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'Controlled traffic' farming: Literature review and appraisal of potential use in the U.K.

by

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Abstract

Review

The review assessed, through international literature, the incidence and impact of soil compaction in cropping systems. Primarily the compaction studied is that imposed by vehicles working the land and tending and harvesting crops. The literature was further scrutinised to determine the likely outcome if the compaction exerted by vehicles were isolated into narrow ribbons within cropped fields, frequently described as controlled traffic.

Soil effects

During the compaction of soils energy is absorbed. This leads to an increased bonding between particles and aggregates making them more difficult to separate by tillage. Tillage of compacted soils therefore uses more energy, loses more moisture and often results in coarse, dry and unsatisfactory seedbeds that lead to poor crop establishment. Different types and intensities of tillage on compacted soils tend to have a very similar outcome, regardless of energy input. Further compaction of soil that is moist during these loosening processes is particularly damaging. Avoiding all soil compaction tends to avoid all the negative outcomes.

Wheel loads at the soil surface are now so high that it is increasingly difficult to keep pressures low enough to avoid stresses reaching deeper into the profile. Because these often exceed historic values (such as those created by in-furrow ploughing), they are changing the subsoil and reducing its ability to function.

It is clear from the literature that sands, sandy loams and some silt soils are more vulnerable to compaction than clays. They tend to have less natural structure that will resist loads and are more likely to develop an implement pan at operating depth, or a traffic and implement pan at ploughing depth. Although they are more easily repaired by cultivation, they have little ability to restructure naturally. Compaction at depth in all soils persists for long periods and on sandy soils often indefinitely. Mechanical loosening (usually subsoiling) is difficult to time correctly and if carried out successfully, may make the soil more vulnerable, often to a greater depth.

Compaction is particularly damaging in terms of drainage, aeration and erosion. This is demonstrated by improved infiltration (84%–400%) if compaction is avoided and through more plant available water (6%–34%). Because compaction reduces infiltration, runoff can increase by around 40% and this increases nutrient and soil loss by a similar amount, even in the presence of crop cover.

Wheel loads of just 5 Mg can reduce the saturated hydraulic conductivity of many subsoils by around 100%. On lighter soils this can happen even with lower loads and likewise topsoils can suffer a 4–5 fold reduction in conductivity. This decline is brought about because both pore size and number are reduced. Typical reductions in pore space due to traffic are around 10%, but up to 70% reduction at 0.5 m depth has been recorded. These decreases in pore size mean that there is less space for water and that water is held more tightly through capillary attraction. Fields therefore return to field capacity earlier but equally, they also run out of plant available water more quickly.

Other than very light firming of seedbeds, compaction has a negative impact on nutrient supply and mobility. Nutrient uptake is impaired through restricted crop rooting, lack of oxygen and greater losses (denitrification) from the soil system that can lead to diffuse pollution. Denitrification is greatest in wet conditions when fertilizer is applied to heavily compacted soils. Sediment losses triggered by compaction and associated poor infiltration increase the consequential loss of P & K in particular. Compaction is also likely to increase losses to the atmosphere in the form of carbon dioxide and methane. Overall, avoiding compaction can increase nutrient recovery by up to 20%.

Although cultivated soils contain less organic matter than virgin soils, the effect of compaction on soil organic matter (SOM) seems to be neutral. Within cultivated soils the level of SOM is determined primarily by cropping and this is confirmed by long-term trials, despite contrary research showing increased short-term loss with greater tillage intensity. Some experiments may not have taken full account of the redistribution of organic matter through the whole soil profile, which can be to a substantial depth, even with zero tillage. Where stratification of SOM in the upper horizon occurs, for example with minimum or no till systems, compaction can increase emissions of greenhouse gases such as nitrous oxide and methane because oxygen supply is reduced.

Because compaction increases the strength of both the soil mass and the aggregates within that mass, tillage for loosening the profile and creating seedbeds invariably needs more draught and energy. In rare prolonged dry conditions where tillage follows tillage without intermediate compaction, there may be little difference in energy requirements between traffic systems.

The effects of soil compaction on soil function and quality are almost exclusively negative. Light firming of loose seedbeds on the other hand is often beneficial, as may be more substantial firming of the profile in dry conditions when capillary rise of water from deeper in the profile can be enhanced.

Crop effects

Crop yield responses to the avoidance of vehicle compaction are invariably positive and range from 82–190% compared with conventional traffic systems. These variations can often be explained if appropriate factors are considered, all of which relate to the correct timing and supply of water, nutrients and air, both during and after crop establishment. These requirements are more likely to be satisfied if crop roots are able to explore the soil profile without hindrance. Excessive compaction tends to preclude this free exploration and the consequential reduction in water and nutrient uptake is often the cause of yield depression. There is a considerable body of evidence to suggest that wheel loads in excess of 5 Mg will cause a permanent 2.5% reduction in yield due to subsoil damage. Although many East European countries have identified optimum soil bulk densities for maximum crop production on different soils, no clear relationship between soil type, yield and compaction could be established from data in this review.

Machinery effects

Zero traffic reduced the draught requirements for shallow (10 cm) primary tillage by up to 60% and for mole ploughing (at 55 cm) by 18%. At intermediate depths (20–25 cm), zero traffic reduced implement draught by up to 48%. Energy demands for seedbed preparation fell by up to 87%, while power requirements for primary and secondary tillage were reduced by 45% and 47% respectively. Practitioners of controlled traffic in Australia have responded to these reduced energy demands by selecting smaller rather than larger replacement tractors. Wear on the soil engaging parts of implements is likely to be reduced in line with draught requirements, but no specific data on this subject were found.

Wheel tracks and soil erosion

In experiments designed to assess the optimum orientation (up/down or across slope) of controlled traffic wheelways, suspended sediment loss was 4.52 Mg ha^{-1} with across slope and 6.74 Mg ha^{-1} with up/down orientation. Soil loss on the other hand totalled 6.2 Mg ha^{-1} with across slope and 4.5 Mg ha^{-1} with up/down orientation. Similar relative soil losses were recorded at another trial site where the equivalent figures were 15.1 Mg ha^{-1} for across slope and 5.2 Mg ha^{-1} for up/down slope orientation. These data prompted the conclusion that up/down orientation may increase sedimentation losses but reduce total soil loss. None of the trials made a direct comparison with any conventional traffic systems. Separate infiltration and run-off (but not soil loss) data including traffic comparisons all suggested a lower potential for soil loss with controlled traffic.

Prediction of the potential for increased or decreased erosion from controlled traffic farming on vulnerable soils in the UK only provided information relative to existing practice rather than in absolute terms. Data suggested a 5–200 fold increase in infiltration on non-trafficked compared with trafficked soils; this implies a reduced risk of run-off and overland flow into permanent wheelways. It is also probable that intermediate but cropped permanent wheelways would moderate the concentration of any overland flow. Calculated flows down permanent wheelways based on directly intercepted rainfall result in relatively modest volumes whose erosive power can be estimated from established formulae.

Appraisal

The review was followed by an assessment of the practicalities, costs, shortcomings and deliverable benefits of controlled traffic farming. As a preface to this, alternative methods of addressing the problem of soil compaction were explored briefly. Consideration of low ground pressure and automation compared with CTF suggested that CTF had the greatest immediate potential for addressing the issues.

Controlled traffic was identified as a simple approach that could be adopted now with today's machinery, but machines might need modification to achieve track width matching and some commonality of implement widths. Although a wide range of benefits have been associated with zero compaction, to what degree will CTF deliver these benefits on individual farms? Equally important is the means by which controlled traffic can be achieved in practice and the costs of conversion. These points and many others have been the focus of a group of farmers actively engaged in assessing the pros and cons of CTF. As a result of their 18-month involvement in a field assessment and demonstration on a commercial scale, a number of new ideas have emerged. There is now therefore a range of methodologies that introduce controlled traffic with different traffic densities and different relative ease.

Benefits, concerns and barriers associated with CTF adoption

The drivers for and obstacles against adoption raised by the farmer group were categorised into benefits, concerns and barriers. The barriers were things that stopped farmers actually using controlled traffic now, whereas the concerns were aspects of the system that could be addressed after adoption.

The main benefits anticipated for CTF were:

- Reduced production costs.
- Increased yields.
- Improved cropping reliability, particularly with low input systems and spring sowing.
- Greater flexibility in cropping, including more spring-sown crops.
- Improved timeliness.
- Improved soil structure and drainage.
- Reduced need for subsoiling.
- Reliable way of cutting costs without risking yield.
- Improved water infiltration.
- Elimination of overlap for all operations.

The main concerns were:

- Can the benefits be realised in practice and on a farm scale?
- How do we know how to set out fields, get the tracks in the right place first time and keep them there?
- How will the permanent tracks perform in wet conditions?
- How do we deal with straw in terms of residual chemicals, physical interference and poor spreading?
- How do we rationalize straw baling and carting when contractors are involved?
- Reliability of satellite guidance systems and delivered accuracy.
- Maintaining sight of your permanent wheelways without satellite guidance.
- Consistency – need to have a simple and easily followed system.
- Incompatibility between crops, crop row spacing and machinery systems.
- Warranty issues with axle extensions carried out on farms or by non-licensed third parties.

The barriers to CTF conversion were:

- Incompatibility of existing equipment, either in track width, implement width or both.
- Matching track width to that of the harvester means all equipment will be wide.
- Costs of conversion, particularly if you want 100% compliance from day one.
- Mindset. Cannot conceive that CTF has any benefits to deliver.
- CTF is not presently on many people's agenda.
- Not wishing to be an early adopter; let others make the mistakes first!
- When no money in farming, no capital to change. When money good, no incentive.

- Farmers rarely see the negative outcomes of compaction in the main body of fields so there is little compelling evidence or incentive to change.
- Share farming when the partner does not have the same objectives or where key machines are not owned.
- Contractors need to have equipment that matches all customers' needs. Conversely, if a farmer uses a contractor for some operations the equipment will probably be incompatible.
- Incorrect association of CTF only with min till and direct drilling. The perception that ploughing is out of the question with CTF makes it a non-starter for some.
- Perception that it is too difficult to convert to CTF.
- Extra discipline and planning needed.

In addition to these issues there were other valuable comments about conversion to CTF. For example there was a fear that it would be associated with "technophobes" and not seen as a serious benefit. The benefits need to be demonstrated on commercial farms before uptake would be widespread. CTF was considered to be all about forward planning and commitment.

Economics

The economics of change to CTF are dominated by the conversion costs, but these in turn can be reduced considerably through knowledge transfer and long-term planning. Of the few economics studies undertaken, profit on a hypothetical UK farm was increased by £18 ha^{-1} on heavy soil but reduced by an equal amount on light land. These systems were however loaded with £57 ha^{-1} for additional chemicals in the absence of ploughing.

More recent predictions of the benefits of CTF based on farm data in the UK are:

- Operational savings of £33 ha^{-1} by changing to CTF within a min till/direct drill system.
- Operational savings of £66 ha^{-1} by changing from conventional min till to a direct drilled CTF regime.

If a CTF system with 8 m wide equipment and wheel tracks covering 25% of the area were used in practice, research data suggest a potential yield increase of 9%.

In Australia, predicted improvements in farm profit ranged from £14 ha^{-1} to £68 ha^{-1} depending upon local circumstances and whether any beneficial changes to tillage and cropping made possible by controlled traffic farming were implemented. There were also circumstances where a change to controlled traffic could not presently be justified because of recent incompatible machinery investments.

Economics studies generally used savings related to tillage, power and energy together with lower long-term investments in machinery. Costs were associated with machinery conversion and guidance but did not include the costs of planning and management. Benefits centred on yield increases, timeliness and rotational improvements that allowed a larger proportion of more profitable crops to be grown on a particular farm.

Australian experience

CTF benefits reported from Australia, where the system has developed from practically no use in 1995 to over one million hectares in 2005, centre on improved yields and frequency of cropping, reduced machinery inputs and investments and improved soil structure. Improved soil structure is cited as the basis for increased yields, created through better use and interception of rainfall and nutrients. The most important considerations when changing to CTF were strategic planning, farm design and field layout, identical wheel tracks and matched implement widths for all machines. In addition, it was essential that the agronomy should be tailored to non-compacted soils.

It was also considered that there was an affinity between CTF and technologies that improved the precision of operations. Included in this was topographic information to ensure that layouts disposed of water quickly and safely. Equally, mapping was invaluable when it came to designing layouts that would not compromise harvest efficiency.

Some Australian operations were on such a large scale that controlled traffic was considered impractical because of the excessive width of machinery. A few farmers have also experienced depth variation in their wheelways with a knock on effect of variable sowing depth.

3 m track systems are now generally accepted as the standard in Australia, but because this results in wide transport widths, are generally considered to be impractical for the UK. As a result, alternatives have already been created.

Conclusions

There is overwhelming evidence from research that the compaction created by vehicles running at random over the soil has a universally negative outcome. It leads to increased energy demands, sub-standard and dry seedbeds, increased loss of moisture and organic matter, poor crop germination and growth and poor infiltration of water, water holding capacity, drainage and gaseous exchange. Very similar conclusions were drawn by a similar review on soil compaction published by other authors in 2005. The reduction in soil quality constrains crop yields, adds considerably to the cost of crop production and has many negative environmental outcomes. Low ground pressure systems may offer some relief to the subsoil, but do little to improve the situation in the topsoil.

This is not to say that crops in the UK are universally and visibly suffering, but it is almost certain that their performance could be enhanced. If compaction were avoided it is likely that productivity would be increased, inputs would be lower and farming systems would be more sustainable. There would also be fewer and less negative environmental impacts. Avoiding compaction will naturally deliver many aspects of “Good Agricultural and Environmental Condition” (GAEC). Fears that there will be an increased risk of soil erosion with controlled traffic farming are almost certainly unfounded.

As much of the research explored in this review is now rather dated in terms of the wheel loads commonly found on cereal farms, it is likely that the effects of soil compaction have been underestimated. One might argue that with larger equipment the traffic density is less, but as is evident from the data, most soils take at least five years to recover naturally and during that period will almost certainly have been compacted at least once again.

The evidence suggests that the complete avoidance of soil compaction should be a key issue in future crop production systems. Continuing with our present machine designs and methodology of use could be seen by future generations as irresponsible and lacking in a duty of care for the soil resource. This is reflected in governmental concerns and new legislation for soil protection in many countries. In Germany for example, there is legislative debate on restricting field traffic axle loads. Research suggests that avoiding soil compaction improves and sustains the health of soils both through natural and physically induced amelioration and through the improved retention of organic matter.

Controlled traffic farming offers an effective means of addressing these issues through compaction management. The engineering of CTF solutions can take a number of forms that have the potential to make farming easier and more profitable. Their low cost introduction relies on careful planning, long-term goals and an understanding of the principles involved. Accurate vehicle guidance is an integral part of CTF and can use physical markers, vision systems or satellite technology, providing peak errors are no greater than around ±5 cm.

Wheelway orientation and management are equally important in terms of sustainability and require consideration of slopes, length of run, field obstacles and effective drainage. The economics are dominated initially by the costs of conversion, but if this is planned carefully they can often be lost within normal machinery replacement. Improved profit relies on reduced time and energy demands, lower investment costs and improved crop returns. The eventual outcome of a change to CTF is likely to be a reduction in fixed and variable costs and an increase in cropping reliability and return, but there are issues that will need to be addressed. These include overcoming the need to work at different angles, maintaining grain to store work rates, increased discipline and awkward-shaped small fields.

Future

If CTF is to be progressed in the UK, the research and development needed should centre on the most effective and cost efficient methods of delivering the benefits. This is likely to require widespread on-farm piloting of different CTF systems that should determine their ease of use, effectiveness in cutting costs, their longer-term sustainability and the range of benefits delivered. Whole farm economics modelling could provide a robust means of using the acquired data to predict the relative profitability of CTF on a wider range of farms quickly, efficiently and at low cost.

Equally important will be raising the profile of CTF nationally and the awareness of farmers to the range of benefits. Training workshops should be part of this progression, as should also the development of a category system that allows farmers to envisage a clear and achievable route to CTF that is a step-by-step process.

Literature review of soil compaction and zero traffic

Introduction

This review is the first part of a project that includes an appraisal of controlled traffic farming and any constraints associated with its adoption.

The review aims to quantify the effects of traffic-induced soil compaction on soils and crops in the UK and what might happen if controlled traffic were widely adopted. Controlled traffic farming (CTF) is simply adopting the principle of not driving at random over the soil. There are therefore various different categories of CTF, but all will have two common features:

1. Specific areas that receive traffic (at different times and of differing intensity)
2. Areas that receive no traffic.

The overall outcome on any particular farm will therefore depend to a large extent on the relative areas that receive and do not receive traffic. The "non-trafficked" areas will have a common treatment, whereas the effect on the trafficked areas will depend upon the traffic intensity, which is the combination of load, ground pressure and frequency of wheeling. These aspects will be dealt with in more detail in the appraisal

The aim of the review is to assess the effect of removing all compaction from the cropped area as well as the impact of intensifying traffic in other areas.

The effects investigated under the terms of this review are those that are likely to have a positive or negative effect on farm businesses, whether this be direct monetary or indirect through incentives such as delivering "Good Environmental and Agricultural Conditions" (GAEC) (Defra, 2005), or regulatory, such as working within the Water Framework Directive to reduce diffuse pollution. Particular risks from this have been identified, such as compaction and tramlines that are maintained throughout the winter (Defra, 2004).

Due to the relative paucity of research in the UK, a number of publications from different parts of the world have been drawn upon to provide generic data on the outcomes of soil compaction. A summary is provided at the end of each section and these are mirrored in the Abstract.

Conversions

The following conversions may assist interpretation:

1 Mg = 1 tonne

10 kN ≈ 1 tonne

100 kPa ≈ 14 psi

The requirements of GAEC likely to be impacted by soil compaction

Two principal publications give us an insight into the areas that are being addressed by GAEC (Rural Payments Agency & Defra, 2006; Defra, 2006) and these focus on:

- Soil structure
- Soil erosion

- Organic matter
- Nitrate management and its impact on diffuse pollution

The following sections therefore concentrate on these aspects as well as those that impact on crop returns and direct costs.

The effect of driving or not driving on the soil

Soil effects

Seedbed and subsoil structure and strength

Overview. Soil structure largely determines the nature of the physical processes that occur within a soil (Dexter, 1988; Kooistra & Tovey, 1994). A good structure is one that exhibits a high degree of heterogeneity between the different components or properties of soil. Strength of the soil tends to increase as soil moisture content decreases, but is elevated by stress-induced increases in bulk density, penetration resistance or shear strength (Whalley et al., 2004). Elevation of these parameters beyond their natural state is generally considered to be degradation in soil structure because it reduces heterogeneity by, for example reducing the size range of soil pores.

In this paragraph the discussion is confined to the physical structure rather than its implications for the processes that occur in the soil such as drainage, which will be discussed in the next section. As the data on the subject in this section are extensive and not all papers can be commented upon individually, Table 1 provides an overview.

Literature. Arvidsson and Håkansson (1996) found that soil compaction increased the strength and size of aggregates within a seedbed and that greater cloddiness was an underlying feature of compacted soils.

In these conditions, different types of tillage tended to result in a similar and unsatisfactory outcome. Voorhees and Lindstrom (1984) working in the USA reported similar effects on a silty clay loam. They found less heterogeneity in the seedbed, little difference in the outcome from tillage method and also a gradual improvement in soil structure with conservation tillage (chisel ploughing) compared with ploughing, both of which were carried out without compaction.

Håkansson (2005) in summarising his many years of work on the subject suggests that seedbed quality is particularly compromised if the layer is compacted shortly before or during seedbed preparation. More tillage and extra tractor passes may be necessary and this tends to compact layers deeper in the profile. In dry topsoil conditions however, the wheelings themselves may crush large clods and thus improve the seedbed.

Chamen et al. (1992a) working on an Evesham series clay found that after ploughing, and subsequently after secondary tillage with a power harrow, aggregates were double the size on trafficked compared with non-trafficked soil (114 mm cf. 56 mm and 45 mm cf. 27 mm respectively). Voorhees & Lindstrom (1984) on the other hand found that compaction increased the proportion of smaller aggregates on a silty clay loam, but this was detrimental because it created conditions conducive to capping and poorer infiltration of water.

Pollard & Webster (1978), applying a fairly extreme form of compaction (vibratory roll) on a sandy loam, found that even after six cropping seasons, the soil structure below 16 cm was significantly poorer on the compacted soil, with coarse platy aggregates, horizontal fissures and a massive structure with a high packing density. And this was despite extensive tillage to 25 cm without further compaction.

Cockcroft & Olsson (2000) found that some weakly structured or hard setting soils exhibited structural decline without compaction in a no-till situation, albeit with irrigation. There may be a few soils in the UK that exhibit similar features. Equally however, Campbell et al. (1986) found that a soil that had been classified as unsuitable for direct drilling was perfectly amenable when all traffic was avoided.

Bennie & Botha (1986) treated the subject in a slightly different way by using controlled traffic to maintain a profile once it had been loosened. They also measured to what extent the traffic lanes could be ameliorated after planting (see 100% area figure in Table 1)

Chamen et al. (1992a) in another approach measured a 9% greater increase in the volume of trafficked compared with non-trafficked soil when it was ploughed, suggesting a less compact initial state.

Jorajuria et al. (1997) looked at the effect of tractor size and number of passes with the same ground contact pressure. Importantly, they concluded that heavier tractors always resulted in greater increases in bulk density in the 30–60 cm depth range but equally, that a lighter tractor with a large number of passes was capable of producing just as much compaction as larger tractors with fewer passes. Voorhees *et al*. (1986) draw a similar conclusion about the load on a wheel and go on to suggest that its damaging effects may not be mediated by decreasing surface pressures or even over-winter freezing to a depth of 70 cm.

Campbell et al. (1986) and Dickson & Ritchie (1996b) were amongst the few researchers who measured the effect of compaction on soil shear strength. Their measurements on a sandy clay loam and a gleysol in Scotland showed that vane shear was always greatest in trafficked systems to a depth of at least 24 cm.

Radford et al. (2000) measured very specifically the impact of a harvester with a wheel load of 4.9 Mg on cracking black clay in Queensland. The mean soil depression was 33 mm and this increased bulk density to 16 cm depth and penetration resistance and shear strength to around 20 cm. Chamen (unpublished data, 2004) measured a 98 mm depression following a harvester wheel load of 7.5 Mg on a similar soil but failed to measure a significant change in cone penetration resistance compared with the surrounding area. This highlights the limitations of cone resistance as a measure of compaction because it is affected, for example, by soil moisture content, soil/metal friction, cohesion and adhesion.

Some of these parameters might reduce the reading as a result of compaction while others may increase it.

Schäfer-Landefeld et al., (2004) make two particularly important observations following their detailed study of compaction on loamy sand and silty clay soils in Germany.

1. A plough pan at 30 cm depth can effectively protect the subsoil from high wheel loads (up to 12.5 Mg)
2. If a plough pan is loosened, it can lead to severe compaction, and particularly of the subsoil.

Equally important of course is whether the pan was having an adverse effect on water movement and/or crop yield, but these aspects were not covered in this work.

Botta et al. (2004) show very explicitly how even relatively small wheel loads with repeated passes can have an impact on the subsoil. On this fine clayey soil, eight passes of a wheel with a load of just 1.4 Mg increased bulk density in the depth range 30–60 cm from 1.87 to 1.97 Mg m^{-3}.

Table 1. Data from the literature on the effect of wheel traffic on bulk density (bd, % or Mg m^{-3}), penetration resistance (pr, % or MPa) and vane shear (vs, %) including soils, depth of readings, wheel loads and percentage area of the ground covered by wheelings. (Conv. denotes conventional practice)

Country	Soil	Depth, cm	Max. wheel load, Mg	% area covered by wheels	Parameter	Comparative values		Paper
						Trafficked	Non-trafficked	
Turkey	Unknown	0-5	1.1	25	bd	110-120%	100%	Yavuzcan, 2000
		10-15	1.1	25	bd	106-112%	100%	
		0-10	1.1	25	pr	130-174%	100%	
		10-20	1.1	25	pr	107-133%	100%	
TX, USA	Clay loam	5-45	Conv.	100	pr	1.23	1.13	Unger, 1996
IA, USA	Silt loam	7.5	c. 1.8	100	pr	1.2	0.2	Hamlett et al., 1990
		22.5	c. 1.8	100	pr	1.2	0.6	
		0-20	c. 1.8	100	bd	1.4	1.1	
RSA	Sand	20-40	Conv.	Conv.	pr	3.1	1.2	Bennie & Botha, 1986
		20-40	Conv.	Conv.	bd	1.76	1.66	
		20-40	Conv.	Conv.	pr	1.50[1]		
		20-20	Conv.	Conv.	bd	1.66[1]		
UK	Lawford clay	30	3	115	pr	113%	100%	Blackwell et al. 1985
UK	Evesham clay	0-45[2]	3.25	Conv.	pr	1.22	1.03	Chamen & Cavalli, 1994
		0-45[3]	3.25	Conv.	pr	2.06	1.60	
		0-17.5	3.25	Conv.	bd	1.00	0.85	
UK	Evesham clay	0-20	3.25	Conv.	bd	0.782	0.722	Chamen et al., 1992a
		20+	3.25	Conv.	pr	182%	100%	
UK	Evesham clay	0-45	3.25	Conv.	pr	135%	100%	Chamen et al., 1990
		0-40	3.25	Conv.	bd	106%	100%	
UK	Sandy loam	10-15 20	Vibratory roll	100	bd	1.78	1.34	Pollard & Elliott, 1978
			Vibratory roll	100	pr	2.5	1.75	
CA, USA	Sandy loam	15-45	2.7	100	bd	1.82	1.65	Meek et al., 1992b
Australia	Vertisols/Red Earths	5-25	Conv.	40	bd	1.26	1.22	Boydell & Boydell, 2003
		5-25	Conv.	100	bd	1.40	1.22	
		25-50	Conv.	40	bd	1.40	1.26	
		25-50	Conv.	100	bd	1.46	1.26	
Australia	Vertisol	7-10	(1x5) then 3	100	vs	170%	100%	Radford & Yule, 2003
		18-33	(1x5) then 3	100	vs	113%	100%	

[1] Loosened wheelway; [2] Date one; [3] Date two

Table 1 continued. Data from the literature on the effect of wheel traffic on bulk density (bd, % or Mg m^{-3}), penetration resistance (pr, % or MPa) and vane shear (vs, %) including soils, depth of readings, wheel loads and percentage area of the ground covered by wheelings. (Conv. denotes conventional practice)

Country	Soil	Depth, cm	Max. wheel load, Mg	% area covered by wheels	Parameter	Comparative values		Paper
						Trafficked	Non-trafficked	
Romania	Various	10-20	1.2	100	bd	125%	100%	Canarache et al., 1984
Germany	Loamy sand/Silty clay loam	15-20	7.5-12.5	Conv.	bd	108%	100%	Schäfer-Landefeld et al. 2004
Argentina	Clay	0-15	1.4	100	bd	1.51	1.33[3]	Botta et al., 2004
		15-30	1.4	100	bd	1.70	1.59[3]	
		30-60	1.4	100	bd	1.97	1.87[3]	
Jordan	Loam	12-25	3	100	bd	1.35[4]	1.15	Abu-Hamdeh, 2003
		12-25	3	100	bd	1.21[5]	1.15	
		36-48	3	100	bd	1.26[4]	1.1	
		12-25	8	100	bd	1.42[4]	1.15	
		12-25	8	100	bd	1.30[5]	1.15	
		36-48	8	100	bd	1.35[4]	1.19	
		0-48	8	100	bd	122%[4]	100%	
		0-48	8	100	pr	139%[4]	100%	
Scotland	Clay loam	0-40	Conv.	Conv.	pr	1.5	0.5	Dickson & Campbell, 1990
Europe	Loam	Topsoil	Conv.	Conv.	pr	100	124	Chamen et al., 1992b
	Loam	Topsoil	Conv.	Conv.	pr	100	78	
	Sandy loam		Conv.	Conv.	pr	100	38	
	Clay		Conv.	Conv.	pr	100	62-90	

[3] 8 passes before significant; [4] No till; [5] Chisel plough

As far as subsoils are concerned, Håkansson (2005) summarises most of the relevant work, all of which suggests that reducing ground pressure with high wheel loads only marginally reduces the stress at depths of 50 cm or more. This relationship is illustrated in Fig. 1 showing that even if the pressure at the surface is kept the same, an increase in load tends to increase the depth to which the stresses reach. These stresses may not always damage the subsoil (beyond its existing state), but an increased potential for damage exists. The existing state is called the pre-consolidation stress, and may have been created by glaciation or more recently, by heavy tractors ploughing in the furrow. With in-furrow ploughing Keller et al. (2002) found that stresses at 30 cm depth were more than twice those generated by tractors working on the land.

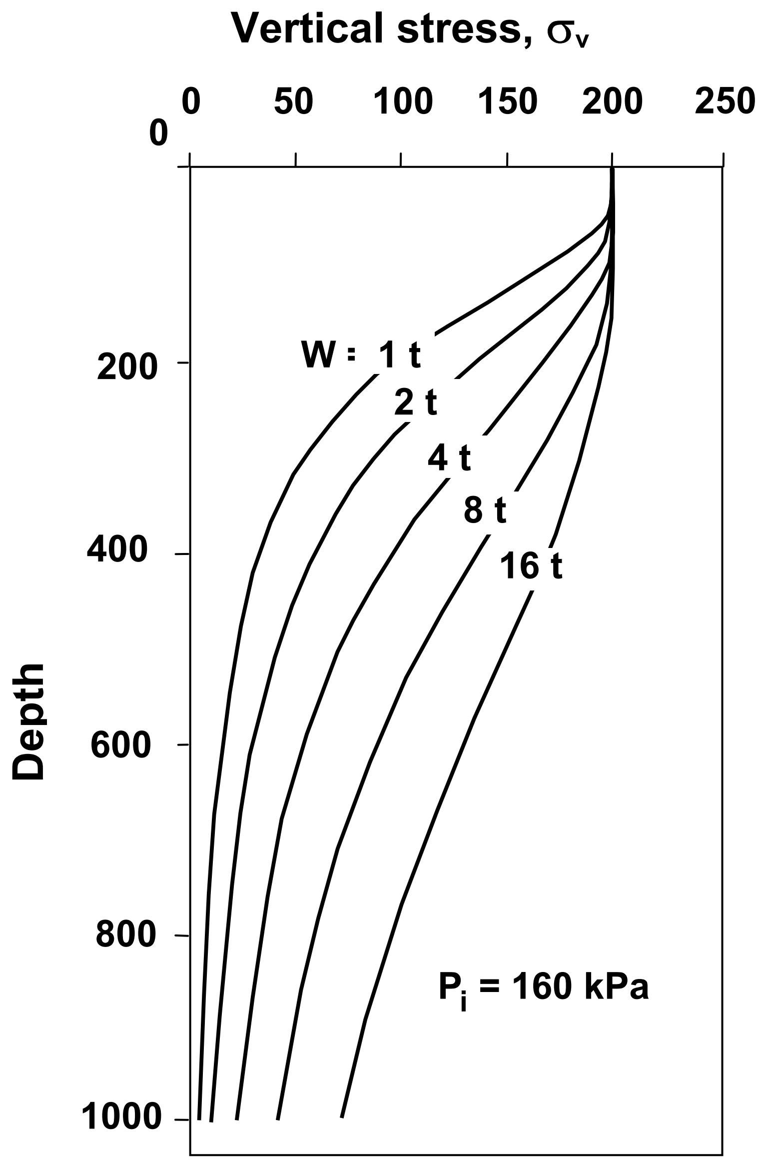

Fig. 1. The effect of increasing wheel load while maintaining the same surface pressure (vertical stress). Larger tyres were used as wheel load increased. W = wheel load in tonnes and Pi = inflation pressure of the tyres

Summary. Compaction effects on soil structure and their implication

Soil compaction tends to create more clods in seedbeds (Fig. 2) and to result in a similar tilth regardless of the type of tillage employed. Tillage of compacted soils uses more energy (see "machinery effects"), loses more moisture and often results in unsatisfactory crop establishment. Compaction just before or during seedbed establishment is particularly damaging.

Sandy soils are more amenable to repair by cultivation (for example they show far less evidence of cloddiness), but they have little ability to restructure naturally. Compaction at depth in all soils persists for long periods and on sandy soils often indefinitely. Mechanical loosening (usually subsoiling) is difficult to time correctly and if carried out successfully, make the soil more vulnerable, often to a greater depth.

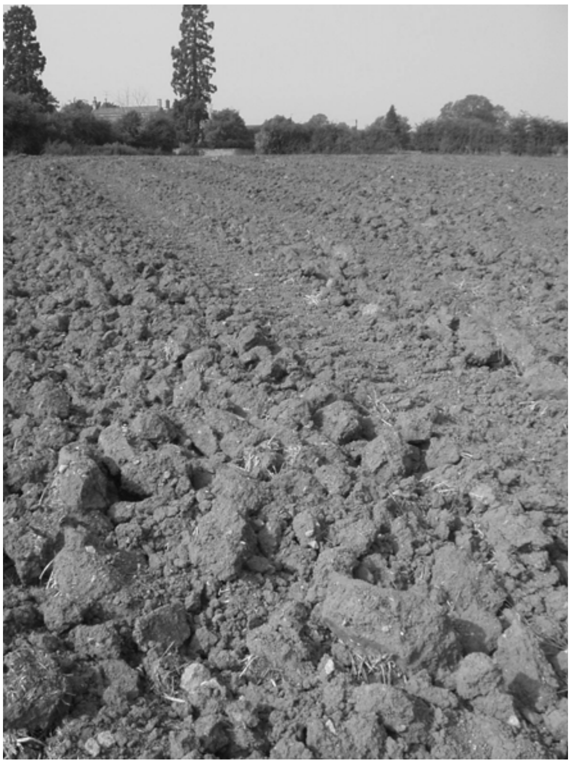

Fig. 2. An illustration of the good and bad effects of compaction under wheels. The foreground shows the massive cloddiness caused by compaction before tillage, whereas the wheel strips show how tyres can crush clods. Both aspects however increase energy.

High wheel loads at the soil surface are now affecting the subsoil because it is becoming increasingly difficult to keep pressures at the surface low enough to avoid stresses penetrating deeper into the profile (see Fig. 1). In many instances these stresses are now exceeding the existing strength of the subsoil and are leading to its deterioration.

Drainage, porosity and erosion

Overview. Drainage is encouraged by good infiltration of water in the surface layers and large continuous pores running through the soil profile that have connectivity with the drainage system. Particularly important is the saturated hydraulic conductivity of a soil, i.e. its ability to maintain a flow of water when the profile is saturated. The papers studied in this section all relate to these aspects of the soil system and comparisons, unless otherwise stated, are between conventional practice with random traffic and zero traffic systems.

Literature. On all soils, compaction had a detrimental effect on the infiltration of water (Hamlett et al., 1990; Boydell & Boydell, 2003; Li et al., 2001; Wang et al., 2003; Tullberg et al., 2001). Without wheel compaction, infiltration increased from 84 to 400% alongside 6–34% increases in plant available water. Hamlett et al. (1990) reported an infiltration rate of 14.5 mm min^{-1} on a non-trafficked bed compared with just 0.5 mm min^{-1} in the permanent traffic lane alongside.

The most important and generally deleterious effect of compaction was a reduction in hydraulic conductivity (Alakukku, 1996; Chamen & Longstaff, 1995; McHugh et al., 2003; Radford et al., 2000; Voorhees et al., 1986, Arvidsson, 2001). Arvidsson (2001) provides graphic data on the effect of high axle load traffic on hydraulic conductivity deeper in the profile (Table 2). Although these data come from trials with sugar beet harvesters, the treatments were applied before ploughing in the autumn and the axle loads closely resemble those on the front axles of present high capacity cereal harvesters.

Table 2. Saturated hydraulic conductivity (mm h^{-1}) measured on field samples taken at 30–35 cm and 50–55 cm depth from the Swedish field trial that imposed wheel by wheel compaction with harvesters having an axle load approaching 20 Mg

	Hydraulic conductivity, mm h^{-1}			
	30–35 cm depth		50–55 cm depth	
Treatment	1996	1999	1996	1999
Without high axle load traffic	7.4	2.3	80.6	23.8
With high axle load traffic	0.8	0.33	5.7	4.7
Significance[1]	ns	**	*	**

[1] ns = not significant; * significant at p<0.1; ** significant at p<0.05

On clays, loams and organic soils, wheel loads of 4 to 5 Mg reduced saturated hydraulic conductivity in the 0.4–0.5 m profile by as much as 98%. On sandy loams, much lower axle loads could induce these detrimental effects. Heavily compacted topsoils experienced a 4-5-fold decrease in saturated hydraulic conductivity. Natural amelioration in the absence of traffic takes some time, but on some soils may be assisted by deep cracking. Chamen & Longstaff (1995) for example recorded significant benefits after eight years of no traffic, but not after a shorter period (Chamen et al, 1990).

Differences in infiltration due to traffic are of particular interest in the UK where run-off and erosion can be critical during the winter. Horton et al. (1994) devise an equation showing how an increase in bulk density has a negative correlation with soil water diffusivity. Increase in bulk density due to compaction has a particularly deleterious effect when it is accompanied by shear and no change in soil volume, something that is common with traction and transport devices, such as wheels and tracks (Koolen & Kuipers, 1983).

Hydraulic conductivity (both saturated and unsaturated) and infiltration are both adversely affected by traffic, and the field measurements of infiltration are a useful approach to measuring its influence (Horton et al., 1994). Ankeny et al. (1990) show infiltration plotted against matric potential for both trafficked and non-trafficked situations. Under no-till, infiltration on non-trafficked soil was 0.36 mm h^{-1} compared with 0.01 mm h^{-1} on trafficked. Under tine tillage the contrast was greater, with equivalent figures of 0.63 mm h^{-1} compared with 0.003 mm h^{-1}. Håkansson et al. (1985) reporting on Swedish trials between 1964 and 1984 quoted an infiltration rate of practically zero using tractors of up to 3.5 Mg (with perhaps wheel loads of only around 1 Mg) compared with 6 mm h^{-1} in nominally non-trafficked conditions (cable and winch).

Decreased infiltration and conductivity due to compaction led to 44% greater water runoff (Fig. 3) from both surface and subsurface flow (Tullberg et al., 2001).

Similarly, a number of studies reported an increase in soil erosion, soil loss and transport of nutrients and applied chemicals compared with zero traffic. Wang et al., (2003) in China measured a soil loss of 1.4 Mg ha^{-1} with no-till and no compaction, but 3.8 Mg ha^{-1} when the only difference was tractor compaction after harvest. Residue cover has a very significant effect on both run-off and soil loss, as demonstrated in the results from Rohde & Yule (2003) shown in Table 3. This experiment was difficult to interpret because of these influences but the authors suggest a very positive effect on run-off and soil loss as a result of traffic control. They cite cumulative total runoff and soil loss from T5 as 175 mm and 12.12 Mg ha^{-1} respectively compared with that from T4 at 89 mm runoff and only 3.54 Mg ha^{-1} soil loss.

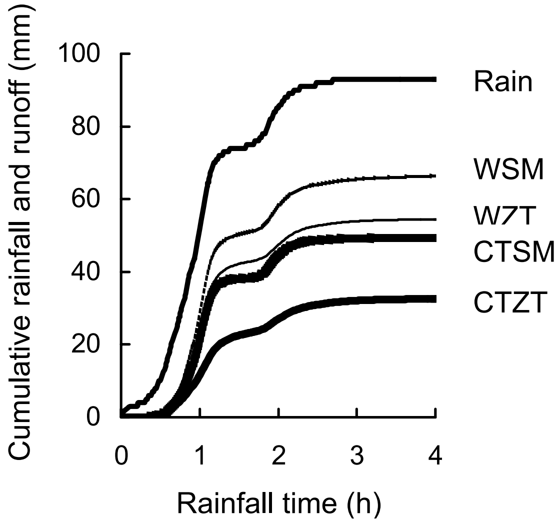

Fig. 3. Traffic and tillage effects on runoff on a clay soil in Queensland. Treatment key:
Wheeled/stubble mulch (tine implement) WSM
Wheeled/zero till WZT
Controlled traffic/stubble mulch CTSM
Controlled traffic/zero till CTZT
(From Tullberg et al., 2001)

Table 3. Ground cover, run-off and soil loss averaged or totalled for six rainfall events (from Rohde & Yule, 2003)

Treatment	Ground cover, % at time of rainfall event	Run-off, mm	Soil loss, Mg ha^{-1}
T1, zero traffic, no till	42.3	101.2	4.69
T2, annual 11 Mg, some till	19.8	133.6	10.12
T3, initial traffic, no till	41.7	96.0	4.96
T4, initial traffic, double crop	40.7	82.8	2.85*
T5, annual 9 Mg, some till	22.9	145.5	10.12

* Double cropped – more ground covered for a longer period

An associated effect of compaction is the need for more tillage and this exacerbates infiltration problems due to a higher percentage of fine aggregates.

Researchers found that vehicle-induced compaction universally reduced the porosity of soils (Ball & Ritchie, 1999; Alakukku, 1996; Blackwell et al., 1985; Campbell et al., 1986; Dickson & Ritchie, 1996). This occurred particularly in moist conditions and through a reduction in macropores (up to 70% at 0.5 m depth). McAfee et al. (1989) assessed the effect of compaction before sowing oats in the spring. The authors note that the compacted soil retained more water per unit volume in the uppermost layers than the control, and was therefore slower to dry out in the early part of the growing season. Equally, the compacted soil reached field capacity after a smaller input of rain owing to slower water movement through the topsoil.

Typically the reduction in pore space reported was in the order of 10% averaged over the 0-0.2 m depth profile, but it could be far greater with repeated passes and nearer the surface. Reduced porosity creates an unfavourable soil structure not only for drainage, but also for crop growth largely as a result of reduced oxygen diffusion and relative diffusivity.

Summary. Drainage, porosity and erosion

Compaction is particularly damaging in terms of drainage, aeration and erosion. This is demonstrated by improved infiltration (84%–400%) if compaction is avoided and through more plant available water (6%–34%). Because compaction reduces infiltration, runoff can increase by around 40% and this increases nutrient and soil loss by a similar amount, even in the presence of crop cover.
Wheel loads of just 5 Mg can reduce the saturated hydraulic conductivity of many subsoils by around 100%. On lighter soils similar effects are possible with even lower loads and likewise topsoils can suffer a 4–5 fold reduction in conductivity. This decline is brought about through a discontinuity of pores that are smaller and fewer in number. Typical reductions in pore space due to traffic are around 10% but up to 70% reduction at 0.5 m depth has been recorded. These decreases are associated with a greater retention of water (smaller pores hold water more tightly and less may be available to plants) and quicker return to field capacity with rainfall.

Fertilizer use efficiency and diffuse pollution

Overview. This subject is addressed not only because of its financial implications for the grower, but also because of its impact on diffuse pollution and greenhouse gases. The effect of soil compaction in the uptake of nutrients is significant and relevant research has been investigated to determine its extent and impact.
Literature. There was widespread evidence of a poorer uptake of nutrients (N, P & K) on trafficked compared with non-trafficked soils (Ball et al., 1999a; Fulajtar, 2002; Wolkowski, 1990; Torbert & Reeves, 1995a). Wolkowski (1990) concluded that the smaller uptake of N, P & K was the result of poor crop rooting and lack of oxygen, the latter reducing uptake (particularly in the case of K) and increasing denitrification. The improvement in recovery with zero traffic was supported by recorded higher concentrations of nutrients post harvest in both the topsoil and subsoil of compacted plots (Fulajtar, 2002). Differences in uptake were often associated with particular ranges of bulk density (Medvedev et al., 2002; Wolkowski, 1990). Consequential loss of N & P through sediment loss was halved by a combination of no till and CTF. No till and CTF on the other hand can lead to a concentration of nutrients (especially potassium), when crop rows remain in the same place from year to year (Mengel and Hawkins, 1994).
Avoiding all traffic compaction reduced nitrous oxide (N_2O) emissions from the soil. As would be expected, losses from compacted soils increased with the application of N fertilizer and particularly in moist conditions (Sitaula et al., 2000; Ball et al., 1999a). Some reduction in N losses could be achieved by light firming of the seedbed (Ball et al., 1999a). This restricted emissions to the atmosphere and also to the subsoil.
There was also evidence of increased carbon dioxide (CO_2) and methane (CH_4) losses from compacted soils (Ball et al., 1999b).

Where chemicals were transported off-site due to poor infiltration, their concentration in the absence of compaction were found to be up to 30% less (Silburn et al., 2002)

Summary: effects of compaction on nutrient uptake and mobility

Other than very light firming of seedbeds, compaction has a negative impact on nutrient supply and mobility. Nutrient uptake is impaired through restricted crop rooting, lack of oxygen and greater losses (denitrification) from the soil system that can lead to diffuse pollution. Denitrification is greatest in wet conditions when fertilizer is applied to heavily compacted soils. Sediment losses triggered by compaction and associated poor infiltration increase the consequential loss of P & K in particular. Compaction is also likely to increase losses to the atmosphere in the form of carbon dioxide and methane. Overall, avoiding compaction can increase nutrient recovery by up to 20%.

Organic matter

Overview. Soil organic matter is the driving force in the generation and maintenance of soil structure and as has already been stated, structure determines the physical and many other processes that go on in the soil (Fig. 2, Holland, 2004), for example water retention and/or drainage and gaseous exchange. Organic matter contains the gums that help build up and maintain structure but not all organic matter is the same and its effects on structure can differ markedly. However, it is almost certainly the case that within practical limits, the more organic matter of any sort contained within the soil, the better. So, in the case of soil compaction, we want to know whether it has positive or negative effects on the amount of organic matter contained in the soil.

Literature. Reicosky (1999) studied organic matter dynamics extensively on a loamy sand, both in the presence and absence of tillage and compaction. Results based on the generation of carbon dioxide (CO_2) as an indicator of oxidation rates, suggested that compaction per se, had no effect on organic matter. Jensen et al. (1996) working on a silty clay loam on the other hand measured a 69% reduction in CO_2 fluxes with compaction, suggesting a slowing up in oxidation. Overall however, they too conclude that compaction has no effect on what they term "microbial biomass". Breland & Hansen (1996) looking at a slightly different aspect using pot experiments, found that compaction reduced N-mineralization and loss of microbial biomass through physical protection. These findings are certainly in line with the fertilizer effect already discussed. In the review by Holland (2004), more intense cultivation was cited as one of the reasons for the decline in soil organic matter. Brady and Weil (1999) support this view, suggesting that tillage accelerates mineralization of organic matter, but they also propose that its rate of decay is slowed if it is left at or near the surface. However, both Holland (2004) and Smith and Conen (2004) express concern that the concentration of organic matter near the surface in conservation tillage systems can increase denitrification as a result of compaction and surface waterlogging. Smith (2004) still puts zero/reduced tillage at the top of the list of measures to increase carbon sequestration, but Smith and Conen (2004) qualify this by suggesting that the advantages of increased sequestration may be outweighed by associated increases in nitrous oxide emissions. In contrast to these findings are those of Deen & Kataki (2003) in their long-term conventional versus conservation tillage experiment, designed to detect differences in carbon sequestration. They found only differences in distribution of organic matter rather than total storage. Principally, organic matter concentration was 11–16% greater with no-till in the 0–5 cm profile and significantly greater in the 40–60 cm profile compared with any of the cultivation systems, but equally, it was lower elsewhere. Sisti et al. (2004) mirror these results in similar 13-year trial, but detected an interesting interaction. They found that no-till compared with tillage systems only conserved more organic matter when the cropping would result in a positive balance, but not otherwise.

A final consideration of this subject is perhaps provided by Brady and Weil (1999), who identify the conditions for rapid decomposition that include a near-neutral pH, sufficient soil moisture, good aeration and warm temperatures – conditions that might easily pertain to no till, particularly in the absence of compaction. As we have seen above however a crucial aspect of this decay is whether the organic matter is in direct contact with the soil. Without such contact decay will be significantly slowed, both as a result of inaccessibility to microbes and because it will tend to remain drier. It is the precise manipulation of organic matter that could be the key to benefits or shortcomings.

Summary: effects of compaction on soil organic matter (SOM)

Although cultivated soils were found to contain less organic matter than virgin soils, the effect of compaction on soil organic matter (SOM) seems to be neutral. Primarily, within cultivated soils the level of soil organic matter is determined by cropping. Although there is widespread evidence that tillage increases oxidation of organic matter, particularly in warm moist conditions, evidence of differences resulting from different intensities of tillage practised over long periods, is less conclusive. Some experiments may not adequately account for the redistribution of organic matter through the soil profile, which even with zero tillage, can be to a substantial depth. Where upper horizon stratification of SOM does occur, such as with minimum or no till systems, associated compaction can increase a tendency towards emissions of greenhouse gases such as nitrous oxide and methane. Avoiding compaction in these circumstances can be particularly beneficial, as can its clear association with lower tillage inputs.

Crop effects

Overview. Soil compaction can have a direct and an indirect effect on crop performance. The direct effect is the degree to which compaction interferes with the crop's ability to extract water, nutrients and air while the indirect effect is associated with timeliness – the additional time it may take to prepare a seedbed, and the quality of the seedbed, once prepared. The latter has already been considered, but the energy (including time) factor will be addressed under the section on machinery.

Research data on crop performance in the UK are limited but it is possible to select those areas or crops in the world that have some similarity to UK conditions to gain a more extensive assessment of the effects of compaction.

Literature. The research methodologies used to compare yields under compacted and non-compacted conditions vary widely, but two main approaches are common. The first is to look at compaction of the whole profile using conventional equipment in a conventional manner compared with no compaction or "controlled traffic". Obviously the weight, pressure and frequency of vehicle use differ markedly between experiments, but the principle remains the same. The other approach is to study subsoil compaction in particular. High wheel loads (3–12 Mg) are used to achieve this, either annually or as a once off operation, and are followed subsequently by conventional vehicles (that never exceed the lowest of the high experimental loads) and tillage to a range of depths. The easiest way of presenting the majority of these results is by tabulation, and Table 4 sets out the relevant yield data in as simple a form as possible.

Table 4. Yields of a range of crops grown with zero traffic and shown as a percentage of yield from conventionally trafficked soil

Crop	Yield as % of trafficked soil	Exp. type[1], profile or subsoil: soil type	Country	Paper
Cereals	91 - 115	Profile: clay, loam, sandy loam, loam	UK, NL, Scot., D	Chamen et al., 1992b
Wheat	119	Profile: fine sand	South Africa	Bennie & Botha, 1986
Wheat	118	Profile: clay	UK	Chamen et al., 1992a
S. Barley	116	Profile: clay	UK	Chamen et al., 1994
Wheat	126	Profile: clay	UK	Chamen & Longstaff, 1995
Wheat	100	Profile: silt loam	UK	Graham et al., 1986
Wheat	136	Raised beds: sands, loams	Australia	Hamilton et al. 2003
Barley	144			
Oilseed rape	133			
Wheat	120	Profile: clay loams	USA	Voorhees et al., 1985
Maize	127			
Soybean	119			
Wheat	107	Profile: loam	Netherlands	Lamers et al., 1986
Barley	100+	Profile: sandy clay loam	Scotland	Campbell et al., 1986
Cereals	145	Profile: clay loam	Australia	Radford & Yule, 2003
	125	Subsoil: clay		
Cereals & grain legumes	112	Profile: Red Brown earth	Australia	Sedaghatpour et al., 1995
Wheat	100	Profile: clay	Australia	Radford et al., 2000
Barley	124–162	Subsoil: sandy loam	UK	Pollard & Elliott, 1978
Cereals	105–115	Profile: various	Ukraine	Medvedev et al., 2002
Cereals	82–130	Profile: various	Poland	Lipiec, 2002
Oats	141	Profile: clay	Sweden	McAfee et al., 1989
Barley & peas	100–130	Subsoil: silt loam	USA	Hammel, 2003
Wheat	100			
Oilseed rape	190	Profile: sodic clay	Australia	Chan et al., 2005
Spring cereals	120–126	Profile: clays	Sweden	Håkansson et al., 1985
Spring barley	119	Profile: gley[2]	Scotland	Dickson & Ritchie, 1996b
Spring osr	125	Profile: gley[2]		
Winter barley	115	Profile: gley[2]		
Cereals	114	Profile: clay	Australia	Tullberg et al., 2001

[1] See text: [2] gley, a sticky waterlogged soil lacking in oxygen

It was recognised some time ago that crop responses to soil over-compaction had a marked interaction with weather (Soane et al., 1982). Voorhees (1987) also recognised an optimum level of compaction for each crop, season and soil. Many of the eastern European countries have produced data that provide an optimum range of bulk densities for crops grown on different soils (Rousseva, 2002; Medvedev et al., 2002; Lipiec,

2002). Rusanov (1991) working on a loamy black earth suggests a yield loss of 15 kg ha^{-1} for every 1 kg m^{-3} increase in bulk density above an optimum of around 1.25 Mg m^{-3} in the 0–0.3 m depth layer, and 8 kg ha^{-1} for a similar increase in the 0.4–0.5 m depth layer. Rousseva (2002) and Lipiec (2002) suggest that fertilizer could not counteract the effect of soil over-compaction. Additional nitrogen simply went to waste.
Javurek (2002) estimated that due to soil over-compaction, there was an average winter wheat yield loss of 8% from the centre of fields and 14% from field headlands. Using information from the Czech Republic Office of Statistics, it was estimated that on a national scale this was equivalent to an annual loss of 128,000 t (0.16 t ha^{-1}) of wheat alone.
A series of 24 long-term subsoil compaction trials were carried out with international cooperation in seven countries in northern Europe and North America (Håkansson 1994 & 2005). Results suggested that wheel loads of 5 Mg caused a permanent 2.5% reduction in yield.

Summary: effects of compaction on crop yield

Crop yield responses to zero compaction are irregular but invariably positive and range from 82–190% compared with conventional traffic systems. These variations can often be explained if appropriate factors are considered (Boone & Veen, 1994), all of which relate to the correct timing and supply of water, nutrients and air, both during and after crop establishment. These requirements are more likely to be satisfied if crop roots are able to explore the soil profile without hindrance. On many occasions, excessive compaction precludes this free exploration and is the cause of yield depression. There is a considerable body of evidence to suggest that wheel loads in excess of 5 Mg will cause a permanent 2.5% reduction in yield due to subsoil damage.
In many East European countries, an optimum soil bulk density for maximum crop production has been identified for different soils. However, no clear soil type effect on crop responses to compaction could be isolated in this review because of the absence of consistent bulk density data.

Machinery effects

Overview. As we have seen from the section on seedbed effects, compaction tends to increase the strength of soils at any given moisture content and this has a direct impact on the draught force needed to pull implements, the strength of the aggregates produced and wear on the implements used. This section deals with these specific aspects.
Literature. Chamen et al. (1992a) working on an Evesham series clay soil in the UK and comparing conventional and zero traffic reported a 60% reduction in draught and energy for shallow ploughing (10 cm) and a 20% reduction in draught for conventional ploughing (20 cm), both in the absence of traffic. Over the whole period of these experiments, draught requirements were on one occasion higher on the non-trafficked plots (Chamen et al., 1994). Although in contrast with all other data, these may be explained by soil moisture, fineness of tilth and cohesion effects in very differently structured soils.

Chamen et al. (1992b) in summarising coordinated projects on the effects of different traffic systems across northern Europe in the early 1980s reported that zero traffic reduced energy demands within cereal rotations by 29–87%. Following a longer period without traffic on the Evesham soil, Chamen & Longstaff (1995) reported a 37% reduction in draught when ploughing 20 cm deep. Similarly, Chamen and Cavalli (1994) report an 18% reduction in the draught of a mole plough working at 0.55 m depth.

Working on an expanding and contracting clay soil (Vertisol, similar to the Evesham above) in Queensland, Tullberg (2003) concluded that approximately half the total power output of a conventional tractor used in a random traffic system can be dissipated in the process of compaction and de-compaction of its own wheel tracks. However, recording draught differences in dry conditions, there was no detectable difference between treatments – in other words no additional compaction had occurred.

Lamers et al. (1986) working in the Netherlands on loam and clay soils reported a 25% reduction in draught in the absence of compaction. They also suggested a 48% reduction in energy due to lower rolling resistance on the permanent traffic lanes and a 20% reduction in tillage depth that was feasible with the system.

Dickson & Campbell (1990) comparing conventional and zero traffic systems over a period of four years on a clay loam in Scotland found that for both direct drilling and ploughing, conventional traffic increased draught forces by 17%. Dickson & Ritchie (1996a) comparing conventional and zero traffic systems for a rotation of spring barley, spring oilseed rape and potatoes for five years on a gley soil in Scotland measured substantial differences in draught forces and power requirements. Nominal depth of cultivation for all treatments was 25 cm, but for the cereal crops with zero traffic this was reduced to 20 cm. The conventional system on average required 92% more draught than zero traffic and 82% and 90% more power for primary and secondary tillage respectively.

Arndt & Rose (1966) working as long ago as the 1960s had already recognised the close link between traffic and the need for tillage. “Excessive traffic necessitates excessive tillage” was a term they phrased and were already suggesting confining compaction to specific areas. As controlled traffic practitioners, Boydell & Boydell (2003) report savings in power during their soil-engaging operations and suggest the possibility of downsizing their tractors. Spoor (1997) on a similar energy theme shows just how much extra pull is needed when hauling trailers across differently managed land. Compared with conventional practice, he found working from a permanent traffic lane reduced rolling resistance by between 24% and 30% depending on soil type.

Williford (1985) working on a sandy loam, albeit with a cotton crop, measured a 34% saving in energy with a controlled traffic production system. Friedrich (2003) providing a global review of conservation tillage systems identified soil compaction as a limiting factor whose repair costs were high.

Surprisingly, no literature on the specific effect of soil compaction on the wear on soil engaging implements has been found to date. However, Owsiak (1999) observed that the wear of spring tine points was 40–100% higher in sandy loam soil compared with light clay soil, and that wear within a tractor wheel track was 17–40% higher than outside the track. Richardson (1967) also suggests that wear on a particular implement is subject to the strength of the abrasive material. It is also well-known that "points" behind implement or tractor wheels wear out more rapidly because they need replacing far more frequently in this position.

Summary: machinery effects

Because compaction increases the strength of both the soil mass and the aggregates within that mass, tillage for both loosening the profile and creating seedbeds invariably needs more draught and energy. In prolonged but relatively rare dry conditions where tillage follows tillage without intermediate compaction, there may be little difference in energy requirements between traffic systems.

Zero traffic reduced the draught requirements for shallow (10 cm) primary tillage by up to 60% and for mole ploughing (at 55 cm) by 18% and energy demands for seedbed preparation fell by up to 87%. At intermediate depth (20–25 cm), zero traffic reduced implement draught by up to 48%, while power requirements for primary and secondary tillage were reduced by 45% and 47% respectively. Practitioners of controlled traffic in Australia have responded to these reduced energy demands by selecting smaller rather than larger replacement tractors.

It is predicted that the wear on the soil engaging parts of implements is likely to be reduced in line with draught requirements but no specific research on this subject was found.

Wheel tracks and soil erosion on sloping land

This section considers firstly research addressed at the specific issue of erosion, and particularly that initiated by wheel tracks and secondly at recognized differences in infiltration between trafficked and non-trafficked soil in an attempt to predict likely outcomes compared with current practice.

Literature

Research directed specifically at this topic for controlled traffic is rather limited, but Titmarsh et al. (2003) working in central Queensland, made a comprehensive study on a range of soils in cooperation with commercial growers. Their experiment compared up and down slope with across slope orientation of controlled traffic wheelways on three properties. Table 5 shows the comparable rainfall events that initiated both run-off and sediment loss measured at the outlet from contour bays (in other words, from both beds and wheelways combined). Sediment loss from catchments tends to be greater with clay soils (there is less likelihood of its deposition before it leaves the catchment) (Evans, 1990), and rates of erosion from clay soils in the UK are generally small (Evans, 2002). Table 6 shows the soil loss via rills for the same sites.

In addition to these data, Titmarsh et al. (2003) ran a model prediction of the likely sediment transport from a conventionally managed catchment close to the McCreath property using contrasting cover levels. This used a 30-minute 1 in 10 year average recurrence interval storm as the basis and this predicted 11.2 Mg ha^{-1} loss from a bare cultivated/young crop situation and 2.6 Mg ha^{-1} from a no-till/high cover condition.

Table 5. Runoff and suspended sediment loss on three farm sites in central Queensland for across slope and up/down slope orientation of controlled traffic wheelways (from Titmarsh et al., 2003)

		Across slope				**Up/down slope**			
Site	Date	Rainfall, mm	Runoff, mm	Sus Sed[a], Mg ha^{-1}	Cover, %	Rainfall, mm	Runoff, mm	Sus Sed, Mg ha^{-1}	Cover, %
Coggan	27/10/02	42.5	10.4	3.1	35	42.5	26.4	3.7	40
	10/12/02	75.8	1.7	0.2	20	75.8	6.5	0.5	35
	15/12/02	29.1	4.5	0.5	20	29.1	12.7	0.9	35
	Totals	**147.4**	**16.6**	**3.8**		**147.4**	**45.6**	**5.1**	
McCreath	2/2/02	70.5	2.1	0.002	95	70.5	5.6	0.01	95
	5/2/02	24.5	7.6	0.015	95	24.5	11.6	0.03	95
	Totals	**95.0**	**9.7**	**0.017**		**95.0**	**17.2**	**0.04**	
Aisthorpe	2/01/00	13.6	1.6	0.02	83	13.6	0.0	0.0	77
	4/01/00	46.4	14.5	0.12	83	46.4	37.2	0.71	77
	19/11/00	20.8	0.2	0.00	70	20.8	0.4	0.01	65
	20/11/00	26.0	15.7	0.19	70	26.0	15.9	0.31	65
	21/11/00	33.4	28.1	0.34	70	33.4	28.2	0.54	65
	Totals	140.2	**60.1**	**0.7**		**140.2**	**81.7**	**1.6**	

[a] Sus Sed = suspended sediment

Table 6. Soil loss via rills for up/down and across slope orientation of controlled traffic wheelways (from Titmarsh et al., 2003)

Site	Across slope, Mg ha^{-1}	Up/down slope, Mg ha^{-1}
Aisthorpe	1.2	0.3
Gibson	4.8	3.1
McCreath	0.2	1.1

The latter is probably more comparable with the field data, but because no rainfall intensity is provided it is not possible to make a direct comparison with the controlled traffic systems. The only thing one can say is that the loss was significantly greater than that recorded for controlled traffic at the McCreath site for any of the rainfall events.

In considering the results the authors reason that because the area of the wheelways is relatively small, the additional runoff from the up/down slope orientation must have been generated by more than just the wheelways themselves [Author note: unfortunately traffic intensity (number of wheelways per unit width) is not stated in the paper]. Tine tillage and/or drilling will almost certainly have been used and this may have been a contributing factor in terms of small furrows running up/down slope. The rather different, or at least uncertain message coming from the rills may also have been an aspect of this. With an across-slope orientation, if rainfall intensity is such that overtopping of small cultivation furrows occurs in hollows, this often initiates rills. This is less likely with an up/down orientation where there is not the equivalent concentration. The authors ultimately conclude that soil loss levels were relatively low (probably because of high cover levels) with no clear distinction between traffic orientations. Regrettably we have no direct comparison with a conventionally trafficked situation.

The Grains Research & Development Corporation (2000) carried out a similar trial on a self-mulching clay soil in Queensland (but again with no conventional traffic comparison). Rainfall at 755 mm was above the annual average (682 mm) and the across-slope controlled traffic resulted in 15.1 Mg ha^{-1} loss of soil compared with just 5.2 Mg ha^{-1} for the up/down orientation, despite only small differences in equivalent in runoff (232 mm and 191 mm respectively). The report suggests that this is because of the rill effect mentioned earlier. They also mention some minor erosion in the permanent wheel tracks with the up/down orientation, and this occurred at the bottom of slopes as it does with tramlines in the UK. Results from another trial still in progress have indicated that the up/down orientation increases soil loss with small rainfall events, but conversely reduces loss under high intensity rainfall.

Tullberg et al. (2001) and Li et al., (2001) provide data indicative of the relative potential for soil loss between conventional and controlled traffic systems. Tullberg et al. (2001) concluded that zero traffic reduced runoff on a clay soil by 63 mm y^{-1} while Li et al (2001) reported a 4–5 fold increase in infiltration in the absence of traffic.

In the absence of comparable data for trafficked/non trafficked soils it is interesting to consider the UK situation on erosion, and erosion from tramlines in particular. Chambers & Garwood (2000) in their study found that tramlines were associated with 14% of erosion events, while wheelings and headlands were associated with a further 19% and 8% respectively. Crop cover and valley features were the other two factors at 22% and 30% respectively. Rainfall events associated with erosion were in 96% of cases >10 mm day^{-1} and in 80% of cases were linked with daily rainfall volumes of >15 mm and maximum intensity of >4mm h^{-1}. Erosion with crop cover of more than 15% was usually due to runoff concentrated in tramlines or wheelings but exacerbated by channelling of runoff by natural features. Erosion control procedures considered important by Chambers & Garwood (2000) in what they report is a 150% future increase in risk due to climate change, include the avoidance of compaction and wheelings. Where controlled traffic systems are being considered in the UK, non-cropped tramlines spaced at around 24 m are still used, but there are also intermediate permanent wheelways that are cropped. These, which are usually spaced at between 6–8 m centres, due to a lesser demand for tillage, might only receive a drill and harvester once a year and an occasional grain cart.

An additional consideration difficult to quantify is the temporary destabilization of soils due to tillage (Watts et al., 1996a&b). These studies confirmed what many farmers have observed, that heavy rainfall soon after tillage causes much greater structural damage than similar rainfall some days later. Imeson & Kwaad (1990) consider that longer-term soil surface degradation is an evolutionary process in response to wetting. The processes all have an influence on soil porosity and are affected by the stability of individual aggregates in water. This in turn is influenced by the manner in which the individual aggregates have been formed. Those formed under biotic rather than tillage processes are relatively more stable in water. Avoiding soil compaction will diminish the need for and the intensity of tillage and should therefore increase the number of these more stable aggregates and reduce the potential for soil surface degradation.

The traditional view of surface roughness in terms of erosion may also have to be modified in the absence of compaction. As will be seen from the preliminary infiltration data on Hanslope clay (Table 7), the non-trafficked soil under no-till would seem to have a significantly higher infiltration compared with no-till in the presence of traffic and perhaps also compared with minimum tillage. All these comparisons have been made on predominantly heavy soils and they are not therefore directly comparable with the sands, loams or shallow lime-rich Lithomorphic soils over chalk or limestone that might be considered at risk in the UK. However, their results are still likely to be of relevance and lead us on to consider the other approach to this subject.

Summary

In experiments designed to assess the optimum orientation (up/down or across slope) of controlled traffic wheelways, suspended sediment loss was 4.52 Mg ha^{-1} with across slope compared with 6.74 Mg ha^{-1} with up/down orientation. Soil loss on the other hand at the same sites totalled 6.2 Mg ha^{-1} with across slope and 4.5 Mg ha^{-1} with up/down orientation. Similar relative soil losses were recorded at a further trial site where the equivalent figures were 15.1 Mg ha^{-1} for across slope and 5.2 Mg ha^{-1} for up/down slope orientation. These data prompted the conclusion that up/down orientation may increase sedimentation losses but reduce total soil loss but none of the trials made a direct comparison with conventional traffic systems. Separate infiltration and run-off data that included traffic comparisons all suggested a lower potential for soil loss with controlled traffic.

The lower tillage inputs associated with controlled traffic may improve the stability of surface aggregates and reduce the potential for surface capping and poor infiltration.

Prediction

The aim here is to look at the infiltration data, assess its relevance to soils in the UK and consider, using rainfall intensity records, whether it would be possible to predict the relative risks associated with controlled traffic systems compared with conventional practice. It should be stressed that these data are only likely to predict <u>relative risk</u> compared with conventional practice. The recent paper by Evans & Brazier (2005) shows just how difficult it is to predict erosion with any degree of certainty, despite robust field data.

Table 7 provides a summary of the literature in relation to surface infiltration rates referenced earlier. Also included are limited infiltration data recorded recently at neighbouring field sites in the UK, including controlled traffic.

As far as rainfall intensity is concerned, the most dramatic events over the past 50 years have all been within the range 10–100 mm h^{-1} (Met Office, 2005). However, events that have caused erosion on vulnerable soils (the South Downs for example) have generally been of a much lesser magnitude, of the order of 30 mm over a period of two days (Boardman et al., 2003). This is an average intensity of just 0.62 mm h^{-1}. Additional precursors to erosion are large fields, cultivation of steep slopes, use of rolls, fine tilths and a soil profile already at field capacity. Not all of the soils identified in Table 7 are likely to be at risk from erosion in the

UK. Most erosion is confined to silts, sands or loams. The South Downs for example has Lithomorphic soils with up to 80% silt. The most appropriate soils to consider are probably those studied by Ankeny, Hamlett et al. and Meek et al.

Table 7. Infiltration data for the top 5 cm of soil taken from literature and from recently recorded but non-verified field measurements

Soil	Tillage	Infiltration, mm h^{-1}			Paper
		Trafficked	Non-trafficked	Wheel-way	
Silty clay loam	None	0.01	0.36		Ankeny et al., 1990
Silty clay loam	Chisel	0.003	0.63		
Heavy clay	Varied	0.1	6.0		Håkansson, 1985
Silt loam	Plough		870	30	Hamlett et al., 1990
Vertisol/	Varied	3.5	11.5	3.5	Boydell & Boydell,
Red Earth	Varied	1.9[1]	3.5[1]	0.4[1]	2003
Sandy loam	Varied		15	3	Meek et al., 1992b
Hanslope clay	Plough	5264			Chamen, 2005: raw
	Min till	576			field data
	No-till	179			
	No-till		904		

[1] 5–25 cm depth

Ankeny's figures suggest a 36–200-fold increase in infiltration compared with current practice and those of Hamlett et al. and Meek et al., 5–29-fold increase on non-trafficked soil compared with a compacted wheelway.

Critical to the debate about whether controlled traffic increases the risk of erosion is the extent to which existing tramline erosion is initiated by runoff from the surrounding soil compared with the extent initiated by rain falling on and running down the tramline itself. The foregoing data would suggest that the extent of runoff from the surrounding soil is likely to be significantly less with controlled traffic. As far as the wheelways are concerned, it is probable that as with annual tramlines, the infiltration on these will be close to zero. The potential for erosion from rain captured on these alone can be calculated. If we assume an infiltration of zero and that the capture width of the wheelway is 0.6 m, then the flow of water per hour per 100 m of slope length for 5 mm h^{-1} rainfall intensity (Chambers & Garwood, 2000) would be 300 litres. This equates to just 5 litres min^{-1} or 83 ml s^{-1}. Whether this would create sediment or soil loss depends on the velocity of flow and this could be calculated using Manning's formula, namely:

$$V = (1/n)R^{0.67}S^{0.5}$$

where n is an empirical number related to the surface roughness, R is the area of flow/wetted perimeter and S is the slope. This will be considered in more detail in the Appraisal section of this contract.

Summary

Prediction of the potential for increased or decreased erosion from farming systems in the UK using controlled traffic on vulnerable soils can only provide information relative to existing practice rather than in absolute terms. Data suggest a 5–200 fold increase in infiltration on non-trafficked compared with trafficked soils; this implies a reduced risk of overland flow into permanent wheelways. It is also probable that intermediate but cropped permanent wheelways would moderate the concentration of any overland flow. Calculated flows down permanent wheelways based on directly intercepted rainfall result in relatively modest volumes whose erosive power can be estimated from established formulae.

Soils of the UK and their relative responses to traffic

Overview. This section is constrained by the relative dearth of information collected from experiments in the UK but those that have been conducted centred on clays, clay loams, sandy loams and a silt loam. Avery (1990) provides a detailed description of soils and their relative occurrence in the British Isles, a summary of which is presented in Table 8.

Table 8. Occurrence of generic soil groups in the British Isles (from Avery, 1990)

Soil	Percent occurrence
Lithomorphic	7
Brown	45
Podzols	5
Gley	40
Peat	3

Data on the relative importance of cereals and oilseed rape in terms of soil erosion are provided by Evans (2002). He suggests that 55.8% of erosion in England and Wales occurs under these crops and that they represent 81% of the national crop area. Morgan (1985) in a broad classification suggested that arable land at risk from water erosion totalled 10,800 km^2 out of a total land area in England and Wales of 151,207 km^2. Evans (1990) created closer classification using "very small, small, moderate, high and very high" categories at risk of erosion. Most land at high and very high risk is in arable production and totals around 8000 km^2. In a more recent study, Evans (2002) isolates different crops in terms of percentage occurrence of erosion and volumes of eroded soil, as indicated in Table9.

Table 9. Percentage occurrence of erosion under different crops as a proportion of total erosion and volumes of soil eroded.

Crop	Percentage occurrence	Mean volume of eroded soil, m^3 ha^{-1}
Winter cereals	42.8	1.85
Spring cereals	11.5	1.75
Oilseed rape	1.5	1.92

Review of all literature cited in terms of soil effects. In terms of crop yield, no soil/yield interaction is obvious and this is not surprising. As already discussed, plants respond primarily to the availability of water, air and nutrients, they do not necessarily react to soils directly. If all these elements are readily available from a soil when needed, full yield potential in that season will almost certainly be realised. Data from East European countries, not all of which are readily available would suggest that optimum bulk densities for maximum yield have been identified. The main shortcoming with this is that in most randomly trafficked fields, levels of bulk density approximately reflect the randomness of the traffic.

There are also insufficient data to draw any firm conclusions about soil compaction interactions with soil type in terms of processes, strength or structure. For example, a compacting stress tends to increase a soil's bulk density and strength, regardless of soil type. The reactions tend to be generic, i.e. the soil itself has the dominating influence over how these processes and characteristics change and to what degree. However, this does not mean that soil compaction has no influence on the risk of a particular outcome on a particular soil. The literature shows very consistently that it does, and almost universally in a negative manner. The conclusion must be therefore that controlled traffic would have a potentially positive outcome on soils at risk. The extent of this outcome may only be determined through field trials and experience.

What is clear from the literature is that lighter, easily worked soils are more vulnerable to compaction than heavier soils. They tend to have less natural structure that will resist loads and are more likely to develop an implement pan at operating depth or a traffic and implement pan at ploughing depth. These soils do not tend to repair themselves naturally and although relatively easy to ameliorate by physical loosening, such loosening may increase vulnerability of the subsoil.

Discussion of Review

While we might all instinctively know that the traffic loads imposed by today's agricultural systems are not good for the soil (what self-respecting gardener for example would allow a 25 t combine to run across their vegetable plot?), the information presented in this review has alerted us to the extent of soil compaction and quantified many of its outcomes. These seem to be universally negative, except perhaps light firming of seedbeds or consolidation of ploughed soil to avoid manganese deficiency. Very similar conclusions were drawn by Hamza & Anderson (2005) in their review who state: "*Soil compaction adversely affects soil physical fertility, particularly storage and supply of water and nutrients, through increasing soil bulk density, decreasing porosity, increasing soil strength, decreasing soil water infiltration, and water holding capacity. These adverse effects reduce fertilizer efficiency and crop yield, increase water-logging, runoff and soil erosion with undesirable environmental pollution problems*".

With all these negative outcomes, one might expect that poor crops and universal problems would be widespread across the UK, but this is clearly not the case as evidenced by even the most cursory look at field crops. What this research suggests however is that perhaps crops could be performing even better and most importantly, performing better with lower inputs, at less cost and at the same time avoiding negative environmental impacts. Agronomists report that crop yields are no longer steadily increasing (Bleach, personal communication, 2005) and many are suspecting soil compaction as the root cause. Similar conclusions have been drawn in other parts of the world, albeit with a very different crop (Pankhurst et al., 2003). It would also seem that as loads on the soil increase, so we are increasing the risk of crop failure and drainage problems, which although not frequent, can have devastating effects on individual growers.

What is clear from this review is that a tremendous amount of research on soil compaction has been undertaken. Within the constraints of the present work it has only been possible to examine details from a relatively small proportion of papers. The impacts and full implications of the information might only be elicited by a more extensive study but whilst gaps in detail may be filled, the overall picture is unlikely to be altered. In addition, because much of the research is now becoming dated in terms of the wheel loads commonly found on cereal farms, it is likely that the effects of soil compaction are becoming more extreme. One might argue that with larger equipment the traffic intensity is less, but as we have seen from the data, most soils take at least five years to recover naturally (and some not at all), and by that time they may have been wheeled again at least once. Amelioration is not straightforward either. Research has shown that effective subsoiling is difficult to achieve (Marks & Soane, 1987) and if it is, the soil, and particularly the subsoil is immediately more vulnerable to compaction. Natural amelioration at this depth may be absent on some soils and often uneconomic to repair.

It is one thing knowing that we have a problem, quite another coming up with workable, cost-effective and sustainable solutions. The next section of this work will look at the options available to us and explore the potential of controlled traffic in particular.

Appraisal of controlled traffic farming

Introduction

The review section of this document concluded that the soil compaction created by today's machinery systems is compromising production efficiency. Although crops in the UK are performing well, it was concluded that if compaction were avoided, productivity would be increased alongside lower inputs, greater sustainability and fewer and less negative environmental impacts. It was also considered that avoiding compaction would deliver many aspects of "Good Agricultural and Environmental Condition" (GAEC). Fears of an increased risk of soil erosion that might arise by using controlled traffic were thought to be unfounded.

The aim in this section is to:

- Consider alternatives to controlled traffic. Are there other solutions that could address the problems?
- Identify the expected benefits and shortcomings of managing soil compaction with controlled traffic.
- Consider the practicalities and constraints to CTF adoption.
- Provide cost/benefit analyses based on farm data.
- List areas of research and/or development whose outcome might enhance the introduction and performance of controlled traffic farming systems.

Managing soil compaction – potential solutions

A severe constraint on solutions to soil compaction is the low value that is put on food and agricultural products in general, despite their being the mainstay of human life. We must therefore accept that growers need relentlessly to pursue improved efficiency, and this is embedded in mechanisation. Presently the route is to larger and more productive machines. Machines increase output and address a shortage of skilled labour, but as we have seen, have an increasingly negative impact on soils. The following paragraphs identify the three main but not mutually exclusive options that can be pursued to address this negative impact. The solution must be in harmony with existing mechanisation and must improve rather than equal present levels of profitability.

Low ground pressure

Reducing pressure at the soil surface is relatively simple, and if pressures are matched to the load carrying ability of the subsoil, permanent damage at this depth might be avoided. If tyres are used to reduce pressure, it is inevitable that a larger area will be compacted on each pass, and although this pressure might be low (around 1 bar), seedbed structure can still be compromised. Low ground pressure may not be an altogether cheap solution either. Equipping a large cereals harvester with 1050 mm rather than 800 mm wide tyres on the front axle (and adding equivalent improvements on the rear axle) would cost an additional £1620. It would also increase the transport width by 0.5 m to 4.3 m, the maximum allowable under Construction and Use regulations. Putting tracks on the front axle would cost an additional £25,000 (plus rear axle tyre conversion, less the value of the tyres displaced), but they would reduce the width slightly.

Tyres have improved dramatically over the past decade and it is anticipated that this will continue, but it is inevitable that the scale of improvements are likely to diminish with time, especially as we have already reached maximum vehicle widths under road regulations. Track systems are therefore likely to respond well to investment and we are seeing this at the moment. Their advantage is that they lay down area in length rather than width. They do not therefore impact on as large an area of soil as tyres and transport width is less of a problem. Their present shortcomings however are durability, transmission efficiencies, soil "scuffing" on turns and unevenness of stress distribution. If the additional cost is added to this they may no longer be seen as a complete solution to the issue of soil compaction.

Automation/Robotics

The opportunities with robotics and automation lie in numerous, low cost, lightweight machines that are active for 24 hours a day, seven days a week. A number of activities (e.g. spot spraying) are already possible with machines of this nature, but planting and harvesting are more of challenge. As potential solutions are needed now, the timescale for this route is almost certainly too long.

Controlled traffic

This route, which concentrates traffic into specific strips, has the advantage that it is achievable with today's machinery (albeit with some adaptation) and can confine compaction to a relatively small proportion of the cropped area. It is a logical, simple and practical approach that can be adopted now, but is it practical and can it deliver the identified benefits? There are also issues of sustainability that need to be addressed as well as more generic questions such as cultivation requirements, orientation on slopes, design of equipment and the appropriateness of crop varieties bred exclusively for compacted soils. Set against these uncertainties are the researched benefits that suggest increased yields and significantly lower inputs if uncontrolled soil compaction can be avoided. The following paragraphs look at the advantages and disadvantages documented from the literature and put farmer's perspectives on the subject by summarising points made chiefly during telephoned interviews.

CTF systems

There is nothing inherently complicated about controlled traffic; it is just adopting the principle of not driving at random over the soil. There is therefore no ultimate or single solution – it is just a question of degree or proportion of the cropped land that is trafficked and at what intensity. Additionally, it imposes no inherent constraints on the type of tillage employed or the cropping pattern followed. The constraints imposed by existing machinery are a different matter however and a group of farmers and industry representatives has been looking at the practicalities and addressing some of the issues by using a field scale commercial trial of CTF (Chamen, 2006). As a result, the "Colworth Project" has identified a number of CTF systems that could be used with existing equipment.

The simplest form of controlled traffic is ComTrac^{CT} (Fig. 4), which uses a single track width. But there are other methods that can be used and many of these are more immediately adoptable in the UK. Those currently under debate and development are listed below.

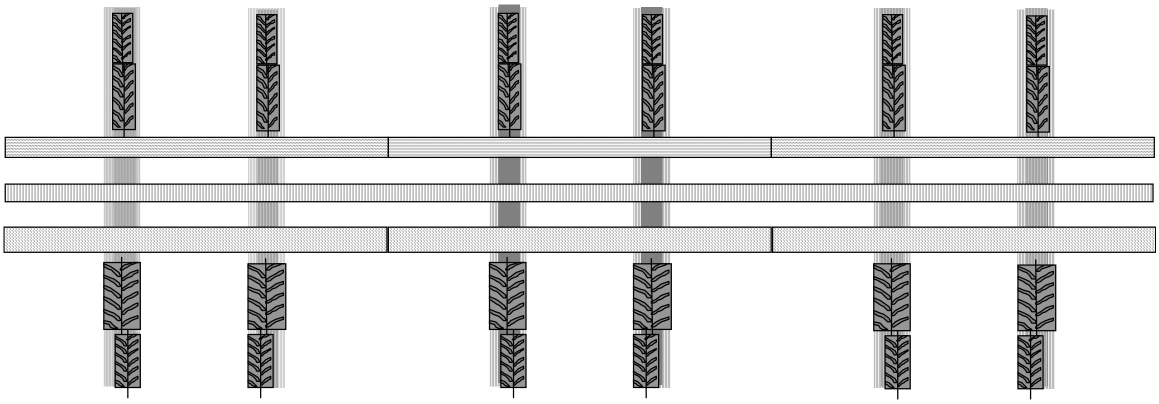

Fig. 4. A controlled traffic farming system based on ComTrac^{CT}. This features a single common track width matched to the vehicle most costly to modify (usually the harvester). Implements can be any common width or direct multiple. (System shown is scaled to a 3 m track width, 8 m primary implements

- ComTrac^{CT} – a system that uses a single common track width to match that of the widest vehicle (usually the harvester). Implements can be any common width or direct multiple of it.
- HalfTrac^{CT} – a system with two track widths, one exactly half the width of the other. Implement widths are a direct multiple of one or other of the track widths.
- TwinTrac^{CT} – a system that uses two track widths. The wider track straddles adjacent passes of the narrower track. Implement width is the addition of the two track widths or a direct multiple of it.
- OutTrac^{CT} – a system that uses a single common standard track width but allows the widest vehicle (usually the harvester) to track "outwith" the narrower tracks while centred on them. Implements can be any common width or direct multiple.
- AdTrac^{CT} – a system with two track widths, the narrower using one track of the wider, resulting in an additional track. Implements can be any common width or direct multiple.

CTF – the pros and cons

This section dwells on the benefits and constraints identified from literature, some of which are quantifiable, others qualitative and some only anticipated for field conditions in the UK.

Benefits

Table 10 lists the principal benefits identified from the literature, but more detail can be found in the review section.

Table 10. The benefits of controlled rather than random traffic in field operations

Aspect	*Benefits*
Tillage	Seedbeds mostly available without tillage
	Tillage implements need 20–60% less draught (depending on depth)
	Tillage power and energy are approximately halved
Timeliness	Fewer and faster tillage operations mean that more time is available and equally that more crop is sown at the optimum time
Yields	An average and conservative estimate is a 12% increase in crop yields
Fertilizer	Less is lost from the soil system – equivalent to the yield increase
Spring cropping	Access on firm traffic lanes and readily available seedbeds mean that spring crops can be established with little danger of significant soil damage
Traction	Firm traffic lanes improve tractive efficiency

Constraints

These aspects are less easy to tabulate but can be dealt with under bullet headings.

- Field working. Controlled traffic constrains field working to two parallel directions. In some cases it can be an advantage to work at an angle, when levelling is required for example. In practice this constraint could be addressed by different implement designs.
- Discipline. CTF requires more discipline; operators cannot drive just anywhere in the field and this will require a significant change in attitudes.
- Grain carting. This is allied to the previous aspect in that special provisions will need to be made to ensure "grain to store" work rates are not compromised. Presently, trailers mostly take the shortest route across the field to return to store.
- Chemical efficacy. Where soil-acting herbicides are applied, chemical efficacy on residue-covered surfaces may be compromised. This aspect is not confined to CTF but is perhaps exacerbated by it because of the reduced need for tillage.
- Field shape and size. Most of the farmers considering CTF have identified small awkward shaped fields as being inappropriate for controlled traffic. Partly this arises from guidance systems that tend to work in straight lines, but also from the disproportionate area of headlands. Trailed machines in particular mean that these will be heavily trafficked.

Drivers for and obstacles against CTF adoption

The main issues identified by farmers

This section deals with the issues raised by growers who have given CTF considerable thought. Some of these have been identified in the section on pros and cons, but others not.

Benefits

Consultation with the farmers and agronomists involved in the Colworth Project revealed a number of expected benefits, namely:

- Reduced production costs.
- Increased yields.
- Improved cropping reliability, particularly with low input systems and spring sowing (Fig. 5).
- Greater flexibility in cropping, including more spring cropping.
- Improved timeliness.
- Improved soil structure to reduce drainage problems.
- Reduced need for subsoiling.
- Reliable way of cutting costs without risking yield.
- Improved water infiltration.
- Elimination of overlap for all operations.

Fig. 5. Example of improved spring seedbed on an 80% clay soil. These oats were sown on the same day at the same depth and photographed subsequently on the same day. The picture on the left is conventional practice, that on the right, controlled traffic. (Photos: Silsoe Research Institute)

Concerns

Similarly, there were a number of common concerns. These included:

- Can the benefits be realised in practice and on a farm scale?
- How do we get the tracks in the right place and maintain straight lines?
- How do we know how to set out fields?
- Will the permanent tracks perform in wet conditions?
- How do we deal with poorly spread straw? (current practice is to pull a rake at an angle to the stubble).
- How do we bale straw in a CTF system, especially when it involves third parties and contractors, often with poor equipment?
- Poor reliability of some satellite guidance systems and delivered accuracy. Don't like to rely on something that might fail and is beyond one's control.
- If you are <u>not</u> using satellite guidance and want to cultivate you are likely to lose sight of your permanent wheelways.

- If CTF means min till, how do we deal with residues for establishing 2nd wheats? Similarly, what about ergot in these circumstances?
- Often need to plough after oilseed rape because of applied chemicals. Is this compatible with CTF?
- Consistency – need to have a simple and easily followed system.
- Incompatibility between crops and cropping systems. For example an arable rotation including sugar beet, where the row spacing of 0.5 m is not compatible with the 1.8 m track gauge of many trailers.
- Need to get the CTF system right the first time – getting it wrong could cost a lot.
- Warranty issues with axle extensions carried out on farms or by non-licensed third parties.

Barriers

These items have been listed separately because they are actual constraints to adoption rather than concerns about how well CTF might work if it is adopted.

- Incompatibility of existing equipment, either in track width, implement width or both.
- Matching track width to that of the harvester means all equipment will be wide.
- Costs of conversion, particularly if you want 100% compliance from day one.
- State of mind or mindset. Cannot conceive that CTF has any benefits to deliver.
- CTF is not presently on many people's agenda.
- Not wishing to be an early adopter; let others make the mistakes first so that we can learn from them!
- When no money in farming, no capital to change. When money good, no incentive.
- Farmers rarely see the negative outcomes of compaction in the main body of fields so there is little compelling evidence or incentive to change.
- Share farming when the partner does not have the same objectives or where key machines are not owned.
- Contractors need to have equipment that matches all customers' needs. Conversely, if a farmer uses a contractor for some operations the equipment will probably be incompatible.
- Incorrect association of CTF only with min till and direct drilling. The perception that ploughing is out of the question with CTF makes it a non-starter.
- Perception that it is too difficult to convert to CTF.
- Extra discipline and planning needed.

General comments

There were also comments that did not neatly fit into any of the above categories and these are included here.

- CTF association with "technophobes"
- CTF is all about budgeting and forward planning. A minimum of 12 months is required.
- GPS guidance alone can return at least 50% on capital over a period of 3 years on 1000 ha.
- Farmers need to know that the benefits of CTF can be realised.

- Drop in pH with direct drill systems might be avoided with CTF.
- I would still plough with CTF after oilseed rape.

Economics

As an introduction to the economics of controlled traffic farming it is useful to look at literature on the subject. This provides an indication of the cost centres involved as well as the benefits.

Review of literature

Overview. This section looks at the cost implications of soil compaction as well as research that has considered these costs set against both the investment needed to avoid them and the benefits likely to be realized. The list below identifies the principal savings, costs and benefits that are an integral part of the economics studies (with abbreviations that are used in the literature section that follows).

- *Tillage inputs*. These include lower energy requirements for a given operation, fewer or shallower passes to achieve the same effect or complete avoidance of tillage, i.e. direct seeding. (Till)
- As a corollary to lower tillage inputs, less power and fuel use per unit area. (P&F)
- As a further corollary to lower tillage inputs, savings in machinery investment both in terms of the type and number of machines and also the power of the prime mover. (Inv)
- *Machinery modification*. This is the cost of altering axle track widths for example, or for extending implement widths and reorganizing soil engaging components. (Mods)
- *Guidance*. Controlled traffic needs a guidance system. This can be provided by physical markers in its simplest form or by more sophisticated techniques, such as satellite-based systems with or without autosteer. In some cases this may be a "contracted-in". (Guide)
- *Timeliness*. If operations take less time, or there are fewer of them, this can have an impact, for example, on the average sowing date of the crop. Equally, the rate of harvesting will be affected by the yield of the crop and in some studies allowances were made for this because it has an effect on the amount of crop harvested at the optimum time and the time available for subsequent operations. (Time)
- *Rotational savings*. This is a more obscure aspect of profitability but some economics models will optimise the areas of each crop grown within a rotation based on maximum profitability. These may only be subtle changes, but where some crops are significantly more profitable than others, optimising the area grown can have a valuable effect on farm profit. (Rot)
- *Tractive efficiency*. When working from permanent wheelways, there will generally be a lower rolling resistance as well as improvements in traction. (Teff)
- *Yield*. A conservative estimate of average yield response to non-trafficked soil in cereal crops is in the order of 12%. This is an extremely variable parameter as will be noted from Table 2 (the numerical average of whose data is around 22%), but it is helpful to have an average to work with. In the economics studies and in reality, it is not possible within a controlled traffic system for 100% of the area to have no

traffic, so most studies make yield allowances for the proportion of the area taken up with permanent wheelways. Research suggests that the yield of cereals around non-cropped wheelways is equivalent to around half the area taken up by those wheelways (assuming a modest wheel width) because crop on either side has extra light and nutrients (Austin & Blackwell, 1980; Darwinkel, 1984). (Yld)

Literature. Chamen & Audsley (1993) using a whole farm model (all except Teff) found that compared with a conventional plough-based system, controlled traffic with straw incorporation was £18 ha^{-1} more profitable on heavy soil but £18 ha^{-1} less profitable on medium soil (both these comparisons assumed a £57 ha^{-1} additional chemical cost in the absence of ploughing). Blackwell et al. (2003) using a farm-based case study in Western Australia (Till, P&F, Mods, Guide, Yld) also considered savings in chemicals through the use of precision guided band spraying. They calculated a net benefit of £22 ha^{-1} compared with conventional practice. Gaffney & Wilson (2003) also in Australia using farm data, suggest a net benefit of £19 ha^{-1} for changing from a conventional traffic and tillage system to direct drilling and controlled traffic. Mason et al. (1995) again using farm-based data in Australia make a number of interesting comparisons within a cereal rotation (Till, P&F, Inv, Mods, Rot, Yld). Using a spreadsheet they calculated:

£14 ha^{-1} extra net farm margin with a change to controlled traffic but retaining existing cropping and tillage;

£29 ha^{-1} extra margin with a change to direct drilling and new cropping;

£68 ha^{-1} increased net margin by changing to controlled traffic and direct drilling with new cropping.

This showed that there was an increased net margin of around £39 ha^{-1} when changing to controlled traffic from a conventional direct drilling regime.

Robotham & Walsh (1995) use two farms in Queensland as case studies. They determine that 55% of Farm One is covered by wheels with a reduced till system and 28% with no-till, while an appropriate controlled traffic system would cover just 12%. If the latter could be achieved within the normal machinery replacement schedule, the Net Present Value would be around £42,000 over ten years on 1000 ha of wheat. On Farm Two, up to 83% of the area is covered by wheels within a rotation of wheat and cotton. As the grower had just purchased some new equipment and used contractors to harvest his crops, he considered it unrealistic to consider change.

Actual proportion of coverage by wheels within a particular CTF system is used by Chamen (2005) to predict yield response. Using a ComTrac^{CT} system on a 3 m track, with 8 m implements and a 24 m tramline, 24 out of every 96 rows of wheat planted at 250 mm centres would not see any yield improvement because the soil will have been wheeled at some stage. If yield response due to no compaction were assumed to be 12%, the net result would be a 9% improvement in yield from the field as a whole. Chamen (2005) also considers the different costs and benefits associated with conversion to CTF (Table 11). Included in this example is the assumption of a lighter direct drill used within a CTF regime. This was based on experience of working on a non-trafficked clay soil where the draught requirements and penetration forces were significantly lower (Chamen et al., 1990). Considering the tractor cost savings (Table 11) it was assumed that power demands for tillage are reduced by around 30% and for direct drilling by around 25%, including the lower rolling resistance that can be attributed to working on the permanent wheelways. Thus a system currently needing a 130 kW tractor for a 6 m direct drill might only require around 100 kW. At 2001 prices (Nix, 2001) this represents a cost saving of 17–25%. Using this option means that the reduced labour demands for drilling may not be available and so the relative value of these two aspects will need to be considered.

Table 11. Factors and variables that impact on the economics of changing from a random traffic to a controlled traffic system, their likely magnitude and level following transition. (from Chamen, 2005)

Factor/variable	Costs, £	Savings/benefits, %
Consultancy for CTF field layout (optional)	40 h^{-1}	
Direct or Conservation Drill price (from Uri, 2000)		11
DGPS guidance with ± 25 cm pass to pass accuracy	3,657	
DGPS guidance upgrade from ± 25 cm to ± 3 cm accuracy[3]	1,371[1]	
DGPS guidance to ± 3 cm with automatic steering[3]	8,800[2]	
Axle conversions to 3 m:		
Tractors – per tractor with full warranty	3,100–5,800	
Drill, Chasers or trailers, per item	430–2,300	
Self-propelled chemical applicators with full warranty (Not needed if tractor-mounted)	3,000–4,000	
Lower power tractor for pulling cultivators or drill (cost/m width)		17–25[4]
Labour		5[4]
Variable costs:		
seed		20
fuel		15
wearing parts – soil engaging elements		20
chemicals		10
wheel way maintenance	2 ha^{-1}	
Crop yield increase		7.5

[1] Additional cost to the ± 25 cm system, i.e. total cost would be 3657 + 1371 = £5028. [2] Additional cost to the ± 3 cm system, i.e. total cost would be 5028 + 8800 = £13828. [3] This option has an annual £760 correction signal fee which must be added to the total. [4] Tractor power or labour reduction, not both.

From Table 11 it can be seen that the principal costs associated with conversion to CTF are in planning and in "aligning" machinery with predicted needs. If the planning is sufficiently long term and carefully considered, costs are likely to be kept to a minimum, as they will with improved CTF machinery and methodologies.

Case studies

Case study 1 is that of a 1000 ha farm on predominantly Evesham series clay. The farm has been direct sown with cereals for some years but the effect of harvester wheelings has always been noticeable, both during establishment and in performance of the crop. It was anticipated that with a change to CTF, a 160 hp tractor could comfortably cultivate or drill 40 ha in an average day because of the easier working conditions. With 40 available days between 1st August and 31st October, this would allow 800 ha to be cultivated and drilled. Similarly in the spring with 30 available days, a further 600 ha could be cultivated and drilled. Even allowing for around 15% of the total area (headlands) to be loosened and cultivated in a different way, a single 160 hp tractor was still considered capable of carrying out all the land work on 1000 ha. Table 12 shows the cost comparisons that were made in a rotation of wheat and oilseed rape. Within the conventional direct drill (DD) system, establishment of wheat after oilseed rape would always use minimum tillage and there would be an additional pesticide application to deal with slugs. With CTF it is assumed that the tillage as well as the improved seedbed will preclude the need for an extra application of slug pellets.

Table 12. The relative operational costs of combinable crops establishment using conventional practice compared with CTF. (Wheat after rape always uses Min Till.)

Operation	Cost, £ ha^{-1}		
	Trafficked		CTF
	Min Till	DD	
Disc	27.00		
Level lifting and rolling headlands at £41 ha^{-1} (75% of the area with Min Till and 15% of the area with DD & CTF)	30.00	6.15	6.15
Cultipress (on 70% of the area under CTF)	20.00		14.00
Roll	11.00		
Drill	27.00	27.00	25.00[1]
Roll	11.00		
Single extra dose of slug pellets compared with min till + application		11.00	11.00
Capital, license and maintenance cost of GPS system		16.00	3.75
Totals	126.00	60.15	59.90
System cost in rotation of wheat and oilseed rape	**126.00**	**93.07**	**59.90**

[1] This is an assumed modest saving in draught with CTF.

The projected savings with CTF are therefore substantial with some leeway for additional unforeseen operations and costs. As this system is only being introduced in 2006, crop yield data are not yet available, but with an AdTrac^{CT} system using 8 m implements and tramlines at 24 m, yield increases should be significant and similar to that identified by Chamen (2005) and discussed above.

Costs for case study 2 have not yet been fully established, but the capital return on satellite guidance has been estimated. Using a spreadsheet to calculate improved work rates and reductions in the use of chemicals (including fertilizer) and seeds against a guidance investment cost, including automated steering, of £24,000, the return on investment was over 12% per annum on 700 ha of cropping.

As an adjunct to these examples it is useful to consider the savings that might be achieved on tyre equipment. With a well-managed CTF system, it should be possible to select narrower tyres for most vehicles. In the case of a harvester, selecting the next smaller tyre size available could provide a list price saving of £3000 for the tyres alone, plus the probable lower cost for rims. In addition to the saving on wheel and tyres directly, the reduced area of soil compacted will increase the potential for additional yield.

Summary: costs, savings and benefits

There have been relatively few in-depth assessments of the cost of soil compaction in the UK, or the benefits associated with avoidance. One study based on a cereals rotation suggested an £18 ha^{-1} increase in profit on heavy soil but a similar level of loss on a medium soil. The study assumed an additional chemical cost of £57 ha^{-1} with the controlled traffic system because ploughing was precluded. More recent predictions of the benefits of CTF based on farm data in the UK suggest savings of £33 ha^{-1} within a min till/direct drill regime and £66 ha^{-1} changing from min till to a direct drilled CTF regime.

Numerous studies in Australia suggested improved profits ranging from £14 ha^{-1} to £68 ha^{-1}. There were circumstances however where a change to controlled traffic could not presently be justified because of recent incompatible investments in machinery.

The Australian experience of CTF

Controlled traffic farming in Australia has developed from just three growers in 1995 to over one million hectares in 2005. Last year also saw the Third Australian Controlled Traffic Farming Conference, with an attendance of 197, most of whom were growers. In a brief report on the conference to the equivalent of HGCA in Australia, several interesting points were made. It was considered for example that ten years experience was enough to prove the applications, opportunities and resilience of CTF for the future – the mistakes had been made, the lessons learnt. It was now possible to change to CTF with confidence and in the most cost-effective and timely manner. Two grower comments were adopted as conference slogans, “Just do it, the basics have been identified” and “Don’t muck about, do it right”. The latter arose from earlier wrong decisions and confirmed the importance of careful planning. The most important CTF basics were considered to be:

- Strategic planning
- Farm design and field layout
- Identical wheel tracks and matched implement widths for all machines
- Best agronomy tailored to non-compacted soils

The term "Information Rich Agriculture" was also coined (although its acronym might not be suitable for use in the UK!) stressing the fact that CTF has the ability to make maximum use of effective new precision technologies. Another telling statement addressed at the grains industry was "if you can't see wheel tracks in a field, it's probably because the whole field is compacted". The point was also made that our experience with mechanised agriculture is all based on degraded, compacted soils and that a change to CTF is showing just how large the associated losses are. It was also stressed that just one wheeling on moist soil was enough to destroy the improved soil structure in that location. The importance of yield mapping was also stressed within CTF. This perhaps reflects the ability to eliminate soil compaction as a source of variation and to look beyond at more fundamental aspects of the soil system. Topographic information was also considered of crucial importance in designing layouts to minimise runoff and erosion. Layouts should remove excess water quickly and safely. Information about the farming operation, from whatever source, was considered invaluable as a tool for improving farm, field and machinery design and overall management. Management was deemed to be the greatest cause of variability within fields.

One grower cited poor soil structure and water infiltration as his prompt to move into controlled traffic. After just one season he found that he could push a probe into the soil after harvest (he had not been able to do that before). Historically his fine soils had no structure, were often been waterlogged when conditions were not over wet, there was little air in the profile and the soils ran together every time it rained. Equally of course there are those who do not see controlled traffic as a way forward. Farming over 17,000 ha and using 20 m wide equipment, they considered that CTF had no future for them.

The standard adopted in Australia for grain crops seems to be 3 m wheel tracks and 9 m implements but road movement is not a big issue. In the UK a compromise or some other system is far more likely and the Colworth Project has identified a number of alternative solutions.

Scanning individual presentations at the above conference provides a focus on the things that we need to get right if widespread CTF adoption in the UK is to succeed. One of these is uneven depth of the wheelways that cause uneven planting depths. Another is to involve the younger generation who are often more familiar with computer driven technologies. These people are needed to develop the systems that can be used by the majority more easily. But the older generation can sometimes put the younger ones in place. An enthused young adopter of CTF told his 81-year-old Dad that he now had a wonderful new tool whereby he didn't have to steer vehicles around the field. His Dad's droll reply was, "funny that, you never had to steer horses either"!

It is appropriate perhaps to conclude and keep in mind comments from two experienced CTF farmers:

> "Remember, farming and economic pressures are changing rapidly, so you must stay progressive and flexible".
> "Don't forget the KISS principle when adopting new ideas – "keep it simple stupid"

Discussion of Appraisal

In-field grain transport

The movement of grain from field to store is a crucial process in terms of harvest work rate. There is no benefit from having a harvester capable of delivering 30 Mg h^{-1} when the field to store transport system can only cope with 20 Mg h^{-1}. On many farms this is often the bottleneck and careful planning is essential if the operation is going to be efficient and effective. If random departures "off track" within CTF fields are to be avoided and work rates maintained, field planning is essential. Australian systems take this fully into account, planning length of runs against probable yields and using headlands as well as wheelways for on the move off-loading. In the UK where yields are much higher, this will be more of an issue, but equally field lengths are probably less. In some situations cross-headlands might be needed, but these will have to be carefully managed if they are to avoid problems when the harvester traverses them.

Permanent wheel tracks

The concerns expressed about the permanent wheelways in a CTF system are largely based on existing practice, where tramlines often rut because they are introduced after ploughing or deep loosening and they also lack repair. The permanent wheelways of controlled traffic systems are managed from the outset to overcome rutting (Fig. 6).

Fig. 6. Example of a controlled traffic permanent wheelway. This has been in use for around 8 years and regularly receives wheel loads of up to 4 Mg.

In addition, controlled traffic immediately diminishes the need for tillage and the draught forces associated with it. This means that the wheelways intermediate to the chemical application "tramlines" may only be accessed two or three times a year and with a lower traction requirement. This and annual management should therefore reduce any problems, but until CTF systems are widely in place, the reality of their performance on UK soils and in average rainfall conditions can only be predicted.

Guidance

Guidance is an essential element of CTF but its importance in conventional systems is also becoming more widely recognised. As we have seen, small errors repeated across fields can have a significant impact on overall efficiency and costs. CTF increases this importance because errors that widen the wheelways not only have these negative traits but also those associated with soil compaction. Errors also limit the functionality of new technologies that can help reduce costs. Tillett (2005) for example found that poor matching of drill passes compromised vision guidance that could reduce chemical inputs in cereal rotations. The level of accuracy required by CTF systems is largely a case of economics, but practical aspects also impinge. If the error exceeds certain values strips of land left unsown may be wide enough to cause weed control problems and equally, strips of crop may not be harvested. CTF systems generally require cereal harvester platforms to be slightly wider than the implement gauge to ensure that all crop is gathered.

Soils and tillage

Introducing controlled traffic on different soils requires a different approach. On self-mulching clays for example found in reasonable condition (perhaps with a history of on-land ploughing) it may be possible to introduce controlled traffic without any mechanical remediation. However, where compact layers have been formed and soil moisture conditions are suitable, physical loosening might be employed prior to CTF introduction. In this situation careful management of the new wheelways will be needed, particularly in the first twelve months. On lighter soils and silts, particularly those exhibiting a hard pan at depth, artificial amelioration will be needed because these soils are unlikely to repair themselves.

The literature has suggested that soil structure under CTF will be considerably improved and that tillage to produce seedbeds will generally be unnecessary. However, there are conditions where tillage will be needed for other reasons, to bury or incorporate residues for example. With incorporation there is no reason to believe that this cannot be carried out from the permanent wheelways, but when it comes to inversion, this will almost certainly mean coming “off track”. The implications of this are not severe, providing the operation is carried out from “on the land”. Indeed, if controlled traffic has been practised for a number of years, heavy soils will almost certainly turn over in a more friable condition, often needing little in the form of intense tillage to create a seedbed subsequently. The short-term disadvantage is that the permanent wheelways will need to be re-established and managed actively in the subsequent year.

Provided that severely compacted soils are loosened prior to introducing a CTF regime, it seems certain that the problem of poor initial crop growth, lowered pH and loss of nitrogen through denitrification, particularly in the early years of minimum and zero tillage, will be diminished. Improved initial growth will be promoted by the lack of a compacted surface layer, often exacerbated by low ground pressure equipment that spreads loads more widely.

Economics

The cost of conversion to CTF centres on planning and machinery “alignment”. Costs for machinery customisation tend to diminish with increasing timescale and similarly are substantially reduced by an adequate investment in planning. Other costs include wheelway maintenance, guidance and possibly, contracted-in advice. Because satellite guidance on farms is becoming commonplace, this may not necessarily be considered a cost that can be set exclusively against CTF, rather only the additional cost of upgrading that may be needed to fulfil the accuracy demands of CTF.

The benefits of CTF are associated with improvements in yield, in more flexible and reliable cropping and with savings on machinery, labour, seed, fuel and chemicals.

In terms of individual growers, it should be possible to predict some of these savings and benefits based on the planned CTF system. The system will determine the proportion of the area that will be wheeled and from this it should be possible to estimate draught forces compared with existing, and as a result, power and

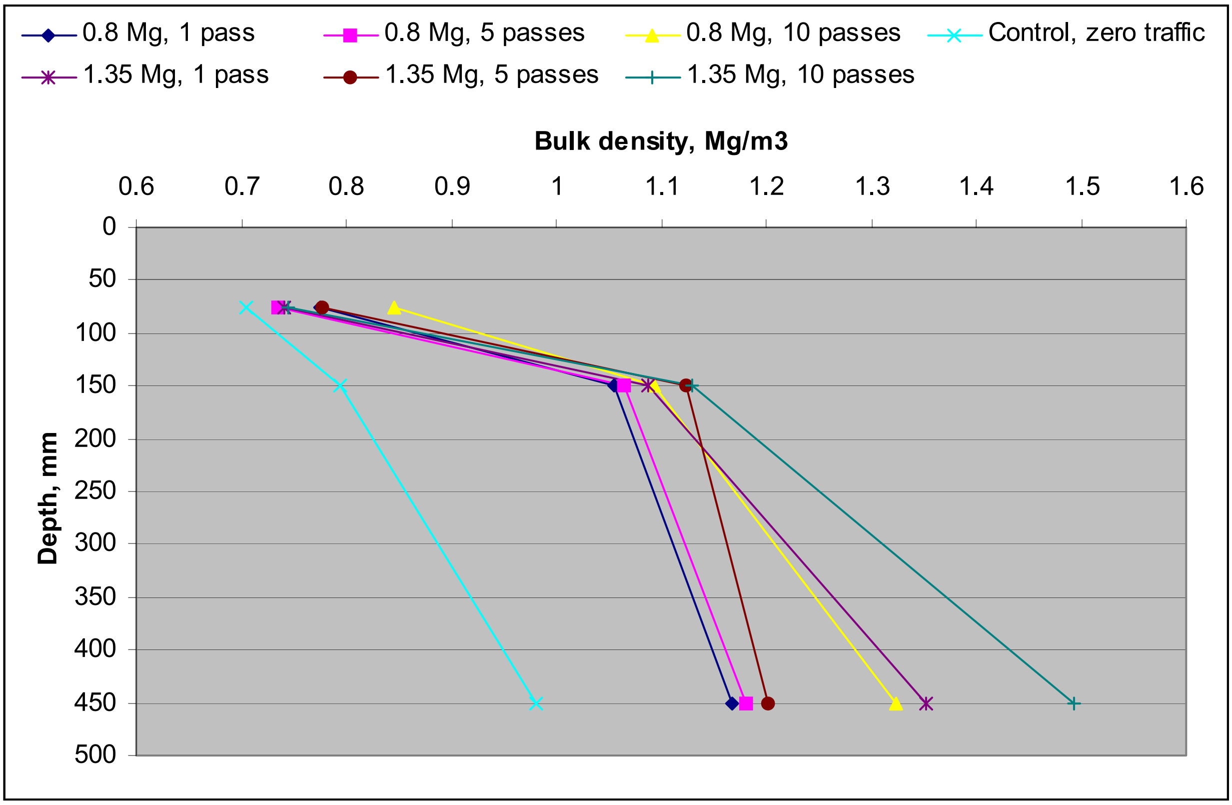

Fig. 7. The effect of repeated wheel passes on soil bulk density with different wheel loads but almost identical contact pressures (after Jorajuria & Draghi, 1997).

tractor size. Equally, crop yield responses should be calculable. Fig. 7 shows the benefit of confining wheelings to as small an area as possible because it is the first pass that causes the most damage, particularly in the topsoil. As we have also seen, unless ploughing or deep loosening is used to repair damage in a random traffic system, it can take many years to ameliorate naturally, by which time further wheelings will have been applied.

Diseases and slugs

There are few data to suggest a consistent and negative link between residues and crop diseases, and certainly nothing that implicates CTF further in this respect. It seems that the effects are positive for some diseases and negative for others. As far as pests are concerned, the slug (*Deroceras reticulatum*) is probably one of the most problematic in cereal crops. It is particularly the case with cropping systems that retain surface residues, and chiefly those with cloddy seedbeds and smeared and open sowing lines (Moens, 1989). Slugs attack crops in two ways – below ground where they eat the seeds and above ground where they eat the young leaves. Above-ground attacks are rarely fatal, but below ground the seed can be so badly damaged that there is no emergence. We need a close understanding of their behaviour if management is to be effective. For example we know that cloddy seedbeds provide places for slugs to hide and space to move. The avoidance of compaction reduces the cloddiness of seedbeds and consequently the number of safe resting places. A related effect is that compacted soils tend to leave more open sowing lines, an ideal environment for them to attack at the most vulnerable stage of crop establishment. Controlled traffic should provide a more amenable seedbed environment and avoid this situation. Similarly, and as we have seen from Fig. 4, more rapid germination and growth will reduce the time when the crop is vulnerable. Overall, CTF brings a greater emphasis to the sowing or planting operation – sowing and harvesting are now the principal non-chemical operations within the crop production cycle.

CTF adoption

There are many useful experiences that can be cherry picked from Australia, but equally some must be treated with caution. Theirs is a farming system that has never had the mouldboard plough as a basis for cultivation and equally, "opportunity cropping" based on water availability is widely practised. Other than this improved "water harvesting", many of the benefits in terms of efficiency are often associated with moving from an "on the contour" or "round and round" system to an "up and back" that has been the mainstay of UK agriculture for many years. With round and round systems, no guidance and wide equipment, overlap was significant. Moving to any formal system of guidance was therefore going to show benefits in terms of inputs and yields, but these benefits are not exclusively related to this issue and controlled traffic has added to these benefits.

Road movement of large equipment is not such a big problem in Australia either and equipment on a 3 m track is more acceptable. Alternative solutions must and have been found for the UK.

Non-adopters at present may not use CTF because the perceived profit gains alone do not fully compensate them for the uncertainties. If CTF is to gain any significance in the UK, the profit gains must be demonstrated in practical farm situations and the uncertainties addressed.

Conclusions

Research suggests that the compaction created by vehicles running at random over the soil has a universally negative outcome. It leads to increased energy demands, sub-standard and dry seedbeds, increased loss of moisture and organic matter, poor crop germination and growth and poor infiltration of water, water holding capacity, drainage and gaseous exchange. Very similar conclusions were drawn by a similar review on soil compaction published by other authors (Hamza & Anderson, 2005). The reduction in soil quality constrains crop yields, adds considerably to the cost of crop production and has many negative environmental outcomes. Low ground pressure systems may offer some relief to the subsoil, but do little to improve the situation in the topsoil.

This is not to say that crops in the UK are universally and visibly suffering, but it is almost certain that they could be doing better. If compaction were avoided it is likely that productivity would be increased, inputs would be lower and farming systems would be more sustainable. There would also be fewer and less negative environmental impacts. Avoiding compaction will naturally deliver many aspects of “Good Agricultural and Environmental Condition” (GAEC). Fears that there will be an increased risk of soil erosion with controlled traffic farming are almost certainly unfounded.

As much of the research explored in this review is now rather dated in terms of the wheel loads commonly found on cereal farms, it is likely that the effects of soil compaction have been underestimated. One might argue that with larger equipment the traffic density is less, but as is evident from the data, most soils take at least five years to recover naturally (and some not at all), and during that period will almost certainly have been compacted at least once again.

The evidence suggests that the complete avoidance of soil compaction should be a key issue in future crop production systems. Continuing with our present machine designs and methodology of use could be seen by future generations as irresponsible and lacking in a duty of care for the soil resource. This is reflected in governmental concerns and new legislation for soil protection in many countries. In Germany for example, there is legislative debate on restricting field traffic axle loads (Sommer, personal communication, 2004). Research suggests that avoiding soil compaction improves and sustains the health of soils both through natural and physically induced amelioration and through the improved retention of organic matter. Controlled traffic farming offers an effective means of addressing these issues through compaction management. The engineering of CTF solutions can take a number of forms that have the potential to make farming easier and more profitable. Their low cost introduction relies on careful planning, long-term goals and an understanding of the principles involved. Accurate vehicle guidance is an integral part of CTF and can use physical markers, vision systems or satellite technology, providing they deliver peak errors no greater than ±5 cm.

Wheelway orientation and management are equally important in terms of sustainability and require consideration of slopes, length of run, field obstacles and effective drainage. The economics are dominated initially by the costs of conversion, but if this is planned carefully they can often be lost within normal machinery replacement. Improved profit relies on reduced time and energy demands, lower investment costs and improved crop returns. The eventual outcome of a change to CTF is likely to be a reduction in fixed and variable costs and an increase in cropping reliability and return, but there are issues that will need to be addressed. These include overcoming the need to work at different angles, maintaining grain to store work rates, increased discipline and awkward-shaped small fields.

Research, development and progression

At this stage in the development and adoption of CTF in the UK, it is probably inappropriate to conduct fundamental research on the subject. More relevant would be research that determines whether the anticipated benefits can be delivered in practice on different soils, on land with varying topography and with a range of combinable crops. Parallel to this would be development of the most appropriate and cost-effective systems and equipment.

If it is accepted that CTF should be pursued as a means of improving farm profitability, there are a number of actions that might be considered.

1. Increase the awareness of CTF and the benefits it can bring. Ideal for this would be a number of farm-based demonstration projects, preferably on contrasting soils and some on fragile soils prone to erosion.
2. In parallel with the demonstration projects should be the acquisition of data to drive a whole farm economics model. This has the considerable advantage that with robust data it should be possible to predict with confidence relative farm profitability on other soils, in other weather scenarios and with different CTF and cropping systems.
3. As an adjunct to awareness is the development of a category system for CTF. Many farmers presently have the impression that it is too complicated and difficult to achieve. A category system that placed existing practices such as tramlines within a well-defined system of progression could be helpful. Tramlines for example could be Category 1, while maintaining them from season to season could be Category 2. Similarly, matching up tillage and drilling could be Category 3. The system may overcome the perception that CTF is too difficult to achieve – many farmers would find that they already have an element of CTF that places them in a favourable position and that the next step on the ladder is not too difficult.
4. Training workshops for CTF. This is a second stage strategy that would provide an overview of the forward planning and processes involved in moving towards CTF. As has been highlighted, planning is crucial in terms of limiting costs and is a key issue in the development of CTF systems.
5. Still further into the process of CTF adoption is the encouragement of manufacturers to provide a guide to the compatibility of their equipment with a particular CTF system. For example, this machine will fit in with the TwinTrac^{CT} or ComTrac^{CT} CTF system. Customising their products to the concept of CTF is crucial to its adoption on farms and the evidence from Australia is that it is a chicken and egg situation. The first adopters are faced with modifying and inventing things themselves, but as interest and demand increases, so does the pressure on manufacturers to supply the equipment needed.
6. Within any CTF system, compaction on the field headlands is still an issue. However, with guidance systems and the ability to steer trailed equipment, this need not be the case in the long term. Trailed

machines that are steered are becoming more commonplace and the widespread adoption of CTF would certainly drive this forward.

There are a number of areas of fundamental research that could be pursued in relation to CTF, but their relative importance at this stage of system uptake is uncertain. Confirmation of anticipated benefits is likely to be of greater value at this juncture.

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