

Effects of soil compaction in potato (*Solanum tuberosum*) crops

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SUMMARY

Since many soils used for growing potatoes in the UK are likely to be close to their plastic limit for cultivation during early spring, there exists the potential for soil compaction to occur during planting which will restrict root penetration. A series of experiments showed that soil compaction delayed emergence, reduced rate of leaf appearance and ground cover expansion, shortened canopy cover duration and restricted light interception, which combined to reduce tuber yield. Rooting density and maximum depth of rooting were reduced, particularly where compaction was shallow. In some soils, irrigation helped alleviate some of the effects of compaction but in others it exacerbated their severity. Using a cone penetrometer, relationships between rate of root penetration and soil resistance (Ω) were established from a number of experiments and replicated blocks in commercial fields and an overall relationship of the form $y = 16.3 - 4.08\Omega$ mm/day was produced. Root penetration rates of *c.* 20 mm/day were measured in the intensively-cultivated ridge zone but growth rates were halved at a Ω of 1.5 MPa. A survey of 602 commercial fields showed that two thirds of fields had Ω s ≥ 3 MPa (where root growth rates would be < 2 mm/day) within the top 0.55 m of the soil profile. Thus, rooting depth is likely to be considerably shallower than desirable and lead to inefficiency of water and nutrient utilization. The use of powered cultivators to separate stones and clods from beds or ridges and produce a fine seedbed is now almost universally adopted in the UK. However, the system is both time and energy inefficient and increases the risk of creating soil compaction, particularly at shallow depths. All cultivation equipment has been shown to cause compaction and it is suggested that the consequences of the shortening of the growing season from delaying planting by a few days to allow the soil to dry are far less than the yield and quality losses caused by compaction.

INTRODUCTION

Over the last 25 years there have been very large changes in the methods of cultivating soil for the potato crop. Systems that involve ploughing, bed-forming, bed-tilling and stone- and clod-separation prior to planting have changed the timing, depth and frequency of soil cultivations. Increased tractor power has allowed growers to cultivate in more marginal conditions and to greater depth but have increased the likelihood that the soil at the interface between worked and unworked soil will be above its plastic limit. As a consequence, it will respond to the shear force of any implement by compressing, becoming more dense and be described as compacted. This increase in bulk density is a potential impediment to

root growth as reported by Boone *et al.* (1978) and Feddes *et al.* (1988) but the frequency and significance of differences in soil bulk density in potato crops are far from clear. Reports of experiments using artificially compacted soils often show very large reductions in yield due to compaction (Timm & Flocker 1966; van Loon *et al.* 1985) but effects of subsoiling (and other treatments aimed at removing or ameliorating compaction) frequently appear to be small. There has been limited study of the effect of soil resistance (Ω) on root growth in potatoes, but in other crops root growth has been shown to slow at Ω s known to occur in soils in which potatoes are grown (Gooderham 1973; Loboski *et al.* 1998). Thus, it seems clear that changes in soil bulk density can have large effects on crop growth and yield in potatoes but there is little understanding of the cause and extent of these effects. As a result, there is limited information to guide soil management and as the surface soil

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Table 1. *List of experiments, location, year, soil type, variety and experimental treatments*

Expt	Location	Year	Soil type	Variety	Treatments
1	Cambridge University Farm (CUF), Cambridgeshire, UK	1994	Sandy clay loam	See treatments	16 varieties (Arran Comet, Atlantic, Cara, Desiree, Erneststolz, Estima, Hermes, Lady Rosetta, Maris Piper, Panda, Pentland Dell, Pentland Squire, Record, Russet Burbank, Saturna and Shepody)
2	CUF, Cambridgeshire, UK	1995	Medium sandy loam	Cara	Two compaction treatments (uncompacted and compacted); two irrigation regimes (unirrigated and irrigated)
3	CUF, Cambridgeshire, UK	1995	Medium sandy loam	See treatments	Two varieties (Estima and Maris Piper); two compaction treatments (uncompacted and compacted); two irrigation regimes (unirrigated and irrigated)
4	CUF, Cambridgeshire, UK	1996	Medium sandy loam	Maris Piper	Five compaction treatments (uncompacted, compacted 0.1 m, compacted 0.4 m, dug out 0.4 m and compacted 0.1 + 0.4 m); two irrigation regimes (unirrigated and irrigated)
5	Deben Farms, Shottisham, Suffolk, UK	1996	Medium sand	See treatments	Three varieties (Estima, Remarka and Saxon); two physiological ages of seed (0 and 300 °C days); two types of covering mulch (fleece and polythene)

Table 2. *List of commercial Sites, location, year, soil type, variety and number of replicates*

Site	Location	Year	Soil type	Variety	Number of replicates
1	Littleport, Cambridgeshire	1992	Peat	Estima	4
2	Blickling, Norfolk	1994	Fine sandy loam	Maris Piper	4
3	Oxnead, Norfolk	1994	Sandy silt loam	Binjtje	4
4	Thornham, Norfolk	1996	Sandy clay loam	Saturna	4
5	Worlington, Suffolk	1999	Medium sand	Estima	4
6	Swaffham Prior, Cambridgeshire	2001	Peaty sand	Maris Piper	4

appears well-cultivated, many growers are unaware of changes in bulk density deeper in their soils caused by their cultivations.

The present paper reports the results of experiments and commercial field sampling over much of the potato production area in the UK that studied the relationship between root growth and soil Ω , the soil Ω s prevailing in soils growing potatoes, the causes of change in soil Ω and the effectiveness of cultivation treatments aimed at removing soil compaction.

MATERIALS AND METHODS

General methodology

The results contain data collected from three main sources: fully replicated, randomized block design

field experiments (Expts), replicate blocks in commercial crops (Sites) and areas of commercial fields where different cultivation treatments were carried out, usually unreplicated strips. Tables 1 and 2 give details of the Expts and Sites used in the study. All fields containing Expts and Sites were autumn-ploughed. Sites were bed-formed, stone-separated and planted over a short period of 1–3 days. Experimental fields at Cambridge University Farm (CUF) and Deben Farms were ridged up (Expts 1 and 5) or power harrowed flat (Expts 3 and 4) prior to hand planting. Experiments 1 and 3 were irrigated using overhead booms (RST Irrigation) attached to Perrot hoses. In Expt 4, drip irrigation was applied with T-Tape (T-Systems) and in Expt 5 spray irrigation was applied using solid-set sprinkler irrigation (Wright Rain Portagrid).

Irrigation treatments were scheduled using the CUF irrigation scheduling model (M. A. Stalham, unpublished) based on a modified Penman–Monteith evapotranspiration (ET) equation using the grass reference crop ET_0 calculations of Allen *et al.* (1998). The model takes account of changing leaf area index, stomatal conductance and canopy surface roughness on the demand side and root growth and limiting soil moisture deficit (SMD) based on soil water tension and rooting depth on the supply side (Stalham & Allen 2004). The ‘limiting SMD’ was defined as the point when the ratio of actual to potential ET (adjusted for canopy cover and height) fell below 1.0 (Stalham & Allen 2004, 2005). Meteorological data were collected at CUF using an electronic logger (Delta-T Devices Ltd or Schlumberger) attached to an anemometer (Vector Instruments), thermistors measuring dry and wet bulb temperature (Grant Instruments), a screened relative humidity sensor (Skye Instruments Ltd) and a pyranometer measuring total incident global radiation (Kipp & Zonen BV). The Meteorological Office MORECS service was used to supply ET data for scheduling irrigation in experiments and commercial Sites outside CUF.

Experimental design and replication

Experimental treatments are detailed in Table 1. Experiments 1, 2 and 4 were fully randomized block designs with three replicates in Expts 1 and 4 and four in Expt 2. Experiment 3 consisted of four replicates in a randomized split-plot design with compaction \times irrigation as main plots and varieties as sub-plots. Experiment 5 was a split-plot design with mulch covering as main plots and variety \times physiological age as sub-plots with three replicates. There were four replicate areas at each commercial Site (Table 2). The assessment of different cultivation equipment in commercial fields was performed mostly on unreplicated adjacent strips.

Specific experiments

Experiment 2

In Expt 2, plants were grown in a series of 1.1 m long, 100 mm internal diameter, grey plastic irrigation pipes. Half of these ‘tubes’ were loosely packed with an oven-dried soil which had been sieved to remove peds larger than 4 mm, resulting in a bulk density of 1.22 t/m³, close to the value achieved under field conditions with clod-free soil at Cambridge. The compacted treatment was consolidated by applying a force of 500 N to an iron disc packer when packing successive 100 mm increments of soil. The 36 tubes comprising the compacted treatment had a mean bulk density of 1.39 t/m³ (s.e. = 0.018 t/m³).

The tubes were filled to the rim with water and left to stand until this had drained into the soil. Further

additions were made over a period of 3 days until water was observed draining out of the base of the tube. The tops of the tubes were then covered with sheet polythene to eliminate evaporation and left to drain and reach field capacity over the next 5 days. The tubes were then re-weighed to determine the quantity of water held at field capacity. Uncompacted tubes contained 27.3 m³/m³ water (volumetric basis) and 28.2 m³/m³ (s.e. = 1.15 m³/m³) in the compacted treatment. Following packing and wetting, soil resistance was determined in four different positions in each of four replicate tubes using the penetrometer (see later description). These tubes were subsequently repacked as above since the path of the penetrometer may have left a channel through which roots could grow preferentially.

The tubes were planted with a single 25–30 mm Cara tuber and covered with fertilizer-enriched soil to a depth of 80 mm. Water was then applied to bring the top layer of soil up to field capacity. The tubes were spaced as in Table 3 and supported vertically in frames within 1 t potato boxes. Plants were exposed to natural light and rainfall conditions. Two irrigation regimes were imposed: a fully irrigated ‘wet’ treatment replacing the potential ET on a daily basis assuming complete crop cover and secondly a restricted ‘dry’ regime. Some irrigation was essential for growth in the ‘dry’ treatment given the paucity of rainfall throughout July and August. Therefore, from 42 days after emergence in the ‘dry’ treatment, irrigation was continued with the same frequency and amount as the fully irrigated treatment but no attempt was made to bring the soil back to field capacity.

Experiments 3 and 4

The soil was irrigated to field capacity 2 days prior to being compacted. In Expt 3, a 5 t tractor was driven over the soil so that all four wheels passed over the entire area of the plot four times. The compacted plots were power harrowed 2 days after compaction, to a depth of 50 mm, to allow shallow planting using hand dibbers. In Expt 4, compaction of the soil surface was carried out as in Expt 3. Compaction at depth was achieved by excavating the soil to 0.3 m depth using a JCB digger, driving on the dug-out plot as for surface compaction, then replacing the soil over the compacted layer. In view of the difficulties experienced in obtaining adequate depth of soil coverage when planting into a shallow seedbed in Expt 3, an additional 0.1 m of top soil was deposited on all plots which was then power harrowed to form a seed bed. The compaction depths were therefore 0.1 and 0.4 m from the soil surface. A dug-out control was included in order to separate the effects of soil disturbance from the effects of deep compaction but it had no significant effect compared with uncompacted soil; therefore the results are not presented.

Table 3. *Date of planting and seed spacing in experiments and commercial sites*

	Date of planting	Date of emergence	Seed size (mm)	Row spacing (m)	Within-row spacing (m)
<i>Expt</i>					
1	29 Apr	1–3 Jun	25–35 to 45–55	0.72	0.20
2	19 May	13 Jun	25–30	0.72	0.20
3	25 Apr	22–29 May	30–35	0.72	0.25
4	24 Apr	31 May to 4 Jun	30–35	0.72	0.25
5	26 Mar	26 Apr to 10 May*	35–45	0.91	0.24
<i>Site</i>					
1	16 Apr	21 May	45–55	0.91	0.30
2	14 Mar	29 Apr	35–45	0.91	0.33
3	20 Apr	10 May	25–55	0.89	0.37
4	12 Apr	21 May	35–45	0.67	0.55
5	31 Mar	30 Apr	40–55	0.67	0.35
6	10 Apr	21 May	35–45	0.91	0.30

* Physiologically old seed emerged 14 days earlier than young seed.

Rooting depth determinations

At emergence, profile pits were excavated using a JCB digger or spade to a depth of 1.2–1.5 m spanning four rows (three rows at Sites 4 and 5). The width of the pit can be estimated from Table 3. The soil underneath each row was then excavated by hand using a spade to determine the maximum depth of rooting. On each occasion on which measurements were made, a fresh face of the root pit was prepared by excavating back two plants from each of the rows. Starting at emergence and continuing every 1–2 weeks, the depth of the ten longest roots in each pit was measured until maximum rooting depth was reached. The difference in mean maximum rooting depth between samplings was used to calculate root growth rates. Since the roots were not extracted from the face of the root pit, it was actually the rate of increase in rooting depth rather than the extension rate of individual roots that was being measured. It proved too time-consuming to remove roots to determine their length and many breakages occurred whilst attempting to do so. Whilst total root length is important with respect to the absorbing potential of the rooting system, the rate of downward progress of the rooting front ultimately determines the efficiency with which subsoil water is used by the crop.

Rooting density

In Expt 2, six destructive harvests were taken at emergence and 21, 42, 62, 85 and 111 days after emergence. Three days prior to harvest, irrigation was stopped to permit the soil to dry out and make extraction easier. Tubes were tapped with a mallet to loosen the soil/tube interface and the entire root/soil core extracted onto a bench. Loose soil was knocked

off roots and the length of the longest root measured. The root network was divided into 0.2 m segments vertically and root length density estimated by washing the roots carefully to remove soils and debris and drying at 90 °C for 48 h, then using the relationship between root length and root dry weight derived by Stalham & Allen (2001).

Root core samples in Expts 3 and 4 were taken by driving a 60 mm window gouge auger (Eijkelkamp) down to a depth of 1.0 m using percussion hammer drill (Atlas Copco Cobra) then extracted using a ball clamp jack (Eijkelkamp). Two cores were taken from each plot, one from the ridge and one from the furrow. Samples were divided into 0.1 m (Expt 3) or 0.2 m (Expt 4) depths and placed in plastic bags and either frozen or kept below 4 °C for subsequent analysis. Roots were separated from soil by washing over two fine mesh grids (1.0 and 0.2 mm) and Newman's (1966) grid intersection technique as modified by Marsh (1971) and Tennant (1975) used to estimate total root length per sample (Stalham & Allen 2001).

Soil resistance readings

The relationship between root growth rates and Ω was established using measurements of Ω taken using an Eijkelkamp Penetrograph penetrometer (60° cone tip with 100 or 200 mm² basal area, 8 mm diameter shaft). Within replicated experiments, at least 20 readings of Ω were taken in each plot. In commercial fields containing Sites, four random locations were marked out after planting and *c.* 30–40 penetrometer readings taken to a depth of 0.8 m over an area of *c.* 4 m wide × 10 m in length. Soil resistance was measured at field capacity in all soils because of the effect of water content on soil strength. Occasionally,

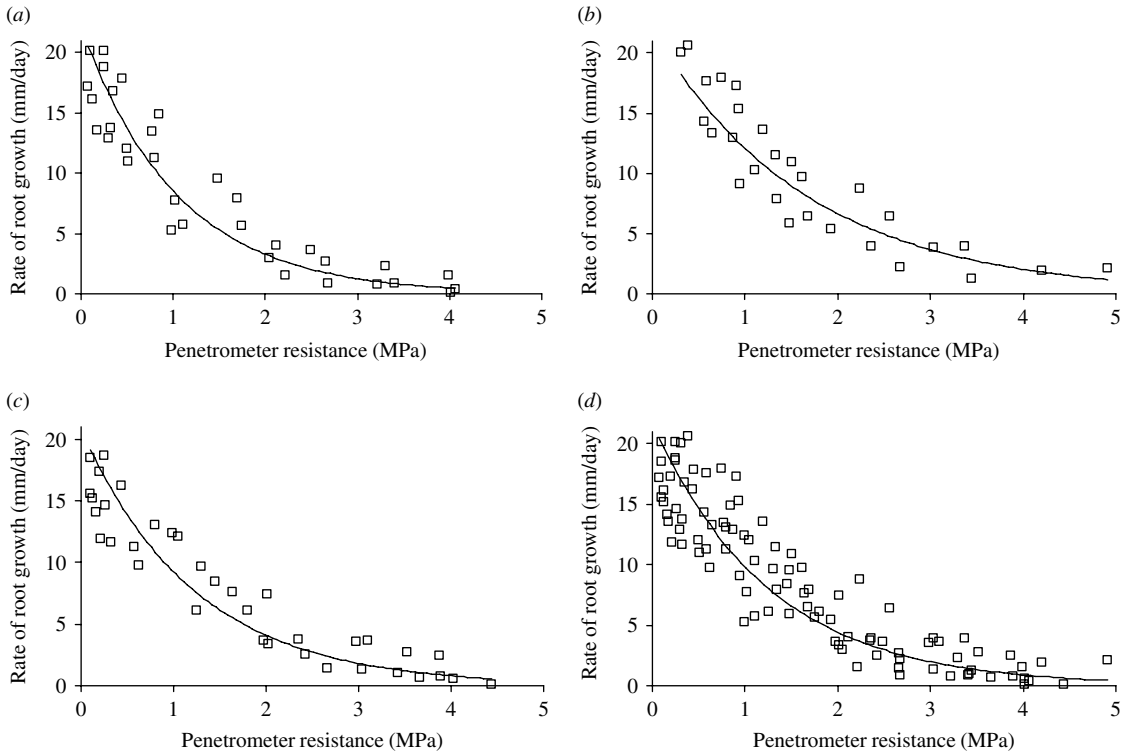


Fig. 1. Root growth rate in relation to penetrometer resistance (Ω) in structureless soils. (a) Expt 5, $y=22.17e^{-0.956x}$, $R^2=0.85$; (b) Site 1, $y=21.87e^{-0.595x}$, $R^2=0.83$; (c) Site 5, $y=20.76e^{-0.813x}$, $R^2=0.85$; (d) combined data from Expt 5 and Sites 1 and 5, $y=21.82e^{-0.799x}$, $R^2=0.79$.

the top 0.1 m was drier than field capacity, but this was above the planting depth of the seed tubers (typically 0.09–0.15 m) where root elongation was not measured. The readings of Ω were averaged for each location and the assumption made that Ω at each depth did not change during the season until the roots had penetrated that layer of soil. The high stone content in the soil of two of the compaction experiments (Expts 3 and 4) prevented the measurement of penetration Ω using the penetrometer.

Crop sampling

Most experiments only had a single final harvest. Harvest areas comprised 6–12 plants taken from guarded harvest rows and surrounded by at least one plant within the row. Tubers were dug by hand fork and graded into 10 mm increments. The proportion of ground cover was estimated using grids that comprised a multiple of the plant spacing and row width (Burstall & Harris 1983). Leaf appearance was followed in Expts 1, 3 and 4 by tagging two plants in each plot. Leaves were numbered acropetally and every fifth leaf tagged with coloured wire to aid the

counting. The number of leaves greater than 5 mm was recorded. In Expts 3 and 4, the length of tagged leaves was also measured.

Survey of compaction in commercial fields

Over the period 1992–2004, a penetrometer was used in 602 commercial fields to measure soil Ω soon after planting on a range of soil types throughout the UK. The Ω s were classified by limits equivalent to root growth rates.

Statistics and analysis

Statistical analysis of experiments was carried out using the statistical package, Genstat 5, Release 6.1 (Payne *et al.* 2002). The degrees of freedom (D.F.) are presented in the relevant Table or Figure. In all Figures, the error bars represent one standard error (S.E.). In the cultivation observations, most treatments were not replicated across fields, but at least 20 readings of Ω were taken in each cultivation regime. The S.E.s, therefore, show only the variation encountered within each treatment and do not permit statistical comparisons between treatments.

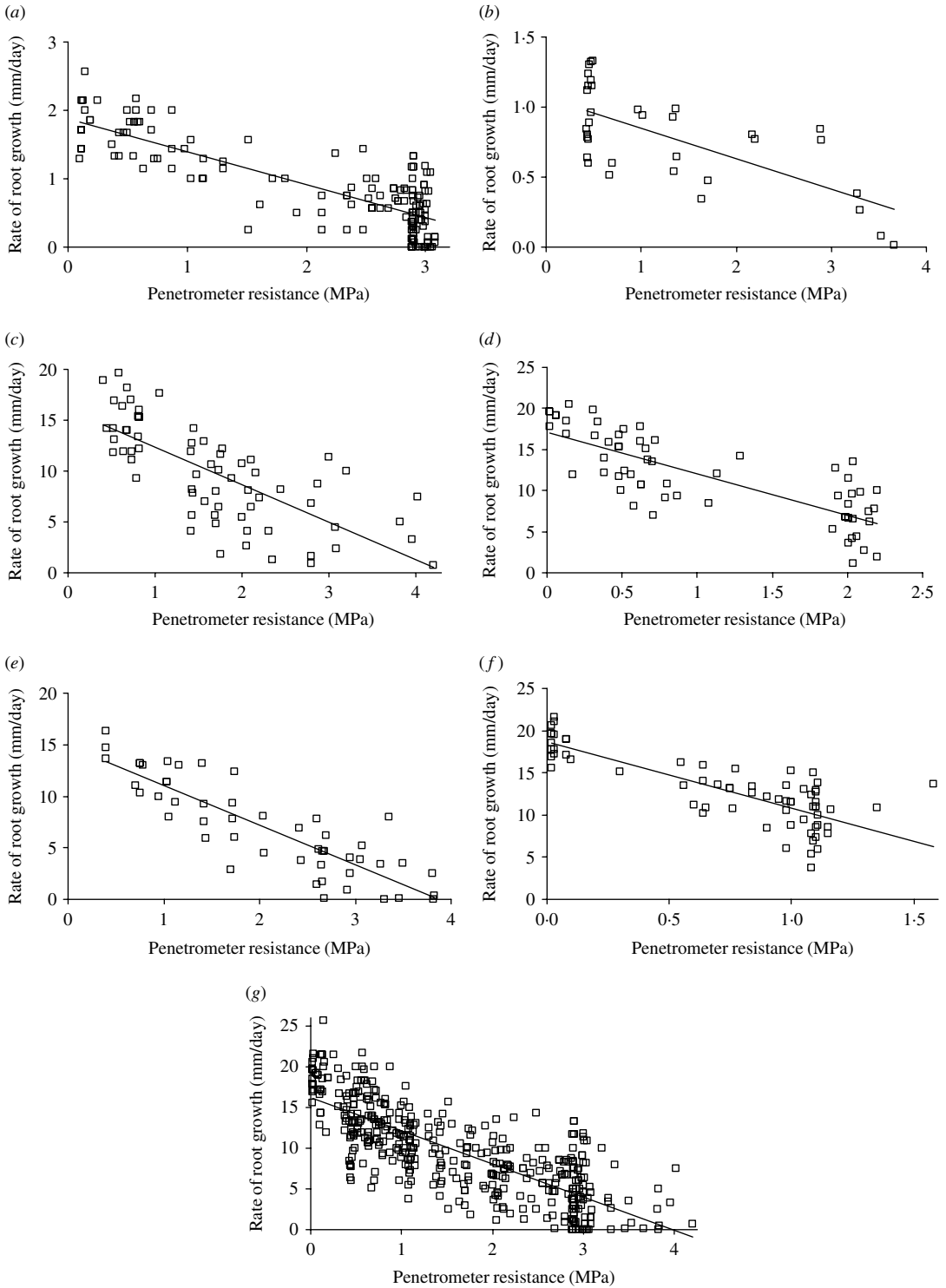


Fig. 2. For legend see opposite page.

RESULTS

Relationship between rate of root penetration and soil resistance

The mechanical resistance to root penetration is most accurately represented by penetrometer measurements in soils with weak, massive or single-grain structures (Ehlers *et al.* 1983; Vepraskas & Miner 1986). For such soils, two stone-free sands and a peaty sand soil, there were close decreasing exponential relationships between root growth rates and penetrometer resistance (Fig. 1). A common regression also fitted the data closely and in such soils root growth rates decreased rapidly with an increase in Ω . The most rapid rates of root growth measured (*c.* 20 mm/day) were comparable to the maximal growth of other temperate crop species, e.g. winter wheat (Gregory *et al.* 1978). The relationship suggests that root growth rates would halve as Ω increased to 1 MPa. At a Ω of ≥ 3 MPa growth rates would be very slow.

For well-structured soils, the relationships were less close and invariably negatively linear. Figure 2 presents the individual and combined results for two Expts and four Sites and shows considerable range in growth rates at any Ω . Maximal rates were again *c.* 20 mm/day close to the soil surface and often minimal at Ω s above 3 MPa. At this resistance, some roots were observed to have been able to penetrate further than others through burrows or voids between peds and were extending freely into deeper horizons particularly in subsoils where cultivation had not disturbed these channels. Such growth contributes to the broader range of rates found in these well-structured soils compared with structureless soils and contributes to variation in root length density with depth.

The results in Figs 1 and 2 suggest that at some point between Ω s of 3 and 4 MPa, most roots cease to grow or are growing so slowly as to add little to root function. Figure 3 shows the significant negative linear relationship between root growth rate and Ω for all Ω s less than 3 MPa. This suggests that root growth rates reduce from *c.* 20 mm/day in intensively-cultivated surface horizons to 2 mm/day at a Ω of 3 MPa.

Effect of compaction on crop growth and yield

In Expt 4, compaction at 0.1 m delayed emergence slightly, reduced the length of the mainstem, reduced

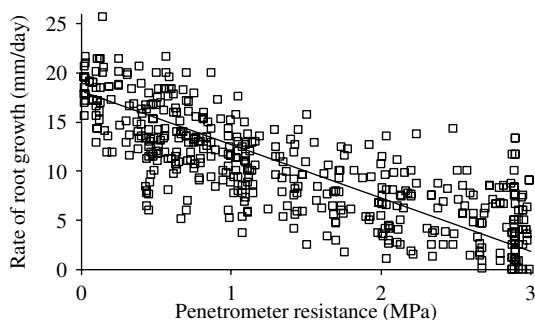


Fig. 3. Root growth rate in relation to penetrometer resistance (Ω) for all soils in Expts 1, 2 and 5 and Sites 1–6. Data restricted to resistance readings ≤ 3 MPa. Linear relationship: $y = 18.1 - 5.41x$, $R^2 = 0.62$.

initial rate of leaf appearance, leaf length and rooting depth compared with uncompacted soil and deeper compaction at 0.4 m (Table 4). Shallow compaction reduced rooting density in all horizons in both Expts 3 and 4 (Tables 5 and 6). This effect was particularly severe in the horizons between 0.1 and 0.4 m in Estima in Expt 3. Irrigation increased rooting density in uncompacted soils but sometimes reduced it in compacted soils. Deeper compaction had no effect on maximum depth of rooting in Expt 4 but slightly reduced rooting density. Compaction reduced root length in all horizons in Expt 2, particularly below 0.4 m (Fig. 4).

Compaction reduced early ground cover considerably in Expts 3 and 4 but only in Expt 3 did it restrict ground cover throughout the season (Figs 5 and 6). Irrigation had little effect on the reduction in both varieties. The effects of deep compaction in Expt 4 were much less severe than shallow compaction.

In both Expts 3 and 4 shallow compaction reduced number of tubers >10 mm, total and graded yields (Tables 7 and 8). The use of irrigation only increased yields in uncompacted soils in Expt 3, while in Expt 4 the effect of irrigation was much greater in uncompacted soils and those with deep compaction than where shallow compaction occurred.

Survey of compaction in commercial fields

The penetrometer survey of 602 commercial fields over the period 1992–2004 measured soil Ω soon after planting on a range of soil types throughout the UK. The Ω s were classified by limits equivalent to growth

Fig. 2. Root growth rate in relation to penetrometer resistance (Ω) in structured soils. (a) Expt 1, $y = 18.8 - 4.82x$, $R^2 = 0.69$; (b) Expt 2, $y = 10.7 - 2.18x$, $R^2 = 0.47$; (c) Site 2, $y = 16.0 - 3.67x$, $R^2 = 0.53$; (d) Site 3, $y = 17.2 - 5.07x$, $R^2 = 0.64$; (e) Site 4, $y = 14.9 - 3.84x$, $R^2 = 0.75$; (f) Site 6, $y = 18.7 - 7.89x$, $R^2 = 0.70$; (g) combined data from Expts 1 and 2 and Sites 2, 3, 4 and 6, $y = 16.3 - 4.08x$, $R^2 = 0.63$.

Table 4. *Effect of compaction depth on plant emergence, mainstem length, rate of leaf appearance, maximum size of leaf and maximum rooting depth in Expt 4. S.E. based on 22 D.F.*

Variable	Irrigation regime	Compaction treatment			
		Uncompacted	Compacted 0.1 m	Compacted 0.4 m	Compacted 0.1+0.4 m
Days from planting to emergence	Unirrigated	37	40	37	41
	Irrigated	37	40	36	40
Maximum length of mainstem (m)	Unirrigated	0.94	0.56	0.80	0.55
	Irrigated	0.92	0.64	0.85	0.62
Initial rate of leaf appearance (leaves/day)	Unirrigated	0.50	0.27	0.46	0.34
	Irrigated	0.60	0.48	0.52	0.41
Maximum length of 10th leaf (mm)	Unirrigated	220	140	150	150
	Irrigated	250	210	240	210
Maximum rooting depth (m)	Unirrigated	0.95	0.78	0.93	0.80
	Irrigated	0.96	0.76	0.93	0.51
	S.E.			0.065	
	S.E.			24.1	
	S.E.			0.056	

Table 5. *Effect of compaction and irrigation regime on root length density on 20 July (km/m³) in Expt 3*

Horizon (m)	Compaction treatment	Estima		Maris Piper		S.E. (12 D.F.)
		Unirrigated	Irrigated	Unirrigated	Irrigated	
0-0.1	Uncompacted	14.1	10.0	22.3	20.4	3.76
	Compacted	12.6	8.2	11.4	19.4	
0.1-0.2	Uncompacted	5.4	7.4	6.6	7.5	1.06
	Compacted	1.5	1.4	2.4	2.0	
0.2-0.3	Uncompacted	3.8	4.2	7.2	9.0	1.46
	Compacted	0.1	1.7	2.3	0.7	
0.3-0.4	Uncompacted	1.8	3.4	3.5	3.9	0.85
	Compacted	0.3	0.2	1.2	0.4	

rates of less than a quarter of maximal rates (<5 mm/day), half to quarter (10–5 mm/day), three quarters to half (15–10 mm/day) and full to three quarters (20–15 mm/day, derived from Fig. 3). Table 9 summarizes the results for each year, showing the average depth at which each resistance limit was exceeded and the proportion of fields with $\Omega_s \geq 3$ MPa in the profile. On average, two thirds of fields had soil $\Omega_s \geq 3$ MPa in the potential zone for root growth and in some years, notably 1992, relatively close to the soil surface. The increase in Ω with depth began at relatively shallow depths and a halving of root growth rate would have occurred at 0.42 m, on average, but at only 0.28 m in 1992.

These results suggest that for the majority of potato crops in the UK, rate (and ultimate depth) of rooting are restricted by soil conditions and many fields have Ω_s at depths which are likely to prevent further

root growth. Thus, rooting depth is likely to be much less than desirable, *c.* 1 m (Stalham & Allen 2001) and lead to inefficiencies in water and nutrient utilization.

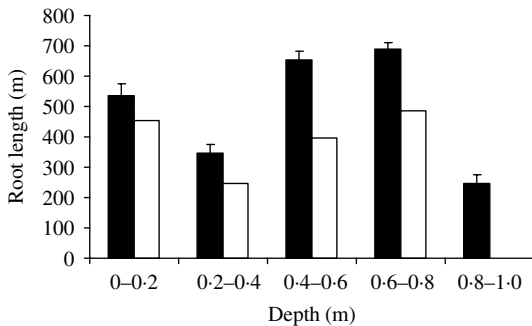
The widespread occurrence of such serious compaction was somewhat surprising and in parallel with further sampling post-planting, the effects of all operations in the cultivation and planting of the potato crop on soil resistance were evaluated. The main findings are summarized in the order of working.

Previous cropping

The majority of the soils examined had $\Omega_s \geq 3$ MPa at *c.* 0.6 m, thus confirming the survey results, but prior to any cultivation the upper horizons were frequently variable. A major contributor to this was the previous crop, particularly its harvesting, and Fig. 7

Table 6. Effect of compaction depth and irrigation regime on root length density (km/m^3) on 31 July in Expt 4

Horizon (m)	Irrigation regime	Uncompacted	Compacted 0.1 m	Compacted 0.4 m	Compacted 0.1+0.4 m	S.E. (22 D.F.)
0-0.2	Unirrigated	15.3	18.2	13.9	25.3	3.86
	Irrigated	11.0	11.6	10.6	27.1	
0.2-0.4	Unirrigated	9.5	3.3	8.7	4.1	3.10
	Irrigated	12.8	4.7	3.0	1.9	
0.4-0.6	Unirrigated	3.8	6.0	4.4	6.6	2.84
	Irrigated	3.0	0.7	4.0	0.5	
0.6-0.8	Unirrigated	5.2	0.3	2.6	0.1	2.12
	Irrigated	0.2	0.2	3.6	0.1	

Fig. 4. Root length 85 days after emergence in Expt 2. Uncompacted (\square); compacted (\blacksquare). Irrigated treatments only. S.E. based on 9 D.F.

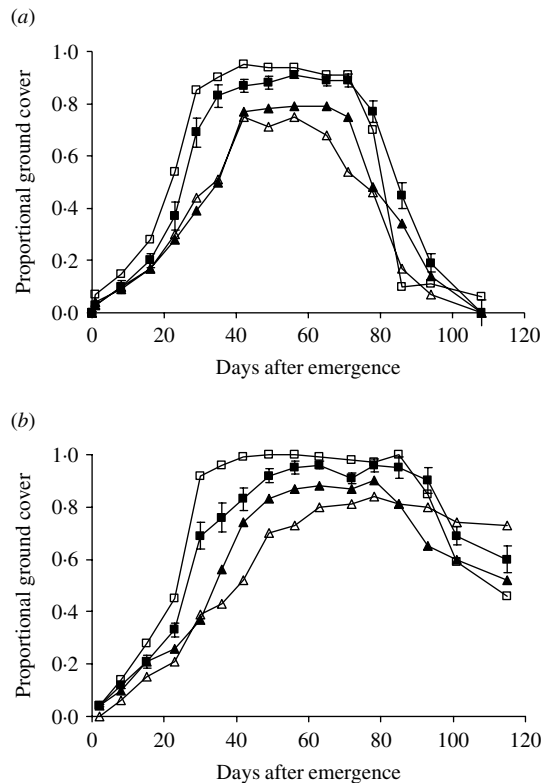
illustrates the effect of sugar beet and wheat in two halves of a large field of uniform sandy clay loam soil. Sugar beet harvesting had materially increased Ω in the upper horizons but below *c.* 0.5 m both subsoils were initially hard enough to minimize root penetration. Below *c.* 0.7 m, Ω began to decline.

Ploughing

This operation is carried out at various times from early autumn to spring and inevitably occurs at a wide range of soil water contents. If soils are at, or above, field capacity, smearing and compaction are to be expected. Figure 8 shows the effect of delaying ploughing over the winter period on a sandy loam soil. Ploughing in December in wet and non-drying conditions increased soil Ω at plough depth, 0.25-0.35 m, compared with earlier ploughing when the entire soil profile was dry (October) and where the top soil was dry (April).

Bed-forming

The creation of deep (0.40-0.60 m) beds as preparation for stone- and clod-separation has been a major change in cultivation techniques in the last

Fig. 5. Effect of soil compaction depth and irrigation regime on proportional ground cover in Expt 3. (a) Estima; (b) Maris Piper. Uncompacted, unirrigated (\blacksquare); uncompacted, irrigated (\square); compacted, unirrigated (\blacktriangle); compacted, irrigated (\triangle). S.E. based on 12 D.F.

25 years. There is little flexibility in timing for this operation, which, with the exception of a few areas of heavy soil, is carried out in spring. The likelihood of the soil being wet (close to or above field capacity) is, therefore, very high, especially at the operational depth of the shares. Figure 9 shows the serious

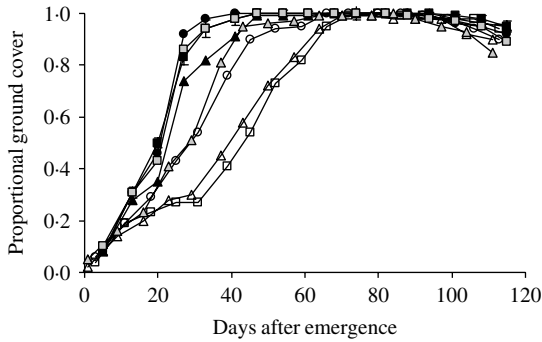


Fig. 6. Effect of soil compaction depth and irrigation regime on proportional ground cover in Expt 4. Unirrigated, uncompacted (■); unirrigated, 0-10 m (□); unirrigated, 0-40 m (▲); unirrigated, 0-10+0-40 m (△); irrigated, uncompacted (●); irrigated, 0-10 m (○); irrigated, 0-40 m (◻); irrigated, 0-10+0-40 m (◻). S.E. based on 22 D.F.

compaction at the base of the furrows, 0.30–0.45 m, created by bed-forming in wet conditions rather than earlier, drier conditions.

Bed-tilling

The cultivation of beds prior to stone separation is common practice and more than one pass is sometimes used. A number of tine designs are used in the powered rotary cultivators and Fig. 10 shows their effect on a clay loam soil. All tines increased soil Ω just below the planting depth and for L-shaped tines to a level at which root growth would be seriously slowed.

De-stoning

This operation is now almost universally used in preparing soil for potato planting and operates at a considerable depth (0.3–0.5 m) in the beds. It is, therefore, inevitable that the soil moisture content at the depth of working will be higher than at the soil surface. Consequently, there is a great risk of compacting the soil at the depth of the leading share, which will become closer to planting depth as a result of the operation. Figure 11 shows that de-stoning loosened the soil in the top 0.15 m of the finished ridge but increased Ω at 0.20 m compared with bed-tilling alone. Increasing the working depth of de-stoners can increase the depth of seedbed without creating compaction but ultimately a severe increase in soil Ω occurs (Fig. 12). In this case, seedbed depth was only increased by *c.* 0.10 m by working the separator 0.23 m deeper and a large increase in soil Ω was created at 0.30 m, which extended for a further 0.10 m. The deepest working depth created more clods, which were placed in the wheelings, leaving an uneven bed for planting.

Soil water content and timing of operation

Figure 13 shows the effect of delaying a re-start to planting after rainfall on a fine sandy loam soil. An attempt to continue was made the next day and produced serious increases in soil Ω from 0.15 to 0.45 m which were completely avoided by waiting a further 3 days for the soil to dry.

Practices aimed at removing compaction

Subsoiling is frequently practised in an attempt to disturb compacted layers and create lower and less changeable soil Ω s in the profile. It can be carried out in the previous crop prior to any specific operation for potatoes, conducted within the planting cultivations or it can be attempted post-planting if respecting the row arrangement of the plants. Figure 14 presents the results of subsoiling in autumn and spring on a clay loam soil which had a serious compacted layer at 0.5 m following cereals. In the autumn, when the soil was dry, subsoiling removed the compacted layer and reduced Ω s from ≥ 3 MPa to < 2 MPa across the width of the bed. In the spring, the same operation did not remove the compaction beneath the rows nor appreciably change Ω in the 0.4–0.5 m horizon as the soil at this depth was above its plastic limit when subsoiled. The Ω s in the upper horizons were reduced as the soil was drier at the time of subsoiling.

Subsoiling carried out post-planting is aimed at removing compaction created during the cultivation and planting operation, often within wheelings, and has to be restricted to tines running along the furrows. Figure 15 shows the results of post-planting subsoiling in a sandy soil at 0.55 m using tines positioned in the centre furrow of a pair of ridges within a bed and another in the wheeling between beds. In the centre of the bed, subsoiling removed compaction below 0.45 m both above the depth of compaction and, importantly, some 0.20 m below the depth of the tine as a consequence of the ‘unloading’ of the soil deep in the profile. However, ‘unloading’ suggests that soils recover from high to low density due to relief in compaction below the depth of cultivation which can occur in sands to a limited degree. More probably, the apparent improvement is caused by a change in the datum reference point owing to a rise in the bed surface or some loss in friction on the penetrometer shaft. Underneath the wheeling, similar effects from 0.45 m down to 0.75 m were found and compaction was also reduced slightly above 0.45 m as a consequence of the movement of the subsoiler through the soil.

DISCUSSION

Unless roots are growing entirely within voids or continuous cracks in the soil, they must exert forces on soil particles to displace them. The mechanical

Table 7. Effect of soil compaction depth and irrigation regime on tuber total yield (t/ha) on 22 September in Expt 3

Compaction treatment	Variety/irrigation regime			
	Estima		Maris Piper	
	Unirrigated	Irrigated	Unirrigated	Irrigated
Uncompacted	37.1	44.9	40.5	53.6
Compacted	27.1	25.2	33.2	32.6
S.E. (12 D.F.)			2.58	

Table 8. Effect of soil compaction depth and irrigation regime on (a) tuber total yield (t/ha) and (b) number of tubers (000/ha) on 1 October in Expt 4

Irrigation regime	Compaction treatment			
	Uncompacted	Compacted 0.1 m	Compacted 0.4 m	Compacted 0.1 + 0.4 m
(a) Yield				
Unirrigated	73.8	46.4	65.3	47.3
Irrigated	87.9	59.4	79.0	56.5
S.E. (22 D.F.)			5.61	
(b) Number of tubers				
Unirrigated	813	685	715	591
Irrigated	676	591	699	611
S.E. (22 D.F.)			43.0	

Table 9. Survey of 602 commercial fields during 1992–2004 showing depths (mm) where soil resistance (Ω) exceeded the threshold for each root growth rate class and the proportion of fields with resistances ≥ 3.0 MPa. Depths relative to top of planted ridge

Year	No. of fields	Growth rate class (mm/day)				Proportion of fields with resistances ≥ 3.0 MPa
		Upper limit of resistance for class (MPa) in parentheses				
		20–15 (0.57)	15–10 (1.50)	10–5 (2.43)	< 5 (3.00)	
1992	34	16	28	40	43	0.75
1993	36	12	42	49	53	0.77
1994	37	14	41	47	53	0.61
1995	49	35	47	52	60	0.76
1996	123	29	45	51	58	0.55
1997	96	32	44	50	55	0.74
1998	43	16	42	52	61	0.79
1999	44	26	45	55	53	0.65
2000	47	32	45	48	50	0.85
2001	37	26	33	40	47	0.57
2002	30	25	41	51	56	0.65
2003	0	–	–	–	–	–
2004	26	26	44	55	61	0.62
Mean		25	42	49	55	0.65

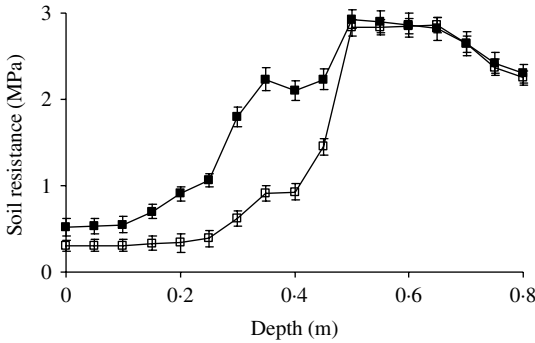


Fig. 7. Effect of previous cropping on soil resistance (Ω) prior to spring cultivation on a sandy clay loam soil. Sugar beet (■); winter wheat (□).

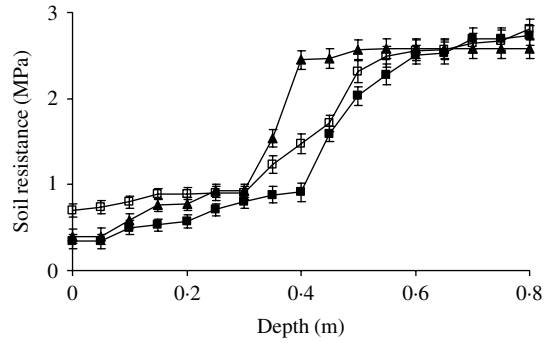


Fig. 9. Soil resistance (Ω) in a clay soil in April 1994 following bed-forming at three different times. Bed-formed in late September 1993 (dry) (■); late October 1993 (wet) (□); April 1994 (wet) (▲). Depths relative to top of bed.

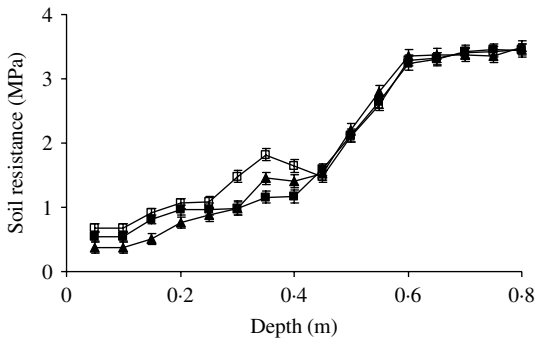


Fig. 8. Effect of time of ploughing on soil resistance (Ω) in a sandy loam soil. October (■); December (□); April (▲). Depths relative to ploughed surface.

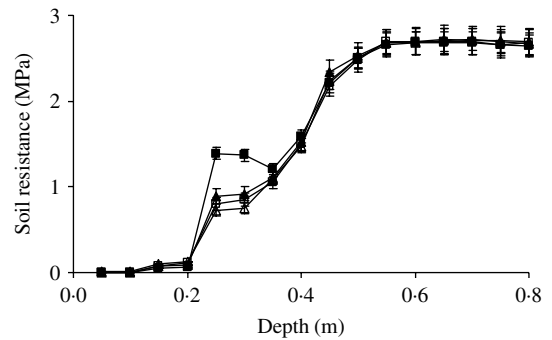


Fig. 10. Soil resistance (Ω) following the use of three different types of bed-tiller working on a clay loam soil compared with zero bed-tilling. L-shaped blade (■); straight rod-type tines (□); 'pick' tines (▲); no bed-tilling, de-stoned only (△). Depths relative to top of planted ridge.

resistance (Ω) to root growth is the reaction pressure of the soil and this will increase as the strength of the soil increases as it dries or its bulk density is increased by compaction. Direct measurement of the forces exerted by roots is difficult but accurate measurement of soil Ω can be obtained by use of a cone penetrometer. Such instruments do not act exactly as roots do and a number of reports show that resistance to them may be several times greater than the pressure exerted by root tips in penetrating soil (Eavis 1967; Stolzy & Barley 1968; Whiteley *et al.* 1981; Misra *et al.* 1986; Bengough & Mullins 1988). However, roots, unlike penetrometer probes, are flexible and by exploiting planes of weakness can grow in soil horizons that have Ω s greater than the maximum axial pressures which they can exert. In addition, the progress of individual roots is frequently aided by the secretion of mucilage lubricants and the shedding of root cap cells (Bengough & McKenzie 1997). Soil Ω readings taken with a penetrometer must, therefore, be interpreted with caution but do allow study of the relationship between root penetration and soil Ω .

The results demonstrate the effects of increasing soil Ω on root growth, which have great significance for potato production as they will affect water and nutrient uptake and thereby yield. The relationships between rate of root growth and soil Ω on different soils were close and some of the reasons for variation have been considered already. There is one other major reason why no close unique relationship across soil types might exist between instantaneous root elongation rate and Ω . When roots grow through hard soil into looser soil, their elongation rates do not immediately increase to that of roots grown entirely in loose soil (Bengough & Young 1993). Instead, the elongation rate remains slower for several days before eventually increasing. Boone *et al.* (1978) observed compensatory increases in root growth of potatoes once a plough pan had been crossed, although root growth had been slowed within the pan. There were only three soils in Figs 7–15 that had a high Ω

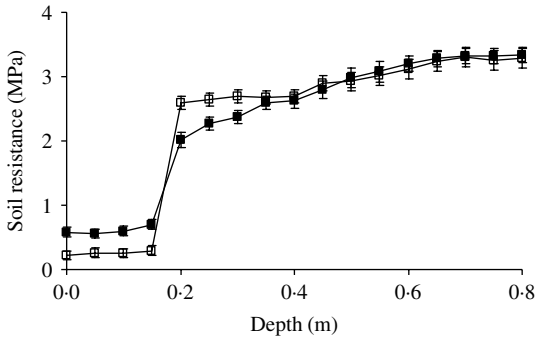


Fig. 11. Soil resistance (Ω) in bed-tilled beds pre- and post-de-stoning in a sandy loam. Beds (■); de-stoned beds (□). Depths relative to top of planted ridge.

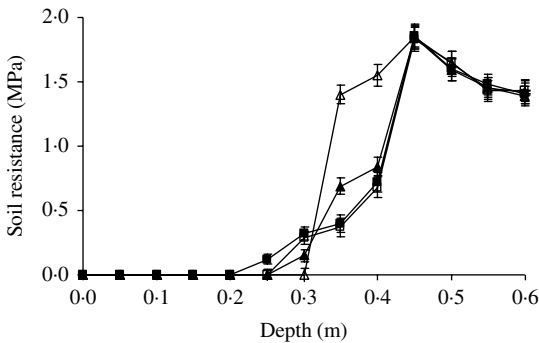


Fig. 12. Effect of de-stoning depth on soil resistance (Ω) in beds prior to planting. 0.20 m (■), 0.25 m (□), 0.31 m (▲), 0.43 m (△) below top of bed-tilled bed. Depths relative to top of de-stoned bed.

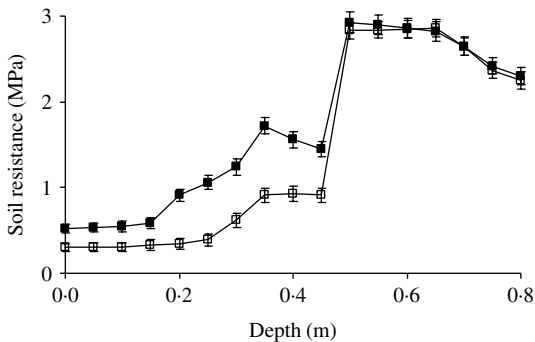


Fig. 13. Effect of delay in planting after rainfall on soil resistance (Ω) post planting in a sandy loam soil. 1-day delay (■); 4-day delay (□). Depths relative to top of ridge.

horizon with lower Ω s above and below and in two of these soils the area of highest Ω was deep (0.65 m). Overall, the results show crops rooting freely near the

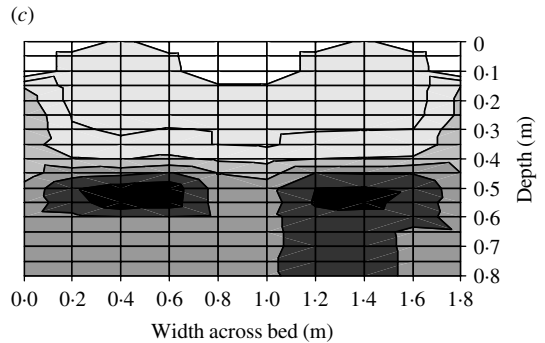
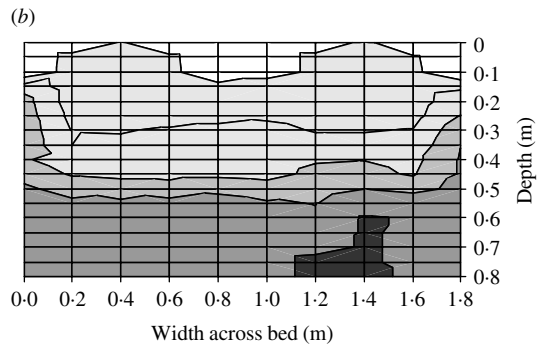
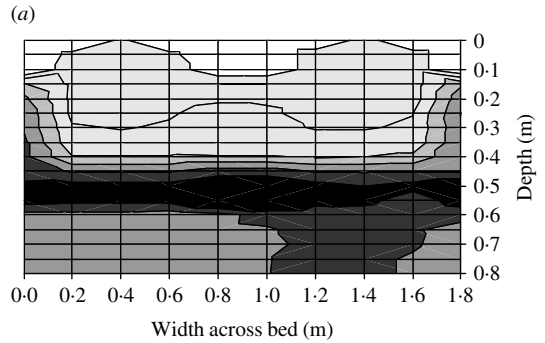


Fig. 14. Profile soil resistance (MPa) in a clay loam following planting. (a) unsubsoiled; (b) subsoiled dry (September); (c) subsoiled wet (April). 0.1–1.5 (□); 1.5–2.0 (□); 2.0–2.5 (■); 2.5–3.0 (■); 3.0–3.5 (■). Depths relative to planted ridges.

soil surfaces at Ω s < 1 MPa and reducing with depth until rates were low or zero at resistances \geq 3 MPa. This agrees with the limited published literature on potatoes (Bishop & Grimes 1978; Boone *et al.* 1978; Heap 1993; Heap *et al.* 2001) and other crops (Vepraskas 1988; Loboski *et al.* 1998).

The survey of commercial fields revealed a remarkably high frequency of serious soil Ω s (> 2 MPa) at relatively shallow depths. A substantial majority of soils in all seasons had soil Ω s \geq 3 MPa (i.e. where most root growth would cease) within the

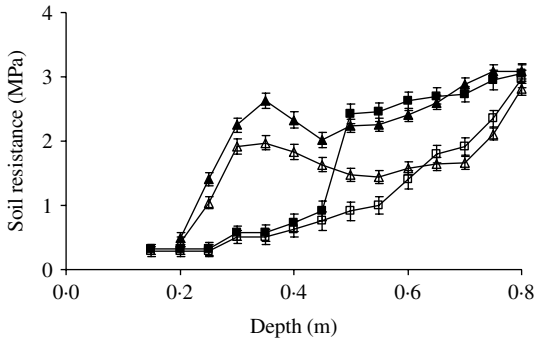


Fig. 15. Effect of post-planting subsoiling in wheeled and centre furrows of beds on soil resistance (Ω) in a sand soil. Centre furrow, not subsoiled (■); centre furrow, subsoiled (□); wheeled furrow, not subsoiled (▲); wheeled furrow, subsoiled (△). Depths relative to top of planted ridge.

expected rooting range of the crop. On these soils, crops would have shallower roots than desirable and therefore restricted access to water and nutrients. The effect of increasing soil Ω is most severe close to the seed tuber as this depth should have relatively rapid rates of root growth and within a fixed period of root growth (Stalham & Allen 2001) any loss of penetration cannot be subsequently recovered. In a small number of fields, only the top 0.12–0.16 m of the ridge had sufficiently loose soil to produce maximal growth rates (15–20 mm/day). In such fields, the rate of growth of roots would be restricted as soon as they were produced below the seed tuber by the resistance of the soil.

It might be expected that the seasons where shallow compaction was more evident would have had difficult planting periods with substantial rain events or more prolonged rainfall making the soils wetter than suitable for cultivation. However, it is difficult to generalize about the relationship between the incidence of compaction and rainfall at planting owing to variation in patterns of rainfall and planting date in the different production areas of the UK that were sampled. Whilst the British Potato Council estimates that on average three quarters of the UK's potato area is planted between 24 March and 11 May (R. Burrow, personal communication), the early areas of Cornwall and Pembrokeshire could be planting 2 months earlier, whereas the frost risk to crops planted in north Cambridgeshire or Lincolnshire combined with the high soil water-holding capacities means that crops are often planted well into May in many years. Late planting also often occurs in northern England and much of Scotland. Nevertheless, there were obvious differences in Ω between wet and dry planting seasons. For example, 1993, 1994 and 1998 were wet springs across much of the UK and compaction was observed in many fields at shallow depths, with

typically only 0.12–0.16 m of loose soil being available for maximal root growth rates (Table 9). Additionally, these three seasons had a very high proportion of fields with Ω s \geq 3 MPa (Table 9) within the rooting zone. In contrast, generally dry springs across all surveyed areas such as 1995 and 1996 resulted in a much deeper (0.29–0.32 m) loose profile in the ridge or bed. In some dry springs, such as 1996, there were fewer fields with totally restrictive rooting depth ($\Omega >$ 3 MPa), mainly as a consequence of a preceding dry autumn and winter period. However, in 1995 there were many fields observed to have restricted rooting profiles at depth as subsoils were much wetter in spring following a wet autumn which restricted subsoiling or the benefits from deep cultivation. In spring 2000, which was generally wet across all the regions surveyed, the substantial rainfall total for April occurred within short periods at the beginning, middle and end of the month, with 2 weeks of drying in between. This allowed cultivation to take place under optimum conditions, providing sufficient time was left after each rainfall event. Superficial drying meant that seedbeds were often compaction free to considerable depth (e.g. $>$ 0.3 m) but severe compaction ($>$ 3 MPa) was more widespread and occurred at shallower depths in 2000 than in any other season despite autumn and winter 1999 being substantially drier than average.

The significance of these effects for crop growth can be illustrated by their effects on water availability and thereby the need for irrigation. If the rate of growth of roots is reduced by increased soil Ω , the slower growth rate will reduce root zone depth whilst elongation continues but may not significantly decrease maximum rooting depth if the effect is temporary, i.e. a thin pan exists which slows growth but does not reduce root growth once the root tips have passed it. However, all temporary effects on root growth rates will reduce the amount of soil water available to the crop and thereby increase its likely need for irrigation as the limiting SMD will be reduced. The scale of the effect on crop growth will be determined by the evaporative demand placed on the crop (Stalham & Allen 2004, 2005). The potential effects on root penetration have been quantified using the growth rates in Fig. 2g for the resistances shown in Figs 9 and 13. In the first example, bed-forming in September produced a 0.1 m increase in maximum rooting depth compared with the same operation carried out in April, resulting in a considerably increased limiting SMD (Table 10). In the second example, delaying planting also resulted in increased maximum depth of rooting and increased limiting SMD (Table 11).

Once root penetration has ceased, differences in maximum rooting will affect irrigation need and efficiency of water used. If rooting depth is recorded, then shallower-rooted crops will simply require more frequent, smaller applications than deeper-rooted

Table 10. Effect of date of bed-forming on maximum rooting depth and limiting SMD at differing daily ET_0 rate. Data calculated from resistance measurements presented in Fig. 9

	Date of bed-forming		
	September	October	April
Maximum rooting depth (m)	0.70	0.67	0.61
Easily available water (<200 kPa, mm)	70.5	67.3	61.1
Limiting SMD at 3 mm/day ET_0 (mm)	56.5	53.9	48.9
Limiting SMD at 4 mm/day ET_0 (mm)	45.0	42.9	38.9
Limiting SMD at 5 mm/day ET_0 (mm)	36.2	34.5	31.3

Table 11. Effect of delaying planting following rainfall on maximum rooting depth and limiting SMD at differing daily ET_0 rate. Data calculated from resistance measurements presented in Fig. 13

	Delay in planting after rainfall	
	1 day	4 days
Maximum rooting depth (m)	0.60	0.63
Easily available water (<200 kPa, mm)	84.0	88.9
Limiting SMD at 3 mm/day ET_0 (mm)	51.3	54.0
Limiting SMD at 4 mm/day ET_0 (mm)	40.9	43.5
Limiting SMD at 5 mm/day ET_0 (mm)	32.9	35.6

ones and in the first example would amount to one or two additional applications per annum. If rooting depth is not recorded in the scheduling process and the assumed depth is for uncompacted soil, then irrigation will be delayed beyond the effective limiting SMD and the crop will suffer a restriction in growth. Such effects on water availability and crop productivity will also occur during root penetration but within a short timeframe and are unlikely to be detected by observation or conventional systems. As the causes of these effects are the result of only small shifts in commercial practices, they represent a sample of the variation in soil conditions found in current potato crops. The examples chosen are by no means extreme: where Ω s increase significantly at shallower depths (<0.3 m) then the effective water supply is reduced by a third. It is, therefore, difficult to escape the conclusion that variation in soil conditions is a major contribution to lost yield potential in potato crops (Allen *et al.* 2005). This effect is, as yet, largely unrecognized by growers and being the consequence, in large part, of the almost universal adoption of a system of production, it will be relatively slow to change.

The use of powered cultivators in beds ultimately separated of stones and clods is now almost universally adopted in the UK but not in many other countries, notably the USA. The system is expensive of time and energy but produces fine soil aggregates to planting depth with serious risks of compaction deeper in the profile. As Stalham *et al.* (2005) showed, all components of the system can cause serious compaction and the risks are exacerbated where cultivations are attempted in late February and March. These risks are the result of growers seeking to maximize the area covered by their machines and

operating over as long a period as possible. They will only be removed if growers appreciate the significance of compaction and exercise greater patience in organizing their planting schedule. For some soils, a review of the justification for all operations in preparing soils is overdue. There is evidence that delaying planting of maincrop varieties from early March to mid-April does not jeopardize yield (Jones 1981) unless the variety is very indeterminate, e.g. Maris Piper or Cara. Soil temperatures in March and early April are often too cold for sprout growth to occur except for short periods of the day, so early planting (e.g. 1 March) often leads to emergence taking 9–10 weeks rather than 4–5 weeks from mid-April plantings, effectively gaining little more than a week in emergence compared with planting 6 weeks later. Such early planting may lead to restricted leaf canopies especially in determinate varieties, e.g. Estima, Lady Rosetta. Consequently, such early planting may restrict yields. In recognition of these risks, there is a move by larger growers towards operating for 24 h per day, providing scope to delay planting until soil conditions become more favourable without undue delay in average planting date.

In Expt 4, emergence was delayed by shallow compaction where planting depth was the same for all treatments. In practice, the effect will be more serious as the uneven planting depth in compacted or cloddy seedbeds is always a contributory factor in lengthening the period of emergence. Compaction or capped ridges also cause stems to thicken or become fasciated (split), which can worsen into coiled sprout or little potato disorder, thereby delaying or even preventing emergence. These effects on emergence ultimately impact on many aspects of crop uniformity and quality, such as tuber size, shape and freedom from common scab and growth defects (e.g. Van Loon & Bouma 1978). Compaction also slowed the rate of leaf appearance and expansion leading to a later

achievement of full ground cover or a reduced peak ground cover (or both) and advanced the onset or rate of senescence. As a consequence of these effects on leaf growth, tuber yields were reduced.

The effects of compaction on water use have implications for nutrient uptake, especially nitrogen, and thereby the extent and duration of canopy growth. Many growers respond to problems of compaction by top-dressing nitrogen and increasing the amount of irrigation applied. The results of Expts 3 and 4 at CUF show that irrigation cannot eliminate the effects of compaction and, as in Maris Piper in Expt 3, may actually increase their severity. In Expt 3, irrigation failed to increase the maximum ground cover attained in either variety grown in compacted soil and in Maris Piper irrigation severely reduced maximum ground cover and delayed its attainment. This may have been a consequence of waterlogging when large doses of irrigation were applied to soil with impeded drainage. By contrast, in Expt 4, small regular doses of irrigation increased the rate of increase in ground cover in crops growing in shallow-compacted soil but did not eliminate the detrimental effects of compaction completely. In both experiments it would appear that nitrogen uptake was reduced by compaction. The overall effects of the reduced size and longevity of the leaf canopy significantly decreased the yield of crops grown in compacted soil owing to a reduction in absorbed radiation. Van Loon & Bouma (1978) and Young *et al.* (1993) also suggested that yield decreases due to compaction were attributable principally to a reduction in leaf area and light absorption.

In view of the clear effects of compaction on growth and yield, it is surprising that the results of experiments on subsoiling are so variable (Stalham *et al.* 2005). In their thorough review of results relating to potatoes, they found only 28 experiments out of 83 showed a significant yield increase as a consequence of subsoiling or reducing traffic, with three experiments showing a significantly reduced yield. In the situations where there was a significant increase in yield from subsoiling (>0.3 m depth as opposed to shallow-tillage or zero traffic experiments), the benefits were small, averaging 5 t/ha, and achieved from pre-planting subsoiling rather than post-planting. Compared with the large significant effects of compaction on yield, these differences are small. In the experiments in which cultivation was carried out below 0.3 m (i.e. subsoil depth), most authors did not

establish that compaction was present prior to cultivation and the reader is left to assume that it was. Many reports fail to detail tractor tyre pressures and wheel loadings, the combined effect of which influences the degree and depth of compaction. Only a third of authors (Ross 1986; Marks & Soane 1987; Ibrahim & Miller 1989; O'Sullivan 1992; Pierce & Burpee 1995) stated that compaction was present prior to subsoiling treatments and most supported these statements by presenting data relating to soil Ω or bulk density. Researchers who stated that they had a compaction problem usually observed a decrease in soil Ω following subsoiling and three quarters of those authors found a yield increase in response to subsoiling. As information on soil conditions during subsoiling, subsequent weather (especially rainfall) and the details of tine depth in relation to soil conditions are frequently lacking, it is less surprising that the effects of subsoiling appear to be small. Unless subsoiling breaks a compacted layer, there is no intrinsic merit in the operation and growers and researchers need to be more effective in relating their cultivations to soil conditions. As Fig. 14 shows, subsoiling in dry conditions is an effective way of reducing soil Ω and leads to improvements in yield and quality.

There is an urgent need for a better understanding of the relationship between root function (i.e. growth and uptake ability) and soil conditions so that more accurate advice can be given to growers to optimize their cultivations. This will reduce over-cultivation with its attendant problems, such as slumping of the ridge, as well as compaction. Since there is a relatively defined sequence in most current UK potato planting operations, there is, unfortunately, considerable opportunity for 'recreational' cultivation, i.e. for a machine to be used purely because it is in the field along with its operator. All cultivations need to be given more consideration by growers in order to improve the energy and labour efficiency of planting.

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REFERENCES

- ALLEN, R. G., PEREIRA, L. S., RAES, D. & SMITH, M. (1998). Crop evapotranspiration – guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper* 56. FAO, Rome.
- ALLEN, E. J., ALLISON, M. F. & SPARKES, D. L. (2005). Physiological and technological limits to yield improvement of potatoes. In *Yields of Farmed Species: Constraints and Opportunities in the 21st Century* (Eds

- R. Sylvester-Bradley & J. Wiseman), pp. 289–309. Nottingham University Press.
- BENGOUGH, A. G. & MCKENZIE, B. M. (1997). Sloughing of root cap cells decreases the frictional resistance to maize (*Zea mays* L.) root growth. *Journal of Experimental Botany* **48**, 885–893.
- BENGOUGH, A. G. & MULLINS, C. E. (1988). Use of a low-friction penetrometer to estimate soil resistance to root growth. *Proceedings of the 11th Conference of the International Soil Tillage Research Organisation* **1**, 1–6.
- BENGOUGH, A. G. & YOUNG, I. M. (1993). Root elongation of seedling peas through layered soil of different penetration resistances. *Plant and Soil* **149**, 129–139.
- BISHOP, J. C. & GRIMES, D. W. (1978). Precision tillage effects on potato root and tuber production. *American Potato Journal* **55**, 65–71.
- BOONE, F. R., BOUMA, J. & DE SMET, L. A. H. (1978). A case study on the effect of soil compaction on potato growth in a loamy sand soil. I. Physical measurements and rooting patterns. *Netherlands Journal of Agricultural Science* **26**, 405–420.
- BURSTALL, L. & HARRIS, P. M. (1983). The estimation of percentage light interception from leaf area index and percentage ground cover in potatoes. *Journal of Agricultural Science, Cambridge* **100**, 241–244.
- EAVIS, B. W. (1967). Mechanical impedance to root growth. *Agricultural Engineering Symposium, Silsoe*, Paper 4/F/39, pp. 1–11.
- EHLERS, W., KÖPKE, U., HESSE, F. & BÖHM, W. (1983). Penetration resistance and root growth of oats in tilled and untilled loess soil. *Soil and Tillage Research* **3**, 261–275.
- FEDDES, R. A., DE GRAFF, M., BOUMA, J. & VAN LOON, C. D. (1988). Simulation of water use and production of potatoes as affected by soil compaction. *Potato Research* **31**, 225–239.
- GOODERHAM, P. T. (1973). *Soil physical conditions and plant growth*. PhD thesis, University of Reading.
- GREGORY, P. J., MCGOWAN, M., BISCOE, P. V. & HUNTER, B. (1978). Water relations of winter wheat. 1. Growth of the root system. *Journal of Agricultural Science, Cambridge* **91**, 91–102.
- HEAP, M. A. (1993). Russets on the beach. *Proceedings of the 7th National Potato Research Workshop, Ulverstone, Tasmania, Australia, 1993*, pp. 148–152.
- HEAP, M., MCPHARLIN, I. & STEVENS, R. (2001). Russets on the beach – revisited. Available online at http://www.sardi.sa.gov.au:82/pages/horticulture/pathology/hort_pn_russetsbeach.htm (verified 3/1/07).
- IBRAHIM, B. A. & MILLER, D. E. (1989). Effect of subsoiling on yield and quality of corn and potato at two irrigation frequencies. *Soil Science Society of America Journal* **53**, 247–251.
- JONES, J. L. (1981). *Effect of date of planting on contrasting potato varieties*. PhD thesis, University of Wales, Aberystwyth.
- LOBOSKI, C. A. M., DOWDY, R. H., ALLMARAS, R. R. & LAMB, J. A. (1998). Soil strength and water content influences on corn root distribution in a sandy soil. *Plant and Soil* **203**, 239–247.
- MARKS, M. J. & SOANE, G. C. (1987). Crop and soil response to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management on a range of soil types. Part 1: response of arable crops. *Soil Use and Management* **3**, 115–123.
- MARSH, B. A'B. (1971). Measurement of length in random arrangements of lines. *Journal of Applied Ecology* **8**, 265–267.
- MISRA, R. K., DEXTER, A. R. & ALSTON, A. M. (1986). Penetration of soil aggregates of finite size. II. Plant roots. *Plant and Soil* **94**, 59–85.
- NEWMAN, E. I. (1966). A method of estimating the total length of root in a sample. *Journal of Applied Ecology* **3**, 139–145.
- O'SULLIVAN, M. F. (1992). Deep loosening of clay loam subsoil in a moist climate and some effects of traffic management. *Soil Use and Management* **8**, 60–67.
- PAYNE, R. W., BAIRD, D. B., CHERRY, M., GILMOUR, A. R., HARDING, S. A., KANE, A. F., LANE, P. W., MURRAY, D. A., SOUTAR, D. M., THOMPSON, R., TODD, A. D., TUNNICLIFFE WILSON, G., WEBSTER, R. & WELHAM, S. J. (2002). *Genstat™ Release 6.1 Reference Manual*. Oxford: Clarendon Press.
- PIERCE, F. J. & BURPEE, G. C. (1995). Zone tillage effects on soil properties and yield and quality of potatoes (*Solanum tuberosum* L.). *Soil and Tillage Research* **35**, 135–146.
- ROSS, C. W. (1986). The effect of subsoiling and irrigation on potato production. *Soil and Tillage Research* **7**, 315–325.
- STALHAM, M. A. & ALLEN, E. J. (2001). Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (*Solanum tuberosum*) crop. *Journal of Agricultural Science, Cambridge* **137**, 251–270.
- STALHAM, M. A. & ALLEN, E. J. (2004). Water uptake in the potato (*Solanum tuberosum*) crop. *Journal of Agricultural Science, Cambridge* **142**, 1–21.
- STALHAM, M. A. & ALLEN, E. J. (2005). Effect of varying evaporative demand on the relationship between actual and potential evapotranspiration at different soil moisture deficits in potato (*Solanum tuberosum*) crops. *Aspects of Applied Biology* **76**, 151–159.
- STALHAM, M. A., ALLEN, E. J. & HERRY, F. X. (2005). *A Review of the Effect of Soil Compaction on Potato Growth and its Alteration with Cultivation*. Research Review Ref. R261. Oxford: British Potato Council.
- STOLZY, L. H. & BARLEY, K. P. (1968). Mechanical resistance encountered by roots entering compact soils. *Soil Science* **105**, 297–301.
- TENNANT, D. (1975). A test of a modified line-intersect method of estimating root length. *Journal of Ecology* **63**, 995–1001.
- TIMM, H. & FLOCKER, W. J. (1966). Responses of potato plants to fertilization and soil moisture tension under induced soil compaction. *Agronomy Journal* **58**, 153–157.
- VAN LOON, C. D. & BOUMA, J. (1978). A case study on the effect of soil compaction on potato growth in a loamy sand soil. 2. Potato plant responses. *Netherlands Journal of Agricultural Science* **26**, 421–429.
- VAN LOON, C. D., DE SMET, L. A. H. & BOONE, F. R. (1985). The effect of a ploughpan in marine loam soils on potato growth. 2. Potato plant responses. *Potato Research* **28**, 315–330.
- VEPRASKAS, M. J. (1988). Bulk density values diagnostic of restricted root growth in coarse-textured soils. *Soil Science Society of America Journal* **52**, 1117–1121.

- VEPRASKAS, M. J. & MINER, G. S. (1986). Effects of subsoiling and mechanical impedance on tobacco root growth. *Soil Science Society of America Journal* **50**, 423–427.
- WHITELEY, G. M., UTOMO, W. H. & DEXTER, A. R. (1981). A comparison of penetrometer pressures and the pressures exerted by roots. *Plant and Soil* **61**, 351–364.
- YOUNG, I. M., BENGOUGH, A. G., MACKENZIE, J. W. & DICKSON, J. W. (1993). Differences in potato development (*Solanum tuberosum* cv. Maris Piper) in zero and conventional traffic treatments are related to soil physical conditions and radiation interception. *Soil and Tillage Research* **26**, 341–359.