Research Review

Soil compaction and potato crops

Ref: R260

Research Review : April 2005

Damian Hatley, Jeremy Wiltshire, Bill Basford, Sheila Royale *ADAS*

Denis Buckley, *TAG*

Paddy Johnson, *PJASOC*

Additional copies of this report and a list of other publications can be obtained from:

Publications
British Potato Council
4300 Nash Court
John Smith Drive
Oxford Business Park South
Oxford
OX4 2RT

Tel: 01865 782222
Fax: 01865 782283
e-mail: publications@potato.org.uk

Most of our reports, and lists of publications, are also available at *www.potato.org.uk*

Contents

LIST OF TABLES

LIST OF FIGURES

1. Summary for growers

1.1 Project aim

The project aim was to review:

- causes of compaction and possible mitigating measures;
- effects on crop development and nutrition;
- methods of compaction measurement;
- remedial action to remove problems.

1.2 Work undertaken, key findings and conclusions

1.2.1 Work undertaken

The review presents an overview of current knowledge of soil compaction, including definitions, methods of measurement, causes, mitigation, remediation, and how compaction affects soil functions and potato crops. Information was sourced from research journals, conference proceedings, specialist texts, and the expert knowledge of the project team.

1.2.2 Key findings and conclusions

What is compaction?

Soil compaction can be defined as a reduction in soil pore volume, together with an increase in soil bulk density. Compaction may be at the surface, often referred to as slumping or capping, or it may be deeper within the soil profile, usually caused by cultivation.

Compacted layers are usually clearly defined, and often range from 20–100 mm in thickness. Thin layers may be associated with smearing caused by a rotary cultivation tool in wet soil conditions. Thicker layers are usually associated with the passage of heavy machinery, again operating when the soil is too wet.

Soil scientists describe the structure of compacted soil layers as typically dense and ‘massive’, which means large lumps!

How does compaction affect the crop and environment?

Yield reductions of up to 37%, caused by compaction, have been recorded experimentally in Holland.

Compaction limits the soil volume explored by the root system and therefore limits the amount of soil moisture available to the crop. This may result in the need for more frequent irrigation, especially where a common scab reduction regime is being followed.

The risks of tuber rot diseases, including blight, pink rot, blackleg and powdery scab, are increased where compaction occurs, as water is held above compacted soil. In the most extreme circumstances, compaction can lead to water logging following heavy rainfall, especially when the rainfall occurs soon after irrigation. On flat fields, water logging can cause yield loss and reduced storability, or in some cases complete crop loss.

Compaction has been shown to influence soil nutrient availability. One of the main effects of compaction is on soil aeration, which can lead to denitrification (loss of nitrogen to the atmosphere). Researchers have also noted a significant reduction in phosphate uptake by barley grown in compacted soils. Such an effect may also occur in potato crops.

Compaction can affect the choice of desiccant because it can lead to rapid changes of soil moisture within the rooting zone.

Tuber quality is likely to suffer in compacted soils as a result of rapidly changing soil moisture conditions, not only in respect of the diseases mentioned above, but also in respect of secondary growth and misshapes. Quality of pre-pack samples can suffer in temporarily waterlogged conditions, as lenticels expand excessively.

Compaction causes a reduction in the ‘porosity’ of the soil so that:

- water no longer drains freely;
- root activity is reduced;
- worm activity is reduced;
- less water is available to the crop.

Compaction affects the rate of water infiltration into the soil. This is the speed at which water can ‘soak’ into the soil without run-off. Following surface compaction, run-off occurs during and after heavy rain or irrigation. The water running off the field carries soil particles holding nutrients and pesticides, causing pollution of the aquatic environment with nitrates, phosphates and sediments.

How can compaction be identified?

Compacted soil can often be identified by a ‘platy’ structure, with horizontal layers in the soil profile. The extent and severity of compaction can be assessed using a spade. If digging is difficult, this will indicate the presence of compacted layers, if there is sufficient soil moisture to allow this work to take place. If a grower has trouble penetrating compacted layers with a spade, he/she can be sure that the crop will have the same difficulty.

How is compaction caused?

The primary factor associated with risk of compaction deep within the soil profile is soil moisture status at the time of cultivation or heavy trafficking. Wet soils are at greater risk than dry soils.

Crop damage to potatoes as a result of subsoil compaction can be the result of compaction occurring in a previous crop, and/or when ploughing. Once ploughing (or other primary cultivation) has occurred, additional cultivation to make a seedbed is normally matched to row or bed widths so that ‘controlled wheeling’ takes place. This means that additional compaction below plant positions can only occur as a result of smearing caused by the cultivation equipment. Compaction may be caused by powered rotary cultivators, the share of a destoner/declodder, or the planter. The ability of such equipment to cause a soil pan should not be underestimated.

Surface compaction may occur as a result of heavy rain soon after cultivation, and is referred to as capping or slumping. This can be significant and can delay emergence, but the delay is usually short.

What can a grower do about compaction?
Sub soiling is undoubtedly the best mechanical way of relieving compaction, but ‘blind’ sub soiling, without prior soil examination both before and during the activity, may well result in a poorly executed job of little or no value. There is little substitute for using a spade to identify the compacted layer(s) and the efficacy of the subsoil cultivation.

Soils with good natural structure, that are compacted, can be returned to good condition with relative ease. The opposite applies to soils of poor natural structure.

Remedial action after structure-damaging events such as sugar beet harvesting should be considered when rotations are planned. Winter wheat after sugar beet is often beneficial, as it normally roots deeply (typically 1–1.5 m) and dries the soil by high evapo-transpiration rates during the spring and early summer. This often allows remedial action, such as sub soiling, following wheat harvest. When a well structured soil dries, this may return the soil to a near-normal condition, without the need for expensive remedial cultivation.

Good drainage is important. It limits the periods when the soil is too wet to carry traffic and therefore it reduces the risk of compaction.

A cover crop over the winter encourages evapo-transpiration and so brings forward the date at which the soil drops below field capacity, allowing more time for cultivation without structural damage.

Bulky organic manures (such as FYM) can help improve soil structure and resilience to compaction, but it takes many applications over years, and should not be regarded as a short term fix.

2. Introduction

Since the 1960s, crop production has intensified. This has involved larger agricultural machines, more continuous arable cropping and more use of marginal land (Ball *et al.,* 1997; Wilhelm *et al.*, 2004). These changes have increased the risk of soil compaction in some situations, but have also allowed work to be done more quickly and under better soil conditions in other situations. The problems caused by compaction resulting from mechanisation are particularly important in wet or moist climates such as that experienced in the UK (Ball *et al.*, 1997).

Compaction is almost universally acknowledged to have negative effects on crop production. Compaction can be disastrous for crop yield and quality. If compaction leads to increased erosion and P loss, then water quality can be impaired. Compaction can also significantly increase cultivation costs (Bailey *et al.*, 1995; Soane, Dickson and Campbell, 1982).

Compaction leads to changes in bulk volumetric properties (by reduction in pore volume) and associated reductions in hydraulic conductivity, permeability and diffusivity of water and air through the pore system. Excess water cannot drain away, as coarse porosity is lost during the compaction process. Root growth is restricted, decreasing uptake of nutrients and water, and thus canopy growth and yield are impaired. Furthermore, compaction within and adjacent to wheeling rows, prior to or at harvest, is linked to tuber damage. The most economically and environmentally viable approach to reduce the risk of these problems, is careful planning to avoid or manage situations that contribute to excessive compaction.

Soil erosion, or the awareness of it, has increased since the 1970s, because of changes in cropping practice and decreases in soil organic matter (Nicholson *et al.*, 1992). Compaction from machinery and capping of structurally unstable topsoils are major factors contributing to soil erosion. This has been an important influence in the introduction of the Department for Environment, Food and Rural Affairs' (Defra) Catchment Sensitive Farming initiative, and the introduction of Soil Management Plans as one of the standards required for Cross Compliance.

In order to meet Good Agricultural and Environmental Condition (GAEC) Cross Compliance requirements, farmers will need to produce a simple Soil Management Plan in 2006, and this must be implemented from 2007 (Cross Compliance Handbook for England, Anon., 2004a). The plan will be based on good practice measures, for different soil types and cropping systems, as outlined in the Defra 'Cross Compliance Guidance for Soil Management' (Anon., 2004b). The plan will address, as appropriate, the control of erosion, maintenance of soil organic matter, and correct cultivation including measures to minimise and remediate compaction.

There are three other GAEC 'Soil Management and Protection' standards, which:

- address post-harvest management of land after combinable crops to reduce run-off and erosion (GAEC 2);
- prohibit mechanical field operations on waterlogged soil (with a few exceptions) to reduce risks of soil compaction and structural damage (GAEC 3);

- prohibit burning of crop residues (with a few exceptions) to aid in recycling organic matter (GAEC 4).

Entry Level Stewardship (ELS) (Anon., 2005a) provides an option for a more detailed soil management plan. This includes the requirement to record, on a field by field basis, the steps that will be taken to minimise the risk of run-off and soil erosion, including how to mange the soil to ensure good structure and maintain the infiltration of rainfall. Higher Level Stewardship (HLS) (Anon., 2005b) provides additional options for resource protection in targeted areas.

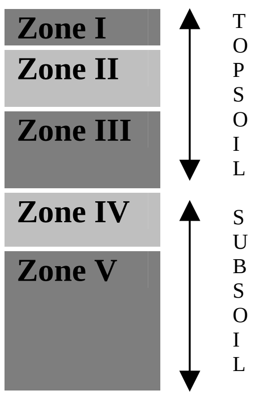
This review presents an overview of current knowledge of soil compaction, including definitions, methods of measurement, causes, mitigation, remediation, and how compaction affects soil functions and potato crops. Information was sourced from research journals, conference proceedings, specialist texts, and the expert knowledge of the project team. The review findings are placed in context with the need of growers to meet GAEC Cross Compliance requirements.

3. Definitions

Soil compaction can be defined as a reduction in soil pore volume and an increase in soil bulk density.

As well as pore volume, the pore structure of the soil is modified by compaction. At a small scale this can be seen as a reduction in the size and number of macropores and a general change in the shape and continuity of pores (Soane *et al.*, 1981).

Bennie and Krynauw (1985) summarised the different compaction zones occurring in a soil in relation to their primary cause. The topsoil was divided into three zones, and the subsoil divided into two zones as shown below. Compaction may be present in none, some or all these zones. Approximate zone depths have been added in brackets, but these will vary with farming practice and soil type.



Zone I Surface crust caused by soil particle consolidation by irrigation or rain (0–5o mm)
Zone II Loose part of the plough layer due to loosening by shallow secondary tillage operations (50–250 mm)
Zone III *Recompacted plough layer due to compaction by vehicular traffic and irrigation after ploughing (0.25–0.35 m)**
Zone IV Subsoil compaction due to wheel traffic in the plough furrow and implement soil interaction during primary tillage operations (0.3–0.7 m)
Zone V Subsoil with naturally high bulk density due to genetic (*sic*) factors (0.7 m and greater)
*Note that this also applies to zones I and II.

The magnitude of any adverse effects resulting from compact zones will depend on the severity of the compaction and whether or not the compact zone is continuous or broken by cracks and fissures that will allow drainage and root penetration.

A degree of soil consolidation is necessary to provide enough soil/root contact in growing crops, for access to water and nutrients and to provide anchorage. Lipiec and Stepniewski (1995) noted that 'moderate compaction' may have benefits for nutrition due to greater water retention, hydraulic conductivity for mass flow transport, diffusion coefficient of ions, and ion concentrations in the soil. This 'moderate compaction', desirable for good crop growth, is usually described as 'consolidation' in commercial agriculture.

Other words and terms, which are related to soil compaction or structure, are defined below.

Massive structure: Dense soil with no discernible aggregates.

Shearing: Soil failure under applied stress, causing adjacent areas of soil to move relative to each other.

Slaking: Dispersal of soil on the surface, leading to surface capping.

Slumping: Structural collapse, usually induced by wetting.

Smearing: Movement of an implement against a wet soil, causing pores to be blocked.

4. Effects on the crop

4.1 Introduction

It is widely accepted that soil compaction has a negative effect on potato crop production. The extent to which this is true is reviewed below, using evidence from published research.

It is important to distinguish between studies that provide evidence for effects of compaction in commercial practice, and those that do not. There are considerable differences in the commercial relevance of the methodology that has been used to study effects of compaction on the crop. For example, surface compaction treatments after seedbed preparation (Blake *et al.,* 1960), or zero-traffic treatments, have less commercial relevance than comparisons of differences in subsoil compaction.

4.2 Establishment

There are few reports of effects of compaction on the successful establishment of potato plants (the group of stems arising from a single seed tuber) or stems, as determined by measurements of population density.

McDole (1975) found that surface compaction delayed emergence by 6 to 10 days, and population density was reduced by 30 to 40 percent. However, there is no information on soil type, and it is not clear how the compaction treatments were applied. In contrast, Blake *et al.* (1960) found no effect on the number of hills (the group of stems arising from a single seed tuber is often referred to as a hill in US/Canadian literature) after surface compaction between seedbed preparation and planting. Such surface compaction and the consequential effect are unlikely to occur in modern commercial practice. Surface compaction may occur as a result of heavy rain soon after cultivation, and is referred to as capping or slumping. This can be significant and can delay emergence, but the delay is usually short.

Compaction below planting depth does not appear to affect establishment. When the subsoil is compacted, canopy density effects are not evident from emergence, but become apparent later and increase in magnitude as the crop develops. In a study reported by van Loon and Bouma (1978), early canopy development was very rapid in a treatment with strongly compacted subsoil (Fig. 1), but foliage growth slowed down later in the season as water became limiting. If plant or stem numbers were decreased by subsoil compaction, an earlier effect on canopy density would be expected. However, in this case, compaction of topsoil did affect early canopy development, suggesting a decrease in establishment, as found by McDole (1975).

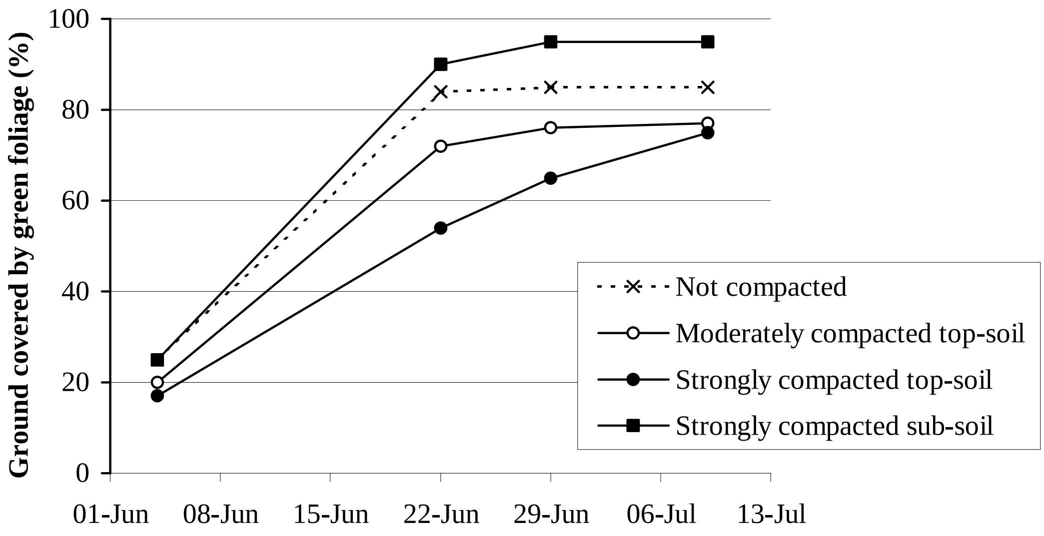


FIGURE 1. GROUND COVERED BY GREEN FOLIAGE (%) DURING THE FIRST PART OF THE GROWING SEASON, CV. BINTJE (VAN LOON AND BOUMA, 1978).

4.3 Root development

The immediate consequences of compaction fall largely on the roots. Plant roots in general have been described as opportunistic (Perry, 1982), with roots growing wherever the soil environment is favourable. An effect of compaction is to limit the volume of soil with a favourable environment for root growth. MacKerron (1993) pointed to reports of potatoes rooting to, or abstracting water from, a depth of 1.5 m. Stalham (2001) argued that most potato varieties are able to root to at least 0.7 m deep, and some, such as Cara, can root deeper than 1 m, but many crops do not root this deeply because soil conditions are rarely optimal through the potential rooting depth of the crop.

Working in a sandy soil, van Oijen, de Ruijter and van Haren (1995) made detailed measurements of potato roots, with differing compaction treatments. The compaction treatments mainly affected soil penetration resistance above 0.3 m, so were not typical of compaction in commercial production, which is likely to be below 0.3 m because of the nature of modern cultivation systems. However, the effects of compaction on roots are of interest. Soil compaction reduced net root length growth, but by less than overall crop growth, indicating that an increased proportion of biomass was allocated to roots. Accelerated root senescence was the main cause of reductions in net root length growth, rather than impaired root growth. This suggests that, in this study, decreased root length in compacted treatments was not a consequence of the inability of roots to penetrate compacted soil, but was a consequence of an inability to survive in compacted soil. This view is supported by Saini (1976), who reported that oxygen diffusion rate correlated with yield loss better than measurements of bulk density or penetration resistance.

Effects of compaction on roots are not always a consequence of an inability to survive in compacted soil, rather than an inability of roots to penetrate compact soil. Ross

(1986) reported that improved subsoil conditions resulted in deeper root penetration, but there was only a small increase in the additional volume of the rooting zone. Inspection of the root systems above thin pans identified root mats along the upper surface, suggesting that roots were diverted along the surface of the pan, instead of growing downwards. This shows that the roots were not able to penetrate the pan.

Boone, Bouma and de Smet (1978) showed that potato roots penetrated most rapidly in a loose soil, but in moderately and severely compacted soils reached a depth of 0.4 m at times of 2 and 4 weeks later respectively. Below the compacted layer root growth was similar for all treatments. Irrigation slowed root growth when applied to severely compacted soils. Although growth in the ridges was similar, at 0.1 m below the ridge root density was increased by a factor of two in loose soil, compared with moderately compacted soil, and by a factor of six compared with severely compacted treatments. Root densities achieved in loose soil at the beginning of June were not reached in severely compacted soil until end of July.

4.4 Nutrient uptake

There is little information on effects of compaction on nutrient uptake. Such effects are likely to be related to both nutrient demand and nutrient supply. The effects of decreased water uptake, leading to decreases in growth rate and nutrient demand, is likely to dominate in commercial potato production, where there is adequate fertilisation and little leaching in the presence of serious compaction.

Effects on root growth, root senescence, or root length density would be expected to influence nutrient uptake. Concentrations of nitrogen, phosphorus and potassium in leaves, stems and tubers were measured by van Oijen, de Ruijter and van Haren (1995). Decreases in response to soil compaction (above 0.3 m, see Section 4.3) were found, and were related to total biomass and root length to calculate nutrient uptake per unit root length per day. Soil compaction reduced uptake of each of the three nutrients. The extent of this reduction was affected by variety and season, and was greatest in the season with most severe soil compaction. In some cases, uptake of each nutrient was reduced by more than 50%. Since potato crops are usually supplied generously with nutrients, and compaction in the top 0.3 m is unlikely, these results may not be directly relevant to commercial potato cropping.

4.5 Irrigation requirement

Soil compaction limits the volume of soil explored by the crop root system. Crops may lose access to 20–30 mm of water because they do not achieve their potential rooting depth in poor soil conditions (Stalham, 2001), and this increases the need for irrigation.

Ross (1986) studied potato crops in a silty-loam soil, with thin tillage pans at 0.30–0.35 m depth, or with these pans disrupted by subsoil cultivation. It was reported that potato yield and quality were similar when near-optimal irrigation was applied. When water was limiting, subsoiling increased yields. Thus, irrigation had a greater effect on yield in the treatment with soil pans, but irrigation, together with high fertiliser applications, overcame effects of soil compaction. McKenzie (2001a) also reported that compacted fields required more irrigation.

In contrast, Allen, Allison and Sparkes (2005) state that use of water to mitigate compaction effects can exacerbate the problem because drainage is impeded, leading to water logging. Such contrasting views and experimental results are not surprising because of the diversity of experimental conditions. Responses of potato crops are affected by irrigation strategy, but there are many other interacting factors, such as soil type, the nature and severity of the compaction problem, nutrition and whether or not this is modified in response to the compaction problem, variety, and environmental conditions.

4.6 Pests and diseases

There is little available information on interactions between soil compaction and potato pests and diseases. However, where compaction leads to poor drainage or water logging, an increased incidence of tuber rot diseases may be expected (N. J. Bradshaw, personal communication). Some examples of diseases that are particularly affected in this way are given in Table 1.

There is a lack of experimental evidence for effects of compaction on the risk of tuber blight. However, following rainfall or irrigation events, soil above a compacted layer becomes wetter than it would if there were no compaction. This would be expected to increase the risk of tuber infection where foliage infection is already present.

In addition to effects of compaction on tuber rot diseases, the risk of common scab (*Streptomyces scabiei*) may also be increased. This may occur through effects of subsoil compaction in limiting root development and reducing the soil volume available for water abstraction (Section 4.5). Under these conditions, the soil moisture deficit may build up quickly in the topsoil, exposing the developing tubers to high risk conditions for longer than in more favourable conditions.

TABLE 1. EXAMPLES OF POTATO DISEASES PARTICULARLY AFFECTED BY POOR DRAINAGE, WITH NOTES FROM LANE, BRADSHAW AND BUCKLEY (2000).

Disease (*infecting organism*)	**Influence of poor drainage**
Blackleg (*Erwinia carotovora*)	Occasionally serious, particularly in wet seasons, irrigated crops and on poorly drained land. During crop growth infected seed tubers rot, release bacteria, and infect progeny tubers. In poorly drained, waterlogged soils the seed tuber rots earlier and the risk of tuber infection is greater.
Rubbery rot (*Goetrichum candidum*)	Outbreaks are invariably associated with heavy irrigation or following rain within three weeks of lifting, especially in warm weather in panned, poorly drained soils.
Pink Rot (Phytophthora erythroseptica)	Usually confined to patches in crops where the drainage is poor. Control relies on maintaining good drainage and a wide rotation.
Watery wound rot (*Pythium ultimum*)	It is important to improve drainage and not to grow potatoes in fields with a history of the disease.
Powdery scab (*Spongospora subterranea*)	Risk depends on factors such as soil type (moisture retention), drainage (avoid poorly drained fields), and previous history of powdery scab.

Boag, (1988) reported that compaction decreased migratory plant-parasitic nematode populations, but van Oijen, de Ruijter and van Haren (1995) found no evidence for an effect of compaction on potato cyst nematodes (*Globodera pallida*), which is non-migratory.

4.7 Canopy development, tuber yield and quality

4.7.1 Canopy development

Total dry matter production of potato crops is proportional to the amount of radiation absorbed by the canopy (Allen, Allison and Sparkes, 2005). Soil compaction has been shown to affect canopy size, with a consequential decrease in yield (Allen, Allison and Sparkes, 2005, citing Rosenfeld, 1997). Water logging in compacted soils may shorten the duration of full ground cover, also limiting yield.

A study by van Loon and Bouma (1978), on a sandy loam soil in a very dry season (1976), showed an initial increase in rate of canopy development in a treatment with compacted subsoil, compared with a non-compacted control (Fig. 1). This was attributed to high capillary transport of water, from the water table upward through the plough pan, early in the season. However, this was not maintained as the season progressed and the water table dropped. Later in the season, this treatment showed more drought stress than other treatments, with visible wilting of the canopy and a final total tuber yield of 42.4 t/ha, compared with 67.4 t/ha in the non-compacted treatment. This 37% decrease in yield is probably an extreme case, but it illustrates that severe financial consequences of compaction are possible.

Ground cover was measured by van Oijen, de Ruijter and van Haren (1995), in an experiment on a sandy soil with differing compaction treatments. The compaction treatments mainly affected soil penetration resistance above 0.3 m, so were not typical of compaction in commercial production. However, the link between compaction, canopy development and yield is of interest. Compaction delayed the time of full ground cover, or prevented it, and altered the time and rate of leaf senescence. The variation in yield largely reflected differences in ground cover. Two varieties were studied in one season, and four in the next. In some instances, senescence was slower and in some it was more rapid. This illustrates the difficulty in interpretation of soil compaction effects, in this case probably because of interacting effects of nutrient and water availability and uptake.

In most crops the duration of the green canopy is ended by chemical or mechanical defoliation. Compaction, because of its influence on soil moisture status, may affect the choice of haulm desiccant. Diquat should only be used where soil conditions are sufficiently moist. In a crop with restricted rooting, and in dry weather, the soil around the roots may become too dry for the use of diquat more quickly than it would if the crop had access to a greater volume of soil. Conversely, glufosinate-ammonium must not be used under water saturated soil conditions. When compaction is present, less water (rainfall or irrigation) is required to produce such water-saturated conditions. It is therefore essential for growers not only to examine soil moisture conditions near to the time of desiccation, but also be aware of any compaction that may cause soil moisture conditions to change faster than anticipated.

4.7.2 Yield

There is evidence, both from subsoiling experiments and from experiments with compaction treatments, that compaction decreases tuber yield.

An early report on the effect of cultivations on potato yield comes from Pereira (1941). Yield was not affected by subsoiling, but there was no evidence of compaction in treatments without subsoiling, and the cultivation treatments were shallow relative to modern commercial practice.

A number of unpublished experiments on effects of deep cultivations were done in the 1980s at ADAS Terrington. Some of these showed effects on potato yield, but many did not. For example, a fertiliser placement experiment was carried out in 1981 and repeated in 1982. One of the treatments involved running two injection tines along the row, 100 mm either side of the row, at a depth of 150 mm below the seed, 6–9 days after planting, but with no fertiliser injected. This treatment increased total yield in 1981 (from 37.3 to 42.4 t ha^{-1}), but did not in 1982 when yields were greater (up to 60 t ha^{-1}). These results suggest that compaction caused yield loss in 1981, but not in 1982.

O'Sullivan (1992) reported that subsoiling increased yield (5.2–11.5%) in zero-traffic conditions, but not when there was normal trafficking. Ross (1986) found that subsoiling increased yields (by around 100%) when water was limiting, but not at near optimum rates of irrigation. At high rates of irrigation, subsoiling decreased yields, and Ross (1986) speculated that this was a consequence of increased nutrient leaching. Russell (1956) reviewed subsoil cultivation studies, and found that there were positive responses of potato yield to subsoiling in 40% of fields. In experiments with different trafficking treatments, reduced ground pressure and zero traffic increased potato yields (11–18%) (Chamen *et al.*, 1992).

These effects of differing cultivation or trafficking add evidence that compaction limits yield in potato crops. Effects on yield were not always observed, and the size of the effects differed greatly, depending on experimental conditions such as the degree and nature of any compaction, soil type, water and nutrient supply and climate.

In an experiment in which compaction treatments were applied, (van Loon and Bouma, 1978), yield was reduced to about 63% of the control by subsoil compaction (See Section 4.7.1).

On a sandy soil with differing compaction treatments, van Oijen, de Ruijter and van Haren (1995), reported that yields in a severely compacted treatment were 54-94% of those in a non-compacted treatment, varying with season and variety. However, the compaction treatments mainly affected soil penetration resistances above 0.3 m, so were not typical of compaction in commercial production.

Rosenfeld (1997, cited by Allen and Scott, 2001) reported that yields of Maris Piper were decreased by compaction at 0.1 m and 0.4 m depth, both with and without irrigation (Table 2).

TABLE 2. EFFECT OF COMPACTION AND IRRIGATION REGIME ON TOTAL TUBER YIELD OF MARIS PIPER IN 1996 (REPRODUCED FROM ALLEN AND SCOTT, 2001, WHERE ROSENFELD, 1997, IS CITED).

	Compaction regime			
Irrigation regime	Uncompacted	Compacted at 0.1 m	Compacted at 0.4 m	Compacted at 0.1 + 0.4 m
Dry	73.8	46.4	65.3	47.3
Wet	87.9	59.4	79.0	56.5
S.E.		5.61		

4.7.3 Tuber quality

There are few reports giving details of direct effects of compaction on tuber quality. van Loon and Bouma (1978) showed increased second growth and misshapen tubers when soil within the tuber zone was compacted. McDole (1975) also reported that compaction increased malformed tubers. Compaction may have indirect effects on quality through effects on disease incidence and severity (Section 4.6).

Compaction can lead to water logging, causing severe crop damage if the water logging persists. Quality in pre-pack crops can suffer even when water logging is temporary, as lenticels expand excessively.

5. Causes of compaction

5.1 Mechanical causes of compaction

There are two main mechanical causes of shearing, smearing and compaction:

1. an angled (shear) force operating in, or immediately below, the plough layer such as that applied by tyre slippage, the forward motion of a plough, a rotary cultivator, a stone/clod separator, or a planter;
2. compressive forces, as a direct effect of axle load, operating throughout the profile into the subsoil (the base of a plough may also produce a compressive force).

The extent to which these forces cause compaction depends on a number of factors. The primary soil factor is soil moisture status. This affects soil strength (Section 6.4), and thus the ability of the soil to withstand compressive or shear forces. The compressive forces applied by machinery depend on the weight of the equipment (including any load being carried) and the area over which the weight is distributed. In addition, Tobias *et al.* (2001) found that reversing or turning heavy vehicles caused more compaction than forward movement. Speed of movement is also a factor. Chamen *et al.*, (2003) reported that, although the speed effect is of much lesser importance than other factors, compaction of the soil is time dependent. Whilst recognising dynamic effects of bouncing and acceleration, which might increase stress on soil with speed, they stated that, on average, as speed over the soil surface increases, the compaction effect decreases.

Alakukku *et al.* (2003) categorised a number of medium- and high-risk operations for subsoil compaction in the UK. Risks are greatest with large loads and moist soils, a combination that often occurs in late autumn and early spring.

Operations with a medium- to high-risk of subsoil damage are:

- deep cultivation after subsoiling;
- ploughing;
- harvesting;
- manure spreading;
- fertiliser application;
- bed forming/cultivation;
- clod and stone separation.

Compaction may be caused before or during cultivations for a potato crop, and in the crop growth period.

5.1.1 Pre-potatoes

Potatoes are normally grown in rotations that include combinable crops and other root crops.

Compaction occurring anywhere in the rotation can persist into the potato crop. This is because it is difficult to remove compaction in intensive arable systems, both because there is often a lack of opportunity for effective remedial action, and because of the re-compacting action of subsequent operations.

Autumn crop establishment in wet soils can be a major cause of compaction. During ploughing the tractor tyre runs in the furrow bottom, and thus its weight is applied directly to the subsoil, and wheel-spin may also smear at this depth (Schuler *et al.*, 1986; Chamen *et al.,* 2003).

Spraying and fertilising commonly lead to tramline compaction, through multiple passes with reduced-width wheels, and equipment with heavy loads. The compressive effects of wheels in the tramlines are high. Subsoiling to ‘take out’ tramlines after combinable crops is now regarded as a routine cultivation practice on many farms.

Combine harvester axle loads are now up to 12 t on the drive axle. Tractors and grain trailers commonly carry 14 t loads, with 3.5 t trailer weights, and axle loads of up to 7 t. Ground pressure could be as high as 500 kPa (5.0 bar or 75 psi), so the risk of compaction is ever present.

Designs, in terms of weights of straw balers, haulage and handling systems (e.g. telescopic handlers), presume dry soil with high load-bearing condition. Thus, use of these machines can cause compaction and rutting in wet years.

In crops such as potatoes that are often harvested in wet conditions, harvesting and trailer loads become critical. Harvesters can have an axle load of 8.8 t, with tyres at 220 kPa (2.2 bar). Much compaction can be caused in difficult harvest seasons with tight harvesting schedules, when soil moisture is greater than would be ideal for trafficking.

Sugar beet is increasingly harvested by contractors using 6-row tanker machines. Vehicle weight may be greater than 30 t, with 10 t axle loads and high ground pressures. These have become commonly regarded as major sources of both topsoil and subsoil compaction, requiring routine remediation when conditions allow. The risk of compaction arises not only because of the weights involved, but also because contractor availability and delivery schedules to factories often result in harvesting when soil conditions are poor.

Other operations within the rotation that are important contributors to soil compaction include application of lime and pea harvesting.

Specific operations can be ranked in order of risk, although this ranking depends on wheel and tyre selection and axle configuration:

1. sugar beet harvesters;
2. haulage tractors and trailers (all crops, but greatest risks are in sugar beet and potatoes because of soil condition);
3. straw handling systems;
4. pea viners;
5. combine harvesters;
6. all tractors.

5.1.2 In the potato crop

From pre-crop cultivation to potato crop harvest, the soil is subject to compacting effects. Typical operations carried out by potato growers are outlined below, and the associated compaction risks considered.

Ploughing is referred to earlier in this section, and the same points apply to ploughing land before potatoes. Important factors are timing, soil moisture content, axle loads, tyres, tyre pressures, speed of operation, etc. The quality of the work determines the need for any restorative cultivation prior to the next operation.

After ploughing, or other primary cultivation, the next cultivation will probably be bed-forming. The risk of creating season-long compaction at this time is relatively small because the tractor runs on the soil surface and subsequent cultivations will work the ground which may be temporarily compacted. This operation defines where wheels will run for the rest of the season. Potatoes are largely grown in rows in which there are no wheelings after the primary cultivation.

Following bed-forming, bed-tilling is likely on many soils. Rotary powered cultivation associated with bed-tilling can easily result in the formation of a shallow, smeared and compacted layer, the severity of which will be largely determined by soil moisture conditions at the time of the operation.

If destoning or declodding is necessary, then wheeling width is normally standardised at: 1.83 m (72 inches) although some growers on lighter soils now operate at 2 m wheelings. Thus, there should be no additional wheelings in the growing area.

The use of a power harrow or other cultivator could lead to wheelings in the growing area. Where such implements are used in the absence of bed-forming, growers should match machine widths, including planters, to avoid this happening. There are also possibilities of soil smearing at tine depth with a range of cultivators.

Planting equipment is unlikely to compact the soil excessively, but smearing of the ridge formed by the planter is a sure indicator of planting in excessively wet conditions.

Spraying and fertiliser application will lead to compaction in relevant wheeling rows. This can cause clod production within ridges (Soane *et al.*, 1982). The presence of clods at harvest leads to increased tuber damage potential in the harvester, the trailer and at store intake. This could lead to losses in store from increased damage.

At harvest, heavy loads in trailers and harvesters may be important, especially in difficult conditions. Tyre sizes are important, and the side of the ridge may be compacted, causing tuber damage and clod formation.

5.2 Natural causes of compaction

Surface crusting or capping is predominantly a natural process affecting structurally unstable soils. Rain falling on soil causes slaking, mechanical disruption of aggregates and compaction. Soil clods are progressively broken apart by wetting/drying cycles, and freeze/thaw cycles. This occurs as a two-stage process that first seals the soil surface (structural crust), causing micro-runoff and producing a thicker, sedimentary or depositional crust (Heppell *et al.*, 2004).

The formation of a crust can be very rapid on unstable soils. Rousseva *et al.* (2002), for example, showed the development of a surface crust through slaking of aggregates on a silty soil during the first minute of simulated rainfall (similar to irrigation).

5.3 Influence of soil properties

Some soil types are more susceptible to harmful compaction; especially fine sandy loams and loamy fine sands. This is because they are structurally unstable (Bennie and Krynauw, 1985). Generally, soils that are less structurally stable are more prone to compaction than more stable soils. In unstable soils the bonds between individual soil particles are weak.

The ability of the subsoil to support loads without suffering compaction damage is dependent on soil type and stability, the packing arrangements of soil particles and aggregates, soil moisture status, and protection of the subsoil by the soil above it at the time of loading (Spoor, Tijink and Weisskopf, 2003).

Spoor *et al.* (2003) used this knowledge to provide guidance for field practitioners. This involved the assessment of soil 'susceptibility' based on subsoil 'packing density' calculated from a knowledge of actual bulk density (Section 6.5) and the clay percentage (Table 3).

$$PD = Db + 0.009C$$

(where PD=packing density (mg m^{-3}), Db=dry bulk density in (mg m^{-3}), C=clay content (%))

The soil vulnerability can then be classified on the basis of soil susceptibility, wetness and the degree of subsoil protection from compression by topsoil (Table 4). From these data, recommendations for maximum ground pressures and tyre inflation pressures can be estimated.

Situations where the subsoil is protected are those where there is a strong layer at depth (usually just below the plough layer) and a strong firm topsoil. Situations with minimal soil protection are those where tractors operate in the furrow bottom during ploughing, or where surface loads are applied under loose weak topsoil conditions.

Spoor *et al.* (2003) recognise that this approach is adopted in the absence of more quantitative data, and acknowledge the importance of local field information in further refining recommendations.

TABLE 3. SUSCEPTIBILITY TO COMPACTION ACCORDING TO TEXTURE AND PACKING DENSITY*, FROM SPOOR *ET AL*. (2003) (SIMPLIFIED). L = LOW; M = MEDIUM; H = HIGH; VH = VERY HIGH.

Texture Class	**Susceptibility to compaction at different packing densities (mg m^{-3})**		
	Low (<1.40)	Medium (1.40–1.75)	High (>1.75)
Coarse	VH	H	M
Medium (<18% clay)	VH	H	M
Medium (>18% clay)	H	M	L
Medium fine (<18% clay)	VH	H	M
Medium fine (>18% clay)	H	M	L
Fine	M	L	L
Very fine	M	L	L
Organic	VH	H	

TABLE 4. VULNERABILITY TO COMPACTION ACCORDING TO SOIL SUSCEPTIBILITY AND WETNESS, FOR MINIMAL SOIL PROTECTION (PROTECTED SOIL IN BRACKETS), FROM SPOOR *ET AL*. (2003) (SIMPLIFIED). N = NOT PARTICULARLY VULNERABLE; M = MODERATELY VULNERABLE; V = VERY VULNERABLE; E = EXTREMELY VULNERABLE.

Susceptibility class	**Wetness condition***			
	Wet	Moist	Dry	Very Dry
Very high	E (E)	E(E)	V(E)	V(V)
High	V (E)	V(E)	M(V)	M(M)
Medium	V(E)	M(V)	N(M)	N(N)
Low	M(V)	N(V)	N(N)	N(N)

*Wet soils are those close to field capacity and very dry soils are at permanent wilting point.

Soil texture also has an important role to play in the recovery of soil from compaction. Preston, Griffiths and Young (1997) showed that soil resilience, or the ability of a soil to regenerate structure on drying, increased with clay content. This is evidenced in the field as deep cracks under dry conditions.

Jones, Spoor and Thomasson (2003) categorised a number of lowland soil series under continuous arable cropping and farmed using large-scale equipment (Table 5).

TABLE 5. SUBSOIL TEXTURE CLASS, CLAY CONTENT AND VULNERABILITY TO COMPACTION OF SEVERAL SOIL SERIES (FROM JONES *ET AL.*, 2003). [N = NOT PARTICULARLY VULNERABLE; M = MODERATELY VULNERABLE; V = VERY VULNERABLE; E = EXTREMELY VULNERABLE.

Soil Series	Subsoil Texture class	Clay content (wt%)	Vulnerability class at field capacity (firm)	Vulnerability class at permanent wilting point (firm)
Naburn	Coarse	6	E	V
Newport	Coarse	5	V	M
Wisbech	Medium	6	V	N
Wick	Medium	11	V	N
Romney	Medium fine	15	V	N
Agney	Medium fine	30	V	N
Hanslope	Fine	35	M	N
Fladbury	Very fine	45	M	N
Evesham	Very fine	60	M	N

Of these soils, potatoes are commonly grown on Naburn, Newport, Wisbech, Wick, Romney and Agney, and less commonly on the others. Naburn and Newport series are easily compacted, but they can be easily corrected and are rarely anaerobic. Wisbech, Wick, Romney and Agney series have more clay and are less susceptible to subsoil compaction. However they are susceptible to shear forces causing damaging disruption following deep cultivation.

6. Methods of measurement

6.1 Introduction

The measurement of compaction often relies on the measurement of soil properties that are associated with a reduction in pore space. The wide variety of techniques available can be assessed on the basis of sensitivity, cost in time and resources and value of the results for interpretative purposes (Soane *et al.*, 1981). In practical soil management situations, consideration should also be given to the level of expertise needed to perform these assessments and evaluate the results. In some cases a combination of techniques may be appropriate. For example, Spoor *et al.* (2003) suggested visual assessment of root development (Section 6.2) combined with penetrometry (Section 6.4.1), utilising the good interpretative qualities of the former with the speed of operation associated with the latter.

Methods of measurement suitable for practical, field application in commercial potato production are discussed below. Other methods, that are less suited for such commercial use, are outlined in the Appendix to this report.

6.2 Visual, structural assessment

Visual soil assessments have been widely used to identify areas of soil compaction largely based on descriptions provided by the Soil Survey Field Handbook (Hodgson, 1976). Compacted areas generally exhibit large, angular or platy structures with few visible pores aggregates with smooth faces. Pictorial representations of structure are provided by Anon. (2004c).

One of the simplest methods for visual assessment of soil structure is the Visual Structure Score, or St Score (Anon., 1977). This method is adapted from that of Peerlkamp (1967), and is a visual assessment of porosity and the uniformity of its distribution (and hence compaction). It is based on numerical structure (St) scores ranging from 10, for the least compact soils, to 1 for a massive structure. Soil compaction with St Scores of less than 4 reduced yields of spring barley as did unconsolidated soils with scores of 7 or higher (Anon., 1977). St scores of 3 or 4 did not, however, reduce yields in winter wheat. The criteria referred to are shape and density of aggregates with some reference to rooting behaviour. The technique is based on a soil depth of 0.2 m so does not identify compaction at greater depths.

Ball and Douglas (2003) advocated a more comprehensive, semi-quantitative visual and tactile approach for assessing soil physical condition when soil is wet enough to cohere. They used soil structure, root growth and soil surface condition as their main criteria. For this method, vegetation is cut off at 50 mm above ground level, and a flat spade is used to loosen a block of soil block 0.2 × 0.1 × 0.3 m deep. The block is then divided into horizontal layers, according to distinguishing features, and the thickness of the layers is measured. A structure score is then assigned using criteria such as structure (shape, size, and strength of aggregates), macropores (number, continuity, orientation), roots (shape, size, distribution), fauna (earthworms), and surface characteristics. For this method, it is necessary to sample when roots are developed.

Shepherd (2000) proposed the Visual Soil Assessment (VSA) system using many of the same criteria. Its strengths are that it requires little training or technical skill. This is because soil observations are compared with reference photographs and figures, and clear score cards are provided for recording results. It also compares scores from areas of interest with those from 'non trafficked' areas of the field, to give an assessment of compaction. As some soil factors or indicators are more important for soil condition relative to others, VSA provides weighted scores.

A key feature of VSA is the drop shatter test where soil is dropped onto a wooden board from a height of 1m to separate aggregates. Hand separation of aggregates by inexperienced operators can be a major source of error in some similar tests. Tests are recommended once each year, after harvest and before cultivation, with optional tests after seedbed preparation to check condition.

The SOILpac score (Daniels and Larsen, 1991) was first developed within the Australian cotton industry to allow a semi-quantitative assessment of soil structural condition. Soil compaction severity is separated into 20 categories ranging from 0–2.0. The procedure is based on visual assessment of soil samples pulled apart by hand. McKenzie (2001a) addressed some of the limitations of this method and related them to their relevance to root growth. Limitations included operator bias, inability to deal with the continuity of vertical macropores, encroachment of under-furrow compaction into the ridges, and the presence of thin smeared layers.

Spoor *et al.* (2003) concluded that the degree of impedance presented by compacted layers could not be readily identified by physical measurements such as bulk density, soil strength and penetration resistance. More appropriate measurements related to macroporosity would be 'rootability', aeration status and/or 'drainability'. Of these three, they concluded that that rootability was most readily assessed by examining the root system of an established, growing crop. As there is no absolute measure of root development, they suggested a visual comparison of areas of good and poor growth by digging soil pits. Rooting characteristics that indicate compaction are taproots failing to grow downwards, horizontal layering of roots, roots being squashed against the side of soil structural units and thickened, rather than slender, roots.

The strengths and weaknesses of the techniques discussed in this section are summarised in Table 6.

TABLE 6. COMPARISON OF VISUAL ASSESSMENT TECHNIQUES.

Method and reference	**Depth**	**Strengths**	**Weaknesses**	**Required operator expertise**	**Key features**
Soil Survey (Hodgson, 1976)	>1 m	Comprehensive	Time consuming, expert interpretation needed	Trained soil surveyors	Can be used by experts to interpret causes as well as effects
St.Score (Anon., 1977)	0.2 m	Simple, rapid	Insensitive to specific compaction zones, topsoil only	Basic	Ease of use
Ball and Douglas (Ball and Douglas, 2003)	0.3 m	Comprehensive	Topsoil only	Trained	Specific zones separated
VSA (Shepherd, 2000)	0.2 m	Procedures simple to follow	Topsoil only	Basic	Photographic comparisons
SOILpac (Daniels and Larsen, 1991)	>1 m	Comprehensive	Time consuming	Trained	Operates to full rooting depth
SOILpac (modified) (McKenzie, 2001a)	>1 m	Comprehensive	Time consuming	Trained	Includes assessment of smearing and pore continuity
Root growth method (Spoor *et al.*, 2003)	>1 m	Simple, compaction easily identified	Concentrates on developed crop so problems can only be remedied in following crop	Basic	Directly aimed at plant response

6.3 Porosity

To understand soil physical properties it is necessary to have an understanding of the functions of soil pores, which are largely dependent on pore diameter. In Table 7, the major functions of pores, of different diameters, are outlined. In general, the larger pores are those that affect drainage, intermediate pore sizes allow the flow of water and nutrients (in soil solution) and provide passage for roots, whilst the smallest pores are inaccessible to plants. The larger pores are those most affected by compaction (Section 9).

TABLE 7. DESCRIPTIONS AND FUNCTIONS OF SOIL PORES (HAMBLIN, 1985).

Pore size (mm diameter)	Description of pores	Functions of pores
<0.0002	Residual	Retain water that plants cannot use
0.0002–0.05	Storage	Retain water that plants can use
>0.05	Transmission	Allow water to drain out and air to enter
0.1–0.3	Rooting	Allow crop roots to penetrate freely
0.5–3.5	Worm holes	Allow water to drain out and air to enter
2–50	Channels	Allow water to drain out and air to enter

Pore space can be calculated from dry bulk density and particle density (usually 2.5–2.8 g cm^{-3}). Total porosity is calculated as follows:

Total porosity = Volume of voids/total volume

Other measurements of porosity do not just focus on the size and distribution of pores (which predominate in visual techniques), but include direct or indirect assessments of the influence of features that may limit water and gas movement, such as continuity of pores, presence of constrictions and direction (Campbell, 1984). Some details of other measurement methods are given in the Appendix.

6.4 Soil strength

Soil strength can be described as the resistance of a soil to fracture by an applied shear stress or to deformation by a compressive stress (Anon., 1977). Cultivation can fracture the soil, whilst wheels exert a predominantly compressive force. In practice there is often a complex interaction of stresses of different types and because of this complexity the techniques used by researchers are generally only empirical or semi-empirical (Soane and van Ouwerkerk, 1981; Anon., 1977).

Soil strength varies in a systematic way with changes in moisture, bulk density and soil texture (Anon., 1977). Tests can be carried out in the laboratory or field. Laboratory tests are generally more complicated, require good quality undisturbed samples, and are more suited to engineering purposes where it is necessary to obtain accurate measurements under specified conditions (Anon., 1977). The most commonly used field tests are described in more detail in the Appendix.

6.4.1 *Penetrometry*

Penetration resistance is measured by flat or, more commonly, cone-shaped probes. This is a simple and highly convenient method of measuring quickly to a considerable depth (Soane and van Ouwerkerk, 1981). The number of determinations required per field depends on the extent of variation within individual fields. Published values for numbers of measurements per field include 10–20 (Smith, 1987) and 10–50 (Anon., 1977).

Penetration resistance increases rapidly as soil moisture content decreases, so quantitative data can only be obtained when comparing soils of similar water contents (Anon., 1977). Smith (1987) also acknowledged the difficulties in interpreting penetrometer readings. Field experimentation has highlighted further difficulties in interpreting results from soils with appreciable stone contents, although these can be minimised by selecting narrow cones and increasing sampling density.

Chancellor (1976) compared data obtained by a number of workers and stressed the desirability that determinations be carried out at field capacity to help minimise variations related to water content. The rate of penetration also significantly affects resistance and a number of authors have tried to equate penetration resistance to the ability of roots to penetrate compacted soils. For example, Bengough, Mullins and Wilson (1997) claimed that in laboratory studies penetration resistance to a probe provided an estimate of the resistance experienced by roots, but penetration resistances were typically 2 to 8 times greater than resistances experienced by roots! Overestimates may be due to roots experiencing negligible friction compared to a probe (as a result of lubrication by root mucilages) and whilst the resistances of many soils show little dependence on penetration rate, Bengough *et al.* (1997) suggested that for direct comparisons, rate must be taken into account. Further confusion arises from their observation that in laboratory tests, remoulded cores (despite having a greater bulk density than intact cores) had smaller penetration resistance. This was believed to be due the contribution to strength of structural bonding and age hardening in the field cores.

Bennie and Krynauw (1985) reported that most authors found a curvilinear relationship with a critical deflection point at about 1-2 MPa, when relating penetrometer resistance to root length, elongation rate or rooting density for a range of crops in South Africa.

Stone (1988) reported that crop production was little affected by resistances of 1.0–1.5 MPa but was noticeably reduced at greater values. It was also noted there was no response to deep loosening in potatoes at a subsoil resistance of 1.0 MPa.

6.4.2 Soil surface and sub-surface deformations

Measurements of the depth, width and cross-sectional area of ruts are a quick and effective way of measuring compaction below ruts (Soane *et al*., 1982). The resultant changes in soil bulk density below ruts will vary with depth, soil physical properties and the amount of lateral movement (Smith 1987). However, Chamen *et al.* (2003) concluded that the ruts generated by wheels or tracks of a vehicle are a good indicator to the farmer of the degree of compaction that has occurred. Further investigation would be needed to investigate the cause, which could be excessive pressure or that the soil was loose. Smith (1987) agreed that a model produced from such data was valuable for assessing the relative contributions to the compaction process made by changes in soil and wheel variables.

6.5 Soil density

Wet bulk density is the mass of soil particles plus the mass of water in a unit volume of soil. To compare soils at different water contents dry bulk density is normally used. This is derived from wet bulk density by subtracting the mass of water present in a unit volume.

The various methods for determining soil bulk density were discussed by Campbell (1994) and Anon. (1977), and these are summarised in the Appendix.

6.6 Modelling

Much work has been carried out recently in modelling, rather than directly assessing, soil characteristics that indicate compaction. The driving force behind much of this work has been to extrapolate expensive field trial measurements to local conditions. More details are given in the Appendix.

6.7 A comparison of methods

McKenzie (2001b) proposed that an ideal procedure, or group of procedures, for soil compaction/root growth assessment, should have the following features.

- Able to directly measure, or be closely correlated with, soil physical factors directly affecting root growth and function (i.e. mechanical impedance and aeration).
- Either not affected by water content, or easily corrected for this factor.
- Able to be carried out with large volumes of soil, and/or be easily repeated to deal with field variability at a scale relevant to root growth and associated processes.
- Not subject to operator or sampling bias.
- Affordable.
- Have operating procedures that are easy to learn and execute.
- Non destructive.

The various methods discussed in the preceding sections have been summarised in Table 8. Other methods, outlined in the Appendix, are summarised for comparison in a similar way, in Table 9.

Although all methods measure compaction (or soil properties directly affected by compaction) critical values are difficult to determine as the methods are all affected by soil type, moisture status and crop root morphology. Furthermore, many experiments have been done in extreme conditions, so are not representative of more usual conditions in commercial agriculture.

Soane *et al.* (1987) found that although measurements of bulk density and penetration resistance were useful comparative techniques, they should be used in conjunction with soil profile examination. Tortuosity and continuity of pores, for example, were only detectable by visual methods.

TABLE 8. A COMPARISON OF PRACTICAL METHODS FOR FIELD ASSESSMENT OF COMPACTION.

Method	Correlation with Physical factors	Effect of water content	Scale	Bias	Cost	Degree of training
Visual	Good	Difficult in dry soils	Large volume	Large volume, so representative location important	Low	Low–High
Penetrometer	Fair	High	Small, but easily repeated	Rate of penetration important Difficult on stony soils	Small initial investment, low running cost	Low
Wheel sinkage/ rut depth	Fair	Not applicable	Easily repeated	Low, but applies to wheelings only	Low	Low

TABLE 9. A COMPARISON OF RESEARCH METHODS FOR ASSESSMENT OF COMPACTION.

Method	**Correlation with Physical factors**	**Effect of water content**	**Scale**	**Bias**	**Cost**	**Degree of training**
Infiltration rate	Fair	Nil	Large or easily repeated	Tendency for ponding	Low	Low
Soil moisture release curve	Fair/good	Not applicable	Small	Negligible	High	High
Fabric analysis	Good	Low	Very small scale	Small scale	High	High
Shear Vane/box	Fair	High	Small, but easily repeated	Speed of revolution important	Low	Medium
Manual bulk density	Fair/good	Nil (adjusted)	Easily repeated	Negligible	Low	Medium
Bulk density by gamma ray/TDR	Fair	Nil (adjusted)	Easily repeated	Negligible	High	High
Predictive models	Potentially good	Nil (adjusted)	Parameters easily adjusted	Negligible	Potentially low	High

7. MINIMISATION and prevention of compaction

7.1 Appropriate use of machinery

7.1.1 In potato crops

Operational widths are often ignored in the scientific literature, but advisory experience suggests these should be considered before wheels, tyres and pressures, as choice of tractors may change with any new system. For example, a destoner may need a tractor of 130 hp (97 kW) or more, dependent on soil type. Tyres should not impinge on the bed. Such a tractor is likely to be fitted with tyres approximately 430 mm in section width and allowing for tyre deflection, an overall width in any furrow bottom of 500 mm should minimise soil damage to adjacent ridges.

A three-bed system of bed forming or making, which we are beginning to see in the larger potato businesses, will demand approximately 220 hp (164 kW), resulting in very different tyre selection. Such tractors might be fitted with 600 mm wide tyres on the front and 710 mm on the rear, selected to minimise soil damage yet provide adequate traction. Allowing for tyre deflection of 50 mm either side of a tyre, such power requires a review of planting working widths. Rationalisation is needed to ensure soil is not compacted, or that the bed making implement can immediately remove any compactive effects. Such systems require a 2 m tractor track width.

Rationalisation around the commonly used width of 1.83 m can allow cultivations to match up, but not to the degree with which a 2 m system can. Common cultivation equipment is sold as 3, 4 or 6 m, which does not match 1.83 m. Many businesses do not have the power available to move to a 2 m system, so cannot achieve some of the benefits from rationalisation. However, cultivations should still be planned to avoid wheelings under growing areas.

Whether grown in beds or rows, potato crop quality, and thus saleable yield, will benefit from adopting differential growing and wheeling widths. The common wheeling standard of 1.83 m allows the imperial system of 0.86 m (34 inches) growing for row centres and 0.97 m (38 inches) for wheeling rows. Thus, with normal slopes of ridge sides, a 0.43 m (16.9 inches) tyre section will fit between rows spaced 0.97 m (38 inches) apart without damage to the ridge sides, and bruising, skin damage and greening are avoided. This principle can be used for bed work, but the choice between beds and rows is usually decided on other criteria such as benefits for moisture retention, tuber size distribution required in the ware crop, and improved cushioning of tubers at harvest.

When all these factors have been considered, operator training involving all equipment is fundamental to the avoidance of compaction. The casual deviation of trailer drivers from set tracks or routes multiplies the need for remediation.

The place of potatoes in the rotation may also influence the practicality of removing compaction that has occurred in other crops. When potatoes are grown after cereals, there is likely to be sufficient time in the autumn, in sufficiently dry conditions, for any remedial action which is necessary, especially subsoiling. On the other hand, it is not ideal to grow potatoes after late-harvested crops that leave insufficient time and unsuitable soil conditions for remedial action.

7.1.2 Throughout the rotation

Throughout the rotation, attention should be given to all machine management. A review of all wheels and tyres should be made for each operational task to aim for all wheels to exert appropriate ground pressures (Spoor *et al.*, 2003).

Avoidance of topsoil compaction during the crop growing season can be achieved by operating at pressures less than 50 kPa (0.5 bar, 7 psi), and less than 100 kPa at other times (Tijink, Doll and Vermeulen, 1995). Practically this is a challenging goal with 75 kPa in the crop, and 150 kPa at other times, being attainable by most tractor operations. Spoor *et al.* (2003) recommended maximum ground pressures according to soil vulnerability class (Section 5.3) of 65 kPa for extremely vulnerable soils, up to 150 kPa for moderately vulnerable soils, and 200 kPa for soils that are not particularly vulnerable. Corresponding inflation pressures of 40, 120 and 160 kPa were also advised. Tractor and trailer tyre fitments can now allow pressures as low as 100 kPa, but for many self-propelled harvesters this is unlikely to be possible.

Guidance on the selection of tyre/wheel combinations, (although often comparing only a limited range of options) has been published by a number of authors, for example, Forristal (2004). However, advisory experience suggests many growers are understandably loath to accept pressures at the lower end of the range, in order to avoid problems with tyre rim creepage and subsequent tyre damage and downtime, and decreased road speeds. Thus many growers may not benefit from reduced compaction by this means.

Tyre slippage can have severe effects on soil structure by blocking vertical pores. Selection of appropriate machinery and tyres should aim at producing slippage of only 8-16% (Schuler *et al.*, 1986) (slippage or wheel slip is the reduction in travel distance as a percentage of the distance that would be travelled if there were no tyre slippage).

The extent to which compaction affects crop production is related to the area of field affected by compaction. Thus, rationalisation of wheelings and operational widths of equipment are key to limiting compaction. Bennie and Krynauw (1985) and Spoor *et al.* (2003) emphasised the benefits of using controlled trafficking for seedbed preparation cultivations, planting and weed control operations, by always staying on the same wheel tracks.

As discussed in Section 5.1.1, ploughing with wheels in the in furrow has been identified as a major cause of subsoil compaction. Bennie and Krynauw (1985) and Spoor *et al.* (2003) recommended ‘on land ploughing’ where the tractor wheels move outside the plough furrow, but this is rarely practised. All types of crawler tractor naturally practise this, but with wheeled tractors, in-furrow ploughing predominates.

Tracklaying tractors, often with ’rubber’ tracks, can weigh 10 t or more. The can exert significant loads on the subsoil, sufficient to affect porosity and drainage. Alakukku *et al.* (2003) stated that it is difficult to draw clear conclusions about comparative effects on subsoil compaction, of tracks or tyres. However, under ‘normal agricultural conditions’, the advantages of less slip and lower rut depth, on wet or soft soils, were noted as beneficial. Potatoes are increasingly being grown in larger unit areas of land, by more specialist growers, who might be more likely have rubber tracked units. These tractors are more powerful than many wheeled units, and may be used to operate wider implement widths. Thus there would be fewer passes over the ground and fewer wheelings. If this is linked to good rationalisation of implement widths, it should lead to less ground area being trafficked, with a resultant decrease in compaction.

Another practise that could be adopted is the avoidance of power-driven implements (e.g. rotavator) that cause smearing, particularly in a wet spring.

7.2 Improving soil structure

Soils are more prone to compaction if soil structural stability is poor, or if they are excessively wet (beyond the plastic limit). Generally the worst compaction occurs on sands and silts because of their poor structural stability. Heavier soils are more stable when dry but become less stable when wet. Thus, long term mitigation measures must seek to improve stability and minimise the periods when soils are too wet for trafficking.

7.2.1 Organic matter additions

Many researchers have reported the benefit of organic matter additions in improving soil structure and trafficability. Wilhelm *et al.* (2004) found that applications of farm yard manure (FYM) increased soil organic carbon, and some physical parameters including soil stability. Others have shown that organic matter additions have improved infiltration rate, water retention, aggregation and aggregate stability in water (Benbi *et al.*, 1998), bulk density and shear strength (Schjonning, Christensen and Carsten, 1994), and soil friability (Watts and Dexter, 1998).

Schjonning *et al.* (1994) highlighted the complex relationship between organic matter additions and soil texture by examining soil physical properties in a long term (over 90 years) experiment in Denmark, on a sandy loam soil. The treatments were unfertilised, FYM and mineral fertilised. Both fertilised and FYM treatments decreased topsoil bulk density but at a given moisture content increased soil shear strength both as measured by shear vane and penetrometry. This demonstrates the cohesive effects of organic matter on light textured soils. Organic matter can increase the strength of a light soil, making it more structurally resilient to deformation. Schjonning *et al.* (1994) produced a compactability index from the reduction in void ratio when subjected to a standard load. They found that soil in the FYM treatment was less compactable than soil from the mineral fertilised treatment.

Samples were taken from the same experiment site by Munkholm *et al.* (2002). The unfertilised soil had little organic matter or microbial biomass, and was dense. Its aggregates were strong when dry and weak when wet. In contrast the manured soil had aggregates that were comparatively stronger when wet and weaker when dry. Mineral fertilised soil was intermediate. The optimal water

content for tillage, and the water content range for which tillage was possible, were largest in the manured soil.

Nicholson *et al.* (2003) examined four experimental sites in the UK, which had received repeated manure additions over 7–9 years. The manure additions were shown to increase topsoil porosity, decrease bulk density and increase plant available water capacity as well as increasing microbial biomass and activity. Large and repeated inputs were needed to produce these results.

Koppi and Douglas (1991), however, pointed out that for soils with little clay content there was no relationship between bulk density and organic matter at organic matter contents less than 10%. Most of the evidence for a relationship between organic matter and soil structural stability comes from long-term experiments, in which relatively large increases in organic matter can occur. Organic matter inputs do not quickly improve soil structure.

Organic residues also have an important part to play in protecting the soil surface from capping. Chan and Mullins (1994), in slaking experiments, found a linear relationship between aggregate stability and soil organic matter concentration in British (Wick series) and Australian, hard-setting soils. Le Bissonnais and Arrouays (1997) found that the degree of crusting and infiltration capacity was related to aggregate stability, which was a function of organic carbon content. At organic carbon contents less than 20 g kg^{-1} (equivalent to 3.4% organic matter) there was a significant reduction in infiltration rate. In erosion studies, Guerra (1994) found that organic matter increased water stable aggregates and hence reduced runoff.

Surface capping commonly occurs on unstable soils, or because of slaking of fine seedbeds. The risk of this occurring can be minimised by leaving a coarse tilth. Trash at the surface can also help to lessen the impact of raindrops, and aid water infiltration (Anon., 2004c).

7.2.2 Drainage

A well designed and maintained drainage system complements a more stable structure and is of critical importance on soils that have a low hydraulic conductivity. Good drainage limits the periods when a soil is wetter than the plastic limit, and reduces the risk of damage to both topsoil and subsoil (Chamen *et al.,* 2003).

7.2.3 Cover cropping

Maintaining a cover crop over winter encourages water losses from depth through evapotranspiration, thus reducing the risk of compaction in the spring. This is particularly important for potato crops, as the topsoil is often dry enough for ridging when the subsoil is too wet for trafficking (Harrison *et al.,* 1985). The importance of this would depend on when the cover crop is destroyed, because, most years, it is not until spring that evapotranspiration exceeds rainfall. A cover crop brings forward the date at which a soil drops below field capacity, allowing a wider window for cultivation without structural damage.

In Norway, on a loam soil, Breland (1995) found that undersowing spring wheat with ryegrass, and allowing it to grow as a cover crop after grain harvest, until mid October, when the land was ploughed, prevented collapse of the ridged plough furrow over winter. In the following May there were improvements in the water stability of aggregates, aggregate size distribution, bulk density, and pore volume. The preservation of the plough furrow profile was mainly attributed to enmeshment by an extensive fine root system.

7.2.4 Soil chemistry

Maintenance of chemical fertility has a role to play in management of soil structure. Soil shear strength has been enhanced by calcium and potassium (Dexter and Chan, 1991), whilst low pH is detrimental (Chamen *et al.,* 2003).

7.2.5 Soil fauna

The importance of earthworms in making and maintaining macropores has also been mentioned in Section 9.5.2. It must be acknowledged, however, that potato cultivations, and use of some nematicides, are catastrophic for earthworm populations. Adopting practices throughout the rotation that minimise damage to faunal activity may allow populations to recover between potato crops, and are likely to have benefits for soil structure.

8. Remedial action

8.1 Physical remediation through the rotation and in-crop

Subsoiling is the only practical way to relieve severe compaction, but subsoiling, without soil examination before and during the activity, may be of little or no value, although at a cost to the grower. This was shown by a number of unpublished experiments on effects of deep cultivations in the 1980s at ADAS Terrington. Some of these showed effects on potato yield (Section 4,7.2), but many did not. Experiments on deep loosening of soil and controlled wheelways from 1983 to 1986 did not show effects on yield, and it is probable that in these cases, either compaction was not present, or the deep cultivations were ineffective because of soil conditions.

If subsoiling is done unnecessarily, or under inappropriate conditions, it can make the situation worse. The aim of subsoiling should be to improve conditions with minimal loss of soil support, leaving natural and biological processes to complete the remediation and stabilise the resulting soil conditions (Spoor *et al.*, 2003).

Soane *et al.* (1987) found that subsoil loosening on silty soils tended to reduce yields in wet seasons. This was probably due to accelerated disintegration of unstable structural units. Subsoil loosening on silty soils should be carried out only if severe subsoil compaction is limiting root growth.

Identification of the compacted layer(s) is a key first step in effective remedial treatment (see Section 6 for a discussion of methods). This should be done as a routine, both to identify possible problems at an early stage and to promote a better understanding of local soil problems (Anon., 2002a; Anon., 2004c).

There are a number of publications that give advice on best practice. These cover time of subsoiling, soil condition and choice of equipment (Soane *et al.*, 1982: Spoor *et al.*, 2003; Anon., 2004c).

The effectiveness of subsoiling legs on ploughs, one on every second furrow to break any pan at plough depth, depends on soil moisture at ploughing. Soane *et al.* (1987) stressed that soil loosened by winged tines after ploughing was less susceptible to recompaction than soil loosened prior to ploughing.

In the case of potato crops it is also important to bear in mind that soil moisture and cultivation condition are unlikely to permit any subsoiling at the time of spring planting operations (Wilhelm *et al.*, 2004). On light soils, however, subsoil pans can often be broken in spring.

After combinable crops, compaction is likely to be within tramlines, combine harvester wheelings and grain trailer routes. This can be corrected by subsoiling of tramlines to appropriate depth, followed by a press roll to level the soil surface. Subsoiling should be done when the subsoil is dry enough to allow fissuring.

Other areas (combine and grain trailer wheelings) should be subsoiled when tested for need and if soil conditions permit. Again, a level surface should be left. Some seasons are not conducive to effective subsoiling. In such seasons it may be best not to try remediation, but to ensure effective ploughing in anticipation of weathering in winter.

On some occasions and soil types it may be possible to subsoil behind the tractor wheels after potato planting, if stones or clods don't preclude this. A twin-legged, winged subsoiler can be used prior to main root development. This should reduce effects of planting operation wheelings, and possible erosion effects from rainfall and irrigation subsequently in the crop.

8.2 Chemical remediation, in-crop

There is little published information on this subject.

O'Sullivan, Henshall and Dickson, (1999) claimed that, generally in crop production, excessive compaction leads to the need for increased inputs to maintain crop growth. However, anecdotal evidence suggests that this need is often over-ridden by other, negative effects of compaction on crop growth.

If poor rooting results in magnesium deficiency, 2% sprays of Epsom salts may be effective in reducing symptoms. High potassium:magnesium ratios can induce magnesium deficiency if rooting is restricted, but rarely, low ratios can result in potassium deficiency.

Potatoes are generously fertilised (Anon., 2002b) and 30% of crops receive applications of organic manures. Therefore, even if rooting is restricted, nutrient availability to the roots is often high.

9 Effects of compaction on soil functions

9.1 Effects on physical functions

The functions of soil pores of different diameters are discussed in Section 6.3. Pores provide the channels for both water movement, gas movement and root growth. Total porosity of soils is usually between 30 and 70% by volume, with critical values, below which root growth restriction occurs, of 35% on sandy soils and 50% on clays (Anon., 1977). Forristal (2004) proposed that a healthy soil should contain 25% air and 25% water. Compaction reduces the number and size of macropores, increases their length through increased tortuosity, and reduces their effective diameters (Section 6.3). Thus we would expect these changes to affect the movements of air and water in the soil.

9.2 Effects on hydrological functions

In practical terms, the increase in bulk density caused by soil compaction results in decreases in total porosity and macropore space and an increase in the volume of micro or capillary pores. This leads to a reduction in hydraulic conductivity when the soil is wetter than field capacity (affecting infiltration and drainage) and an increase in soil water conductivity (affecting transfer of solutes within the soil) in drier soils (Wilhelm *et al.*, 2004).

Similar observations were made by Richard *et al.* (2001), who saw a decrease in water retained at water potentials of -5 to -20 kPa (representing pore diameters of 60–15µm) whilst water retained at -20 to -80 kPa (representing pore diameters of 4–15µm) increased. This he attributed to more contact between aggregates in compacted soil, with greater continuity between the pores filled with water, compared with a loose soil.

Thus, compacted soils are likely to become waterlogged (or produce runoff) following heavy rainfall events, but they can hold more water at high tensions in times of drought. In practice, however, this does not benefit the crop because of impaired root growth.

9.3 Effects on aeration and gas diffusion

Water can be retained, and is available to plants, in pores of <0.05 mm, but the passage of air is controlled by larger pores that are more affected by compaction. Consequently, experimenters have observed large changes in aeration following compaction.

Following five tractor passes, field compaction of silty clay loam soils, under permanent pasture or continuous cereals, reduced surface CO_2 fluxes by 58-69% because of the highly reduced air permeability of the topsoil (Jensen, McQueen and Shepherd, 1996). In cereals compaction also caused a 45% decrease in oxygen diffusion rate.

McAfee, Lindstrom and Johansson (1989) applied a tyre stress of 200 kPa to a clay soil in Sweden before harrowing and drilling oats in the spring. Air permeability was measured soon after drilling and at harvest. At harvest, permeability was considerably less in the compacted treatment (Table 10).

TABLE 10. AIR PERMEABILITY (MM S^{-1}) MEASURED *IN SITU* AT THE BEGINNING AND END OF THE GROWING SEASON, BY MCAFEE *ET AL.* (1989) (*P = <0.05).

Soil layer (mm)	Date	Control	Compacted
0-50	30 May	64.5	30.3*
	2 Sep	12.3	9.8
100-150	30 May	32.3	0.17*
	2 Sep	12.3	1.63*
250-300	30 May	1.63	0.42*
	2 Sep	1.63	2.45

McAfee *et al.* (1989) also concluded that a gas diffusion rate of 1 mm s^{-1} was sufficient for effective root growth at an air filled porosity of 10%.

As compaction can severely restrict drainage through loss of transmission pores, there is a high risk of water logging during the season after excess rainfall and irrigation. The diffusion coefficients of oxygen and carbon dioxide in water are 1000 times less than in air (Marshall and Holmes, 1988). Hence Boone *et al.* (1978) found that compaction decreased gas diffusion in a sandy loam and had a transient effect on oxygen concentration in the presence of irrigation.

9.4 Effects on chemical functions

Effects of compaction on nutrient uptake by the potato crop are discussed in Section 4.4. The effect of compaction on transport of nutrients to the roots depends on the amount of compaction and on nutrient and water supply. In well-watered and high fertility soils, some consolidation may have a beneficial effect due to greater water retention, hydraulic conductivity for mass flow transport, diffusion coefficient of ions, and ion concentrations in the soil (Lipiec and Stepniewski 1995).

Forristal (2004) summarised the difficulties in interpreting the relationship between compaction and nutrition because crop response is influenced by many factors including crop type, soil type, degree of compaction and moisture status and thus is critically affected by drought and water logging.

Lipiec and Stepniewski (1995) summarised that compaction modifies the soil nitrogen balance in three ways:

1. alteration of the soil aeration process which contributes directly to denitrification, gaseous nitrogen losses, and decreased nitrogen mineralisation rate;
2. alteration of the soil water properties which induce changes in nitrogen transport and leaching;

3. alteration of the arrangement of soil particles resulting in changes to root configuration, root/soil contact and ion diffusivity.

In terms of crop nutrition, the most important factor affecting nitrogen uptake in compacted soil is likely to be a decrease in the volume of soil available for root exploration. Weaker root development in compacted soil may also lead to a reduction in uptake of many nutrients (Bennie and Krynauw, 1985).

Phosphorus is relatively immobile, so uptake is mostly related to the configuration of the root system. In barley, compaction caused a significant reduction in phosphorus uptake, but other researchers have observed that uptake could be partially compensated for by increased uptake from non compacted soil zones, through increased uptake per unit length of root compared with unrestricted root systems (Lipiec and Stepniewski, 1995).

Potassium uptake by soya beans was reduced by compaction and was mostly attributed to the decrease in root surface area. Magnesium and calcium uptake were reduced in winter wheat and oats whilst manganese and iron concentrations were greater in peas on compacted headlands (Lipiec and Stepniewski, 1995).

Schuler *et al.* (1986) stated that compaction can reduce nutrient uptake in maize by restricted rooting, making nutrients below rooting depth inaccessible. In addition, poor aeration increases the potential for denitrification, leading to nitrogen deficiency. Phosphorus deficiency, reduced potassium uptake and increased levels of manganese and aluminium were also reported. Magnesium deficiency in potatoes is aggravated by soil compaction, water logging or water stress (Scaife and Turner, 1983), and is often an early indication of such problems.

The presence of a severely compacted subsoil layer causing anaerobic conditions may lead to ethylene production causing severe root and yield damage (Campbell and Moreau, 1979). This may be one of the mechanisms that leads to effects of compaction on nutrient uptake.

9.5 Effects on biological functions

9.5.1 Rooting

Effects of compaction on root growth of potato plants are discussed in Section 4.3.

Marks and Soane (1987) showed that subsoil loosening increased the yield of spring-sown crops (particularly sugar beet) on sandy soils, but only in years of moderate drought. This was associated with deeper rooting and improved water extraction. However, only one potato crop out of seven showed any yield benefit (see also Section 4.7.2).

9.5.2 Soil fauna and flora

Whilst soil fauna, particularly earthworms, can help mitigate the effects of soil compaction through burrowing and recycling of organic matter, populations are likely to be reduced in compact soil.

Earthworm populations under intensive arable cropping are generally low. Edwards and Lofty (1977) reported numbers in UK arable situations of 18-287 m^{-2} compared to 389-524 m^{-2} in grassland. In general terms, the greater the organic matter content of the soil, the greater the earthworm population and the greater the intensity and frequency of cultivations, the fewer the earthworms (Edwards, 1980). Cultivations for potato crops are very damaging to earthworm population density.

Koppi, Douglas and Moran (1992) noted that the number of pores produced by faunal activity were greater under zero and reduced trafficking than in conventional practice. This may be because differences in populations or larger losses of pores under conventional trafficking. Chamen and Longstaff (1995) saw similar results which they attributed to increases in number and/or activity. This is of particular significance as soil fauna, along with plant roots, are important in creating vertical channels in the soil which aid aeration and drainage. These vertical pores are less likely to collapse under load pressure than horizontal pores created by cultivation (Jones *et al.*, 2003).

Langmaack *et al.* (1999) inoculated compacted and uncompacted monoliths (small, vertical columns of undisturbed soil, removed from the field) with earthworms. The continuity of burrows was changed in compacted soil and attributed to a change in burrowing activity to minimise energy expenditure. Conservation tillage had higher earthworm numbers than conventional systems.

A thirty-fold decrease in protozoan populations with compaction in laboratory studies has been attributed to increased moisture content and reduced aeration rather than a direct effect of structure (Griffiths and Young, 1994).

Microbial activity is likely to be influenced by changes in the structure of pores, which influence predation (Crawford, Matsui and Young, 1995).

10 Conclusions

- Soil compaction can be defined as a reduction in soil pore volume and an increase in soil bulk density.
- Compaction is almost universally acknowledged to have negative effects on crop production.
- Soil compaction adversely affects canopy size and/or duration, with a consequential decrease in yield.
- Yield reductions of up to 37%, caused by compaction, have been recorded experimentally.
- Compaction can lead to decreased root growth, either through an inability to survive in compacted soil, or an inability of roots to penetrate compacted soil.
- Soil compaction limits the volume of soil explored by the crop root system, thus limiting access to soil water.
- Compaction may lead to poor tuber quality, either directly (e.g. misshapen tubers) or indirectly (increase in tuber rot diseases and common scab).
- The most practical methods for assessment of compaction in commercial potato production are based on the digging of a soil pit, followed by visual examination.
- Compaction occurring anywhere in the rotation can persist into the potato crop.
- Soil moisture status affects soil strength, and is the primary soil factor influencing soil susceptibility to compaction.
- Risks of compaction are greatest with large loads and moist soils, a combination that often occurs in late autumn and early spring.
- Soil types that are structurally unstable, especially fine sandy loams and loamy fine sands, are more susceptible to harmful compaction than other soil types.
- Subsoiling is the only practical way to relieve severe compaction of subsoil, but subsoiling without soil examination before and during the activity, may be of little or no value.
- Large soil pores are those that provide drainage, and these are more affected by compaction than smaller pores.
- Frequent additions of manure improve soil structure and structural stability.
- The ability of a soil to recover from compaction, by regeneration of structure on drying, increases with clay content.
- In order to meet Good Agricultural and Environmental Condition (GAEC) Cross Compliance requirements, farmers will need to produce a simple Soil Management Plan in 2006, and this must be implemented from 2007.

11 References

Alakukku L., Weisskopf P., Chamen W.C.T., Tijink F.G.J., van der Linden J.P., Pires S., Sommer C. and Spoor G. (2003). Prevention strategies for field traffic induced subsoil compaction: a review. Part 1 Machine/soil interactions. *Soil Tillage Research*, **73:** 145-160.

Allen E.J. and Scott R.K. (2001). *Potato Agronomy.* BPC Research Review, British Potato Council, Oxford.

Allen E.J., Allison M.F. and Sparkes D.L. (2005). Physiological and technological limits to yield improvement of potatoes. In Eds: Sylvester-Bradley R. and Wiseman J. *Yields of farmed species: constraints and opportunities in the 21st century.* pp. 289-309. Nottingham University Press, Nottingham.

Anon. (1977). *Techniques for measuring soil physical properties.* MAFF advisory paper 18, HMSO, London.

Anon. (2002a). *A Guide to better soil structure.* National Soils Research Institute, Cranfield University.

Anon. (2002b). *The British Survey of Fertiliser Practice – Fertiliser use on farm crops for crop year 2002.* BSFP Authority, Peterborough.

Anon. (2004a). *Cross Compliance Handbook for England* (PB 10222A). Defra, London.

Anon. (2004b). *Cross Compliance Guidance for Soil Management* (PB 10222B). Defra, London.

Anon. (2004c). *Target on Establishment.* Vaderstad/Soil Management Initiative, Sweden and UK.

Anon. (2005a). *Entry Level Stewardship Handbook* (PB *10355*). Defra, London.

Anon. (2005b). *Higher Level Stewardship Handbook* (PB 10382). Defra, London.

Bailey A.C., Raper R.L., Johnson C.E. and Burt E.C. (1995). An integrated approach to soil compaction prediction. *Journal of Agricultural Engineering Research,* **61:** 73-80.

Ball B.C. and Douglas J.T. (2003). A simple procedure for assessing soil structural, rooting and surface conditions. *Soil use and management,* 19: **50-56.**

Ball B.C., Campbell D.J., Douglas J.T., Henshall J.K. and O'Sullivan M.F. (1997). Soil structural quality, compaction and land management. *European Journal of Soil Science,* **48:** 593-601.

Benbi, D.K., Biswas C.R., Bawa S.S. and Kumar K. (1998). Influence of farmyard manure, inorganic fertilizers and weed control practices on some soil physical properties in a long-term experiment. *Soil Use and Management,* **14:** 52-54.

Bengough A.G., Mullins C.E. and Wilson G. (1997). Estimating soil frictional resistance to metal probes and its relevance to the penetration of soil by roots. *European Journal of Soil Science,* 48: **603-612.**

Bennie A.T.P. and Krynauw G.N. (1985). Causes, adverse effects and control of soil compaction. *South African Journal of Plant and Soil,* **2:** 109-114.

Blake G.R., Boelter D.H., Adams E.P. and Aase J.K. (1960). Soil compaction and potato growth. *American Potato Journal,* **37:** 409-413.

Boag B. (1988). *Influence of ploughing, rotary cultivation and soil compaction on migratory plant-parasitic nematodes.* In: Tillage and traffic in crop production. Proceedings of the 11th international conference of the International Soil and Tillage Research Organization, Edinburgh, UK, 11–15 July 1988, pp. 209-214.

Boone F.R., Bouma J. and de Smet L.A.H. (1978). A case study on the effect of compaction on potato growth in a loamy sand soil. I. Physical measurements and rooting patterns. *Netherlands Journal of Agricultural Science,* 26: **405-420.**

Breland T.A. (1995). Green manuring with clover and ryegrass catch crops undersown in spring wheat: effects on soil structure. *Soil Use and Management,* 11: **163:167.**

Campbell D.J. (1994). Determination and use of soil bulk density in relation to soil compaction. In Eds: Soane B.D. and van Ouwerkerk C. *Soil compaction in crop production*, Elsevier Science Publishers, B.V., Amsterdam, Netherlands.

Campbell R.B. and Moreau R.A. (1979). Ethylene in compacted field soil and its effect on growth, tuber quality and yield of potatoes. *American Potato Journal,* **5:** 199-210.

Chamen T., Alakuku L., Pires S., Sommer C., Spoor G., Tijink F. and Weisskopf P. (2003). Prevention strategies for field traffic induced subsoil compaction: a review. Part 2 Equipment and field practices. *Soil Tillage Research,* **73:** 161-174.

Chamen W.C.T. and Longstaff D.J. (1995). Traffic and tillage effects on soil conditions and crop growth on a swelling clay soil. *Soil Use and Management,* 11: **168-176.**

Chamen W.C.T., Vermeulen G.D., Cambell D.J. and Sommer C. (1992). Reduction of traffic-induced soil compaction: a synthesis. *Soil and Tillage Research,* **24:** 303-318.

Chan K.Y. and Mullins C.E. (1994). Slaking characteristics of some Australian and British soils. *European Journal of Soil Science,* 45: **273-283.**

Chancellor W.J. (1976). *Compaction of soil by agricultural equipment.* Bulletin 1881, Division of Agricultural Science, University of California.

Crawford J.W., Matsui N. and Young I.M. (1995). The relation between the soil moisture release curve and the structure of soil. *European Journal of Soil Science,* 46: **369:375.**

Daniels I.G. and Larsen D. (Eds) (1991). *SOILpac: a soil management package for cotton production on cracking clays.* NSW Agriculture: Narrabri, NSW, Australia.

Dexter A.R. and Chan K.Y. (1991). Soil mechanical properties and exchangeable cations. *Journal of Soil Science,* 42: **219-226.**

Edwards, C.A. and Lofty J.R. (1977). *Biology of earthworms.* Second Edition. Chapman & Hall, London.

Edwards C.A. (1980). Interactions between agricultural practice and earthworms. In *Soil biology as related to land use practices.* Proceedings of VII International Colloquium of Soil Zoology, pp3-12.

Forristal D. (2004). Machinery, tyres and the soil. Teagasc, Crops Research Centre, Oak Park, Eire. www.teagasc.ie/publications/2003/conferences/nationaltillage/paper07.htm accessed 01 February 2005.

Griffiths B.S. and Young I.M. (1994). The effects of soil structure on protozoa in a clay loam soil. *European Journal of Soil Science*, **45:** 285-292.

Guerra A. (1994). The effect of organic matter content on soil erosion in simulated rainfall experiments in West Sussex, UK. *Soil Use and Management,* **10:** 51-55.

Hamblin, A.P. (1985). The influence of soil structure on water movement, crop root growth and water uptake. *Advances in Agronomy,* **38:** 95-158.

Harrison D.J., Dawson E.M., Birkenshaw J.E. and Davies A.C.W. (1985). The effect of compaction on the yield and quality of vegetable crops. *Research and Development in Agriculture,* **2:** 71-75.

Hepple C.M., Chapman A.S., Bidwell V.J., Forrester G. and Kilfeather A.A. (2004). A lysimeter experiment to investigate the effect of surface sealing on hydrology and pesticide loss from the reconstructed profile of a clay soil. 1. Hydrological characteristics. *Soil Use and Management,* **20:** 373-383.

Hettiaratchi D.R.P. (1987). A critical state soil mechanics model for agricultural soils. *Soil Use and Management,* **3:** 94-106.

Hodgson J.M. (Ed) (1976). *Soil Survey Field Handbook,* Technical Monograph No. 5. Soil Survey of England and Wales, Harpenden, England.

Jensen L.S., McQueen D.J. and Shepherd T.G. (1996). Effects of soil compaction on N-mineralisation and microbial C and N. *Soil Tillage Research,* **38:** 175-188.

Jones R.A., Spoor G. and Thomasson A.J. (2003). Vulnerability of subsoils in Europe to compaction: a preliminary analysis. *Soil Tillage Research,* 73: **131-143.**

Koppi A.J. and Douglas J.T. (1991). A rapid, inexpensive and quantitative procedure for assessing soil structure with respect to cropping. *Soil Use and Management,* 7: **52-56.**

Koppi A.J., Douglas J.T. and Moran C.J. (1992). An image analysis evaluation of soil compaction in grassland. *Journal of Soil Science,* 43: **15-25.**

Lane A., Bradshaw N.J. and Buckley D. (2000). Pests and Diseases of Potatoes. In Ed: Alford D.V., *Pest and Disease Management Handbook,* Chapter 5, pp. 123–165. Blackwell Science Limited, Oxford.

Langmaack M., Schrader S., Rapp-Bernhardt U. and Kotzke K. (1999). Quantitative analysis of earthworm burrow systems with respect to biological soil-structure regeneration after soil compaction. *Biology and Fertility of Soils,* **28:** 219-229.

Le Bissonnais Y. and Arrouays D. (1997). Aggregate stability and assessment of soil crustability and erodability: II Application to humic loamy soils with various organic carbon contents. *European Journal of Soil science,* **48:** 39-48.

Lipiec J. and Stepniewski. W. (1995). Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil and Tillage Research,* 35: **37-52.**

MacKerron D.K.L. (1993). The benefits to be gained from irrigation. In Ed: Bailey R.J. *Irrigating Potatoes,* UK Irrigation Association Technical Monograph 4', UK Irrigation Association, Silsoe College, Bedfordshire.

Marks M.J. and Soane G.C. (1987). Crop and soil response to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and susequent soil management on a range of soil types. *Soil Use and Management,* **3:** 115-122.

Marshall T.J. and Holmes, J.W. (1988). *Soil Physics,* Second edition. Cambridge University Press, Cambridge.

McAfee M., Lindstrom J. and Johansson W. (1989). Effects of pre-sowing compaction on soil physical properties, soil atmosphere and growth of oats on a clay soil. *Journal of Soil Science,* **40:** 707-717.

McDole R.E. (1975). Influence of cultural practices and soil compaction on yield and quality of potatoes. *American Potato Journal,* **52:** 285-286.

McKenzie D.C. (2001a). Rapid assessment of soil compaction damage. I The SOILpak score, a semi-quantitative measure of soil structural form. *Australian Journal of Soil Research,* **39:** 117-125.

McKenzie D.C. (2001b). Rapid assessment of soil compaction damage. II The relationship between the SOILpak score, strength and aeration measurements, clod shrinkage parameters and image analysis. *Australian Journal of Soil Research,* **39:** 127-141.

Munkholm L.J., Schjonning P., Debosk K., Jensen H.E. and Christensen B.T. (2002). Aggregate strength and mechanical behaviour of a sandy loam soil under long-term fertilisation treatments. *European Journal of Soil Science,* 53: **129-137.**

Nicholson F., Bhogal A., Chalmers A. and Chambers B. (2002). Benefits of farm manure additions to soil quality. Abstract in: The draft soil protection strategy: implications for the agricultural and environmental sectors. SCI meeting, 12 March 2002.

O'Sullivan M.F. (1992). Deep loosening of clay loam subsoil in a moist climate and some effects of traffic management. *Soil Use and Management,* **8:** 60-67.

O'Sullivan M.F., Campbell D.J. and Hettiaratchi D.R.P. (1994). Critical state parameters derived from constant cell volume triaxial tests. *European Journal of Soil Science,* **45:** 249-256.

O'Sullivan M.F., Henshall J.K. and Dickson J.W. (1999). A simplified method for estimating soil compaction. *Soil and Tillage Research,* **49:** 325-335.

Peerlkamp P.K. (1967). *Visual estimation of soil structure.* In Eds: DeBoodt M., Frese H., Low A.J. and Peerlkamp P.K. *West European methods for soil structure determination II.* pp 11-12. State Faculty of Agricultural Science, Ghent, Belgium.

Pereira H.C. (1941). Studies in soil cultivation. IX The effect of inter-row tillage on the yield of potatoes. *Journal of Agricultural Science, Cambridge,* **31:** 212-231.

Perry T.O. (1982). The ecology of tree roots and the practical significance thereof. *Journal of Arboriculture,* **8:** 197-211.

Peterson C.T. (1994). Modelling soil distortion during compaction for cylindrical stress load paths. *European Journal of Soil Science,* **45:** 117-126.

Preston S. Griffiths B.S. and Young I.M. (1997). An investigation into sources of soil crack heterogeneity using fractal geometry. *European Journal of Soil Science,* **48:** 31-37.

Richard G., Cousin I., Sillon J.F., Braund A. and Guerrif J. (2001). Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. *European Journal of Soil Science,* **52:** 49:58.

Rosenfeld A.B. (1997). *Effects of nitrogen and soil conditions on growth, development and yield in potatoes.* PhD thesis, University of Cambridge.

Ross C.W. (1986). The effect of subsoiling and irrigation on potato production. *Soil and Tillage Research,* **7:** 315-325.

Rousseva S., Torri D. and Paglai M. (2002). Effect of rain on the macroporosity at the soil surface. *European Journal of Soil Science,* 53: **83-93.**

Russell E.W. (1956). The effects of very deep ploughing and of subsoiling on crop yields. *Journal of Agricultural Science, Cambridge,* **48:** 129-144.

Saini G.R. (1976). Relationship between potato yield and oxygen diffusion rate of subsoil. *Agronomy Journal,* **68:** 823-825.

Scaife A. and Turner M. (1983). *Diagnosis of mineral disorders in plants, Volume 2: Vegetables.* HMSO, London.

Schjonning P., Christensen B.T. and Carsten B. (1994). Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. *European Journal of Soil Science,* 45: **257-268.**

Schuler R.T., Lowery B., Wolkowski R.P. and Bundy L.G. (1986). *Soil compaction: causes, concerns and cures.* Agricultural Bulletin A3367, University of Winsconson, Madison, Winsconsin.

Shepherd T.G. (2000). Visual soil assessment – Volume 1. *Field guide for cropping and pastoral grazing on flat and rolling country.* Manaaki Wheua Press, Landcare Research, Palmerston North, NZ.
Smith D.L.O. (1987). Measurement, interpretation and modelling of soil compaction. *Soil Use and Management,* 3: **87-93.**
Soane B.D., Blackwell P.S., Dickson J.W. and Painter D.J. (1981). Compaction by agricultural vehicles: a review. I. Soil and wheel characteristics. *Soil and Tillage Research,* 1: **207-237.**
Soane B.D., Blackwell P.S., Dickson J.W. and Painter D.J. (1981). Compaction by agricultural vehicles: a review. II. Compaction under tyres and other running gear. *Soil and Tillage Research,* 1: **373-400.**
Soane B.D., Dickson J.W., and Campbell D.J. (1982). Compaction by agricultural vehicles: a review. III. Incidence and control of compaction in crop production. *Soil and Tillage Research,* 2**: 3-36.**
Soane B.D., Godwin R.J., Marks M.J. and Spoor G. (1987). Crop and soil responses to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management on a range of soil types. Part 2: Soil structural conditions. *Soil Use and Management*, **3:** 123-130.
Spoor G., Tijink F.G.J. and Weisskopf P. (2003). Subsoil compaction: Risk, avoidance, identification and alleviation. *Soil and Tillage Research*, **73:** 175-182.
Stalham M. (2001). Irrigation - Scheduling for the future (National Potato Conference 2001, Paper 2). Teagasc Publications. http://www.teagasc.ie/publications/2001/potatoconference/paper02.htm, accessed 03 February 2005.
Stone D.A. (1988). Subsoil strength and yield of vegetable crops. *Soil Use and Management,* 4: **10-14.**
Tijink F.G.J., Doll H. and Vermeulen G.D. (1995). Technical and economic feasability of low ground pressure running gear. Soil and Tillage Research, ***35:*** *99-100.*
Tobias S., Hennes M., Meier E. and Schulin R. (2001). Estimating soil resilience to compaction by measuring changes in surface and subsurface levels. *Soil Use and Management,* 17: **229-234.**
Van Loon C.D. and Bouma J. (1978). A case study on the effect of soil compaction on potato growth in a loamy sand soil. 2. Potato plant responses. *Netherlands Journal of Agricultural Science*, **26:** 421-429.
Van Oijen M., de Ruijter F.J. and van Haren R.J.F. (1995). Analyses of the effects of potato cyst nematodes (*Globodera pallida*) on growth, physiology and yield of potato cultivars in field plots at three levels of soil compaction. *Annals of Applied Biology*, **127:** 499-520.
Watts C.W. and Dexter A.R. (1998). Soil friability: measurement and the effects of management and organic carbon content. *European Journal of Soil Science,* 46: **73-84.**
Wilhelm W.W., Johnson J.M.F., Hatfield J.L. Voorhees W.B. and Linden D.R. (2004). Crop and soil productivity response to corn residue removal: A literature review. *Agronomy Journal*, **96:** 1-17.

Appendix

Methods of measurement for research applications

Porosity

Infiltration rate

Infiltration rate is the maximum rate at which rainfall or irrigation water can be accepted by the surface without causing ponding or runoff. A simple field measurement can be made using a metal cylinder, normally of 0.25–0.5 m diameter, but sometimes larger (Anon., 1977). The cylinder is driven into the soil to a depth of 30 mm and filled with water until a constant rate of infiltration is achieved (this commonly takes 4–5 hours). Although less accurate, a simple infiltrometer can be made out of an 80 mm pipe cut into 150 mm lengths. The rate at which water infiltrates is then recorded. The rate of infiltration is determined by the least permiable layer. Infiltration rates in agricultural topsoils range from 20–800 mm/hr with lowest rates on clays and highest on coarse sands (Anon., 1977). Problems are encountered with surface ponding on swelling soils.

Soil moisture release curve

The soil moisture release curve is one of the tools used for inferring the structure of pore spaces in the soil (Marshall and Holmes, 1988). The curve reflects the pore size distribution of a soil, with large pores draining at small soil-water suctions and small pores at higher suctions. This can be closely related to the function of pores as described by Hamblin (1985). However, Crawford *et al.* (1995) assessed the validity of using soil moisture release curves for inferring the structure of pore space in soils and found the interpretation ambiguous. This is because the release curve is a function of both the pore size distribution and the connectivity.

Fabric analysis

Fabric analysis is a visual method used in the laboratory with prepared soil samples. Image analysis by computer is used for the characterisation of porosity. Data obtained in this way can be readily handled by computer for analysing the statistical distribution of structural elements (Soane *et al.* 1981). This can be performed on a microscopic scale to provide information on deformations in the soil matrix, or at larger scales to give information on the size, distribution and orientation of pores.

Fabric analysis is particularly useful as it provides information on both the structure of the pore space and the solid matrix. These are factors associated with the spatial distribution of gas, since the latter defines the moisture distribution, which limits the free pathways in the pore space for gas diffusion.

Crawford *et al.* (1995) compared moisture release curves with image analysis of thin soil sections and found that, although limited to only two dimensions, image analysis gave a better indication of pore behaviour in terms of gas and moisture retention.

Current uses of fabric analysis centre around producing a better understanding of the effects of compaction on soil pores.

Soil strength

Shear strength

Shear strength is the internal resistance of the soil to external forces that cause two adjacent areas of soil to move relative to each other. It is generally considered to be a function of cohesion between soil particles and inter-granular friction (Anon., 1977). Field measurement is normally carried out using either a shear vane or a shear box. The shear vane consists of four equally spaced vertical blades at the lower end of a shaft that connects them to a torque recorder. The vane is pushed into the soil to the required depth and the torque recorder rotated at constant speed. The rotation of the blades generates a cylindrical shear surface at the outer edges of the blades and the torque required to shear the soil is recorded. In moist clay soils, the shear strength can be assumed to be equal to the cohesion of the soil. Although easy to use and rapid, it is unsuitable for use on stony and dry, hard soils.

The shear box is a cylinder with internal blades at the lower end. The cylinder is pressed into the soil and the soil in contact with the outer surface removed. It is rotated in the same way as the shear vane and the torque is recorded. By applying different normal loads and recording vertical load, sinkage, torque, and angular displacement, the shear strength of soil can be resolved into cohesion and friction components (Anon., 1977). The shear stress-displacement relationships obtained are in some respects analogous to the slip-shrinkage effects found with wheels (Soane *et al.*, 1982).

For moist soils at or near field capacity, the measurement of shear strength can be interpreted in terms of degree of consolidation. As an approximate guide, soils with strengths below 25 kPa have a low degree of consolidation and soils with strengths above 50 kPa have a high degree of consolidation (Anon., 1977). High values are likely to indicate a degree of compaction.

Koppi and Douglas (1991) measured strength of topsoil with a hand-held shear vane at non-limiting (at least 10% air filled pore space) soil bulk density for crop growth and at, or near, field capacity to obviate the effects of water content on soil strength. They found a linear relationship between shear strength and soil clay content (Fig. A1). They inferred that values significantly above the line indicated dense structural conditions with some form of aggregation that restricted root growth, whilst values below the line indicate less than optimal soil/root contact. Strength values that exceed the values on the line by at least 40 kPa suggested unsatisfactory structure for topsoils.

Soil density

Core sampling

An open-ended metal cylinder is pressed or hammered into the soil, then excavated to give a sample of known volume. This is most effective in cohesive soils with water content close to field capacity, but extraction of the complete core may be difficult with sands and gravels. Compression in wet soils and shattering in dry soils may occur during sampling. Rotary core samplers have been developed which have the potential to minimise these effects.

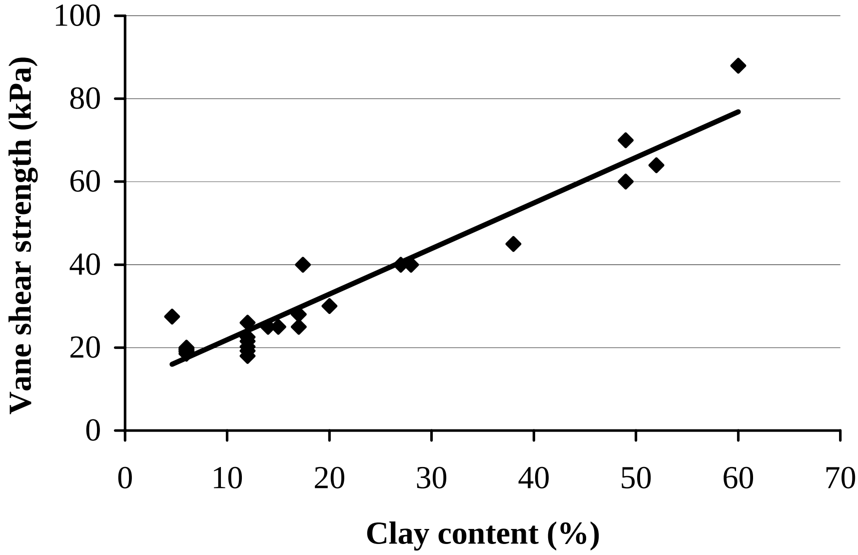


FIGURE A1. THE RELATIONSHIP BETWEEN SHEAR STRENGTH AND SOIL CLAY CONTENT, AFTER KOPPI AND DOUGLAS (1991). SHEAR STRENGTH (KPA) = 10.929+1.098×CLAY%. R=0.96.

Sand replacement
A volume of soil is excavated, weighed, and the excavation is filled with a known weight of dry sand. The volume of excavation is determined from the volume and bulk density of sand. Hard-setting foam, plastic balls, oil, water (with appropriate liners like plastic) or a rubber balloon have also been used as alternatives to sand.

Measurements of clods
Measurements of clods, instead of whole soil, have been achieved by coating the clods in wax and weighing them in air and water. Wax can be replaced by resins, rubber solution or immersing in dense fluids which do not penetrate the clods. Measurements of this type ignore large fissures between clods and so can be used to overcome structural anomalies in cracking clays, for example.

Radiation methods
The power of a soil to absorb gamma rays increases with both dry bulk density and water content. Thus, if the water content is known, this relationship can be used to measure dry bulk density. Gauges must be calibrated against samples of known bulk densities. This is discussed further by Campbell (1994).

Absorption and scattering of radiation increase with soil bulk density. The gamma probe bulk density gauge comprises a radioactive source and facility for counting transmitted or scattered gamma rays.

Radiation methods have the advantage of not disturbing the bulk fabric of the soil. However, the high cost and safety issues concerning the storage of low level radioactive sources preclude their use for anything other than research.

Time domain reflectrometry (TDR)
TDR was originally designed for measurement of soil moisture and measures the dielectric constant of a soil. This can be used to calculate bulk density if volumetric moisture content is known.

Perdok *et al.* (1996) took this one stage further by using a frequency domain sensor, which operates at a frequency of 20 MHz (rather than 200 MHz as usually used for TDR). They identified a procedure whereby bulk density can be accurately and rapidly calculated in a field from determination of dielectric constants. One suggested use is the detection of the immediate effects of traffic, as moisture content will remain unaltered for a short time after soil manipulation.

TDR has similar advantages to gamma probes (particularly in the lack of disturbance caused by determinations) but it is without the problems associated with a radioactive source. Development of this type of methodology continues, but at this stage it can only be regarded as a research tool.

Modelling

The most promising models involve critical state theory, which is derived from soil engineering. Critical state models aim to relate soil strength, volume change, moisture status, and microstructure to the mechanical behaviour of soil (Hettiaratchi, 1987). Soils are subjected to a range of laboratory compression and shear tests, based on load, volume, and stress measurement at variable soil state and moisture content. This information can then be used to predict soil behaviour under a range of conditions.

Further modifications have since been introduced by several authors, including O'Sullivan, Campbell and Hettiaratchi (1994), Peterson (1994), and Kirby, O'Sullivan and Wood (1998).

An alternative, simplified approach was adopted by O'Sullivan *et al.* (1994), who produced a simple, spreadsheet-based model to estimate soil bulk density under the centre-line of wheel tracks. This was based on finite element models, tyre details, soil type, and profiled bulk densities and water contents. Although not perfect for all situations, the model allows comparison of tyre alternatives for specific operations. Primarily designed to demonstrate soil mechanical principles to students (and more technically minded growers?), the authors suggested that this model may be useful for consultants to better evaluate costs of tyre purchases against the perceived benefits of reduced compaction. This shows the potential of the model for decision support.

Comparisons with experimental data have been good, but as methods are insufficiently advanced to allow extrapolation to more general situations Jones *et al.* (2003) suggested, as an intermediate measure, a more general guide to subsoil vulnerability based on existing soil and climatic data.

Spoor *et al.* (2003) used the approach advocated by Jones *et al.* (2003) to provide guidance for field practitioners. This involves the assessment of soil susceptibility based on subsoil packing density, derived from a knowledge of actual bulk density and the clay percentage (Section 5.3). The soil vulnerability to compaction is then classified on the basis of soil susceptibility, wetness, and subsoil protection from above. From these data, recommendations for maximum ground pressures and tyre inflation pressures can be estimated.

