Research Review

Effects of soil compaction on potato growth and its removal by cultivation

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M A Stalham, E J Allen, F X Herry *CUF*

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Abstract

Soil compaction, as a consequence of increased soil strength or resistance, restricts the rate of downward extension of roots and their lateral movement within compacted pans, which reduces the potential uptake of nutrients and water. Potatoes are very sensitive to compaction at all stages of growth from emergence to harvest but particularly in the first 3-4 weeks after emergence when growth rates of roots are most rapid in loose soil, typically 1.5-2 cm/day. Shallow compaction immediately below the seed piece is therefore more damaging than deeper compaction since it is encountered when roots are growing most rapidly and impeding them at this stage can have serious repercussions on later growth. Symptoms of compaction that growers can recognize include: delayed and uneven emergence; slow, incomplete and curtailed ground cover development; premature or rapid senescence; wilting of leaves on hot days even in wet soils; chlorotic or conversely dark green foliage owing to impaired nutrient or water uptake; severely reduced yield; increased outgrades from misshapen, bruised or green tubers.

Compaction is frequently caused by working soil when it is at, or above, its plastic limit. Soil then shears by compressive rather than brittle failure leading to a smeared profile at the cultivation depth. Across all agriculture, there is a trend for the use of increasingly heavy machinery and often powered cultivation implements which are capable of carrying out work on soil that was once deemed too wet for working. This, in conjunction with the quest to plant increasingly large areas of potatoes in a shorter time, has increased the probability that operations will be carried out on soils that are too wet and therefore liable to compaction. Earlier planting increases the chances of operations being carried out in conditions where compaction is likely to occur. Growers therefore have to balance the advantages of planting early to establish early canopy cover with the disadvantages of compacting the soil which will considerably reduce canopy expansion and subsequent yield. The effects of compaction will persist throughout the season and, once created, are almost impossible to remove completely in the growing crop.

Unpublished data from measurements and experiments conducted by Cambridge University Farm in commercial potato fields showed that the downward extension of the rooting front could be predicted by measurements of soil resistance using a cone penetrometer. Growth rates were rapid when resistance was low (< 1 MPa) but slowed to half their maximal rate at resistances of *c*. 1.5 MPa and one-quarter rate at *c*. 2.4 MPa. Root growth was very slow at resistances of *c*. 3-3.5 MPa in most soils, although roots continued to extend deeper into well-structured subsoils using natural fissures and burrows. In structureless sands, there was a more rapid decrease in growth rate with increasing resistance: growth rates were reduced to half at a resistance of only 1 MPa and to a quarter at 1.8 MPa.

A survey of 602 commercial fields between 1992 and 2004 revealed that two-thirds of fields had resistances ≥ 3 MPa, the upper limit for root growth, in some part of the potential rooting profile. In 50 % of fields, this limiting resistance was encountered at *c*. 55 cm below the top of the ridge, or *c*. 45 cm below the surface of a flat profile. On average, resistances which reduce root growth rates to one-half or one-quarter of their maximum were encountered at 42 and 49 cm, respectively, below the tops of planted ridges. Thus, the survey data showed that most potato fields have moderate to severe restrictions to root growth after planting, leading to inevitable restrictions on the use of available resources, e.g. water and nutrients. Applying

irrigation, or increasing the frequency and reducing the amount of irrigation, was shown to reduce the effects of compaction but did not remove them completely. In some cases, irrigation of compacted soil even with moderate doses of water leads to severe waterlogging and poor crop growth. In sloping fields, run off from compacted soil into low-lying areas is often a problem and poor infiltration of water into compacted ridges or beds leads to over-application of irrigation during common scab control.

The literature revealed 16 experiments where potatoes were grown in artificially compacted soil (*c.f.* loose soil), of which 13 showed a significant yield decrease owing to compaction. Some of the differences in yield between compacted and uncompacted soil were massive (25-38 t/ha) but 18 t/ha on average with a mean yield of 54 t/ha in the absence of compaction. In contrast, a review of published yield responses to subsoiling in potatoes showed that only 28 experiments out of 83 had a significant yield increase in response to subsoiling, with three experiments showing a significantly reduced yield. Many of these experiments measured a significant decrease in soil resistance or strength as a consequence of the subsoiling operation but the effects on yield were often small (e.g. 5 t/ha) or not significant. The average yields in these experiments were lower (*c*. 42 t/ha) than in the compaction experiments possibly indicating that some factor other than soil conditions was reducing yields. Some researchers have failed to quantify the extent of any compaction in their experiments prior to imposing their cultivation treatments and the reader is left to assume that the soil was compacted before any treatments were carried out. This point is crucial, since subsoiling uncompacted soil is likely to have little benefit.

Clearly, compaction can have severe consequences on potato yield and quality but the effect of subsoiling below the plough layer has variable effects. This is partly because soil conditions determine the effect of subsoiling and frequently restrict its beneficial effects. Subsoiling is either carried out when the soil is too wet to achieve adequate shattering or at the incorrect depth or, alternatively, the more damaging compaction is often created more superficially (i.e. shallower than 30-35 cm depth) whilst preparing the seedbed subsequent to subsoiling. Typical operations that cause such shallow compaction are bed-tilling and destoning. One major disadvantage of destoning is that soil compaction cannot be avoided if the soil is too wet. Since the destoner is usually the rate-determining step during seedbed preparation, the operation frequently occurs in advance of planting in marginal soil conditions. As a consequence, destoning frequently results in soil compaction at *c*. 30 cm as the soil is too wet, which slows root growth early in the crops' life.

Soil compaction is clearly a frequent and serious issue in potatoes. It results in severe yield depression and reduces the efficiency of use of resources: soil, water and nutrients. Growers need to be more aware of the significance of soil conditions during soil preparation and planting in determining the quality of the soil environment created for crop growth.

Introduction

There are a number of requirements for the ideal potato seedbed. It must have a suitable air : moisture : soil ratio for root respiration and water and nutrient uptake. It must be warm enough for potato sprouts to grow rapidly following planting. It should have a fine tilth to aid herbicide activity, for effective irrigation to control common scab and for prevention of greening. It should be of uniform depth to improve the accuracy of the planter in terms of spacing and depth control. If required, it should permit the uniform incorporation of fertilizer and nematicides at the correct depth. A stone- and clod-free ridge will reduce damage to tubers at harvest and speed work rates. Most importantly, the seedbed should be freely rootable. Potato crops planted into soil with a resistance greater than the threshold for root penetration will develop shallow, restricted rooting systems with a limited capacity for exploiting reserves of water and nutrients in the soil. Water uptake in such crops will almost certainly be limited and, as a consequence, canopy growth, light interception, water use and ultimately yield will be reduced. The last requirement of a potato seedbed should be that it uses the minimum amount of energy in its creation. This is a formidable list and many of the desirable characteristics are not easily visible to the eye so growers must become more aware of how to judge the quality of their seedbeds. The last 25 years has seen a major change in the methods of soil cultivation for potatoes which has increased rather than decreased the risk of creating poor soil conditions. Potato planting nowadays commonly involves (four) or five cultivation operations: ploughing, bedforming, (bedtilling), destoning or declodding and planting. Large volumes of soil are moved which requires a high energy input in terms of diesel and tractor and labour hours. Vigorous churning or sieving of soil can destroy soil structure completely in light soils whilst it may prove beneficial in heavier soils by breaking down clods. In many cases, fewer operations would lead to more stable soil structure and reduce the energy and labour requirement. Often seedbed cultivation is ‘recreational’ or ‘mechanistic’, i.e. all cultivation operations are carried out in all fields in a planting programme without thought to whether each operation is necessary.

Soil conditions should become an increasingly acknowledged and important aspect of growing potatoes as this review will show that potatoes are very sensitive to compaction. Compacted soil is characterised by a high bulk density and/or strength and consequently a high penetration resistance to the roots. This review begins by summarizing the symptoms of plant growth resulting from compaction in order to allow growers to recognize whether they have seen compaction or not. The second section deals with the causes of soil compaction and its effect on soil physical properties and water and nutrient availability. The third section covers root growth, including establishing the relationship between rate of rooting and soil resistance and assessing how widespread compaction is in commercial potato fields in the UK. The fourth section addresses the question as to whether subsoiling is always beneficial by examining the results of compaction and subsoiling experiments. The last part of the review is devoted to the effects of cultivation practices during potato production on soil resistance.

Effects of compaction on plant growth and development

Compaction occurs where soil is compressed by traffic or smeared by cultivation equipment working in wet soil. Such compaction is frequently shallow (< 40 cm) and, unless removed or reduced, will impact on early crop growth. Clods on the soil surface which resist breakdown by rain or cultivation may indicate compaction, whilst deep ruts, ponding or wheeltracks may be more obvious. In compacted soil profiles, dense, often impenetrable, layers are found, commonly with horizontal, plate-like structure (i.e. hard-pan). Compacted subsoils often have a massive or ill-defined structure, with peds breaking only with considerable force or tearing across rather than along normal fracture lines.

Compacted seedbeds cause several major problems for early growth in the potato crop. First, cloddy ridges or beds can rapidly dry out following planting, in some seasons to such an extent as to impede water uptake by the seed tuber which delays sprout growth and consequently emergence. Table 1 shows the effect of poor cultivation conditions at planting on emergence in a hand-planted experiment, where crops took an extra eight days to emerge where soil was too wet at cultivation.

TABLE 1. EFFECT OF SOIL CONDITIONS ON DAYS FROM PLANTING TO EMERGENCE (ALLISON & STALHAM 1998)

	Soil texture (Moisture content at cultivation)			
Sand (Dry)	→	→	Sandy clay loam (Wet)	
Strip 1	Strip 2	Strip 3	Strip 4	SED
13	14	16	21	1.1

Secondly, planting in poor seedbeds (compacted, cloddy) also increases the variability of planting depth compared with good seedbeds (uncompacted, fine tilth; Table 2). The uneven planting depth in cloddy seedbeds is always a contributory factor in lengthening the period of emergence. This impacts on many aspects of crop uniformity and quality, such as tuber size, shape and freedom from common scab. Thirdly, a compacted or capped ridge causes stems to thicken or become fasciated (split), which can worsen into coiled sprout or little potato disorder, thereby delaying or even preventing emergence.

TABLE 2. EFFECT OF SOIL CONDITIONS ON VARIATION IN PLANTING DEPTH IN TIGHTLY-GRADED SEED (ALLEN & BOOTH 1989)

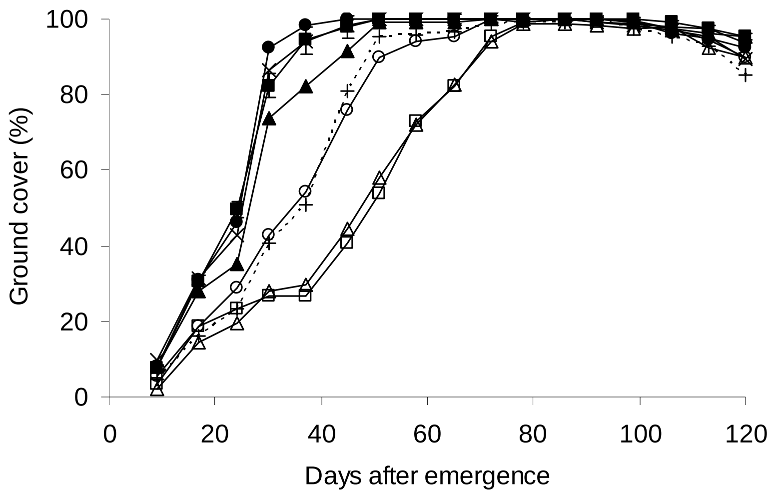
		Planting depth (cm)			
Site	Seed size (mm)	Mean	Maximum	Minimum	CV (%)
Uncompacted /	45-50	16.5	23.4	9.8	13
fine tilth	50-55	16.8	22.8	11.7	12
Compacted /	45-50	11.4	15.7	4.0	27
cloddy tilth	50-55	11.1	17.6	3.2	28

Fourthly, compaction results in a reduction in root growth leading to reductions in the rate of uptake of nutrients and water during early crop growth. As a consequence, plants in compacted soil are often shorter than those in loose soil as stem extension is reduced (Timm

& Flocker 1966; Stalham *et al.* 1997). Other important features of canopy growth are also affected. Compaction slows 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 advances the onset or rate of senescence (Rosenfeld 1997; Stalham *et al*. 1997). The overall effects of the reduced size and longevity of the leaf canopy thereby significantly decrease the yield potential of crops grown in compacted soil owing to a reduction in intercepted 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 interception.

Van Loon & Bouma (1978) and Van Loon *et al.* (1985) found that the depth of soil compaction altered the pattern of ground cover production. Shallow compaction (< 35 cm) resulted in an early restriction in canopy growth, followed by an increase in the rate of canopy growth once the roots had penetrated the compacted layer. Deeper compaction did not affect early canopy growth but resulted in earlier senescence. This suggests that canopy growth is affected as soon as root growth is restricted, as found in work at CUF (Stalham & Allen 2001). The extent of the changes can be large. Rosenfeld (1997) and Stalham *et al.* (1997) found that shallow (10 cm) compaction delayed the achievement of full ground cover in Maris Piper, in some cases by up to 5 weeks (Figure 1). In Estima, compaction prevented ground cover exceeding 75 %. These effects of compaction on canopy growth cannot be eliminated by additional irrigation (Figure 1) and may be exacerbated if waterlogging occurs (Rosenfeld 1997).

FIGURE 1. EFFECT OF SOIL COMPACTION DEPTH AND IRRIGATION REGIME ON GROUND COVER IN MARIS PIPER. UNIRRIGATED, UNCOMPACTED, ■; UNIRRIGATED, 10 CM, □; UNIRRIGATED, 40 CM, ▲; UNIRRIGATED, 10+40 CM, Δ; IRRIGATED, UNCOMPACTED, ●; IRRIGATED, 10 CM , ○; IRRIGATED, 40 CM, ×; IRRIGATED, 10+40 CM, +. (STALHAM & ROSENFELD 1996).



Compaction can reduce the efficiency of plant and soil water use and increase the requirement for irrigation, usually through increasing the frequency of irrigation required (Rosenfeld 1997; Stalham *et al.* 1997). In compacted soils, plants are often chlorotic from lack of nitrogen or magnesium or initially the converse, very dark green, as a result of dehydration. Plants will wilt prematurely on hot days, even if the soil is wet, primarily as a consequence of the restricted total root length and the inability to access freely-available water in the subsoil. Van Oijen *et al.* (1995) also found that compaction caused a reduction in the efficiency with which light energy was converted into dry matter.

Soil compaction has also been shown to affect the pattern of senescence in potatoes. Van Loon & Bouma (1978) showed that deep compaction resulted in more rapid senescence than in loose soil since root growth was restricted later in the season. However, Rosenfeld (1997) and Van Oijen *et al.* (1995) found that senescence was not significantly advanced by compaction but that the rate of senescence was decreased in compacted crops as the smaller number of leaves in these crops reduced the incidence of self-shading of leaves lower in the canopy.

The effects of compaction on leaf growth lead to significant reductions in number of tubers and yield (Table 3) and frequently increase the proportion of outgrades arising from secondary growth, mis-shapes, cracking, greening, lenticel eruption and common scab (Rosenfeld 1997; Stalham *et al.* 1997). Van Loon & Bouma (1978) found that moderate and severe compaction in the topsoil increased secondary growth defects dramatically where irrigation was not applied (Table 4). Size grading is often affected by compaction where poor planting conditions lead to variation in planting depth and spacing and consequentially delayed and uneven emergence. Compaction may increase tuber bruising owing to the physical presence of clods at harvest or the vigorous web agitation required to separate soil from tubers on the harvester.

TABLE 3. EFFECT OF SOIL COMPACTION DEPTH AND IRRIGATION REGIME ON (A) TUBER TOTAL YIELD (T/HA) AND (B) NUMBER OF TUBERS (000/HA) ON 29 SEPTEMBER IN MARIS PIPER. (STALHAM *ET AL*. 1997)

	Compaction treatment			
Irrigation regime	Uncompacted	Compacted 10 cm	Compacted 40 cm	Compacted 10 + 40 cm
		(a) Yield		
Unirrigated	73.8	46.4	65.3	47.3
Irrigated	87.9	59.4	79.0	56.5
S.E.		5.61		
		(b) No. of tubers		
Unirrigated	813	685	715	591
Irrigated	676	591	699	611
S.E.		43.0		

TABLE 4. EFFECT OF COMPACTION AND IRRIGATION ON PERCENTAGE OF SECONDARY GROWTH DEFECTS IN A MARINE SILT LOAM. (VAN LOON & BOUMA 1978)

Compaction treatment					
Uncompacted, unirrigated	Uncompacted, irrigated	Compacted, unirrigated	Compacted, irrigated	Severely compacted, unirrigated	Severely compacted subsoil, unirrigated
18	0	39	1	56	6

In summary, potatoes are sensitive to compaction at all stages of growth from emergence to harvest but particularly in the 3-4 weeks after emergence when growth rates of roots are normally rapid in loose soil. Compacted soil can result in uneven stands of plants which produce leaf area slowly, have a truncated period of maximum ground cover and therefore intercept less light and produce lower yields than crops grown in soil with minimal resistance to root penetration. The effects on yield are serious and combined with less uniform grading and increased defects reduce the value of the crop considerably. Irrigation can partially alleviate the effects of compaction but never removes them completely, emphasizing the importance of avoiding compaction.

Causes of soil compaction

Compaction caused by wheels

The two main causes of soil compaction are wheelings and cultivation implements. Driving or towing trailed implements on the soil results in compressive force giving rise to compacted soil which is characterised by high bulk density, low pore volume and increased soil resistance. The extent to which wheels cause soil compaction depends on a number of factors including the weight of machinery, water status of the soil, soil type, tyre pressure and the number of passes made. Many studies in the field have found that increasing axle load increases the degree of soil compaction and that the effects are more likely to occur when the soil is at a higher moisture content (Salokhe & Ninh 1993; Carman 1994). Howard *et al.* (1981) suggested that the water content of a soil was the most important factor in determining susceptibility to compaction and that the differing response in soil types could be mainly attributed to differences in their water holding capacity. The pores in moist soil contain water, which acts as a lubricant. Under loading, the soil particles in wet soils move more readily and pack together more tightly. Compaction commonly occurs away from the actual contact point of the implement or tyre with the soil and as the energy wave moves away from this contact point, soil particles are re-aligned and packed. Soils wetter than their "plastic limit" (i.e. the moisture content where a soil deforms in a plastic manner) will smear and compact under tyres and cultivation implements. During winter and spring, clay soils are more prone to compaction at depth than sands since they are likely to be wetter than their plastic limit below the surface.

Coarse, sandy soils with low packing densities (< 1.4 g/cm^3) and low water holding capacity, however, experience the largest changes in bulk density following compaction since their air capacity is large and small increases in compressive force result in large reductions in total pore space. Archer & Smith (1972) stated that the optimum bulk density for Newport Series loamy sand was 1.75 g/cm^3 whereas it was only 1.20 g/cm^3 for Ragdale Series clay loam, which can largely be explained by the available water holding capacity in sand soils being increased considerably following consolidation owing to the large increase in fine pore spaces.

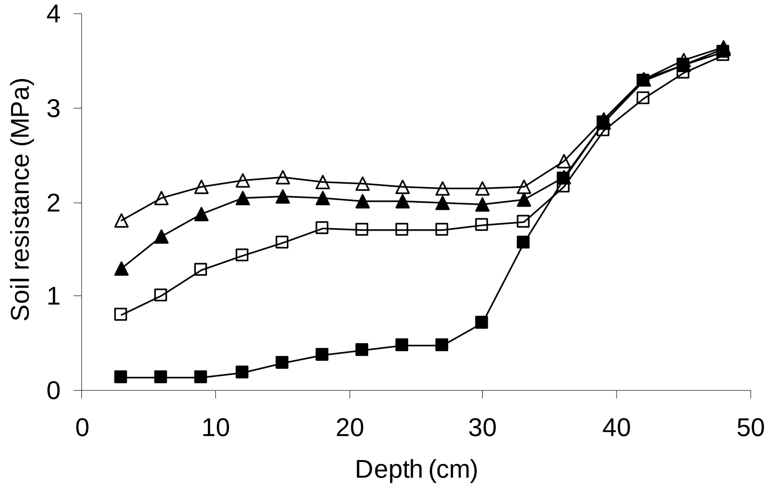
There seems to be an apparent contradiction in the "compactability" of clay soils, since Spoor *et al.* (2003) stated that as the proportion of clay and packing density increased, soils become more resistant to compaction. Air-filled horizontal pores and voids are much more susceptible to closure than vertical pores and therefore soil structural type and crack or fissure development are important factors controlling the degree of compaction that occurs (Jones *et al.* 2003). The greater the number of vertical macropores for similar soil ped stability and strength, the greater the resistance to compaction, particularly traffic loading. However, vertical biopores such as worm and root channels collapse easily under the horizontal shearing forces imposed by cultivation implements or slipping wheels. Therefore, clay soils are more prone to compaction in horizontal planes than sand soils. There are also other soil characteristics such as increased organic matter content which have been shown to reduce the extent to which bulk density increases when a soil is compacted (Ekwue & Stone 1995).

It is common practice in potatoes to restrict traffic to defined wheelings. Although this ensures that compaction by wheels is restricted to localised zones, it may encourage growers to carry out operations too early when the soil is still close to, or above, the plastic limit.

Slow moving machinery has the greatest potential to compact the soil (Carman 1994), therefore potato planting is particularly prone to compaction under wheelings. There is also the risk that the effects of compaction from wheelings may affect the edges of the beds or ridges, leaving the potential for clods at harvest or soil cracking and exposure of tubers to light thereby encouraging greening. Indeed, growers often ask about the benefits of wider tyres in potato operations on controlled wheelings which reduce ground pressure but may scuff or compress the flanks of ridges or beds unless the wheelings are increased in width to accommodate the tyres. Salokhe & Ninh (1993) found that the extent of soil compaction could be reduced by a reduction in tyre pressures, although axle weight was still found to be the main determining factor. For a given load, the narrower the tyre in the furrow, the deeper the severely compacted area, the greater the volume of soil with increased resistance and the greater the restriction on total root length per plant. Wider, lower pressure tyres compress the soil over a bigger contact area but still permit more root growth in soil horizons closer to the surface than narrow tyres since the average increase in soil resistance is less with wide tyres than narrow (O'Sullivan *et al*. 1987). The width of the tyres in potato production is limited by the width of the furrows between beds. Wider tyres would be more beneficial in reducing severe soil compaction but must not be wide enough to compress or scuff the sides of the ridge since greening of exposed tubers may take place. Reducing the spacing between rows within the bed (e.g. from 91 cm to 86 cm or even 81 cm) whilst maintaining wheeltrack width widens the gap for wheels and has been adopted by many growers, though the motive behind this seems to be aimed at reducing greening rather than soil compaction.

Most compaction occurs after the first passage in controlled-wheeling systems and the amount of additional compaction decreases with subsequent passes. Stalham (1996, unpublished) found that the initial wheelings produced by the bedformer compacted the soil to the greatest extent (Figure 2). Subsequent compression with the destoner and planter had progressively smaller effects on increasing resistance but the effects were cumulative, thereby supporting the conclusions of Salokhe & Ninh (1993), who suggested that most compaction occurred after the first pass and that the amount of additional compaction decreased exponentially with subsequent passes. Stalham (1993, unpublished) detected an increase in penetration resistance as deep as 60-70 cm following trafficking of wheeled furrows during a full season of cultivation, planting and spraying operations. Such serious and deep compaction reduces root growth considerably below wheeled furrows when compared with the centre of the bed. Stalham (1989) also observed that no roots were present in the furrow bottoms where stones were deposited during destoning and root length density was decreased for a depth of 20 cm below the stone layer compared with the centre of the bed.

FIGURE 2. EFFECT OF TRAFFICKING DURING PLANTING ON SOIL RESISTANCE BELOW THE WHEELED FURROWS IN A SANDY CLAY LOAM SOIL. INITIAL PLOUGH, ■; BEDFORMER, □; DECLODDER, ▲; PLANTER, Δ. DEPTHS RELATIVE TO FLAT SOIL SURFACE. (STALHAM 1996, UNPUBLISHED).



Compaction caused by cultivation implements

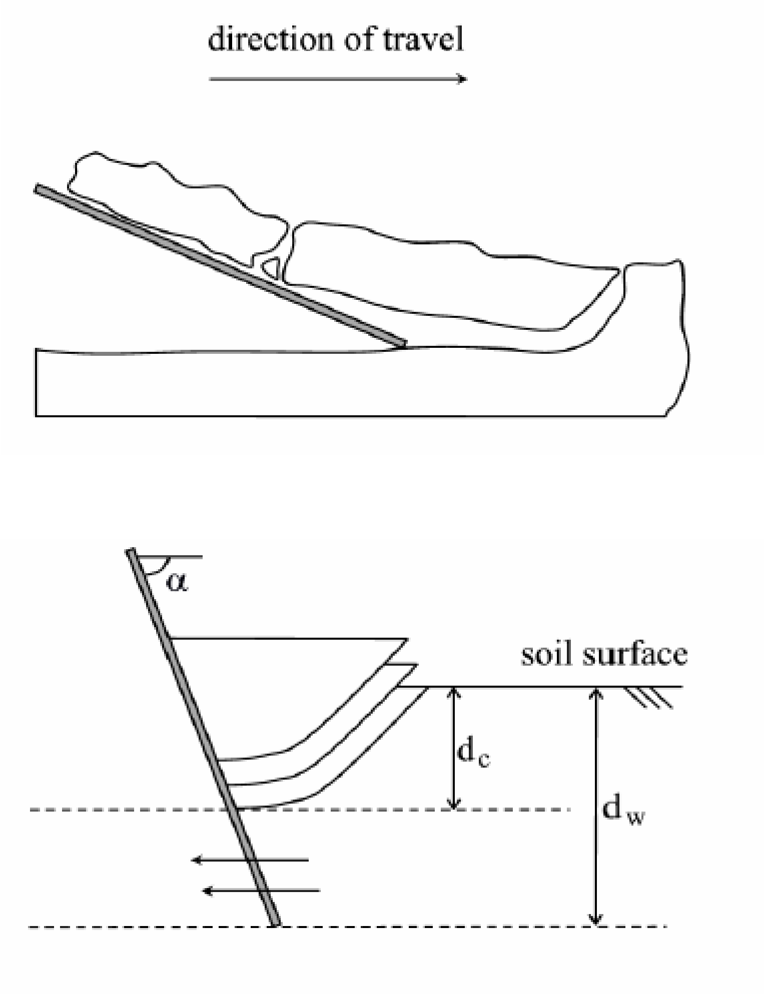
In addition to compaction by wheels, compaction may be caused by cultivation implements if they are used in soil close to, or above, the plastic limit. Although a detailed review of the mechanics of various cultivation implements is beyond the scope of this review, some explanation of the forces involved is necessary in order to understand how the risk of soil compaction can be minimised. Cultivation implements aim to reduce bulk density and clod size through brittle failure which occurs when particles shear along a small number of well defined planes. However, if the soil structure shears along many undefined planes, there will be an increase in bulk density resulting in compressive failure. Spoor & Godwin (1979) tested three types of soil under compression and found that brittle failure was more likely to occur under low compressive forces, whereas compressive failure was more likely to occur under high compressive forces. When the share of a plough or destoner, a subsoiler wing, or indeed any tine with a lifting component, is drawn through the soil, soil beyond the share will move forwards and upwards, resulting in tensile failure, fracturing the soil and reducing bulk density (Figure 3a).

FIGURE 3. A SCHEMATIC ILLUSTRATION OF TYPICAL FAILURE PATTERNS IN SOIL CUTTING DURING CULTIVATION: (A) TENSILE FAILURE; (B) SHEAR FAILURE; (C) PLASTIC FLOW. A: RAKE ANGLE; D_C: CRITICAL DEPTH; D_W: WORKING DEPTH. (KELLER 2004).

(a)

(b)

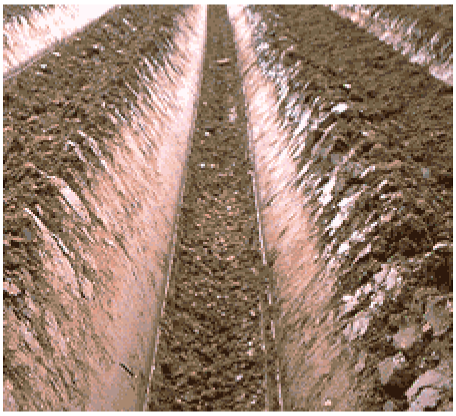
(c)



However, for soil below a critical depth, the confining force of the soil above will prevent soil beyond the tine moving upward (Figure 3b; c), so that it will only move forward, resulting in compressive failure. Therefore, ploughing, destoning or subsoiling below the critical depth will cause soil compaction resulting in increased bulk density and roots of the subsequent crop will encounter increased penetration resistance. Spoor & Godwin (1979) determined that the transition from tensile or brittle failure (shattering) to compressive failure (smearing) occurred at lower pressures when the soil was at a higher moisture content. In practical terms, if ploughing or cultivation depth is too deep in moist or wet soil, compaction and smearing will result. Since during spring the moisture content of the soil generally increases from the soil surface down to the plough depth, unless the soil is allowed to dry either naturally or by progressively opening the soil structure with shallow cultivations, the critical working depth will be shallow, often above the plough depth. Soil moisture therefore has a major influence on the likelihood of compaction and smearing occurring when conducting primary (e.g. ploughing) or secondary (e.g. ridging, destoning) cultivations. Critical depths are typically 30-40 cm (Godwin & Spoor 1977) but can be shallower and are influenced by a range of factors apart from soil moisture. If the cultivation is below the critical depth then the risk of doing harm to soil structure outweighs the benefits of cultivation. The soil must be allowed to dry out before attempting to cultivate or the drying speeded up by shallower cultivations.

The critical depth of cultivation can be increased by a number of modifications to tines or shares. A decrease in rake angle, α (Figure 3a), will increase critical depth as will the attachment of wing tines. The use of 'progressive' type implements which loosen the soil in a sequence of increasing depths ahead of the deepest tines, reduces the confining forces on soil at depth allowing soil to move upwards as well as forwards. This reduces the risk of compressive failure in front of the deepest tines or shares, thereby increasing the critical working depth and reducing compressive 'smearing' (Spoor & Godwin 1978). An example of compressive failure during bed-forming is shown in Figure 4. There is clearly compaction at the base of the flanks of the bed and in the furrow between beds caused by both the leading share and the bodies of the bed-former. Bed-tilling the beds would remove the thin smeared layer on the flanks of the ridge but the furrow compaction is more serious. This could be somewhat alleviated by the action of deep winged tines attached behind the bed-former but these may themselves create compaction deeper in the profile unless the soil is dry.

FIGURE 4. SMEARING OF RIDGE FURROWS AND SIDES IN DEEP BEDS DRAWN UP WITH A BEDFORMER



In potatoes, in addition to ploughing, the soil is often destoned or declodded. The benefits of destoning or declodding are typically a 30-50 % decrease in severe tuber damage during harvest and up to a 40 % increase in the harvesting spot rate of work and the creation of a fine seedbed for scab control (Whitney & McCrae 1992). A destoner lifts pre-formed beds using shallow-angled shares on the front of the machine. Clods and stones are then either separated through a web or series of fingered 'stars' and deposited in an adjacent furrow. Smaller clods are broken up through a series of oscillating blades, stars or finer webs and remaining soil is sifted and then redeposited on the beds. One major disadvantage of declodding or destoning is that soil compaction cannot be avoided if the soil is too wet. As the operation has a slow rate of progress, it is usually the rate-determining step during seedbed preparation and consequently the operation frequently occurs in advance of planting in marginal soil conditions. As a consequence, the destoning operation frequently results in soil compaction as the soil is too wet (see later). Measurement of penetration resistance showed that under such conditions the shares of a destoner compacted the soil at 30-35 cm below the top of the planted ridge and therefore slightly shallower than the ploughing depth.

Often, great value is attached to the cosmetic appearance of ridges following planting. The common belief is that such ridges offer major advantages in terms of retaining water from rainfall or irrigation which will therefore benefit scab control or yield. The fine structure on the surface of the ridge also improves the efficacy of herbicide action. However, the sieving or pulverisation of soil by destoners can create a lack of structure causing ridges to slump to varying extents following rain or irrigation. In fine-textured soils seedbeds should be cloddier at planting than required at harvest to prevent slumping of the ridge after breakdown of small soil peds, and this is achieved by increasing the web pitch or widening the star spacing on the destoner. Frequently, the 'manicured' appearance of the ridge surface contrasts with the compacted soil structure at the base of the ridge. Despite the slow forward speed of these machines and the inherent risk of destructuring the soil, the use of destoners/declodders has become widespread across all areas of the UK, in many cases on soil types where any improvements on ridge tilth, harvesting workrate and damage reduction would be marginal. In other areas of the world, e.g. Europe and USA, they are not commonly used.

Although all soils are at risk from compaction, it is the process of conducting operations on wet soil that is most likely to result in soil compaction. There is a trend for the use of increasingly heavy and powerful machinery and PTO-driven cultivators which are capable of carrying out work on soil that was once deemed impossible for working. This, in conjunction with the quest to plant increasingly large areas in a shorter time, has increased the probability that operations will be carried out on soils that are too wet and therefore liable to compaction. The greatest potential for increasing radiation interception in the potato crop is at the beginning of the season by encouraging earlier canopy cover. However, earlier planting increases the chances of operations being carried out in conditions where compaction is more likely to occur. Nevertheless, there are occasions in late February or early March in the UK when soil conditions can be conducive to working at shallow depth but soil temperatures are well below the threshold for sprout elongation in potatoes, so there is no benefit in planting other than completing planting sooner. The crucial word here is shallow: soils are unlikely to dry out appreciably at depth in early spring without moving wet soil to the surface or progressively cultivating deeper to create drying pathways that lead to the soil surface. Growers have to balance the advantages of planting early to establish early canopy cover with the disadvantages of compacting the soil which will considerably reduce canopy expansion and subsequently yield as shown in Figure 1 and Table 3. Planting into wet soil has a high probability of creating compaction, the effects of which will persist throughout the season and be impossible to remove completely, so there has to be an increased awareness amongst growers of the need to wait until soil conditions in spring are suitable for cultivation.

Effects of compaction on soil properties

Physical properties

Compaction affects many soil properties which are known to restrict both root growth and water uptake. Most widely quoted is an increase in bulk density under compaction (Wolkowski 1990; Douglas & Crawford 1991; Salokhe & Ninh 1993; Horn *et al*. 1995) and increases from 1.4 to 1.7 g/cm³ have been observed as the result of a formation of a plough pan (Barraclough & Weir 1988). Associated with an increase in bulk density is an increase in soil strength or resistance to penetration which will reduce root growth and a reduction in pore size which may be up to ten-fold as observed by O'Sullivan & Ball (1993). Sands *et al.* (1979) found that a sandy soil compacted from 1.4 to 1.5 g/cm³ resulted in an increase of penetration resistance from 1 to 3 MPa. This is similar to the values of 2-3 MPa observed in the severely compacted treatments of Boone *et al.* (1978). The relationships between root penetration rate and soil resistance will be covered in depth later in the review.
The depths at which compaction has been measured show considerable variation in the literature. Alakukku (1996) reported a large increase in penetration resistance at depths of 50 cm after driving on the soil. Van Oijen *et al.* (1995) measured an increase in penetration resistance from *c.* 1 to 4 MPa at depths of 30 cm in one season after driving on the soil with a roller when the soil was wet, whereas in the following year when the soil was dry, little effect of the same treatment was measured below 15 cm. Stalham (1998), using a power harrow to create the seedbed, cultivated the soil either whilst dry or 14 hours after an irrigation of 17 mm. He found that cultivating whilst the soil was above its plastic limit increased the bulk density between 5 and 20 cm deep from 1.25 to 1.34 g/cm³. Ploughing implements generally create compaction around or just below 30-35 cm and Barraclough & Weir (1988) measured an increase in penetration resistance from 0.5 to 4 MPa at depths of 35-45 cm as the result of the formation of a plough pan.

The reduced conductivity of the soil when compacted also results in impeded drainage (Wolkowski 1990; Douglas & Crawford 1991; Horn *et al*. 1995) so that soil becomes more susceptible to waterlogging. Soils with impeded drainage within the ridge have an increased risk of associated problems such as poor root growth, increased pink rot if disease inoculum is present, lenticel eruption and difficult harvesting conditions. Boone *et al.* (1978) also suggested that reduced conductivity of soil decreased the potential for capillary rise so that less water could be extracted from lower profiles by the root system.

The effect of soil compaction on aeration capacity of the soil is also likely to affect root growth and water and nutrient uptake. Although Boone *et al.* (1978) suggested that there was sufficient oxygen in the soil for root growth in potatoes under compacted conditions, these experiments were carried out under unusually dry conditions so may not be representative of a typical growing season. A soil does not have to be saturated for the oxygen concentration in fine soil pores to be insufficient for root growth (Gregory 1993) and oxygen diffusion in water is several thousand times slower than in air-filled pores (Kramer 1969). Boone *et al.* (1986) suggested that the soil moisture content at which oxygen diffusion rate was reduced to a critical limit was lower in a compacted soil than an uncompacted soil. When compacted soil is irrigated, the reduced drainage capacity is likely to increase the moisture content of the upper profiles of the soil. Increased moisture content in conjunction with a reduced oxygen diffusion rate increases the risk of anaerobic conditions occurring, which can lead to root death and impaired water and nutrient uptake.

Water availability

There is evidence that compaction reduces water use in potatoes (Van Loon & Bouma 1978; Feddes *et al.* 1988; Rosenfeld 1997; Stalham *et al.* 1997) and a range of other crops including maize (Arvidsson & Jokela 1995) and winter wheat (Barraclough & Weir 1988). Compaction increases the penetration resistance to roots and reduces soil porosity and movement of water in the soil. Restriction of root growth reduces the volume of soil from which the root system can extract water, making the plants more susceptible to water stress in compacted soil (Van Loon & Bouma 1978; Kirkegaard *et al.* 1993; Tardieu 1994; Unger & Kasper 1994). Such a change in rooting volume decreases the allowable deficit that can be tolerated between irrigations and, as a consequence, more frequent irrigation is often necessary. Accordingly, Ekwue & Stone (1995) found that the effects of compaction on maize were reduced if irrigation was applied in smaller, more frequent doses.

There is also clear evidence that the ability to extract water within the compacted layer is reduced (Boone *et al.* 1978; Ohu *et al.* 1987; O'Sullivan & Ball 1993). In most soils, the reduction in average pore size caused by compaction causes water to be held at much higher suction pressures, decreasing the easily available water considerably. This restricts the ability of roots to extract water from the soil. In sandy soils, by contrast, compacted soil can create a more profuse network of smaller pores which hold more water but at tensions accessible to plant roots. Hence, in terms of easily-available water, the optimum bulk density is higher and porosity lower in sands than in clay-dominated soils.

Nutrient availability

Since compaction reduces the extent of the rooting system and therefore water uptake, a concomitant decrease in nutrient uptake would be expected. This has been found for uptake of nitrogen, phosphorus and potassium in potatoes (Van Oijen *et al.* 1995) and nitrogen in winter wheat (Barraclough & Weir 1988; Haunz *et al.* 1992). Allison (2004) observed that *c.* 85 % of total nitrogen uptake occurs by 45-65 days after emergence, therefore restricting early root growth would seriously reduce the potential for nitrogen uptake. Restricted leaf area as a result of compaction would also reduce the evapotranspirative demand and therefore slow the rate of transpiration and nutrient uptake by mass flow. The decreased conductivity of the soil as a result of compaction observed by Boone *et al.* (1978) reduces the extent to which nutrients can move through the soil to the root by diffusion. There is also evidence that soil compaction can reduce nutrient availability. Haunz *et al.* (1992) found that compacted soil in wet conditions resulted in a 30 % reduction in mineralisation of nitrogen in organic matter to nitrate and 20 % increase in loss of nitrogen by denitrification of fertiliser nitrogen. Wolfe *et al.* (1995) found that there was increased chance of waterlogging in compacted soil and anaerobic conditions reduce nutrient uptake by roots. Therefore compaction reduces nutrient uptake not only through restricting the extent of the root system, but also by reducing the movement of nutrients through the soil and decreasing nutrient availability.

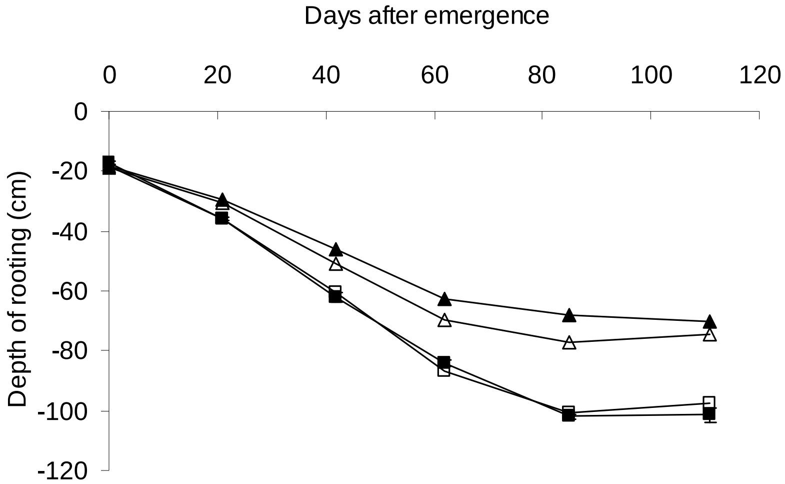
Soil compaction and root growth

Whilst the above-ground symptoms of compaction are easy to recognise, examining root growth remains difficult or impractical for both researchers and growers. Owing to these difficulties, very little work has been done on the effects of soil compaction on root growth in potatoes. The available results clearly show that compaction reduces both density and depth of rooting. Stalham & Allen (2001) reported that differences in maximum depth of rooting between cultivars were a consequence of differences in the duration of root growth rather than the rate. However, soil compaction principally causes a reduction in the rate of rooting rather than altering the time when roots cease growing. One study by Boone *et al.* (1978) found that effective rooting depth was reduced by a compacted plough layer from 80 to 40 cm in early July but by the end of the season there was little difference in maximum rooting depth. Feddes *et al.* (1988) found that compacted top soil slowed growth of roots from emergence but growth rate increased once roots were through the compacted layer and roots ultimately reached the same depth (100 cm) as in loose soil. However, there was a much lower density of roots below 50 cm in the compacted topsoil treatment than the loose soil. Their ploughpan treatment (topsoil removed to 40 cm, soil compacted and topsoil replaced) restricted rooting (and water uptake) to 65 cm. De Roo & Waggoner (1961) found greater root branching underneath trafficked furrows than under non-traffic furrows and Boone *et al.* (1985) observed lateral root thickening from 0.25 mm to 0.37 mm for roots growing in a ploughpan compared with loose soil. Van Oijen *et al.* (1995) also found that both horizontal and vertical extension of roots was reduced by compaction and that root senescence was increased. Rosenfeld (1997) and Stalham *et al.* (1997) found that maximum depth of rooting was restricted to *c.* 71 cm in treatments compacted at 10 cm but in uncompacted soil and soil compacted at 40 cm maximum rooting depth was over 20 cm deeper (Table 5). Stalham (1995), growing plants in 1 m long tubes, found that compaction reduced the rate of root growth. This was caused by roots drying the soil ahead of the rooting front in unirrigated tubes which increased the soil strength and slowed rooting (Figure 5). However, wetting compacted soil increased root extension rates by preventing the increase in soil strength at the rooting front.

TABLE 5. EFFECT OF SOIL COMPACTION DEPTH AND IRRIGATION REGIME ON MAXIMUM DEPTH OF ROOTING (CM) IN MARIS PIPER (STALHAM *ET AL*. 1997).

	Compaction treatment			
Irrigation regime	Uncompacted	Compacted 10 cm	Compacted 40 cm	Compacted 10 + 40 cm
Unirrigated	95.3	77.7	92.5	80.2
Irrigated	96.0	75.8	92.7	50.8
S.E.	5.61			

FIGURE 5. EFFECT OF COMPACTION AND IRRIGATION ON DEPTH OF ROOTING OF PLANTS GROWN IN ROOT TUBES. UNCOMPACTED, UNIRRIGATED, ■; UNCOMPACTED, IRRIGATED, □; COMPACTED, UNIRRIGATED, ▲; COMPACTED, IRRIGATED, Δ. (STALHAM 1995).



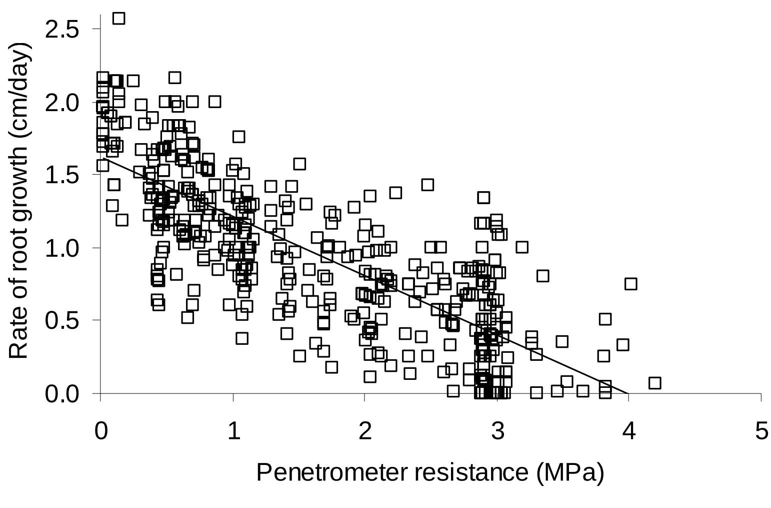
Developing a relationship between root elongation and soil resistance and determining the threshold soil resistance for root growth

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 resistance to root growth is the reaction pressure of the soil. This pressure will increase as the strength of the soil increases as the soil dries or if the bulk density of the soil is increased by compaction. Root elongation in a range of crops is known to be significantly reduced at penetration resistances (Ω) equal to those reported for unloosened subsoils. Short of direct measurement of the forces that roots exert, cone penetrometers provide the best estimates of resistance to root growth (Bengough & Mullins 1990). A range of workers have shown that soil resistance to a cone penetrometer can be several times greater than the pressure exerted by root tips in penetrating the soil (Eavis 1967; Stolzy & Barley 1968; Whiteley *et al.* 1981; Misra *et al.* 1986; Bengough & Mullins 1988). However, living roots, unlike penetrometer probes, are flexible, and by exploiting planes of weakness, can grow in soil horizons which have Ω's in excess of the maximum axial pressures that roots can exert. Also, the progress of an individual root through the soil matrix is aided by the secretion of mucilage lubricants and the shedding of root cap cells (Bengough & McKenzie 1997). Soil resistance readings taken with a penetrometer must therefore be interpreted with care if they are to be used to predict root growth. Although the maximum root growth pressure is of interest and relevance to the penetration of pans or hard layers of soil by roots, an equally important parameter is the extent to which more moderate soil strengths restrict the elongation of roots (Russell & Goss 1974; Russell 1977; Bengough *et al*. 1997). This is important for spring-planted crops where a rapid increase in rooting depth with time is required so that plants have access to water reserves deep in the soil profile.

Relationships between rate of rooting and Ω have been established for measurements in several experiments and many commercial fields (Stalham, unpublished). Measurements of resistance were taken using an Eijkelkamp Penetrograph (1 or 2 cm^2 60º cone tip, 8 mm diameter shaft). In commercial fields, 3 or 4 locations were marked out and *c.* 20 penetrometer readings were taken within 2-3 weeks of planting to a depth of 0.8 m on a 0.91 x 0.91 m grid over an area of *c.* 4 x 4 m. In experiments, *c.* 20 penetrometer readings were taken in each plot at planting. These penetrometer readings were averaged for each location or plot and the assumption made that resistance at each depth did not change during the season until the roots had penetrated that layer of soil. A pit was dug using a JCB digger or spade in the centre of each location spanning four rows in width. On each occasion measurements were made, a fresh face of the root pit was prepared by excavating back two plants from each of the four rows using a spade. Starting at emergence and continuing every 1-2 weeks, the depth of the ten deepest roots in each pit was measured. Measurements were made on 5 to 11 occasions throughout the season. The rate of rooting measured was actually the increase in rooting depth rather than the extension rate of individual roots. 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 and nutrients are used by the crop.

There were reasonably close (R^2 = 0.50-0.75) significant negative relationships between growth rates and Ω for individual locations. Figure 6 presents data for six well-structured soils. Maximal growth rates were typically 2 cm/day within or just below the ridge where Ω was low. However, for any particular Ω, there was a large range in growth rate (*c.* 1.3 cm/day). When the soil reached a resistance of *c.* 3 MPa, some roots ceased to extend further but others were observed to have found natural fissures and burrows or voids between peds and were extending freely into deeper horizons, particularly in the subsoil where cultivation did not disturb these channels for root growth.

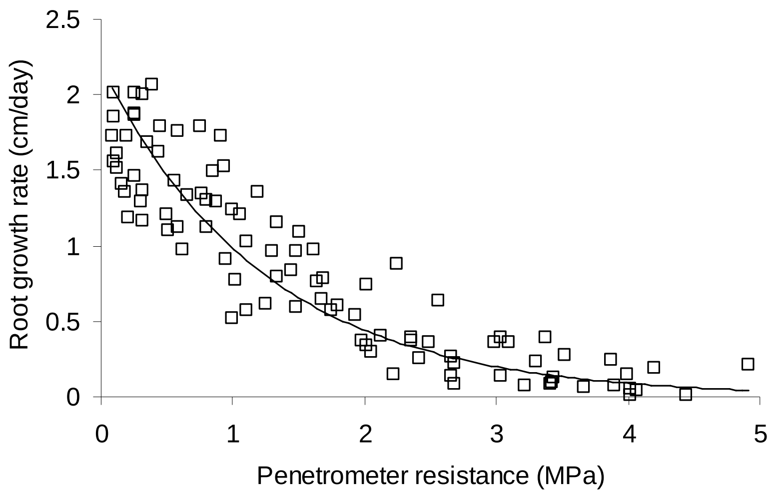
FIGURE 6. RELATIONSHIP BETWEEN ROOT GROWTH RATES AND SOIL PENETRATION RESISTANCE IN TWO EXPERIMENTS AND FOUR COMMERCIAL FIELDS ON STRUCTURED SOILS INVOLVING 17 VARIETIES DURING 1994-2001. $y = -0.41x + 1.63$, $R^2 = 0.63$. (STALHAM, UNPUBLISHED).



There is one other major reason why no simple close and unique relationship across soil types might exist between the instantaneous root elongation rate and Ω. When roots grow through hard soil into looser soil, their elongation rate does not increase immediately to that of roots grown entirely in loose soil (Bengough & Young 1993). Instead the elongation rate remains slower for a period of several days before increasing. Boone *et al.* (1978) observed compensatory increases in root growth once a plough pan had been crossed although root growth had been slowed within the pan. These observations are crucial since they indicate that shallow compaction will impede overall rooting depth very dramatically since compensatory growth below cannot make up for the time lost in penetrating any compacted layer. However, all of the soils measured in Figure 6 had a progressive increase in resistance as soil depth increased and there were no pans which had lower resistance soil on either side.

It has been reported, however, that the mechanical resistance to root growth is better approximated by penetrometer measurements in soils with weak, massive or single grain (i.e. sand) structure (Ehlers *et al.* 1983; Vepraskas & Miner 1986). In two stone-free, structureless sands and a peaty sand soil, the fit of the individual relationships was closer than in structured soils (R^2 = 0.85) and the rate of downward progress of the rooting front was more closely related to Ω with a decreasing exponential relationship rather than a linear decrease (Figure 7; Stalham 1992; 1996; 1999, unpublished).

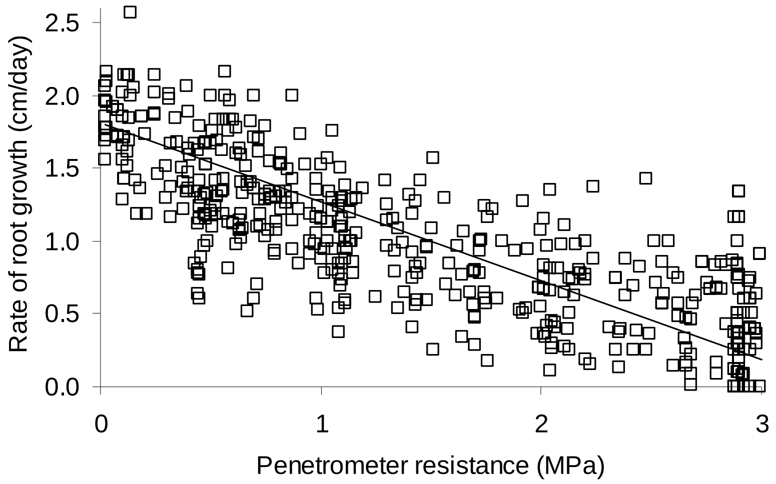
FIGURE 7. RELATIONSHIPS BETWEEN RATE OF ROOT PENETRATION AND SOIL RESISTANCE IN THREE STRUCTURELESS SOILS. $Y = 2.18E^{-0.799X}$, $R^2 = 0.80$. (STALHAM, UNPUBLISHED).



It can be seen from Figure 7 that root growth rates decrease rapidly, especially in subsoils where Ω usually exceeds 2 MPa. According to the relationship in Figure 7, a halving of the maximum rate of root growth (i.e. from 2 to 1 cm/day) would occur at *c.* 1.0 MPa and a growth rate of 0.5 cm/day (quarter rate) would correlate with a resistance of 1.8 MPa. At a resistance of 3 MPa, growth rates would be around one-tenth of the maximal rate, i.e. 0.2 cm/day. From Figure 7, it can be calculated that an increase in Ω in a sandy soil from 1.1 MPa (a low resistance subsoil) to 2.5 MPa (a more typical average subsoil resistance) would reduce maximum rooting depth by 29 cm over the course of growth of a typical maincrop.

From the results in Figure 6 and Figure 7, at some point between 3 and 4 MPa most roots appeared to either cease growing or were growing very slowly but owing to the ability of roots to grow through natural fissures, it is difficult to be certain of the soil resistance which ultimately prevented roots from extending further. Figure 8 shows the combined data for all soils, structured and structureless but restricted to Ω's < 3 MPa since this was approximately the resistance where root growth rates were first observed to be zero. For resistance readings between 2.7 and 3.3 MPa, 70 % of the points lay above the fitted line. The plethora of points at *c.* 3 MPa made the slope of the linear relationship shallower in structured soils since the growth rate varied from 0 to 1.3 cm/day. Selecting a growth rate of 10 % of the maximum (i.e. 0.2 cm/day) as "severely impeded", would indicate a resistance of *c.* 3.0 MPa using the relationship in Figure 8.

FIGURE 8. RELATIONSHIPS BETWEEN RATE OF ROOT PENETRATION AND SOIL RESISTANCE OF ALL SOILS COMBINED. RESISTANCE READINGS CONFINED TO < 3.0 MPA. $y = -0.541x + 1.81$, $R^2 = 0.66$. (STALHAM, UNPUBLISHED).



As a conclusion, root growth rates are rapid when growing in loose soil as typified by the ridge and plough layer. Compacting these shallow horizons during planting will impose a massive limitation on root growth and therefore restrict water and nutrient uptake and should therefore be avoided at all costs. Growth rates in most subsoils are much slower than in the intensively-cultivated layer as a consequence of the greater soil resistance. Eliminating compaction below the plough depth will aid root penetration into deeper horizons, especially where soil resistance exceeds 3 MPa.

Comparing the thresholds for root growth with the literature

There are limited data in the literature relating root growth rates with Ω in potatoes when compared with other crops but in those found there is considerable variation in what are regarded as the limiting and ultimate Ω for root growth. The considerable unpublished dataset produced by Stalham supports most of the literature that exists for potatoes. Bishop & Grimes (1978) stated that root extension in potatoes was severely reduced at all soil depths by soil strengths exceeding 1 MPa in a sandy loam soil. Heap (1993) and Heap *et al.* (2001) stated that Ω's in excess of 1.5 MPa restricted root growth in sands and that many structureless sand soils in South Australia where potatoes are commonly grown have resistances > 2 MPa below 25 cm. Maximum rooting depth in these soils rarely exceeds 30 cm which often coincides with compacted pans that are quick to form at 25 cm depth following potato seedbed cultivation. Our observations on root growth and the presence of thin pans in sandy Cuckney Series soils in Nottinghamshire would support these views. Ovaa

& de Smet (1984) stated that 2 MPa was limiting for potato root penetration. Boone *et al.* (1978) found that in alluvial loamy sands with natural or artificially-created ploughpans 1-2 MPa reduced root growth rates, whilst Ω's > 3 MPa in stongly compacted topsoil slowed roots considerably but they eventually progressed through the compacted layer into looser soil underneath. Boone *et al*. (1985) found that growth rates slowed to *c*. one-quarter of the maximum at 2.5 MPa. Whilst they did not set upper limits for Ω in relation to root extension, examination of their data suggests that roots failed to penetrate the ploughpans when Ω exceeded 4 MPa at field capacity and that root growth was slowed severely by the pan when Ω was in the range 3-4 MPa. In one dry season when Ω in the plough pan increased to > 3 MPa, root penetration was prevented completely. Root growth in a soil without a ploughpan appeared to proceed rapidly (*c*. 1 cm/day) through regions where Ω was < 2 MPa.

Boone *et al*. (1986) set the lower limiting mechanical resistance as 50 % of the maximal rate of rooting, with the upper limit being the resistance where root growth ceased completely. From the combined data in Figure 8, the lower limit (i.e. 1 cm/day) occurred at 1.5 MPa for the potato data of Stalham. Therefore, the comprehensive analysis of Stalham's data suggests that potatoes roots extend freely up to a resistance of 1.5 MPa and are restricted to < 10 % of their maximal rate at Ω's of *c*. 3.0 MPa.

How frequently is soil resistance in commercial fields an impediment to rooting?

Having determined the limits of soil resistance for potato root growth, the likely commercial significance of soil compaction can be established from the frequency with which such resistances occur in commercial fields. A survey of commercial fields across the UK from 1992-2004 was conducted where penetrometer resistance readings were taken soon after planting. Table 6 shows the results of this survey of 602 fields categorizing Ω in classes where root growth rates would be between full and three-quarter rate (2-1.5 cm/day), three-quarter to half rate (1.5-1.0 cm/day), half to quarter rate (1.0-0.5 cm/day) and less than quarter rate (< 0.5 cm/day). Using Figure 8, these growth rate classes correspond to Ω's of < 0.57, 0.57-1.5, 1.5-2.43 and 2.43-3.0 MPa, respectively. Table 6 shows the depths in the profile where Ω exceeded these class limits. Additionally, Table 6 presents the proportion of fields with Ω > 3.0, judged as the resistance where roots cannot penetrate except through fissures and channels created by soil fauna.

TABLE 6. SURVEY OF 602 COMMERCIAL FIELDS IN 1992-2004 SHOWING DEPTHS WHERE SOIL RESISTANCE 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. (STALHAM, UNPUBLISHED)

Year	No. of fields	Growth rate class (cm/day) Upper limit of resistance for class (MPa) in parentheses: 2.0-1.5 (0.57)	1.5-1.0 (1.50)	1.0-0.5 (2.43)	< 0.5 (3.00)	% of fields with resistances ≥ 3.0 MPa
1992	34	16	28	40	43	75
1993	36	12	42	49	53	77
1994	37	14	41	47	53	61
1995	49	35	47	52	60	76
1996	123	29	45	51	58	55
1997	96	32	44	50	55	74
1998	43	16	42	52	61	79
1999	44	26	45	55	53	65
2000	47	32	45	48	50	85
2001	37	26	33	40	47	57
2002	30	25	41	51	56	65
2003	0	-	-	-	-	-
2004	26	26	44	55	61	62
Mean	602	25	42	49	55	65

It can be seen that *c*. two-thirds of fields had resistances greater than 3 MPa, the upper threshold for root growth, in some part of the potential profile for root growth. On average, this limiting resistance was encountered at *c*. 55 cm below the top of the ridge, or *c*. 45 cm below the surface of a flat profile (generally, typical ridges on 91 cm rows were *c*. 10-12 cm higher when compared with a level soil surface). A cultivation depth of 45 cm is easily achievable by most subsoiling implements with multiple tines, for example on bedformers. Looking at the mean depth for individual seasons, the maximum depth of cultivation required would have been *c*. 50 cm below a flat soil surface but there were obviously some soils with deeper compaction which could not be reached without deeper, more dedicated subsoiling implements, i.e. those not attached to some other cultivation toolbar. In some seasons (e.g. 1992, 2001), root growth would have been severely impeded at depths just below the plough layer. It is imperative that such shallow compaction is removed before planting since the growth rate of roots would be slowed considerably or even stopped in such circumstances, leading to shallow rooting systems with a limited ability to extract water and nutrients.

Generally, very rapid rates of root growth would only occur throughout the loose soil within the ridge profile (< 25 cm depth) but in a limited number of fields only the top 12-16 cm of the ridge had sufficiently loose soil to produce root growth rates of 1.5-2 cm/day. This means that as soon as roots were produced below the seed tuber, their progress would be restricted by the strength of the soil. On average, resistances which would reduce growth rates to less than half of the maximum were encountered around 42 cm below the top of the ridge or *c*. 32 cm below a flat surface. This corresponds closely with the plough depth in many of these fields. The rate of extension of roots would slow rapidly from 1 to 0.2 cm/day between 40 and 60 cm below the ridge apex with a resistance of *c*. 2.4 MPa (equating to a growth rate of one-quarter of maximum) typically occurring at *c*. 50 cm depth. Therefore, in general, root growth rates will be most rapid in the ridge profile which is usually created by a destoner, slower in the rest of the plough layer and then decrease rapidly thereafter. If soil below the plough layer could be reduced to 2 MPa as opposed to 2.5 MPa, maximum rooting depth would be 11 cm deeper, equivalent to *c*. 8 mm of available water on a medium sandy loam soil.

These data show that for most potato crops in the UK, the rate and depth of root penetration are restricted by soil conditions. Two-thirds of fields have soil resistances likely to impede root penetration severely, if not completely, within the top 80 cm of soil (measured from the top of the ridge). Around half of the fields surveyed had an upper limiting resistance for root growth at less than 65 cm below the top of the ridge, with 10 % of fields having a severe restriction as shallow as 45 cm. This survey, therefore, shows the extent and severity of the problem of soil compaction in potato crops. This is undoubtedly leading to a waste of valuable resources as well as severely reducing tuber yield and quality.

Alleviating the effects of compaction through cultivation

It is important to understand that whilst compaction has a severe effect on potato growth, cultivating soil without first quantifying the extent and severity of any compaction may not prove to be advantageous if a) compaction is not present, b) soil conditions are too wet to achieve shattering of any pan or compact zone or c) the soil recompacts over a short period of time. In order to put the benefits of any cultivation, and especially subsoiling, into context, it was decided to compare the results of artificial compaction experiments with subsoiling and cultivation experiments.

Results from compaction experiments

The results from many experiments since the 1940's that have measured the effects of artificial compaction of soil in a range of crops have shown almost universally that crop yield is decreased in compacted soil compared with uncompacted soil. In the 16 experiments that could be found that involved potatoes, 13 experiments showed a significant ($P < 5$ %) yield decrease owing to compaction (Table 7). Some of the differences between compacted and uncompacted soil were massive 25-38 t/ha (Timm & Flocker 1966; Van Loon *et al.* 1985; Stalham *et al*. 1997). Over all these experiments, artificial compaction reduced yield by *c.* 18 t/ha so there can be no issue that potatoes are severely affected by compaction.

TABLE 7. FREQUENCY OF SIGNIFICANT EFFECTS AND THE DIRECTION OF THE EFFECT OF COMPACTION ON TUBER YIELD IN POTATOES

Author	No. of expts	No. of expts with significant effect (P ≤ 5 %)	Effect on total tuber yield (significant results only and size of effect, t/ha)	Notes
Flocker *et al.* (1960); Timm & Flocker (1966)	3	3	Decrease 1. Uncompacted 37.0; Compacted 23.8 2. Uncompacted 38.4 Moderately compacted 25.2 Severely compacted 20.9 3. Uncompacted 53.8 Moderately compacted 31.8 Severely compacted 15.5	Severe compaction significantly decreased the proportion of plants emerging and increased the proportion of deformed tubers.
McDole (1975)	1	1	Decrease 1. Uncompacted 39.8 Compacted 25.8	Compaction increased the quantity of malformed tubers.
Van Loon & Bouma (1978); Van Loon *et al.* (1985)	4	2	Decrease 1. Uncompacted 67.4 Compacted subsoil 42.4 2. Uncompacted 56.8 Compacted subsoil 49.2	Compacted subsoil was worse than topsoil compaction. Topsoil compaction increased the proportion of tubers with secondary growth.
Van Oijen *et al.* (1995)	2	2	Decrease 1. Uncompacted 12.4 (dry weight) Severe compaction 7.8 2. Uncompacted 11.4 Severe compaction 9.1	
Rosenfeld (1997); Stalham *et al.* (1997)	3	2	Decrease 1. Uncompacted 44.0 Compacted 29.5 2. Uncompacted 80.9 Compacted 40 cm 72.2 Compacted 10 cm 52.4	Shallow (10 cm) compaction was worse than deep (40 cm). Irrigation only partially compensated for compaction in second season whilst in first season irrigation had no effect in compacted soil.
Stalham (1998)	1	1	Decrease 1. Cultivated dry 68.1 Cultivated wet 59.8	Cultivating seedbed whilst wet reduced yield significantly compared with dry conditions but artificial compaction had no significant effect.
Copas & Bussan (2004)	2	2	Decrease	
Total	16	13		

Results from cultivation and subsoiling experiments

Clearly, compaction has a severe effect in potatoes and there is considerable risk of it being created by modern equipment both in potatoes and preceding crops. Depending on the depth of the compaction, cultivations can be targetted at breaking up compacted layers but their efficacy is dependent on soil conditions, principally soil water content. In logic, deep cultivation operations are only of interest if they produce beneficial changes in soil properties. In a literature review of crops other than potatoes, 49 experiments where subsoiling was carried out showed that 43 of them produced a decrease in soil resistance, bulk density or soil strength by subsoiling. However, less than half (24) of the experiments showed a significant ($P \leq 5$ %) yield increase as a consequence of subsoiling and five showed a significant yield decrease. In a more thorough review of the data relating to potatoes, 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 (Table 8). In the situations where there was a significant increase in yield from subsoiling (> 30 cm 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.

TABLE 8. FREQUENCY AND DIRECTION OF SIGNIFICANT EFFECTS OF CULTIVATION AND SUBSOILING TREATMENTS ON TUBER YIELD IN POTATOES

Author	No. of expts	Expts with signif. effect (P ≤ 5 %)	Effect on yield (mean of significant results only (t/ha), where given)	Notes
McDole (1975)	1	1	Increase	Cultivation depth 30 cm. Spring ploughing better than autumn ploughing resulting in higher total and US No 1 yield and fewer malformed tubers.
Bishop & Grimes (1978)	8	7	Increase Conventional 45.6 Precision subsoiled 49.4	Cultivation depth 60 cm. Only effective where subsoiled in year of production not in previous year.
McEwen & Johnstone (1979)	4	0		Cultivation depth 23-46 cm
Rowse & Stone (1980)	1	1	Increase Normal 29.9 Subsoiled 34.1	Cultivation depth 45 cm.
Stone (1982)	1	0		Cultivation depth 90 cm
Buxton & Zalewski (1983)	3	1	Decrease Chisel (spring) 59.2 Chisel (autumn) 51.9	Cultivation depth 40 cm. Chisel ploughing and bedding in autumn followed by chisel ploughing beds in spring reduced yield *c.f.* spring-only cultivations including normal chisel and mouldboard ploughing.
Ross (1986)	1	1	Increase Conventional 24 Deep tillage 32	Cultivation depth 40-50 cm. Deep chiselling beneath rows increased yield when seasonal irrigation < 200 mm but no effect when irrigation > 200 mm.
Marks & Soane (1987)	7	1	Decrease Control 55.1 Subsoiled 50.4	Cultivation depth 45 cm
Ibrahim & Miller (1989)	2	2	Increase Not subsoiled 56.4 Subsoiled 62.3	Cultivation depth 45 cm. Subsoiling only increased yield where irrigation was infrequent (4 days on sand, 14 days on loam soil).
Parker *et al.* (1989)	1	0		Double Digger increased total root length but had no effect on yield
Dickson *et al.* (1992)	3	3	Increase Zero traffic 52.5 Conventional traffic 46.1	Fewer clods in zero traffic systems.

Continued

Author	No. of expts	Expts with signif. effect (P ≤ 5 %)	Effect on yield (mean of significant results only (t/ha), where given)	Notes
O'Sullivan (1992)	1	1	Increase Normal traffic 47.5 Zero traffic 54.6	Cultivation depth 40 cm. Subsoiling only increased yield where no traffic. No effect with normal traffic.
Halderson *et al*. (1993)	3	1	Decrease Conventional 35.7 Subsoiled 31.9	Cultivation depth 38-46 cm. Subsoiling 35 days after planting within furrows reduced yield owing to root pruning. Earlier subsoiling no effect.
Sojka *et al*. (1993a; b); Westermann & Sojka (1996)	10	2	Increase Conventional 38.9 Zone subsoiling 42.8 Disk 34.2 Disk + zone subsoil 41.5	Depth of cultivation 46 cm. Subsoiling increased infiltration of water and decreased erosion.
Young *et al*. (1993)	1	1	Increase Conventional 40.3 Zero traffic 48.1	Size of rooting system was increased in zero traffic.
Pierce *et al*. (1995)	4	2	Increase Mouldboard plough 38.9 No mouldboard plough 44.0	Non-mouldboard ploughing (rotavator or Paratill®) in spring increased yield *c.f.* autumn ploughing.
Ekeberg & Riley (1996)	7	3	Increase Conventional 32.6 Direct planting 34.5	Direct planting increased tuber yield at final harvest *c.f.* autumn mouldboard ploughing.
Carter *et al*. (1998)	3	0		Cultivation depth 20-30 cm. Shifting primary tillage from autumn to spring or replacing mouldboard with chisel plough had no effect on soil properties or yield.
Holmstrom & Carter (2000)	8	0		Subsoiling gave marginal improvement in soil physical conditions.
Carter *et al*. (2001)	6	1		Cultivation depth 20 cm. Moving from conventional mouldboard plough in autumn to chisel plough in spring had no effect.
Wolkowski & Breuer (2003)	1	0		Cultivation depth 36 cm. No effect on yield when comparing mouldboard ploughing, chisel ploughing or Paratill® subsoiling
Copas & Bussan (2004)	7	0		Cultivation depth 40 cm.
Total	83	28		

So why are the results from compaction and subsoiling experiments apparently conflicting? It is possible that some factor other than soil conditions might be reducing yields. The yields of uncompacted plots in compaction experiments (54 t/ha; Table 7) were much greater than in the subsoiling experiments (mean *c*. 42 t/ha; Table 8), suggesting that some factor other than soil conditions was having an effect. Accepting that subsoil compaction is indeed present in many UK potato soils (Table 6), should there not be more positive yield responses to subsoiling? Table 8 would suggest that only one third of fields would respond. So why is there little response when compaction has such a severe effect?

First, the presence or absence of compaction prior to subsoiling treatments being imposed is crucial. In the experiments in Table 8 in which cultivation was carried out below 30 cm (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. Only a third of authors (Ross 1986; Marks & Soane 1987; Ibrahim & Miller 1989; O'Sullivan 1992; Pierce *et al.* 1995) stated that compaction was present prior to subsoiling treatments and most supported these statements by presenting data relating to soil resistance or bulk density. Researchers who stated that they had a compaction problem usually observed a decrease in soil resistance following subsoiling and three-quarters of those authors found a yield increase in response to subsoiling. In the absence of any information on compaction, it is difficult to determine whether subsoiling would be expected to be beneficial or not.

Secondly, subsoiling conducted when soil is too wet to achieve brittle failure is unlikely to loosen the subsoil. O'Sullivan (1992) admitted that the clay loam soil in his experiment was not loosened very effectively because the subsoil was wetter than the plastic limit at the time of cultivation even though the growing season prior to subsoiling was drier than average. On two silt soils stated "not to be suffering from subsoil compaction" prior to subsoiling, Marks & Soane (1987) found that subsoiling reduced yields. An explanation offered was that these soils were structurally unstable at depth and therefore likely to be detrimentally affected by cultivation. In Table 8, many of the subsoiling experiments were cultivated at depth in the spring immediately prior to planting when most soils would be above their plastic limit for cultivation. Where soil type was given in Table 8, *c.* 56 % of fields were of sand or sandy loam origin, with the balance being sandy clay loam, silt loam or clay loam, soils likely to be in a plastic state in the spring and unlikely to respond to subsoiling. To be most effective, subsoiling needs to be carried out in the preceding summer or autumn on most soils when the subsoil is likely to be at its driest.

Thirdly, tines working at the incorrect spacing or depth, either too shallow or too deep, may fail to fracture any pan or remove the loading on compacted subsoils at depth. Cultivating too deeply below a pan can fail to shatter the pan itself. Compaction is usually comparatively uniform where it is created artificially in experiments using rollers etc., whereas in a field it may be inherently variable. Some areas may therefore not require subsoiling whilst other areas would benefit. The extent of the compacted area in a field would then determine the overall yield benefit from subsoiling. Some experiments have also reported the effects of altering the entire cultivation strategy rather than either subsoiling or not subsoiling, e.g. from mouldboard ploughing to reduced or minimal tillage with subsoiling, therefore confounding the effects. Sojka *et al.* (1993a), in applying their zoned tillage cultivations, had to traffic every furrow during planting and subsoiling whereas non-subsoiled plots had half the number of wheelings. Therefore, zone-subsoiling was most likely creating additional compaction. Angled subsoil tines were positioned under the rows rather than directly under the wheels, so compaction created by the subsoiling tractor may have remained after cultivation.

Fourthly, adequate rainfall or supplementary irrigation may reduce the benefit of a larger rooting system created by subsoiling, particularly in dull, wet years. Parker *et al.* (1989) found an increase in rooting density from subsoiling with a Wye Double-Digger but only where irrigation was applied (Table 9), yet there was no significant effect of subsoiling on yield. Ibrahim & Miller (1989) found that subsoiling only increased yield where irrigation was infrequent (4 days on sand, 14 days on loam soil) but not where frequently applied (daily and 7 days, respectively). In clay-dominated soils, where subsoiling may aid drainage in wet seasons, the presence of tile, plastic or mole drains may reduce the benefits of subsoiling.

TABLE 9. EFFECT OF CULTIVATION AND IRRIGATION REGIME ON TOTAL ROOT LENGTH (KM/M^2; PARKER *ET AL*. 1989)

	Irrigation regime		
	Unirrigated	Irrigated	SE
Ploughed	10.1[ab]	7.9[a]	Not given but CV = 37.6 %
Wye Double-Digger subsoiled	12.5[b]	17.2[c]	

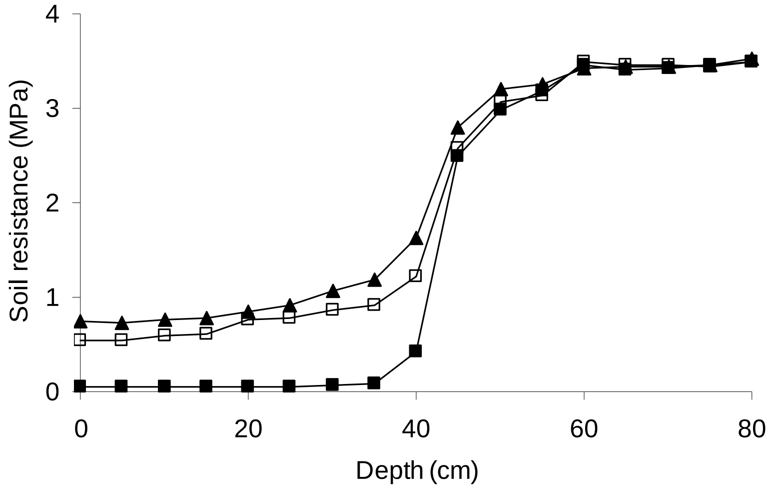
[abc] Values with same letter suffix were not significantly different at P=5 % level

Fifthly, subsoiling post-planting is often carried out on sandy soils to reduce soil resistance created by planting cultivations. Owing to the ridge configuration of potatoes, these subsoiling operations are by nature ‘controlled’ or ‘precision’ cultivations, i.e. targeted in the furrows or wheelings of potato beds to avoid disturbing planted seed tubers. Roots will not be damaged by such cultivations if conducted soon after planting but by 3-4 weeks after emergence roots will have met under the furrows of adjacent rows (Stalham & Allen 2001). Severe root pruning will occur if subsoiling is carried out too late, undoing many of the possible benefits. Halderson *et al.* (1993) carried out precision subsoiling in one year at 35 days after planting but this resulted in significant disruption of the ridge, exposed the sprouts of seed tubers by 5-8 cm and caused a significant reduction in yield. Precision subsoiling at 15 days after planting had no effect on yield.

Lastly, the rate of re-compaction following cultivation is important. If subsoiling is conducted in the autumn, subsequent operations in the spring during planting may undo some of the benefits of subsoiling due to recompaction by traffic. Subsoiling well-structured soils, or those with appreciable clay content, under dry conditions often achieves considerable catastrophic shattering of the profile which persists for one or more seasons unless recompacted. By contrast, in sandy soils or those with little structure, fissuring can be minimal and the soil particles often rearrange themselves in much the same structure as prior to cultivation. A number of papers have shown that subsoiling effects on structureless soils are often short-lived, only lasting the duration of the cropping season (Porro & Cassel 1986; Mead & Chan 1988; Evans *et al.* 1996; Willis *et al.* 1997; Hamilton-Manns *et al.* 2002). Busscher *et al.* (1986) found that whilst the residual effects of subsoiling on soil resistance could be seen in the year following cultivation, soil strength had increased beyond 1.5 MPa which was regarded as root-limiting. Frequently, subsoiling takes place in the autumn in the UK when the soil should be at its driest. With sandy or structureless soils, sufficient reconsolidation may occur over winter to reduce the effectiveness of the cultivation. To achieve the maximum benefit, such soils would be better subsoiled in the spring, providing their water holding capacity is low enough to ensure they are below their critical limit for brittle failure. However, any soil with clay content > 10-12 % (i.e. loamy sand) is likely to be above its critical moisture limit for cultivation at depth during a typical UK spring.

Busscher *et al.* (2002), addressing the problems of reconsolidation of structureless loamy sands during the winter between growing seasons, found that the cumulative rainfall was largely responsible for the reconsolidation of soils following initial deep tillage operations. Intensive irrigation on structureless sands, or soils rendered structureless through over-cultivation such as destoning and bed-tilling during potato planting, can lead to serious reconsolidation of the soil profile within a few months or even weeks. An example is given in Figure 9 where a medium-coarse sand was planted after vigorous destoning in February whilst the soil was wet. The soil both in the ridge and below the plough layer recompacted appreciably in the first three weeks after planting following heavy rainfall and continued to reconsolidate over the next six weeks following three irrigation events after emergence. One of the consequences of using a high energy input during secondary cultivations (e.g. bed-tilling or destoning) whilst the soil is wet is a decreased wet aggregate stability which increases the risk of surface capping and poor water infiltration to the ridge.

FIGURE 9. SOIL RESISTANCE IN A SAND SOIL IMMEDIATELY AFTER PLANTING AND THREE AND NINE WEEKS LATER. AT PLANTING, ■; THREE WEEKS AFTER PLANTING, □; NINE WEEKS AFTER PLANTING, ▲. DEPTH RELATIVE TO TOP OF PLANTED RIDGE. (STALHAM 1997, UNPUBLISHED).



As a conclusion to this section, the apparent lack of effect of subsoiling in experiments is likely to be the result of experimental deficiencies rather than intrinsic merit as compaction has been shown to have a severe effect. Often researchers have failed to quantify the extent of any compaction in their experiments prior to imposing their cultivation treatments and the reader is left to assume that the soil was compacted before any treatments were carried out. This point is crucial, since subsoiling uncompacted soil is likely to be of little benefit. Where soil parameters have been quantified, significant reductions in bulk density, resistance or other measures of soil loosening have been reported. In some cases, subsoiling has been conducted in soil too wet for widespread soil loosening to occur and there is clearly a limited window for subsoiling on heavy clay-dominated soils in the UK, typically August-October before the soils refill over winter. Where sandy soils readily re-compact following cultivation, there will be only a short-term benefit from cultivation which may not persist long enough if conducted in the autumn prior to spring crops being planted. Therefore, subsoiling (in the presence of compaction) is only likely to be of benefit if timed correctly in the cropping sequence and its timing is a recurrent requirement of good soil management. As this review has shown, severe compaction with respect to potatoes is often encountered within 55 cm of a flat soil surface but major reductions in soil resistance below the plough depth would also be beneficial to root growth. Potato growers should be trying to avoid cultivations that create compaction during planting since there is very little that they can do post-planting to undo the effects of compacted soil once present.

Using the thresholds of soil resistance to judge when to cultivate

The data in this review would suggest that large increases in the rootability of the profile would be made if Ω was kept below 1.5 MPa in the topsoil and < 2.4 MPa in the subsoil, with 3.0 MPa being especially targeted for corrective action. These limits, 1.5, 2.4 and 3 MPa, correspond to half-, quarter- and tenth-rate of average maximal growth rate. The minimum limit of soil resistance is set by the ability to travel with machinery in the field without undue sinkage, although the area between wheelings could be maintained at very low resistance in controlled wheeling systems. However, judging resistance is difficult and penetrometers of the type used in this review are expensive (*c*. £3-4000) and therefore beyond the reach of most individual growers. There are simpler models (e.g. Dickey John, *c*. £200) that record soil resistance using a dial gauge which can be used to quantify the degree of compaction but the relationship of the resistance reading to the Eijkelkamp penetrometer used here is unknown. Mini- or pocket-penetrometers have limited penetration depth (i.e. a few cm), have blunt rather than pointed tips and are really only suitable for identifying pans or zones of high resistance using profile pits. These cheaper tools are, however, suitable for examining the effects of cultivation operations on soil resistance, such as subsoiling or operations that compact the soil at certain depths in wet soil as well as loosening it at shallower depths. A key challenge for growers is to relate the visual characteristics of their soil profiles to the quantitative measures reported here.

Having identified compaction or areas of high soil resistance, at what depth should the soil be cultivated? Unless the area of resistance is beyond the depth of cultivation equipment, then the answer would be at, or a few cm below, any pan, or as deep as possible where the resistance progressively increases down the profile. The exception to the latter rule would be where there is insufficient loosening or shattering owing to the weight of soil or degree of compaction in the horizons nearer the surface of the soil. Occasionally, removing superficial compaction will 'unload' the subsoil and reduce soil resistance deeper than the cultivation depth. The last question would be when to cultivate? The answer would be at the optimum moisture content to achieve the desired effect of maximum lateral and vertical shattering, which means drier soils than generally recognized as necessary for benefit. The only exception would be where increased soil strength in dry soils post-harvest makes it impossible to pull deep or multi-tined implements.

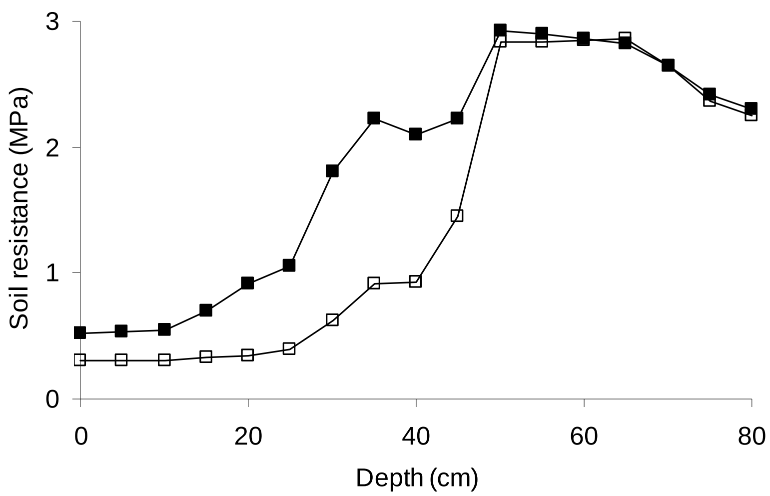
Examples of cultivation practices which can remove or create compaction in potato fields

This section of the review presents measurements of the effects of cultivation practices on soil resistance, sometimes beneficially and on other occasions, detrimentally. The order follows the logical sequence of cultivation for potato crops. The depth in relation to a flat soil surface or the top of the planted ridge is given in the figure caption.

Previous cropping

In wet seasons, compaction can be created by harvesting (e.g. combines and root or salad crop harvesters). This compaction, if superficial, can mostly be removed by ploughing or shallow cultivations, but often the effects extend deeper into the subsoil which needs remedial action at depths below the plough layer (Figure 10). Sugar beet harvesting in wet soil with towed trailers often leads to compaction at considerable depths. It should be noticed that there was pan at 50-65 cm in both fields, with the resistance decreasing below 65 cm.

FIGURE 10. EFFECT OF PREVIOUS CROPPING ON SOIL RESISTANCE IN SPRING PRE-PLOUGHING. DEPTHS RELATIVE TO FLAT SURFACE. SUGAR BEET, ■; WINTER WHEAT, □. (STALHAM 1994, UNPUBLISHED).

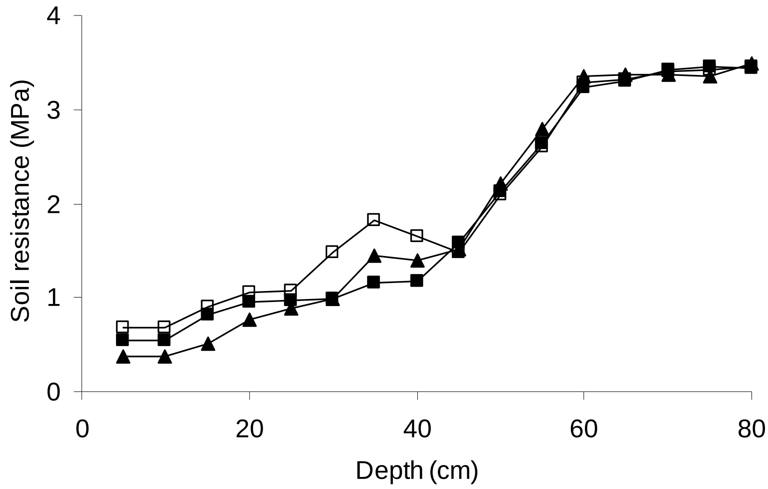


Ploughing

Ploughing for potatoes is often carried out in winter when soils are at field capacity and therefore prone to smearing and compaction. Figure 11 shows an example of the soil resistances of October (dry), December (wet) and April (wet) ploughing conducted over the winter-spring period in the same field with a uniform sandy loam soil type. It clearly shows the pans created by December and April ploughing at 30-35 cm depth, with the effects of the

December ploughing being particularly severe. Using the relationship in Figure 8, it would take roots 12 days to grow from 25 to 40 cm depth with October ploughing compared with 18 days for December ploughing. In addition, rooting would be restricted to *c*. 60 cm for all three ploughing dates owing to soil resistance exceeding 3 MPa at this depth. In soils such as sands and loamy sands, however, the soil can be adequately ploughed immediately prior to planting unless there is appreciable trash to bury and decompose.

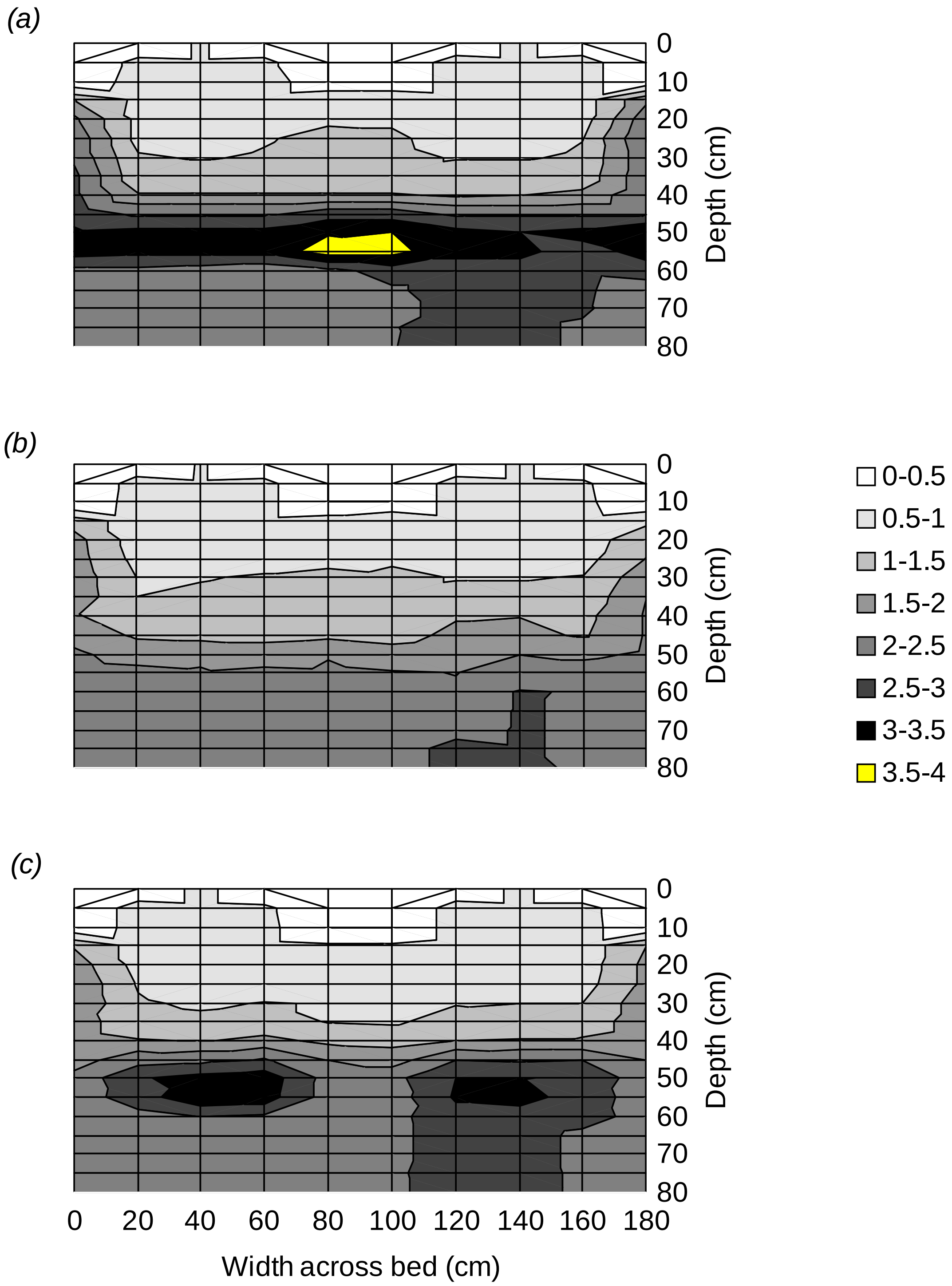
FIGURE 11. EFFECT OF TIME OF PLOUGHING ON SOIL RESISTANCE IN A SANDY LOAM SOIL. OCTOBER (DRY), ■; DECEMBER (WET), □; APRIL (WET), ▲. DEPTHS RELATIVE TO PLOUGHED SURFACE. (STALHAM 1996, UNPUBLISHED).



Subsoiling

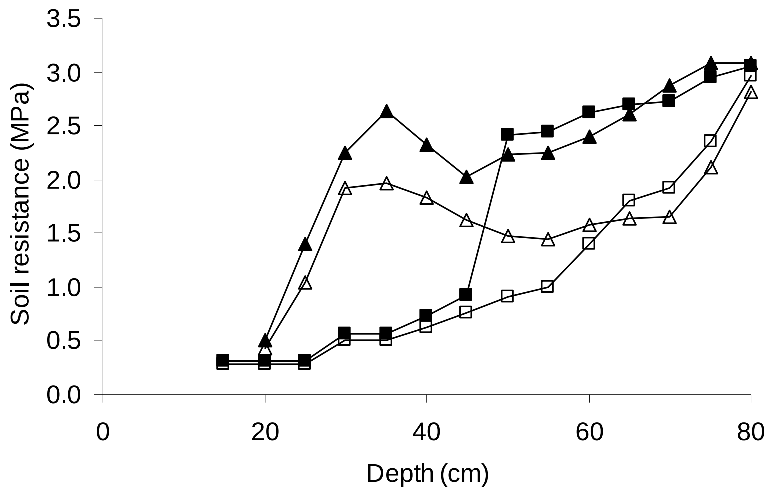
Figure 12 shows the effect of subsoiling on profile soil resistance following planting in a field known to have compaction problems at 40-50 cm depth below the surface of the stubble, sufficient to prevent root penetration (i.e. > 3 MPa resistance). Subsoiling was carried out using a bedformer with four winged (25 cm width) subsoil tines operating at 50 cm depth. Subsoiling in the autumn when the soil was dry and friable resulted in the removal of the compacted pan, the resistance being reduced from 3-4 MPa to 1.5-2 MPa across most of the width of the bed, thereby allowing roots to penetrate down to over 80 cm rather than 50 cm. Subsoiling in wet soil at planting in April failed to remove the compaction underneath the rows since there was little shattering from the subsoil wings as a consequence of the soil exceeding its plastic limit for cultivation. Many growers feel that they can tackle subsoil compaction in the spring at planting with subsoil tines on the bed-former but it is unlikely that the soil would be sufficiently dry at depth to prove beneficial in terms of soil shattering as shown by the example in Figure 12. The soil has to be coarsely-textured for subsoiling in spring to have any appreciable positive effect and, more importantly, below its plastic limit.

FIGURE 12. PROFILE SOIL RESISTANCE (MPA) IN A CLAY LOAM FOLLOWING PLANTING. *(A)* UNSUBSOILED; *(B)* SUBSOILED DRY (SEPTEMBER); *(C)* SUBSOILED WET (APRIL). DEPTHS RELATIVE TO PLANTED RIDGES. (STALHAM 1993, UNPUBLISHED).



Subsoiling is occasionally carried out post-planting in order to remove compaction created during the planting operation but obviously is restricted to the furrows in order to prevent the planted beds or rows being disturbed too much. Figure 13 shows the results of post-planting subsoiling at 55 cm below the top of the ridge on a sand soil. One tine was 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 45 cm, both above the depth of cultivation and, importantly, some 20 cm below the depth of the tine as a consequence of the 'unloading' of the soil deep in the profile. Underneath the wheeled tramlines, the same positive effects down to 75 cm were observed as for the centre of the bed. Subsoiling also reduced compaction slightly above 45 cm as a consequence of the movement of the subsoiler leg through the soil.

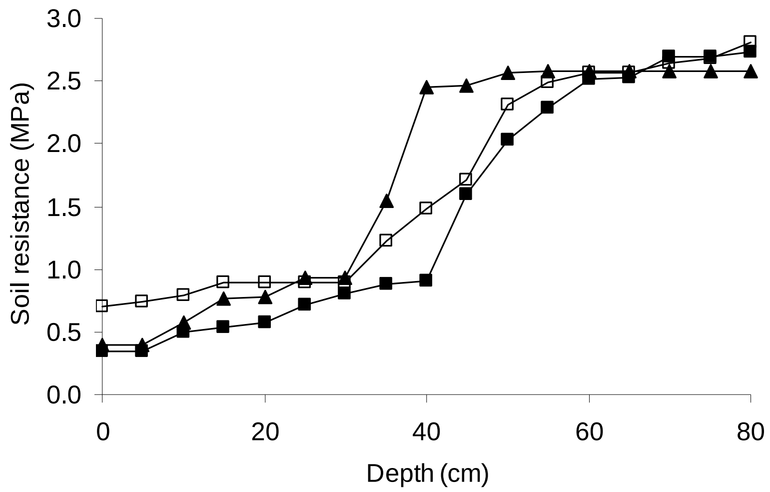
FIGURE 13. EFFECT OF POST-PLANTING SUBSOILING IN WHEELED AND CENTRE FURROWS OF BEDS ON SOIL RESISTANCE ON A SAND SOIL. CENTRE FURROW, NOT SUBSOILED, ■; CENTRE FURROW, SUBSOILED, □; WHEELED FURROW, NOT SUBSOILED, ▲; WHEELED FURROW, SUBSOILED, Δ. DEPTHS RELATIVE TO TOP OF PLANTED RIDGE. (STALHAM 1993, UNPUBLISHED).



Bed-forming

Damage created when bed-forming frequently arises from the towing tractor which often has to generate significant draught on a cultivated soil. There is also little flexibility in timing for this operation which, with the exception of a few areas of heavy soil around the UK, is generally carried out in the spring when the subsoil can be very wet. Particular attention should therefore be paid to the tractor and its tyres. The tyres should be as large as possible and set at the lowest safe inflation pressure. For all subsequent operations on the bed or if beds have to be re-formed, the potential for damage increases dramatically, since any tines or shares are working much closer to the subsoil. Any rain on over-wintered beds or beds drawn up some time ahead of planting will be concentrated in the furrows. Bed-forming when the soil is wet can create serious smearing at the base of the furrows (Figure 4). Cultivating beds in the spring when the soil was wet and had slumped over winter was found to create compaction between 30 and 45 cm deep at the edges of the bed (Figure 14). There was a smaller increase in compaction at similar depths in beds drawn up in late October following rainfall in early October. The lowest resistance readings were obtained from bed-forming when the soil was at its driest at the end of the summer. It must be emphasized that it is the soil conditions (i.e. wetness) not the calendar date that is crucial. In some winters following dry summers, well-structured subsoils can be relatively dry at depth owing to the channelling of winter rainfall through cracks and fissures which prevents uniform wetting of the subsoil. In the example presented in Figure 14, if the compaction was not removed subsequently, the roots of crops grown in the beds drawn up in April would take 62 days to grow from 30 to 60 cm depth compared with only 40 days in beds formed in September. This is a considerable reduction in root growth rate and therefore maximum rooting depth. Unless bed-tilling or destoning is carried out at, or below, the base of the bed or remedial subsoiling is carried out, compaction of this type would remain throughout the life of the crop and restrict rooting below alternate furrows of planted beds.

FIGURE 14. SOIL RESISTANCE 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. (STALHAM 1994, UNPUBLISHED).

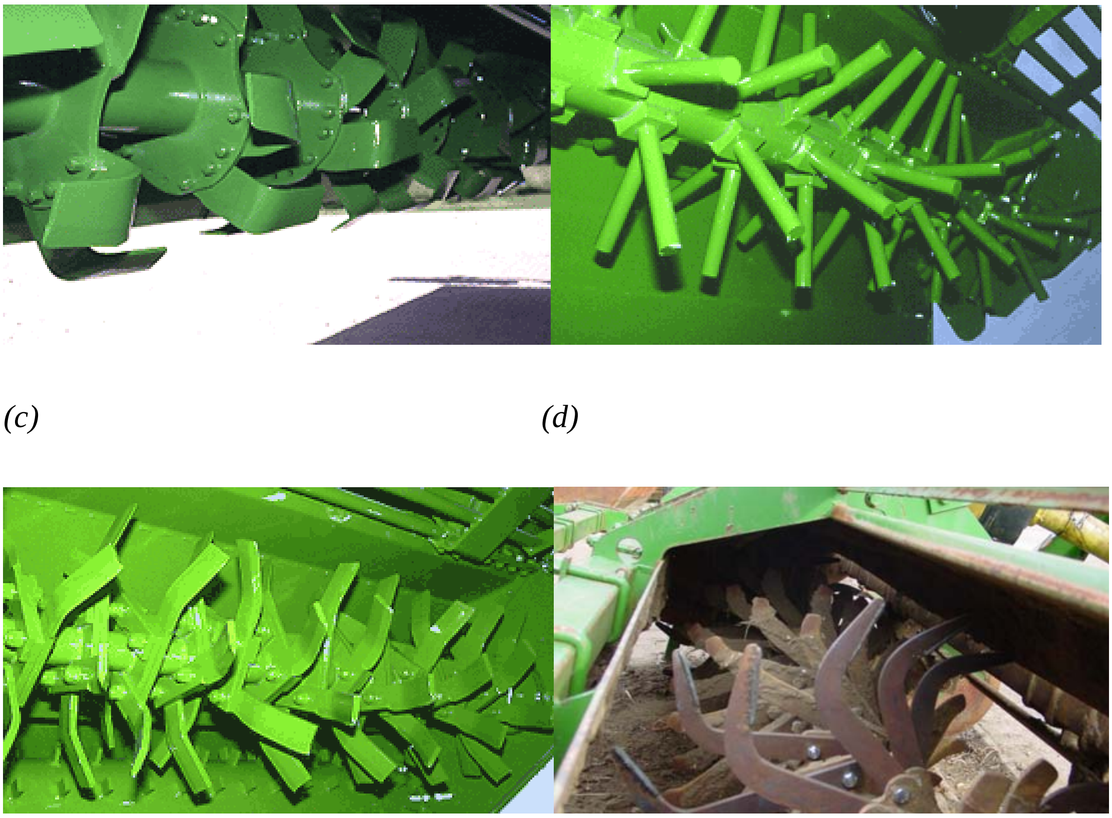


Bed-tilling

Bed-tilling is carried out when the clay content of soils is sufficiently high for clods to form during initial cultivation(s) which can dry out and lead to tuber damage at harvest and also to produce a finer tilth for common scab control. There are three basic types of rotary bed-tillers: those with conventional L-shaped blades, those with straight spikes or rods and those with hooked tines (Figure 15). With high-powered tractors, there can be a tendency to produce an over-fine tilth resulting from a combination of slow forward speed and high rotor velocity. This slows the operation, wastes power, wears out tines and gearboxes faster and creates ridges with unstable, structureless soil. Bed-tillers with L-shaped blades can cause smearing at the base of the cultivated area often leading to shallow pans even in moderately sandy soils and particularly on clay-dominated soils where bed-tillers tend to be used to create a clod-free growing medium. Increasing the forward speed and slowing the rotor will help reduce the risk of a smeared pan. Spiked rotors leave a coarser clod structure than L-blades but significantly reduce the risk of a compact pan. Hooked tines come in a variety of profiles and lengths but ‘pick’ the soil rather than cutting.

FIGURE 15. TYPES OF TINE ON BEDTILLERS. *(A)* CONVENTIONAL L-SHAPED; *(B)* SPIKE OR ROD; *(C)* ANGLED BLADE; *(D)* PICK TINE

(a) *(b)* *(c)* *(d)*



As with any rotary cultivator working along a horizontal axis, smearing of the soil at the base of the cultivation depth is a problem on all soils, especially when wet. Figure 16 shows the effect of different types of tines on soil resistance during a bed-tilling operation. The L-shaped blade smeared the profile at 25-30 cm depth below the top of the ridge. Clearly, in this example, the use of this implement was detrimental to soil structure at the base of the ridge and would slow root growth appreciably. The bed-tilling operation, even with bladed tines, did not improve the ridge soil structure to any extent visually compared with a destoner working on untilled beds and there was some evidence that rod and pick tine bedtillers created a pan at 30 cm, albeit slight. The bed-tiller is a tool to use with care during planting, particularly with respect to soil wetness and depth of cultivation. Figure 17 shows the smeared cuts made with pick tines working in soil much wetter than its plastic limit.

FIGURE 16. SOIL RESISTANCE FOLLOWING THE USE OF THREE DIFFERENT TYPES OF BEDTILLER WORKING ON A CLAY LOAM SOIL COMPARED WITH ZERO BED-TILLING. L-SHAPED BLADE, ■; STRAIGHT ROD-TYPE TINES, □; 'PICK' TINES, ▲; NO BED-TILLING, DESTONED ONLY, Δ. DEPTHS RELATIVE TO TOP OF PLANTED RIDGE. (STALHAM 1996, UNPUBLISHED).

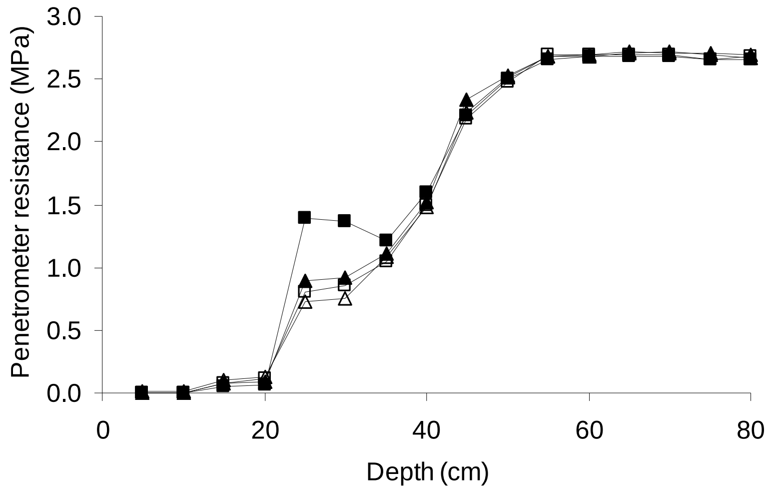
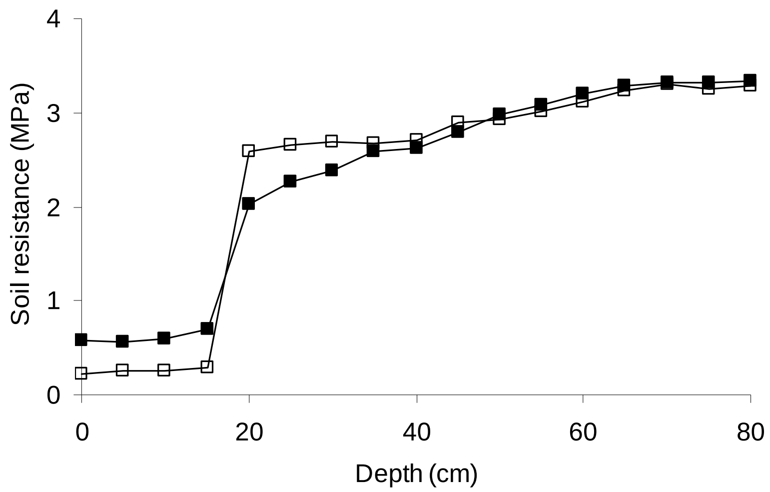


FIGURE 17. SMEARED PAN CREATED BY PICK TINE BED-TILLER WORKING IN SOIL ABOVE IT PLASTIC LIMIT

Destoning

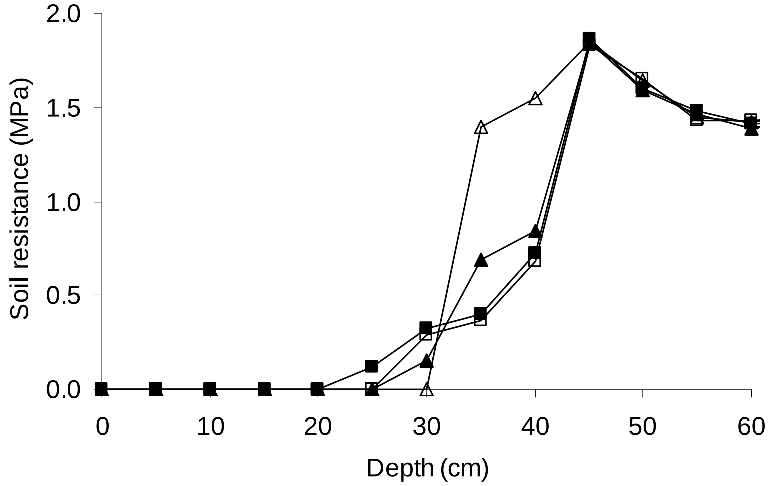
Figure 18 shows the effect of destoning in wet conditions on soil resistance in a sandy loam soil following bed-tilling. Although the soil was loosened soil in the top 15 cm of the bed, the destoner clearly caused an increase in soil resistance at 20 cm below the top of the ridge through working too deep in wet soil. Rather than creating a deeper zone of friable soil, in this case the operation of the destoner would have restricted root growth in the first two weeks after emergence. One major disadvantage of destoning is that soil compaction cannot be avoided if the soil is too wet. Since the destoner is usually the rate-determining step during seedbed preparation, the operation frequently occurs in advance of planting in marginal soil conditions. As a consequence, the destoning frequently results in soil compaction as the soil is too wet.

FIGURE 18. SOIL RESISTANCE IN BED-TILLED BEDS PRE- AND POST-DESTONING IN A SANDY LOAM. BEDS, ■; DESTONED BEDS, □. DEPTHS RELATIVE TO TOP OF PLANTED RIDGE (STALHAM 1993, UNPUBLISHED).



Destoning too deeply in an effort to create a fine seedbed can increase the amount of clod produced as soil is worked at a depth where plastic failure occurs. This leads to smearing of the profile immediately underneath the destoner share, an increased clod removal to the wheelings and, consequently, a shallower rather than deeper seedbed. Figure 19 shows how progressively increasing the depth of destoning of bed-tilled beds from 20 cm to 41 cm initially improved the depth of seedbed without creating compaction. Increasing the depth to 30 cm increased the seedbed depth only marginally but slightly compacted the profile at 30-35 cm. Increasing the depth to maximum resulted in a severe increase in soil resistance underneath the destoner share which extended for *c*. 10 cm. Seedbed depth was only 30 cm despite working the bed 10 cm deeper since significantly more clod was produced by cultivating at the plough depth where the soil was wet. Much of this clod ended up in the wheelings and left an uneven bed surface making depth control difficult for the planter. Destoners should be run at a depth that achieves 5-6 cm of loose soil under the seed tuber and 13-15 cm of settled soil above it. Often this is shallower (i.e. 25-28 cm) than most growers think.

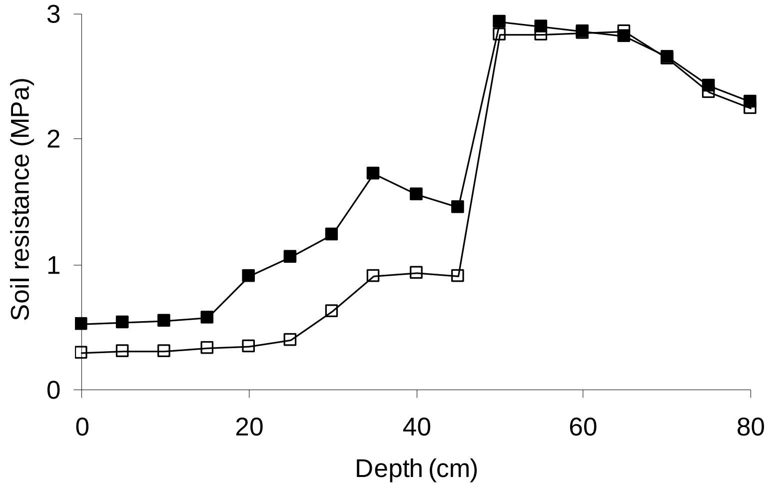
FIGURE 19. EFFECT OF DESTONING DEPTH ON SOIL RESISTANCE IN BEDS PRIOR TO PLANTING. 20 CM, ■; 25 CM, □; 31 CM, ▲; 43 CM, Δ BELOW TOP OF BED-TILLED BED. DEPTHS RELATIVE TO TOP OF DESTONED BED. (STALHAM 2005, UNPUBLISHED).



Combined planting operation (bed-forming, destoning, planting)

Figure 20 show the effect of delaying planting on soil resistance in planted rows. A slight (7 mm) rain shower caused planting to stop. The following day, an area was planted but it was still judged too wet to continue planting. Three further days elapsed before planting began again. Allowing three days' extra drying, even in early April, caused the soil to dry sufficiently at depth to allow planting without soil compaction. Allowing insufficient delay following rainfall created compaction from ridge apex down to 45 cm. All cultivation operations could be credited with causing the observed compaction. From the initial bed-forming, which was done at depth in wet soil, to the destoner and finally the planter which capped the soil with the re-ridging bodies, all machines created some degree of compaction at different depths throughout the profile. The increase in soil resistance created by planting too soon after rainfall in this example would increase the time taken for the rooting front to reach 60 cm from 72 to 86 days. At the point when root growth would cease (*c*. 70 days after emergence for a typical maincrop), the allowable soil moisture deficit would be reduced by 5 mm in the early-planted example compared with the crop planted after an additional two-day delay. Clearly, there is an obvious benefit to delaying planting until soil conditions are dry enough to work the soil without compaction occurring, even on relatively coarsely-textured soils.

FIGURE 20. EFFECT OF DELAY IN PLANTING AFTER RAINFALL ON SOIL RESISTANCE POST PLANTING IN A SANDY LOAM SOIL. 1-DAY DELAY, ■; 4-DAY DELAY; □. DEPTHS RELATIVE TO TOP OF RIDGE. (STALHAM 1994, UNPUBLISHED).

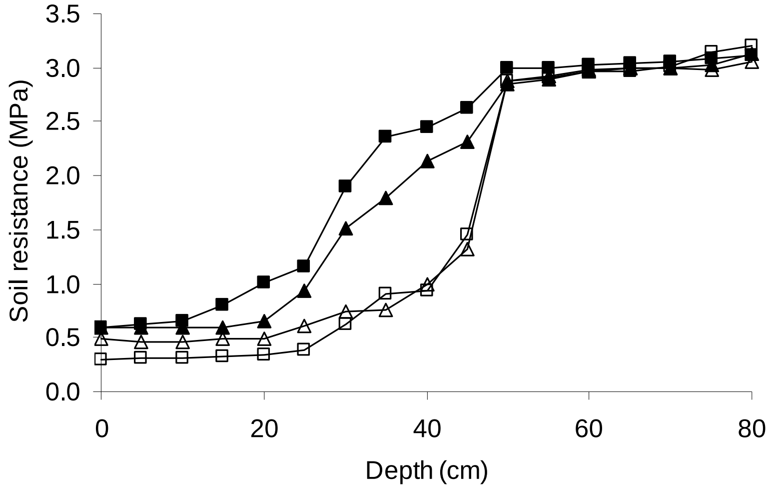


Non-plastic soils which do not readily smear can safely use ridge former plates or hoods on planters without the risk of creating a capped ridge. These can create a ridge profile which is less prone to slumping following heavy rain or irrigation or aid capture of water during irrigation for common scab control. Heavier soils are likely to be capped by planter formers and this is a serious problem on some soils in the USA.

Harvesting

Harvesting potatoes in wet conditions with trailers being towed off fields in poor traction conditions can lead to severe rutting and compaction. Tuber damage levels are also likely to be severe under such conditions or soil tare greatly increased, so harvesting should not be conducted under such conditions. However, the risk of losing crops completely if they are not harvested by late autumn often forces growers to mistreat the soil. An example of the persistent effects of a wet potato harvest on soil resistance is shown in Figure 21. It shows that in the third season after the potato crop, soil resistance was still much higher than where potatoes were not grown in the field. Remedial subsoiling after the potato crop and after the succeeding cereal crop failed to remove the subsoil compaction to any great extent. Admittedly, the first subsoiling operation was carried out immediately following the potato crop when the soil could not have been dry but the second was carried out after a moderately dry summer when the subsoil was dry and easily fractured into platy-type structure by hand. Despite subsoiling, soil resistance was high enough below 50 cm to prevent potato root growth, irrespective of previous cropping (Figure 21).

FIGURE 21. EFFECT OF POTATO CROP HARVESTED IN WET OCTOBER ON SOIL RESISTANCE IN THE SUCCEEDING CEREAL CROPS COMPARED WITH A CEREAL-OILSEED RAPE ROTATION. SEASON FOLLOWING POTATOES IN YEAR 1, ■; SEASON FOLLOWING WINTER WHEAT IN YEAR 1, □; THIRD SEASON AFTER POTATOES IN YEAR 1, ▲; THIRD SEASON FOLLOWING WINTER WHEAT IN YEAR 1, Δ. DEPTHS RELATIVE TO FLAT SOIL SURFACE. (STALHAM 1997, UNPUBLISHED).



Conclusions

There are a number of requirements of a potato seedbed, one of the most important being freedom from compaction. Soil compaction, as a consequence of increased soil strength or resistance, restricts the rate of downward extension of roots and their lateral movement within compacted pans. This reduces the potential uptake of nutrients and water. Soil compaction affects the physical properties of the soil such as the water release characteristics, the air capacity and nutrient availability, to different extents and directions depending on texture. It also reduces drainage potential, thereby increasing the risk of waterlogging.

Potatoes are very sensitive to compaction at all stages of growth from emergence to harvest but particularly in the first 3-4 weeks after emergence when growth rates of roots are rapid in loose soil, typically 1.5-2 cm/day. Shallow compaction immediately below the seed piece is therefore worse than deeper compaction since roots are growing most rapidly when they encounter the compaction and impeding them at this stage can have serious repercussions on later growth. Symptoms of compaction that growers can recognize include: delayed and uneven emergence; slow, incomplete and curtailed ground cover development; premature or rapid senescence; wilting of leaves on hot days even in wet soils; chlorotic or conversely dark green foliage owing to impaired nutrient or water uptake; severely reduced yield; increased outgrades from misshapen, bruised or green tubers.

The two main causes of compaction are wheelings from traffic and pans created by cultivation implements. Controlled wheelings in potatoes restrict the extent of compaction during planting and subsequent spraying operations but the draught force required to produce a seedbed often means severe compaction occurs in wheelings which restricts lateral movement of roots between beds. Wider, lower pressure tyres compress the soil over a bigger contact area but still permit more root growth in soil horizons closer to the surface than narrow tyres since the average increase in soil resistance is less with wide tyres than narrow. The width of the tyres in potato production is limited by the width of the furrows between beds. Wider tyres would be more beneficial in reducing severe soil compaction but must not so be wide as to compress or scuff the sides of the ridge since greening of exposed tubers may take place.

Compaction is frequently caused by working soil when it is at, or above, its plastic limit. Soil then shears by compressive rather than brittle failure leading to a smeared profile at the cultivation depth. Across all agriculture, there is a trend for the use of increasingly heavy and powerful machinery which is capable of carrying out work on soil that was once deemed impossible for working. This, in conjunction with the quest to plant increasingly large areas of potatoes in a shorter time, has increased the probability that operations will be carried out on soils that are too wet and therefore liable to compaction. Earlier planting increases the chances of operations being carried out in conditions where compaction is likely to occur. Growers consequently have to balance the advantages of planting early to establish early canopy cover with the disadvantages of compacting the soil which will considerably reduce canopy expansion and subsequent yield. On clay-dominated and other heavy soils, primary operations such as ploughing and bed-forming, must be carried out when the soil is below its plastic limit. This means in the early autumn in most seasons. Any effects of compaction will persist throughout the season and, once created, are impossible to remove completely.

The most important effect of compaction is the increase in soil strength or resistance. Unless roots are growing entirely within voids or continuous cracks in the soil, they must exert forces on soil particles to displace them. It is the reaction pressure of the soil that is the mechanical resistance to root growth and cone penetrometers currently provide the best estimates of resistance to root growth. Unpublished data from Cambridge University Farm from experiments conducted in commercial potato fields has shown that the downward extension of the rooting front can be predicted by measurements of soil resistance using a penetrometer. Growth rates were rapid when resistance was low (< 1 MPa) but slowed to half their maximal rate at resistances of 1.5 MPa and one-quarter rate at 2.4 MPa. Root growth was very slow at resistances of *c.* 3-3.5 MPa in most soils, although roots continued to extend deeper into well-structured subsoils using natural fissures and burrows. In structureless sands, there was a more rapid decrease in growth rate with increasing resistance: growth rates were reduced to half at a resistance of only 1 MPa and to a quarter at 1.8 MPa.

A survey of 602 commercial fields between 1992 and 2004 revealed that two-thirds of fields had resistances ≥ 3 MPa, the upper limit for root growth, in some part of the potential rooting profile. In 50 % of fields, this limiting resistance was encountered at *c.* 55 cm below the top of the ridge, or *c.* 45 cm below the surface of a flat profile. On average, resistances which reduce root growth rates to one-half or one-quarter of their maximum were encountered at 42 and 49 cm below the top of planted ridges. The existence of potentially damaging compaction is therefore widespread and much shallower than most growers imagine. Judging the soil resistance that warrants corrective action in terms of cultivation is difficult but large increases in the rooted volume of soil could be achieved if resistance could be kept below 2 MPa and certainly below 3 MPa throughout the profile. Increasing resistance in a sandy soil from 1.1 MPa (a low resistance subsoil) to 2.5 MPa (a more typical average subsoil resistance) would reduce maximum rooting depth by 29 cm over the course of growth of a typical maincrop which could reduce water availability by 7 mm on a sandy loam soil and reduce the nitrogen absorbance capacity of the rooting system.

The data from the survey show that most potato fields have moderate to severe restrictions to root growth after planting. This affects other agronomic practices and leads to a considerable waste of resources, e.g. water and nutrients. Applying irrigation, or increasing the frequency and reducing the amount of irrigation, reduces the effects of compaction but does not remove them completely. In some cases, irrigating compacted soil even with moderate doses of water leads to severe waterlogging and poor crop growth and in sloping fields, irrigation run-off from compacted soil into low-lying areas is often a severe problem. Additionally, poor infiltration of irrigation into slumped or capped ridges or beds often leads to over-application of water during common scab control as growers find that ridges wet insufficiently following irrigation. Water is consequently lost by drainage from the furrows.

The literature revealed 16 experiments involving potatoes grown in artificially compacted soil, of which 13 showed a significant yield decrease owing to compaction. Some of the differences between compacted and uncompacted soil were massive (25-38 t/ha) but averaged 18 t/ha. In contrast, a review of yield responses to subsoiling in potatoes showed that only 28 experiments out of 83 had a significant yield increase in response to subsoiling, with three experiments showing a significantly reduced yield. Many of these experiments measured a significant decrease in soil resistance or strength as a consequence of the subsoiling operation but the effects on yield were often small (e.g. 5 t/ha) or not significant. The yields in these experiments were lower (mean *c.* 42 t/ha) than in the compaction experiments (54 t/ha in uncompacted treatments) suggesting that some factor other than soil conditions was reducing yields. Many researchers have failed to quantify the extent of any compaction in their experiments prior to imposing their cultivation treatments and the reader is left to assume that the soil was compacted before any treatments were carried out. This point is crucial, since subsoiling uncompacted soil is likely have little benefit.

Clearly, compaction can have severe consequences on potato yield and quality but the effect of subsoiling below the plough layer has variable effects. This suggests that a) the subsoil was sufficiently loose enough not to warrant subsoiling, b) subsoiling was carried out when the soil was too wet to achieve adequate shattering, c) subsoiling was done at the incorrect depth or tine spacing, d) that the subsoil recompacted quickly after cultivation (e.g. sands), or alternatively e) that compaction was often created superficially (i.e. shallower than 30-35 cm depth) whilst preparing the seedbed. Typical operations that cause such shallow compaction are bed-tilling and destoning.

In potato cropping, the soil is often destoned or declodded. The benefits of destoning are typically a 30-50 % decrease in severe tuber damage during harvest and up to a 40 % increase in the harvesting spot rate of work and the ability to create a fine seedbed for scab control. One major disadvantage of destoning is that soil compaction cannot be avoided if the soil is too wet. Since the destoner is usually the rate-determining step during seedbed preparation, the operation frequently occurs in advance of planting in marginal soil conditions. As a consequence, destoning frequently results in soil compaction as the soil is too wet, which slows root growth early in the life of the crop. During spring, the moisture content of the soil generally increases from the soil surface down to the plough depth and unless the soil is allowed to dry either naturally, or by progressively opening the soil structure with shallow cultivations, the critical working depth will be shallow, often shallower than the depth at which destoning occurs. Measurement of penetration resistance shows that under such conditions the shares of a destoner compact the soil at 25-35 cm below the top of the planted ridge and therefore shallower than the ploughing depth which is usually located *c*. 40 cm below the top of the ridge. Destoning too deeply in an effort to produce a seedbed can lead to the creation of clods as soil is worked at a depth where plastic failure occurs. This leads to smearing of the profile below the destoner share, an increased clod removal to the wheelings and, consequently, a shallower rather than deeper seedbed which has an uneven surface making depth control difficult at planting. Destoners should be run at a depth that achieves 5-6 cm of loose soil under the seed tuber and 13-15 cm of settled soil above it: often this is shallower (i.e. 25-28 cm) than most growers think. A second disadvantage of destoning is the value attached to the cosmetic appearance of ridges following planting. The common belief amongst growers is that such ridges offer major advantages in terms of retaining water from rainfall or irrigation which will therefore benefit scab control or yield but this often proves not to be the case. Over-vigorous sieving or pulverisation of soil by destoners creates a lack of structure causing ridges to slump to varying extents following rain or irrigation. This can lead to hydrophobic soils which are difficult to wet. In fine-textured soils, seedbeds should be cloddier at planting to prevent slumping of the ridge after breakdown of small soil peds and this is achieved by increasing the web pitch or reducing the star spacing on the destoner. Large volumes of soil are moved during planting which requires a high energy input in terms of diesel and tractor and labour hours. Vigorous churning or sieving of soil can destroy soil structure completely in light soils whilst it may prove beneficial in heavier soils. In many cases, fewer operations would lead to more stable soil structure and reduce the energy and labour requirement.

Soil compaction is a more serious issue in potato production than realised by many growers. It can result in severe yield depression, cause considerable over-irrigation and result in large amounts of nutrients being left in the soil post-harvest. However, its less dramatic effects are the most important as they are reducing yields and the efficiency with which major inputs of water and nutrients are used in most of the crops recorded. In many cases, the growers may be unaware of its effects. They must become more conscious of the impact of soil conditions at planting on crop growth and be prepared to be more patient in deciding to plant.

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