. These simplified methods of cultivation result in an increased soil bulk density and resistance to a cone penetrometer, particularly in the surface layers of soil[14,15,23,26].

The rate of root extension is decreased by mechanical resistance in the soil[27]. In laboratory studies extension of roots subjected to relatively small pressures was markedly slower[1,19]. However, the restraints imposed on root growth by mechanical stress may not be assessed simply from measurements of the bulk

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properties of the soil. In the field roots grow down ped faces and through pores, including the continuous cylindrical channels produced by earthworms. Thus the structural qualities of the bulk soil may not provide a reliable indication of the ability of the roots to ramify through the soil; the continuity of pores of sufficient diameter is of greater importance.

The response of cereal root systems to compacted soil in the field varies considerably. Many of the published investigations have, however, been carried out on coarse textured soils within 25 cm of the soil surface[14,17]. In the early stages of plant development on these soils the seminal root axes extended more slowly in undisturbed or shallow (5 cm) cultivated soil than in ploughed or deep (20 cm) cultivated soil, and lateral branching was earlier. On the other hand Bakermans and de Wit[3] working on a sandy soil, found that although in the 10–30 cm horizon there were fewer roots on direct-drilled than on cultivated soil, in lower horizons the rooting density was at least as great as on cultivated soils.

However, root growth of cereals has not previously been studied in soils with a large clay fraction that swell and shrink and develop natural fracture planes. These soils constitute nearly half of the total cereal area in the UK[6]. Shrinkage cracks along ped faces and earthworm channels are both more prevalent on direct-drilled than cultivated land[4,15].

The effort and time required to separate fine roots from these heavy soils without considerable loss has resulted in a lack of information on root growth in them irrespective of cultivation treatment. For the present work representative information from large field plots was required to follow changes in the root growth of cereals after different cultivation systems. A simple and rapid procedure was essential so the type of method originally proposed by Hellreigel[22] and developed by Schuurman and Knot[28] and Garwood and Williams[18] was considered. The method involves counting the number of living roots per unit area of horizontal surfaces of soil at different depths. It had been shown[25] that the number of roots intersecting a plane through a soil core was related to the root length per unit volume of soil. In the present investigations where crops were maintained weed free, the number of roots passing through horizontal planes in the soil were closely correlated with the length and weight of the main axes of cereal roots per unit volume of soil[10].

The measurements of root growth we report are from experiments comparing different cultivation treatments on clay soils. Limited measurements from samples collected on a sandy loam soil are also included for comparison. Agronomic details of the experiments[7], information on shoot growth[7,8], crop yields[7], soil physical conditions[7,20] water removal by crops[20], measurements of the soil atmosphere[5], and nutrient content of the surface soil[9] have been published. Our present purpose is to review the results obtained on root development during a period of years with contrasting weather patterns when variable amounts of rainfall were recorded (Table 1). We have concentrated mainly on winter wheat, since this crop is of greatest practical relevance in considering the advantage of timeliness for adopting simplified cultivation, including direct drilling.

EXPERIMENTAL METHODS

a) *Measurements of root distribution*

Steel tubes (7.0 cm dia.) with case hardened cutting edges were used to take a minimum of four cores from each plot. There were 3 to 5 replicates of each cultivation treatment. Thus a total of twelve to twenty-five cores were taken per treatment. Each tube was fitted with an aluminium liner consisting of two hemi-cylindrical sections to contain the soil core. The cutting diameter of the tube was less than the internal diameter of the liner[13,31] so avoiding compaction during the sampling process. After the liner was withdrawn from the tube one half was removed exposing the core of soil. The core was divided into 5 or 10 cm lengths. In clay soil this was done by marking at appropriate depths and then breaking them across by bending by hand. This method exposed roots on both surfaces without further preparation. Examination of both surfaces was necessary to ensure that roots were evenly broken and not pulled from the horizontal face. On soil with large sand or silt fractions the core was cut into the desired lengths and the horizontal faces were washed with a fine jet of water to expose the cut root ends.

Samples were usually collected when the soil was moist, and the plants had developed a root system extending to depths greater than 15 cm from the soil surface. Samples were not taken after anthesis since the weight of roots has been found to decrease thereafter[21,29,30].

Samples were usually obtained immediately below the row of plants since previous studies[14,30] have shown that when cereals are grown in rows 15 cms apart more than half the roots are within the band of soil 4 cm either side of the centre line of plants. The sampling technique was rapid and enabled root numbers to be assessed directly in the field so that information could be obtained on the rate of penetration of roots to depth at frequent intervals throughout the winter period, November to March. The maximum depth of penetration was defined as that where roots were seen on the horizontal surfaces at least 20 per cent of the cores examined. Living roots were always seen on samples 5 cm above this depth and occasionally some penetrated appreciably deeper; for example, when they followed channels created by earthworms or natural fractures in the soil.

b) *Experimental sites*

Roots were studied at four experimental sites where cultivation treatments were being compared (Table 2). The core method of examination was used first on a sandy loam soil at Begbroke, Oxfordshire, where winter wheat (var. Capelle Desprez) was grown on four cultivation treatments between 1971–1975. The texture of this soil facilitated identification of roots passing through the horizontal surfaces and the experience gained enabled the method to be adopted for use on more clayey soils. Measurements were made during the period 1972 to 1975 of winter wheat roots (var. Capelle Desprez) in a clay soil (Evesham series). The investigations were intensified in 1976 when measurements were made on two other clay soils (Lawford and Denchworth series) where winter wheat was grown. Samples were also taken from these two sites in 1977 (winter oats) and 1978 (winter wheat).

The average coefficient of variation for measurements of roots in the surface 60 cm of soil based on 5 cores per plot was 23 per cent between plot means compared with 32 per cent between individual samples. Greater variability below 60 cm reflected the small numbers of roots present and their tendency to follow planes of weakness or grow within channels in the soil. This limitation is equally applicable to other methods of root examination (see Gregory *et al.*[21]) and the variation observed with our method is closely similar to that found with more laborious procedures including separation of roots from soil by washing and measuring root volume.

c) *Rainfall*

Rainfall has been considered for two periods in each year, the winter growing period of crop establishment and early root growth, and the remaining months of rapid growth leading to harvest. Winter rain is especially important to autumn sown crops, because the speed of return of the soil water content to field capacity and the incidence of subsequent waterlogging will be major factors in the winter development of the root system.

In the period 1971–75 when root counts were made on the sandy loam (Sutton/Aldreth var.) and clay (Evesham series) sites, annual rainfall was generally similar to the long term average as it was again in 1977–78. However, in October–March 1975/76 rainfall was less than half of long-term average and in the next six months it was only 60% of the average. This resulted in extensive deep cracking of clay soils, so that although winter rainfall in 1976/77 was 40% greater than average, the soil did not return quickly to field capacity (Table 1).

RESULTS

Since no consistent differences were found in root development between direct-drilled and shallow tine cultivation treatments, or between ploughing and deep tine cultivation, reference is restricted to the two extreme treatments. In the early stages of plant establishment root systems of plants recovered by digging did not reveal any significant difference between cultivation treatment on the numbers of seminal roots or the density of lateral development.

a. *Development of the root system in winter*

Measurements throughout the winter on the sandy loam and the Evesham series clay soil, during the period 1971 to 1975 (Fig. 1) show a progressive increase in depth of penetration throughout the winters on both soils irrespective of cultivation method. During this period, when no climatic extremes were recorded (Table 1), the average rate of penetration was approximately 5 mm per day.

Although the roots continued to grow downwards, growth nearer to the soil surface was not always continuous and sometimes between two successive sampling occasions the numbers of roots in the surface layers decreased.

The extent of decrease in root numbers sometimes varied between cultivation treatments. The effect can be illustrated by results obtained on a clay soil

Table 1. Rainfall (mm) during the periods when root samples were collected at the various sites. Fractions of the longterm average (1941–70) in parenthesis*

Period of year		Location of site and soil texture			
		Begbroke sandy loam	Buckland calcareous clay	Northfield clay	Compton Beauchamp clay
1971–72	Oct–Mar	291 (0.92)	–	–	–
	Apr–Sept	345 (0.76)			
1972–73	Oct–Mar	190 (0.60)	208 (0.65)	–	–
	Apr–Sept	353 (1.10)	351 (1.11)		
1973–74	Oct–Mar	276 (0.87)	230 (0.72)	–	–
	Apr–Sept	354 (1.10)	363 (1.15)		
1974–75	Oct–Mar	355 (1.12)	349 (1.09)	–	–
	Apr–Sept	247 (0.77)	256 (0.81)		
1975–76	Oct–Mar	–	–	123 (0.35)	165 (0.50)
	Apr–Sept			193 (0.58)	212 (0.67)
1976–77	Oct–Mar	–	–	468 (1.34)	499 (1.50)
	Apr–Sept			316 (0.95)	326 (1.03)
1977–78	Oct–Mar	–	–	302 (0.87)	373 (1.12)
	Apr–Sept			230 (0.69)	242 (0.77)

* Records provided by the Meteorological Office

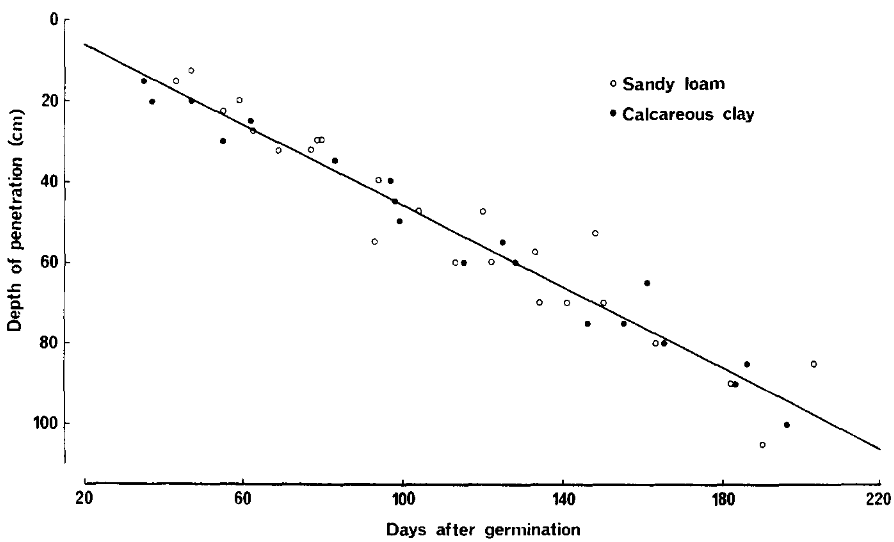

Fig. 1 Maximum depth of penetration of roots of winter wheat. Results for a sandy loam soil and a calcareous clay during the period 1971 to 1975.

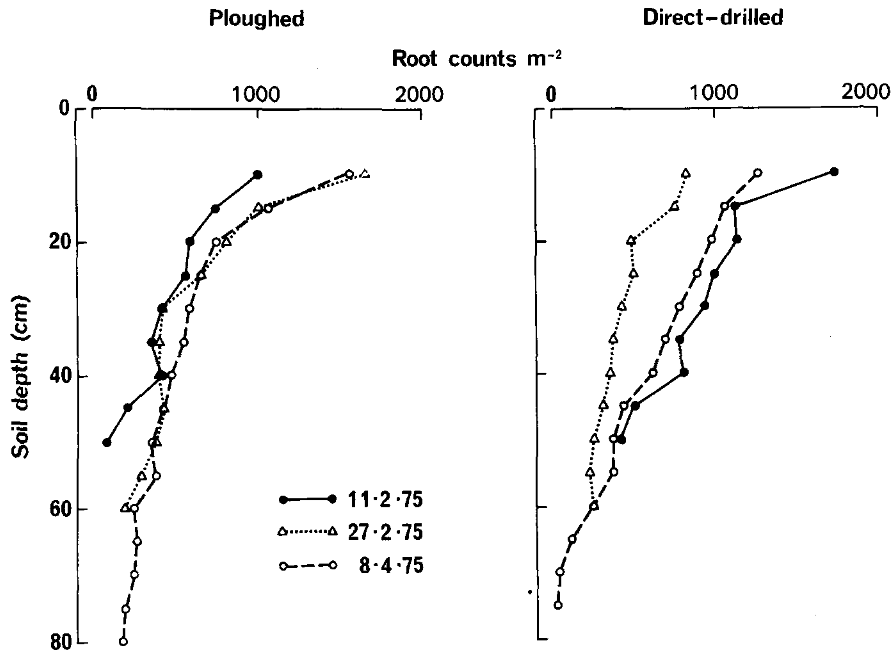

Fig. 2. Root growth of winter wheat on ploughed and direct-drilled areas on a clay soil during the period 11 February to 8 April 1975.

(Evesham series) in 1975 (Fig. 2). During the period from the beginning of February to mid-March, extensive ponding of water occurred on this site, especially on the direct-drilled areas. The water content of the surface 5 cm of soil on the direct-drilled was consistently higher than on the ploughed areas, although the converse occurred between 5 and 20 cm depth[15]. Root measurements were made on 11th and 27th February and on 8th April (Fig. 2).

However, during the period between the first two sampling occasions there was a sharp decline in the root count in the soil between 20 and 50 cm on direct-drilled areas, whereas on ploughed plots a small increase occurred at some depths. During March and early April growth took place on the direct-drilled land, largely compensating for the earlier losses; at the same time there was no change in rooting density recorded on the ploughed land. Although these patterns of growth varied greatly on the two cultivation treatments, in both cases downward penetration continued between 50 and 80 cm at much the same rate.

Although under average climatic conditions the rate of downward penetration was about 5 mm per day, it was faster in the dry soil conditions in spring 1976 on the Lawford and Denchworth clay soils and slower in 1977 and 1978 when wet conditions prevailed (Table 3 and Fig. 3).

Table 2. The sites, soil types and crops for comparisons of rooting density between cultivation treatments

Location of site	Begbroke Oxfordshire	Buckland Oxfordshire	Northfield Oxfordshire	Compton Beauchamp Oxfordshire
Soil texture	Sandy loam	Calcareous Clay	Clay	Clay
Soil series*	Sutton/ Aldreth var.	Evesham	Lawford	Denchworth
U.K. classification**	Argillic brown earth with Cambric gley	Calcareous pelosol	Pelo stagnogley	Pelo stagnogley
Crop	Winter wheat	Winter wheat	Winter wheat Winter oats	Winter wheat Winter oats
Years sampled	1971–75	1972–1975	1976 1977 1978	1976 1977 1978
Cultivation treatments***	DD, ST, DT & P	DD, ST, DT & P	DD, ST & P	DD & P

* Typical soil descriptions are given by Jarvis[24]. The Lawford series was originally included in the Rowsham series.
** See Avery[2].
*** The cultivation treatments, direct drilling (DD), shallow tine cultivation 5–8 cm (ST), deep tine cultivation, 16 cm (DT) and ploughing (P) were applied to the same areas in each year of our experiment.

Table 3. Average rate of penetration of winter wheat or winter oats roots, between germination and shoot elongation, on two clay soils in 1976, 1977 and 1978

Soil series	Number of days after germination	Root growth depth of penetration cm		Rate of penetration mm day^{-1} Mean direct-drilled and ploughed
		Direct-drilled	Ploughed	
Wheat harvested in 1976				
Lawford	182	> 100	> 100	> 5.5
Denchworth	186	> 100	> 100	> 5.3
Wheat harvested in 1978				
Lawford	181	70	65	3.6
Denchworth	183	50	45	2.6
Oats harvested in 1977				
Lawford	178	80	60	3.9
Denchworth	177	60	65	3.5

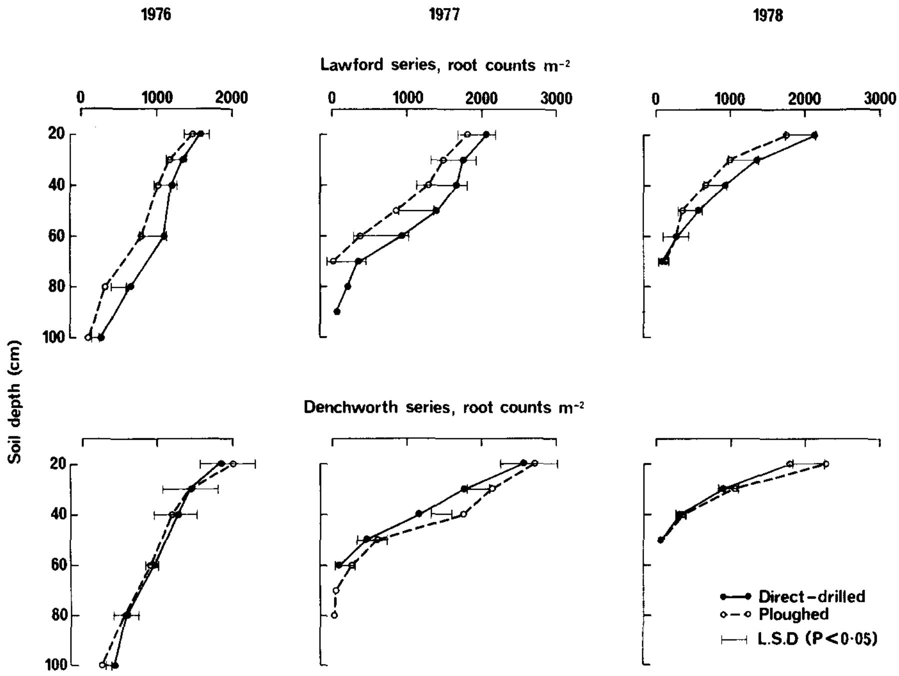

Fig. 3. Number of roots traversing horizontal faces at different depths from the soil surface. Soil cores obtained on Lawford and Denchworth series soils when the stems of plants began to elongate.

Table 4. Root count profiles for winter wheat on direct-drilled and ploughed calcareous clay soil (Evesham series)

Soil depth	Root counts m^{-2}	
	Direct-drilled	Ploughed
20	1010	850
30	810	650
40	610	490
50	440	370
60	340	270
70	130	160
80	20	10
Total	3360	2800

Measurements made at the beginning of stem elongation
Mean results for three years (1973–75)

b. *Samples collected at the beginning of stem elongation*

For winter wheat on the Evesham series clay soil the sum of counts shortly before stem elongation on horizontal soil faces at depths of 20, 30 cm *etc.* down the soil profile, was consistently greater on direct-drilled than on ploughed land (Table 4) and averaged over the three years this difference attained statistical significance ($P < 0.05$).

More detailed investigations were initiated in spring 1976 on clay soils of the Lawford and Denchworth series. These soils had cracked extensively in the previous year and cracks had not fully resealed during the relatively dry winter (Table 1). On the Evesham soil the cracks penetrated to greater depths on the direct-drilled land[15] and root penetration in 1976 thus seemed likely to differ between cultivation treatments. On the Lawford series consistently more roots were counted throughout the soil profile after direct drilling compared with ploughing in each of the years 1976, 1977 and 1978. The differences were significant for depths between 40 and 100 cm ($P < 0.01$), in 1977 at 50 cm ($P < 0.05$) and in 1978 at 20, 30 and 50 cm ($P < 0.05$). In 1977 the maximum depth of rooting was 20 cm greater on the direct-drilled areas (Fig. 3).

A similar effect was also seen on the Denchworth series in 1976, although significant ($P < 0.05$) only at the greatest depth sampled, 100 cm. On this soil in the two subsequent years winter rainfall exceeded the average (Table 1) and also exceeded the amount on the Lawford site. Roots penetrated less deeply and more numerous roots were found on the ploughed than the direct-drilled areas, although only when no appreciable loss of water had been recorded from the soil before the root samples were taken.

c. *Samples collected at anthesis*

Although differences were frequently recorded between the numbers of roots found on plants from direct-drilled and ploughed plot earlier in the year, no differences were apparent in the same horizons at anthesis; more rapid growth on ploughed plots had compensated for differences recorded earlier and roots were more abundant at all depths by this stage.

In 1978 only small quantities of root were recorded at the maximum depth of sampling of 100 cm, but in the dry conditions and extensive fissuring of the soil in 1976, much larger quantities of root were recorded at this depth on both treatments, so roots extended well below 100 cm by anthesis.

DISCUSSION

Care was taken to compare root growth of plants at similar stages of physiological development, since in some instances cultivation may affect the time and uniformity of germination, and subsequent plant development[15]. The lack of significant effects of cultivation on seminal root growth of winter wheat in these well structured soils contrasts with the findings of a one year experiment carried out on a sandy loam soil, considered less suitable for direct drilling. Here the extension rate of seminal root axes was slower in undisturbed than in deep cultivated soil[17], but lateral development was enhanced and an effectively shallower seminal root system persisted throughout the season. In experiments[14] with spring barley on a sandy loam soil, we have similarly found seminal root axes to be shorter after direct drilling in the first year but when the treatments were re-applied to the same areas in successive seasons, differences between treatments were more transient, suggesting that the soil conditions may have become more favourable for root growth. The large differences in the first year were associated with the seed being placed in a smeared slot.

In the present experiments straw residues were burned and the passage of the direct drill always produced a friable tilth favourable to rapid germination. Burning the straw can increase the stability of aggregates in the surface of clay soils[11] and dries it so encouraging the production of a friable seed-bed after the passage of the drill[16]. Earthworms have been found in larger numbers in land direct-drilled rather than ploughed and these help to produce a friable tilth[4]. These favourable processes associated with direct drilling seem to have offset, on these weakly structured soils, any adverse effect of increased bulk density.

Root growth is not necessarily related to the bulk properties of the soil[27]. The large continuous pores on direct-drilled land caused by shrinkage cracks and the action of soil fauna facilitate root growth through otherwise compacted layers and permit diffusion of gases into and out of the soil. This would explain higher concentration of oxygen measured in winter after direct drilling compared with after ploughing a clay soil of the Evesham series[12]. However, in wet conditions larger concentrations of nitrous oxide have been measured in direct-drilled clay soils[5], indicating the presence of anaerobic zones within the soil peds. It is not surprising, therefore, that during wet periods in winter root growth may not progress continuously in the surface horizons, and that in some periods death of roots may occur. The fact that these effects can occur at different times in direct-drilled or ploughed crops accords with different water contents measured in the two treatments[15].

Root counts made in spring, at the beginning of stem elongation, have shown a consistent trend to a higher number of roots at depth on direct-drilled compared to ploughed land on two clayey soils, provided that appreciable water loss from the soil takes place before the time of sampling. Where a lower root count was obtained on direct.drilled land than on ploughed, as on the Denchworth series, during the winter periods of 1976–77 and 1977–78 rainfall was high (Table 1) and neutron moisture meter readings indicated a high soil water content by volume during the month before sampling. (Goss, M. J., private communication) and no appreciable loss of water from the soil was recorded until after root samples had been collected when the stems of the plants had begun to elongate.

Rapid root growth on direct-drilled land in response to the lowering of the water content of the soil, is not surprising in view of the more rapid movement of water through direct-drilled soils[20], which must reflect the more extensive soil cracking[15] and greater number of earthworm channels[4] that occur on this treatment.

Differences in root growth were not found between cultivation treatments when counts were made at anthesis. Sampling did not, however, extend below 1 m where roots were frequently present and obviously extended beyond this depth.

The possibility that because of the nature of the soil structure direct-drilled roots are better able to reach and exploit the sources of water in the soil at depths greater than 1 m is consistent with the heavier yields that have been obtained from this treatment under drought conditions[15]. In these circumstances not only did the structural properties of the direct-drilled soil afford greater potential access for roots to penetrate to depth but the undisturbed soil maintained significantly larger water contents than the ploughed soils below 50 cm. During dry summer 1976 the crop was able to extract up to 22 mm more water from uncultivated soil and this was associated with better crop growth, resulting in heavier grain yields than after ploughing[20].

Our experiments show that root growth on clay soils after direct drilling was impaired only after soil waterlogging during the winter. Whenever the soil has dried appreciably in the period before sampling a greater abundance of roots has been measured on the direct-drilled treatment than on the ploughed. This effect was particularly marked and consistent in the dry conditions of 1976.

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