Protection of the subsoil through improved field practices

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Abstract

The function and importance of the subsoil, defined as that soil which lies below the depth of regular cultivation, is described, and the causes of damage identified. Principally, damage is associated with the loads imposed by modern farm machinery and the corresponding compaction arising from wheels and tracks. The level of stresses from these has gradually risen over time and they create the greatest potential for damage on fragile, wet or loosened subsoils. In-furrow ploughing by heavy high-powered tractors and contact pressures that create noticeable ruts in the topsoil are indicative of subsoil damage. Vulnerability of particular subsoils to damage and methods of soil inspection that involve assessment of active crop rooting as an indicator of damage, are described. Indiscriminate loosening of the subsoil can have detrimental rather than beneficial effects. Loosening is only recommended if there is extensive evidence of subsoil damage. Repair should always be undertaken guardedly. Emphasis is placed on subsoil protection which is achieved principally through reducing loads and contact pressures and by increasing the bearing capacity of the topsoil. Subsoils are particularly vulnerable to damage immediately after loosening.

Methods of protection are divided into soil and machinery aspects. Particular emphasis is placed on drainage and on improving topsoil structure and bearing capacity. Minimising tyre contact pressures through rigorous but simple means of identifying appropriate inflation pressures for the prevailing soil and tyre load conditions are also emphasized. Methods for reducing the dangers of subsoil compaction from in-furrow ploughing are suggested. The benefits of controlled traffic and wide-track farming systems are described in terms of the confinement of subsoil compaction.

Keywords: Subsoil compaction, in-furrow ploughing, ruts, ground pressure, tramlines, controlled traffic, deep loosening

1 Introduction

There is considerable evidence to suggest that subsoils are increasingly being damaged by the loads and stresses imposed upon them by today's machinery operations. Unless improved management practices are introduced, subsoil over-compaction is likely to increase and become uneconomic to repair. The aim of this paper is to provide guidance in the recognition of subsoil compaction and its alleviation but most importantly, to suggest practical measures that can be taken to reduce or avoid subsoil damage. These recommendations are the outcome of a working group within the European Union Concerted Action contract N° FAIR 5 CT97 3589 "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction". The aim of the working group was to provide a framework and knowledge base that would help the industry avoid situations that could lead to subsoil compaction.

Further reading may be found in papers by Alakukku *et al*. (2003), Chamen *et al*. (2003) and Spoor *et al*. (2003).

2 What is the subsoil?

A broad definition of the subsoil is: "the soil which lies below the depth of regular cultivation". This definition correctly implies that the depth to the subsoil is dependent upon cultivation depth, and this may be decided by a number of factors including a depth change in soil properties, the crop being grown and the degree of topsoil compaction. Depth of cultivation based on a change in soil properties emphasizes the undesirability of mixing topsoil and subsoil.

The actual thickness of the subsoil in which we have an interest is both the rooting depth of the crop and also the zone which determines the drainage characteristics of the soil. Where an artificial drainage system is present, the depth to this will generally be considered to be the depth extent of the subsoil. Where there is no artificial drainage, the crop rooting depth will indicate the maximum depth of interest.

Because the subsoil can extend over a large depth range and it is often appropriate to manage it differently over this range, it is convenient to divide the subsoil into two distinct layers:

1. *The pan layer*. This is a relatively stronger and sometimes less permeable layer frequently found just below the regularly cultivated depth. It may be formed as a result of previous implement actions and by tractor wheels running in the open furrow during ploughing. In many instances it is the main reason for poor subsoil function and

equally, is the layer that is most often targeted in normal subsoil loosening operations.

2. *The true subsoil*: This is the deeper layer that remains undisturbed by normal tillage but which will be disrupted during drainage operations, such as mole ploughing. It will need careful treatment if it has been damaged. The functionality of this deeper layer is critical in terms of crop performance, particularly in years of drought or flood.

3 What does a subsoil do and how?

In addition to acting as a storehouse for water and nutrients, the subsoil provides support for the growing crop, for the topsoil and all the operations carried out at the surface. To perform these functions, it needs to have a stable structure with an extensive network of pores of varying size. A proportion of these should interconnect and should reach into both the topsoil above and into an effective drainage system below. This allows the subsoil to exchange water, air and nutrients and to make them available to the growing crop. Such a subsoil structure optimises growth in dry conditions, but also provides sufficient aeration and drainage in periods of high rainfall.

4 What is subsoil damage and why do subsoils need protecting?

Subsoil damage is any physical change that interferes with and reduces the essential functions of the subsoil described above. Principally, such damage occurs through a reduction in the size and continuity of its macro pores and these are the main providers for the movement of water and gases. Vertical pores are the most resistant to compaction from above, but they need lateral connectivity, and it is these horizontal pores that most often get damaged. Damage is mainly caused by stresses acting from the surface of the soil which travel downwards through the profile and squash and seal up horizontal pores. Although stresses can occur as a result of natural processes (drying and wetting, chemical imbalances), they are most frequently associated with mechanical inputs. Tab. 1 provides data that clearly show how these mechanical inputs have, over the last sixty years, led to a dramatic increase in soil stresses. As will be seen, the loads on the running gear of today's machinery impose much higher stresses at depth in the soil than the methods and machines that were used in the past. In addition, and thanks to its increased mobility, this machinery can be used even under poor soil conditions.
The main economic consequence of damage is poor crop growth resulting from poor root function. Crops may also suffer unnecessarily from drought on the one hand and water logging on the other. The latter increases the risk of water run-off, soil erosion, nutrient leaching and contamination of water courses. Such contamination and erosion is now increasingly likely to attract financial penalties from environmental legislators, while run-off increases the likelihood of flash floods. Gaseous exchange may also be reduced, resulting in denitrification, ammonia and methane emissions as well as poor absorption of methane. Once damage to the subsoil has occurred, it is often expensive or even uneconomic to repair effectively.

There are therefore convincing economic and environmental reasons why subsoils should be protected.

Table 1.
The major principal soil stresses under stationary loads with a constant mean principal stress at the soil surface of 3.0 bar (Calculated from Koolen *et al*., 1992).

Source of load on the topsoil	Load on the topsoil, kg	Year	Inflation or surface pressure, bar	Stress at different depths, bar: 0.4 m	0.6 m
50 woman	50	1600	0.5	0.019	0.009
70 kg woman	70		0.6	0.026	0.012
850 kg horse	300/hoof*		2.4#	0.11	0.05
Bias ply tyres		1940	1.5		
11.2–28	990		1.5	0.35	0.16
16.9–34	2200		1.5	0.70	0.35
18.4–38	2825			0.86	0.44
Radial ply tyres			1.6		
11.2 R 24	1265		1.6	0.44	0.21
16.9 R 34	2600		1.6	0.81	0.41
650/75 R 32	4680		1.6	1.24	0.67
710/75 R 34	6000	2003		1.46	0.82

* Generous estimate, maximum load per hoof rarely exceeds 30% of animal weight (Ortiz-Laurel, 1992).
\# Area in contact estimated at 0.0125 m^2

5 How vulnerable is any particular subsoil to damage?

Subsoils vary in their ability to support loads without suffering damage to their pore structure. This ability is very dependent upon the more stable properties of soil type and the packing arrangement of particles and aggregates. It also relies upon the soil moisture status and the protection the subsoil receives from the topsoil at the time of loading. The degree of protection provided by the topsoil depends upon its looseness or firmness. In most soils which have been under arable cropping, there is frequently a compact and stronger layer just below cultivation depth (pan layer, as defined above). Providing this layer does not restrict root development, gas exchange and drainage, it can play an important role in absorbing compaction stresses before they reach the true subsoil. Disrupting and weakening such a layer would only make the subsoil more vulnerable to compaction. Unfortunately, it is often difficult to determine whether a pan layer is causing impedance or not. This problem is dealt with in the next section.

In summary we can say that the subsoil is likely to be more vulnerable if:

- it is very moist (net result of rainfall, irrigation and water extraction by an actively growing crop);
- the topsoil is very moist and/or has been loosened. Large ruts are created when driving across it;
- ploughing in the furrow is being carried out in moist conditions, and particularly if wheel slip is significant (greater than 12%) and a large tractor is being used (axle loads of perhaps 3 t or more);
- the subsoil (either pan layer or true subsoil) has been loosened within the last 12 months.

6 How do you know if the subsoil has been damaged?

The most appropriate and effective way of identifying subsoil damage is to study crop rooting in an area where damage is suspected (poor crop growth, water standing on the surface in periods of high rainfall). The best time to assess whether roots are developing properly is when the crop is growing actively without stress (plenty of water, warmth and no recent herbicide applications). In these conditions the roots should be extensive and growing deeply into the soil profile (1.5 m depth is not uncommon). Tap-rooted crops such as carrots, parsnips and sugar beet should not display evidence of fanginess (branching of the tap root). Actively growing plant roots should be very visible at this time, even to the untrained eye, as indicated in Fig. 1. They are white, not brown and are elastic rather than brittle. As there is no absolute measure of optimum root development, it is often helpful to examine cropped areas where the crop is growing well, in addition to where growth is poor or a problem is suspected. A comparison of root development in the two situations provides a much clearer indication of whether there is impedance, whether it is serious and what is causing it.

Profile pits are the most practical way of making these root assessments. Pits can be dug either with a spade or hydraulic excavator. Removing smear from the side of the pit with a trowel helps in identifying roots, their location and their distribution. Further useful information can be gained by taking out undisturbed spades full of soil from the side of the pit.

These undisturbed samples when carefully broken apart by hand, can reveal the extent and nature of root development. Comparisons can be made between samples taken from a pit in an area of good crop growth and ones taken from where it is poor. Are macro-pores and root channels present in one and not the other? Visible symptoms of severe impedance are tap roots 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 number and size of roots within a compacted zone are unlikely to be as high as in the soil above or below. Providing however that roots

Figure 1.
Unimpeded profile showing widespread distribution of roots

have been able to grow through this area and are developing well in the subsoil below, there may be no need for subsoiling. This is particularly the case if there are also no signs of prolonged impeded drainage above the more compacted layer (e.g. foul smelling poorly rotted residues, blue-green colouring of the soil).

In many instances subsoil loosening is carried out as a routine measure. It is particularly important that this approach is avoided. The philosophy should be – ‘if in doubt, leave well alone’, or more colloquially, ‘if it’s not broken, don’t mend it’.

7 How can a damaged subsoil be repaired?

Where an impedance problem has been found, repair will almost certainly be needed. In some situations biological activity and natural weathering alone may be sufficient, but in many others, they may be too slow or inadequate. In such cases mechanical repair will be needed, and the prime aim will be to improve conditions without losing too much of the supporting capacity of the soil. This allows natural and biological processes to stabilise the soil and complete the remediation process without leaving it excessively vulnerable to compaction in the future.

Subsoiling operations to alleviate soil compaction are frequently associated with considerable loosening, soil rearrangement and loss of bearing capacity; a type of disturbance most inappropriate for subsoil protection from future mechanical stresses. The prime aim is the creation of tensile failure and cracks. These fissures should be created from just below and pass up through the damaged zone. In this way they will restore the conditions needed for rooting and drainage, but they should leave the main soil mass largely intact, unbroken and strong - in effect, "fissuring without disruption".

Tensile failure and cracking should be generated by lifting the soil mass evenly but not excessively. This relies on working at the right depth, with the right type of subsurface blade and with the correct spacing between the blades (Spoor *et al.*, 2003). Appropriate cultivation tools for inducing this type of failure are winged subsoilers, subsurface sweeps and where available, slant leg subsoilers (Fig. 2). With the latter, the soil bends over the tine leg and the adjustable flap controls the magnitude of the tensile forces induced, and hence the degree of fissuring achieved. In general, a small lift combined with a wide tine spacing, moist conditions and deep working may induce little or no fissuring. On the other hand, a large lift with closely spaced tines working relatively shallow in dry soil can create considerable loosening and profile rearrangement. The optimum is

Figure 2
Slant leg subsoiler working in grassland. This machine can provide good fissuring without extensive disruption and loosening

somewhere between these two extremes and is under the control of the operator who, with knowledge and care, can achieve the desired results in a wide range of conditions.

8 How can the subsoil be protected?

By far the best strategy is to prevent or minimise compaction of the subsoil. As machinery loads are the primary source of subsoil compaction and damage, these are the principal target for protective measures. Loads are transmitted as pressure onto the soil through the running gear of the machines, whether these are tyres or tracks. In turn, this pressure creates stresses in the soil that are transmitted both vertically and laterally through the profile. The vertical stress always decreases with depth, but the rate at which it decreases is related to the load at the surface – the higher this is, the lower is the rate at which the stress in the soil reduces with depth. As an example, let us take a wheel with a load of 2.8 t. fitted with a tyre that exerts a pressure of around 1 bar at the soil surface[1]. If this load is increased to 5.9 t, but a larger wheel and tyre are fitted so that the pressure at the surface remains the same, the stress at say 30 cm depth may now be 20–30 % higher than under the wheel with the lower load (see Table 1). It is difficult to say exactly what the stress will be, but there will always be this trend with increasing load. The aim therefore is to minimise the load <u>and</u> the contact pressure. The higher the wheel load, the lower the pressure should be at the surface in order that stresses at depth do not increase uncontrollably.

The pressure at the surface can be reduced by fitting larger or more tyres and minimising the inflation pressure for the load being carried. Both these actions have the effect of increasing the contact patch and spreading the load over a larger area (Fig. 3). Spreading of load at depth can also be achieved by increasing the bearing capacity of the topsoil. This in effect disperses more stress laterally as it travels down through the profile and thus reduces its concentration.

Figure 3
Fitting extra tyres and lowering inflation pressures minimises the risk of subsoil damage (Photo: Silsoe Research Institute)

Measures taken to protect the subsoil have two principal aims:

1. To reduce the loads and pressures applied and keep them as close to the soil surface as possible.

[1] As a reasonable average, the pressure exerted by a tyre at the soil surface is 1.25 times the tyre inflation pressure

2. To increase the bearing capacity of the topsoil so that pressures exerted at the surface are spread over a greater area at depth.

For convenience we can divide the field practices needed for subsoil protection into two main categories, namely:

- soil measures
- machinery measures

8.1 Soil measures to protect the subsoil

Soil measures attempt to reduce the actual wetness of the soil and/or improve its bearing capacity at a specific point in time.

8.1.1 Drainage. This is probably the most important of all soil measures in a temperate and moist climate. Without adequate drainage, heavy rainfall may often be followed by extended periods when the soil is too wet and remains vulnerable to damage. It is not within the remit of these notes to give guidance on drainage systems or installation, but if fields are lying wet, then a rigorous inspection should determine whether a drainage system has been installed and whether it is working correctly. Simple measures to ensure efficient operation include making sure that outfalls are functioning and are above free water level. Make sure that water levels are as low as possible by cleaning out ditches on a regular basis. Consider mole ploughing if soil type and conditions permit. If no drainage system is present, expert advice and design will be needed to get the work done. A mid-drain perched or natural water table level at 0.5 m depth should be aimed for. Contacts for advice on drainage can be obtained from the Soil and Water Special Interest Group of the European Society of Agricultural Engineers (http://www.eurageng.net/).

8.1.2 Irrigation management. Irrigate only to bring the soil to field capacity and anticipate rainfall. Ensure application intensity does not cause ponding (free water lying on the surface) and to give the soil a chance to dry, leave as large a time gap as possible between the cessation of irrigation and a field operation.

8.1.3 Increasing the topsoil bearing capacity. As we have seen, a well structured healthy topsoil can help protect the subsoil. It drains more readily and allows a seedbed to be produced using shallower and less intensive tillage. A healthy topsoil can be promoted by checking and correcting any imbalance of nutrients or pH, by adding organic matter, by retaining crop residues and by avoiding over-compaction and resultant poor drainage. These conditions can be promoted by avoiding, where possible, deep and rigorous cultivation, particularly of warm, moist soil which tends to increase respiration and oxidation of organic matter. Increased bearing capacity can also be achieved by avoiding unnecessary deep loosening and by reducing tillage in general. Direct seeding of crops is particularly beneficial in terms of an increase in topsoil bearing capacity.

8.1.4 Tillage. Protection in this instance is afforded by the minimisation of tillage depth and intensity. The limitation of depth will be governed by a range of factors. These could include plough design, degree of rutting from other operations, the crop being sown, weed control, management of residues and the need for subsoil repair. In practice, a reduction in tillage depth may only be achieved by a gradual and planned improvement in operations that removes a number of constraints. For example, shallower ploughing may require an alternative plough, but equally wheel rutting will have to be minimised if the plough is to work effectively. Similarly, management of residues is likely to be a combination of machinery, cropping and disease constraints, all of which may need to be addressed before shallower tillage can be achieved. Controlled traffic (see later section) is also a key measure that can allow tillage depth and intensity to be reduced, as well as limiting damage to narrow sacrificial strips. Whatever methods are used, minimising tillage depth should be a consistent and on-going strategy to improve soil care.

There are also timing considerations. For example, when repairing a subsoil, the work should be carried out as late as possible in any sequence of field operations because this reduces the risk of re-compaction from subsequent wheelings. However, some firming with rolls may be needed where crops have just been sown, but the tractor must "tread" very lightly on this soil. The longer the treated profile can be left to stabilise before being subjected to further loading, the greater the regain in soil strength and the more permanent and successful the repair is likely to be. It is important to complete stabilisation by quickly establishing a vigorous, deep rooting crop. In an ideal world, tillage should be timed to avoid conditions when the subsoil is likely to be wet, but there is little flexibility when crop yields are highly dependent on achieving an optimum sowing date. The most relevant advice therefore is to minimise damage by adopting the measures described above and in the following sections. Not only will these measures help avoid costly repair, they will also increase flexibility and improve the efficiency and speed of field operations.

8.1.5 Cropping. The economics of any farming system are likely to be governed principally by the range of crops being grown. Thus, any unnecessary constraint on a cropping programme through poor subsoil management will be particularly damaging to farm profit. Equally however, soil and weather conditions may make the growing of some crops uneconomic. For example, a rotation may not be sustainable if a particular crop always has to be harvested in wet conditions and this increases the costs and lowers the yields and profitability of following crops. Economics will always be the driving force but the whole rotation must be assessed rather than each crop in isolation.

As far as soil health and subsoil compaction are concerned, bare fallows or set-aside are an especially negative aspect of cropping systems and particular care is needed in their management. This is distinctly the case if weed cover is sprayed off early in the season (April), as any further rainfall will not be extracted by plant growth. This means that the whole soil profile can be very moist when cultivations are carried out later in the season. A better approach is to sow the area with a green manure such as Phacelia, forage rye or mustard, which under present European Union rules for set-aside can remain in place until 31 August. New rules also now make it possible to consider adding grassed headlands as set-aside. Adjacent to permanent water courses, ponds or lakes, these may now average just 10 m rather than the 20 m normally required. Headlands managed in this way are less likely to suffer subsoil damage because they remain drier and have a stronger topsoil associated with them.

On particularly problematic land which always remains wet, there may be an opportunity to grow a deeper rooting crop (wheat roots to around 1.4 m depth) as a temporary measure to create rooting into the subsoil. However, the whole rotation economics will determine whether this is feasible.

8.1.6 Livestock. Animals are mentioned here not so much to identify problems but to suggest that animals themselves are unlikely to have a significant impact on the subsoil (see Tab. 1 – horse data). However, operations associated with livestock such as manure application do have an impact and are dealt with in a later section.

8.2 Machinery measures to protect the subsoil

These measures rely on keeping vertical stresses (loads/pressures) as close to the soil surface as possible and on minimising their magnitude.

To help achieve these aims, it is possible to match differences in topsoil strength with "safe" tyre pressures, as indicated below:

1. Low topsoil strength (deeply cultivated and moist). Inflation pressures should be no greater than 40 kPa[2].
2. Medium topsoil strength (medium depth cultivation and generally friable conditions). Inflation pressures should not exceed about 80 kPa.
3. High topsoil strength (non-cultivated or direct drilled soils in medium to dry condition) overlying a non-loosened subsoil. Keep inflation pressures below about 150 kPa. If the subsoil has been loosened within the past 12 months, keep pressures below 80 kPa.

In all of these situations, rut depth is the main practical indicator of the potential degree of damage and the author suggests that rut depths should be no more than around 20 mm. The machinery shown in Fig. 3 was on soil with very low topsoil strength, but satisfactory operation was made possible simply by fitting extra standard tyres and lowering their inflation pressure. The importance of selecting tyres and setting their inflation pressures correctly is emphasized by devoting section 8.2.2 to the subject.

8.2.1 Choosing tyres or tracks. In practice, well designed tracks used properly tend to impose similar ground contact pressures to those found under agricultural traction tyres set at the minimum recommended pressure. A track system consists of a number of rigid road wheels (or idlers) which run over the track (or belt) when it has been laid on the ground by the front sprocket. These road wheels impose localised and relatively high pressures on the soil, but they are needed to ensure that the tracks penetrate the ground. The amount of pressure exerted by the idlers is dependent upon their number and the tension in the belt. The more idlers and the higher the belt tension, the more even will be the pressure distribution, i.e. peak pressures will be reduced.

The specific advantages of tracks are their superior traction characteristics, their compact design and their ability to ride over weak spots in the soil. These latter two advantages provide particular potential for root crop harvesting operations where vehicle width is constrained and soil conditions might change from medium to low topsoil strength.

The disadvantage of tracks is their higher cost, their higher power transmission losses compared with tyres, the transfer of vibration to the soil (particularly metal tracks) and with two track designs, their potential for poor weight distribution. This latter is created through front uplift of the tracks when vertical draught or mounted implement loads are applied at the rear.

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[2] These pressures assume the use of agricultural tyres. Care of the soil will be severely compromised if transport rather than agricultural wheels and tyres are used.

8.2.2 Selecting tyres, setting inflation pressures and planning a tyre strategy for the future. To achieve these aims both a short and a long term view are needed. Initially, the most efficient and cost effective investment in tyre selection and use is in self or provided tuition. Tyre/load relationships are relatively easy to assimilate and this knowledge is vital if correct selection and use is to be accomplished. (A useful website for information is http://www.teagasc.ie/publications/2003/conferences/nationaltillage/paper07.htm). Where high tractive loads are also anticipated, correct selection and ballasting may require expert advice in addition, and this can easily be justified.

In the short term, axle loads should be minimised and pressures on existing tyres should be set to the minimum for the load being carried (all the tyres on an axle should be included in this calculation, i.e., if duals are fitted, it is safe to assume that the load on each wheel is the axle load divided by four). Setting pressures correctly can only be achieved by consulting a tyre data book (available free from tyre manufacturers and dealers). It is also necessary to have a pressure gauge (a reliable one!) and preferably a means of measuring axle load. However, in the absence of the latter, there are dependable alternative methods of achieving the correct settings and a particular example is given in the Annex.

Achieving protection measures in the longer term relies on selecting the most appropriate tyres when replacing or buying new machinery. Experience with existing equipment should provide a good starting point. For example, to what extent have planned rut depths been exceeded? Are there alternative tyres being offered with the new machine that might provide the inflation pressures required? Dealers and tyre suppliers should be able to provide guidance, but a tyre data book (or books) are essential if a fully informed and practical choice is to be made. Fig. 4 shows what can be achieved in practice with a relatively modest investment in time and money.

8.2.3 Ploughing. It is common practice to drive in the open furrow while ploughing. This practice creates a high risk of subsoil compaction, particularly in moist conditions (for example after set-aside), because the tractor wheels interact directly with the upper part of the subsoil. The alternative of driving on the unploughed surface, where the full depth of the arable layer helps disperse the stresses under the tyre, is much preferred. This system lowers the peak stresses reaching the subsoil by:

- adding a buffer in the form of the topsoil;
- confining to the top-soil the shear stresses associated with pulling forces;
- enabling larger or dual tyres at lower pressures to be used.

If it is impossible to plough on the land with existing equipment, it is not inappropriate and may be economically desirable, to consider using a larger tractor and plough combination. This could allow larger or dual wheels to be fitted and for inflation pressures to be kept at or below 150 kPa. This fits in with the pressure recommendations, avoids instability problems and reduces the traffic intensity by minimising passes. However, such a strategy must form part of a long term plan.

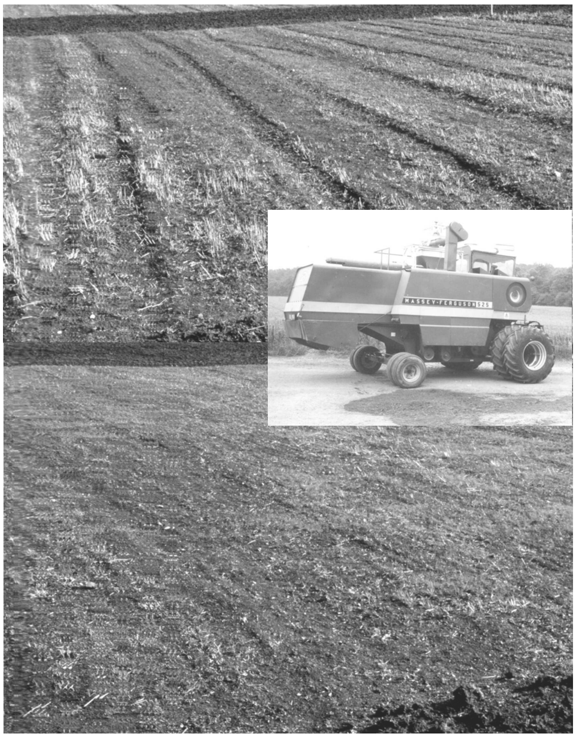

Figure 4
These plots were harvested on the same day by the same machine but with single wheels (top) and with dual wheels (inset) at lowered inflation pressure (bottom) (Photos: Silsoe Research Institute)

If ploughing in the furrow is unavoidable, lower inflation pressures can usually be achieved with ploughs of up to three bodies by using the largest tyres that fit in the furrow (45 cm wide for wide-furrow ploughs). Tyres of this size provide sufficient loading capacity and traction at an inflation pressure of about 80 kPa to operate a three-furrow plough. For four to six furrow ploughs, other technical options and alternatives to decrease the soil stresses in the upper part of the subsoil can be applied. These include:

- the use of tyres up to 65 cm wide in 45 cm wide furrows. These can be used without adversely affecting the uniformity of the work and the degree of soil inversion. Wide tyres such as this make it possible to operate 4-furrow ploughs at low ground contact pressure, albeit at the expense of some re-compaction of the freshly ploughed soil.

- Tyres wider than 65 cm can be used if the last plough share is fitted with a furrow slice attachment. This cuts a strip of soil of the required extra width from the landside at about half the ploughing depth and deposits it in the furrow. Such a strip prepares a wide, curved surface for the tyre.

Ploughing at low speed with a high level of wheel slip, whether in or out of the furrow, is likely to be particularly damaging to the subsoil. This should be avoided by ensuring correct ballasting of the tractor or by removing a plough body. Not only will the latter reduce wheel slip, it will almost certainly permit an increase in forward speed.

8.2.4 Transport operations. These can be particularly damaging to the subsoil because high loads are often carried in moist conditions on inappropriate tyres. Although financially there is an inclination to fit transport rather than agricultural tyres, this should be resisted at all costs. This is because the savings are likely to be far outweighed by the negative outcomes, even if these are not always obvious. The incompatibility between tyre settings for high speed road transport and for low speed field operations is best overcome by fitting a central tyre inflation/deflation system. However, until such systems are widely available at the right price, the optimum approach is always to fit and adjust tyres selected for the field and to drive at field speeds when on the road.

In addition to this optimum and essential approach, other measures might also be used. For example, when applying slurry, consider the use of an umbilical system that allows the tanker to remain on the field headland. Similarly, and although not strictly a machine measure, additional manure storage facilities can allow application of both solid and liquid manures to coincide with dryer periods. Alternatively, where soil conditions are poor, part loading might be used.

8.2.5 Controlled traffic farming (CTF). CTF is defined as a crop production system in which the crop zone and traffic lanes are distinctly and permanently separated. However, for the purposes of this paper, both permanent and temporary CTF systems (the latter including tramlines and beds) will be included. Although CTF cannot remove the spectre of subsoil compaction completely, appropriately designed permanent systems can confine the damage to limited and well defined areas.

8.2.5.1 Temporary CTF systems.

Tramlines. These are evenly and usually widely spaced pairs of wheelways introduced at or soon after crop sowing. They are used to improve the accuracy of chemical applications and crop management. Planning and setting out tramlines carefully can help reduce random trafficking of the field. Such planning could include consideration of potential crop yields and harvester capacity. For example, would introducing tramlines parallel to a shorter side of the field allow harvesters always to be unloaded on the headland without compromising work rate? This might increase headland turning, but if used in conjunction with headland set-aside, would be of little overall consequence. Alternatively, a cross headland might be introduced to allow harvester loads to be transported out of the field without introducing extensive random damage, or existing tramlines used as illustrated in Fig. 5.

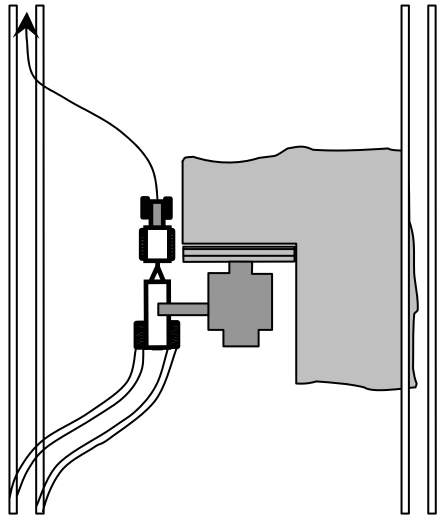

Figure 5
Specify large capacity unloading augers if possible and use tramlines to reach the harvester. Consider unloading with the harvester stationary

With further developments in Differential Global Positioning Systems (DGPS) some now offer an alternative means of introducing tramlines, and the accuracy of these is improving rapidly while the cost is diminishing (see http://www.trimble.com/gps/ for background information). Guidance systems can be hired for short periods and the costs justified, particularly if the tramlines are re-used from crop to crop as described in the next section.

Beds. These are normally created and destroyed within a single crop and are often termed “raised”, as they become proud of the wheelways that are created between them. These wheelways are often at only 1.8–2.0 m centres and therefore afford little protection of the subsoil on a field scale. They do however minimise damage in the cropped area, but due to the incompatibility of machinery wheel track widths, they are often abandoned for harvesting, which is one of the most damaging operations as far as the subsoil is concerned. This is likely to have a negative outcome for the subsoil as well as the performance of the following crop. Only long-term planning, appropriate machinery purchase and axle modification to achieve matching of track widths are likely to improve the situation. The most appropriate and practical alternative is the system of wide-track farming described briefly in the following section on permanent CTF systems.

8.2.5.2 Permanent CTF systems. These can be considered as an extension of the tramline system where the wheels of machines always run on narrow sacrificial strips and crops are grown on the remaining area. A plough regime is generally incompatible and unnecessary within the system. Unlike annual tramlines, the wheelways are managed and repaired (filled in, not loosened). In theory, permanent CTF is probably the most effective means of protecting the subsoil, but further development of the system, increased awareness and demand from growers and involvement of machinery manufacturers in standardising track widths is needed before significant advances can be made. Where livestock are present on a farm, free range management will compromise the system to a degree, but significant advantages will still be available.

It is appropriate to divide these CTF systems into tractor-based and wide-track operations.

Tractor-based systems. These have been adopted widely in Australia where farmers have improved the profitability of their businesses by realising both soil and crop yield benefits. (see http://www.grdc.com.au/growers/res_upd/south/02s/rupanyup8.htm

The module width is usually matched to the least width machine and within a cereals rotation, this is likely to be the harvester, which then also defines the track width of the system. This setting of track width often leads to problems in many parts of Europe where highway legislation and narrow farm tracks restrict the movement of wide vehicles. Particular care is also needed in setting up CTF systems in relation to drainage and subsoil protection in these regions. These combined constraints make tractor-based CTF more difficult to establish in many parts of Europe compared with Australia.

In awkward shaped fields, careful route planning, perhaps in association with a GPS system, can significantly reduce the wheeled area. More information about the system can be obtained from http://www.controlledtrafficfarming.com.

Wide-track operations. This is a system where the track width of machinery is significantly extended (anything above 5 m). Implements are generally constrained to a maximum of the track width (except for chemical applications) while the vehicle moves lengthways when moving between fields or along the road. Part width operations are perfectly feasible and only one wheel track is introduced for each module width (Fig. 6). This system has significant potential for the confinement of subsoil damage and is a practical machine replacement for most crops and farming systems. It is probably the only effective means by which subsoil damage can be confined in root and vegetable cropping systems.

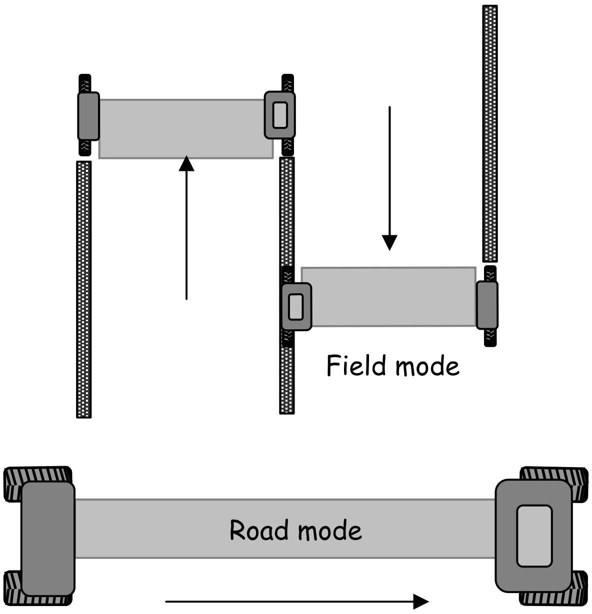

Figure 6
Illustration of field and road mode operations with a wide-track controlled traffic farming system

9 Summary of key factors and measures to reduce the potential for subsoil damage

Factors. The highest potential for risk of subsoil over-compaction and damage arises from:

- High loads and contact pressures and their close proximity to the subsoil.
- Low topsoil strength.
- Low subsoil strength, particularly that induced by subsoil loosening.

Measures. These are a combination of edification, recognition of financial advantages and attention to detail. They should:

- Create enlightenment about and careful use of the relationships between wheel load and tyre selection to achieve the lowest possible inflation pressure on all field machinery.
- Minimise axle loads and keep them as close to the soil surface as possible, e.g., plough on the land rather than in the furrow.
- Improve top and subsoil bearing capacity:
  - improve drainage;
  - avoid subsoiling;
  - correct chemical imbalances;
  - minimise depth and intensity of tillage;
  - allow as long as possible for the soil to dry before running on it;
  - avoid bare fallows, particularly in moist climates.

- Allow adoption of some form of controlled traffic farming and particularly one that provides for the permanent separation of traffic lanes and crops.

9 Conclusions

Stresses on the subsoil from machinery loads at the surface have increased considerably over the past sixty years. These are now at a level where damage is almost inevitable and unless improved machinery and management practices are adopted, over-compaction and impairment of subsoil function will increase. In many instances this level of compaction will compromise crop and field drainage performance, but will also be uneconomic to repair.

Although there is no panacea for the complete avoidance of subsoil damage, there are a number of practical measures that can be taken to reduce the risk. Understanding the mechanics and relationships involved in the compaction process is the first step towards avoidance. Attention to detail and long term planning to reduce soil stresses from machinery and to improve topsoil conditions are essential elements in this evasion process.

10 Acknowledgments

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Annex.

Setting tyre inflation pressures correctly using only a tyre data book, a reliable pressure gauge and a tape measure

The following example is provided to assist in the process of minimising tyre pressures, soil contact stresses and the potential for damage to the subsoil.

An autumn stubble has been disc cultivated to 100 mm depth. A trailed drill is being used in conjunction with a 150 hp tractor. The rear wheels are fitted with 600/65 R 38 tyres and the front with 480/65 R 28 tyres. The axle loads are unknown. From the tyre data book the rear tyre laden radius is listed as 766 mm. From the three soil conditions listed in section 7.4, it can be assumed that we are operating under condition 2 – medium topsoil strength and that a pressure of around 80 kPa should not be exceeded.

With the tractor standing on a hard and level surface and supporting the load that it will carry in the field, lower the inflation pressure until the laden radius is 766 mm (see Fig. 7), but no less. Now check that the pressure is not below the minimum listed in the load/inflation tables for this particular tyre. If it is, inflate the tyre to this minimum pressure. If the pressure is above 80 kPa when a radius of 766 mm is achieved, can some weight be removed from the tractor? If this not feasible and the pressure is significantly higher than 80 kPa, consideration in the longer term should be given to the purchase of larger tyres or for dual wheels to be fitted.

The same procedure is now needed for the front tyres, which according to the data book, should have a laden radius of 593 mm. In this case, if the inflation pressure is too high, it may be practical to remove weight in the form of the tractor front end weights, particularly if a trailed implement is being used as in this case. If there is a mounted implement, stability will have to be monitored.

If dual wheels are fitted, both tyres will need to have their inflation pressures reduced in roughly equal increments to reach the recommended radius.

Finally, two points to remember:

1. When adjusting the pressure for the first side of the tractor or machine, notice how much tilt the machine adopts. If this is noticeable, it may be prudent to lower the pressure on the other side to some degree, otherwise excess weight will be shifted to this first side.
2. If any measured laden radius is less than the listed value at the maximum recommended pressure for the particular tyre, the load is excessive and damage to the tyre is likely. Reduce the load, change the tyre for a larger one if possible or fit dual wheels. In some instances, but only with advice from the tyre manufacturer, it may be possible to work with a slightly smaller radius at lower travel speeds.

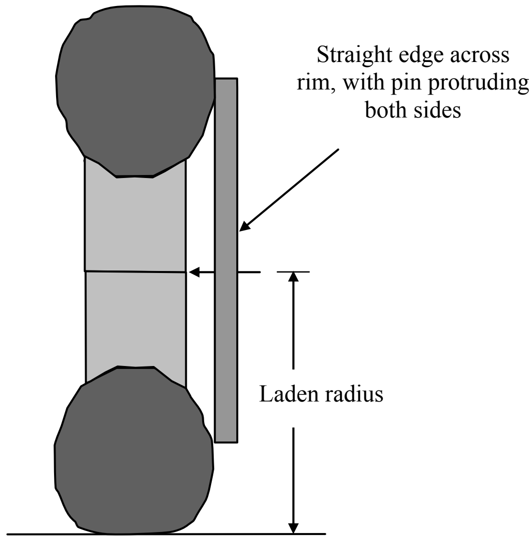

Figure 7
Illustration of wheel, tyre and laden radius together with a convenient and practical method of measuring the radius