CRANFIELD UNIVERSITY

W.C.T. CHAMEN

THE EFFECTS OF LOW AND CONTROLLED TRAFFIC SYSTEMS ON SOIL PHYSICAL PROPERTIES, YIELDS AND THE PROFITABILITY OF CEREAL CROPS ON A RANGE OF SOIL TYPES

SCHOOL OF APPLIED SCIENCES

PhD THESIS
Academic year: 2010-2011

Supervisors:
Dr A.M. Mouazen
Prof R.J. Godwin
April 2011

CRANFIELD UNIVERSITY

SCHOOL OF APPLIED SCIENCES

PhD THESIS
Academic year: 2010-2011

W.C.T. CHAMEN

The effects of low and controlled traffic systems on soil physical properties, yields and the profitability of cereal crops on a range of soil types

Supervisors:
Dr A.M. Mouazen
Prof R.J. Godwin

April 2011

This thesis is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Abstract

Soil compaction is an inevitable consequence of mechanised farming systems whose machines are degrading soils to the extent that some are considered uneconomic to repair. A number of mitigating actions have been proposed but their ability to reduce or avoid damage has not been well tested. The aim of this research was to determine whether actions to reduce damage have been, or are likely to be effective and to assess whether the practice of controlled traffic farming (confining all field vehicles to the least possible area of permanent traffic lanes) has the potential to be a practical and cost effective means of avoidance. The literature confirmed that soil compaction from field vehicles had negative consequences for practically every aspect of crop production. It increases the energy needed to establish crops, compromises seedbed quality and crop yield, and leads to accelerated water run-off, erosion and soil loss. It is also implicated in enhanced emissions of nitrous oxide and reduced water and nutrient use efficiency. Replicated field trials showed that compaction is created by a combination of loading and contact pressure. Trafficking increased soil penetration resistance by 47% and bulk density by 15% while reducing wheat yield by up to 16%, soil porosity by 10% and infiltration by a factor of four.

Low ground pressure systems were a reasonable means of compaction mitigation but were constrained due to their negative impact on topsoils and gradual degradation of subsoils whose repair by deep soil loosening is expensive and short lived. Controlled traffic farming (CTF) was found to be practical and had fundamental advantages in maintaining all aspects of good soil structure with lowered inputs of energy and time. On a farm in central England, machinery investment with CTF fell by over 20% and farm gross margin increased in the range 8-17%.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my wife Chris without whose unstinting support, patience, good counselling and many hours spent helping me in the field, I would not have been able to complete this work. I am also most grateful to Dr Abdul Mouazen and Professor Dick Godwin, my supervisors at Cranfield University, whose reviews of my work and thesis have been invaluable and have kept me focused.

In relation to Chapter 5, I would also like to acknowledge the financial support of the Douglas Bomford Trust, the Chadacre Trust and the Morley Foundation for carrying out the research. Acknowledged also is the input of Jo Philpott who initiated and applied the treatments in the first year some of whose words I have used in the Introduction to Chapter 5. Thanks also go to F.B. Parrish and Sons and to Unilever R&D Colworth for the use of their land and facilities and to Simba International for their loan of a cultivator. I would also like to thank Richard Long, Whitbread Farms Ltd and L.E. Barnes and Son for the loan of equipment and drivers.

Table of Contents

The effects of low and controlled traffic systems on soil physical properties, yields and the profitability of cereal crops on a range of soil types 2
Abstract 3
ACKNOWLEDGEMENTS 4
Table of Contents 5
Figures 10
CHAPTER 1 1
1.1. Introduction 1
1.2. Aim 5
1.3. Specific objectives related to the hypotheses 6
1.4. Outline methodology 7
CHAPTER 2 8
2. Literature review 8
2.1. Introduction 8
2.2. The global soil resource 9
2.2.1. Global Agro-eco Zones study 9
2.2.2. Soil degradation and threats to the environment 10
2.3. Conservation agriculture 11
2.4. Reviews on the effects of soil compaction in agriculture 13
2.4.1. Soil physical aspects 14
2.4.2. Crop nutrients 19
2.4.3. Soil biology 19
2.4.4. Discussion of reviews on the effects of soil compaction in agriculture 21
2.5. Soil structure 22
2.5.1. Soil organic matter and nitrous oxide 22
2.5.2. Seedbed quality 25
2.5.3. Soil strength and bulk density 26

2.5.4. Pore space, water holding capacity, infiltration and drainage characteristics ... 32

2.6. Crop production efficiency ... 39

2.6.1. Crop responses ... 39

2.6.2. Fertiliser use efficiency ... 45

2.6.3. Vehicle and implement performance ... 48

2.7. Controlled traffic farming systems ... 51

2.7.1. Economics of conversion to and maintenance of controlled traffic farming systems ... 51

2.7.2. Practical aspects of CTF systems ... 55

2.8. Conclusions to the literature review ... 65

2.9. Gaps in research ... 67

CHAPTER 3 ... 69

3. Papers published by the author addressing the principal hypothesis ... 69

3.1. Introduction ... 69

3.2. Methodologies ... 69

3.3. Discussion of papers ... 70

3.3.1. Chamen et al., 1990. The effect of tyre soil contact pressure and zero traffic on soil and crop responses when growing winter wheat ... 70

3.3.2. Chamen et al., 1992a. Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime ... 93

3.3.3. Chamen & Longstaff, 1995. Traffic and tillage effects on soil conditions and crop growth on a swelling clay soil ... 117

3.3.4. Chamen & Cavalli, 1994. The effect of soil compaction on mole plough draught ... 128

3.4. Conclusions ... 138

CHAPTER 4 ... 139

4. The effects of CTF systems on crop growth, yield, soil structure and infiltration in non-replicated field studies ... 139

4.1. INTRODUCTION ... 139

4.2. Methods ... 140

4.2.1. Colworth 140

4.2.2. Regional studies on non-restructuring soils 144

4.3. Results and discussion 146

4.3.1. Colworth 146

4.3.2. Regional studies on non-restructuring soils 165

4.4. Conclusions 171

CHAPTER 5 173

MANAGING COMPACTION IN SHALLOW CULTIVATION SYSTEMS 173

5.1. INTRODUCTION 173

5.1.1. Topsoil compaction 174

5.1.2. Subsoil compaction 174

5.1.3. Methods for reducing and alleviating soil compaction 175

5.1.4. Project aim and objectives 176

5.2. TREATMENTS AND SITES 177

5.2.1. Treatments 177

5.2.2. Sites 182

5.3. MEASUREMENTS 183

5.3.1. Soil 183

5.3.2. Crop 185

5.4. RESULTS 185

5.4.1. Morley 185

5.4.2. Chicksands 188

5.4.3. Colworth 199

5.5. DISCUSSION 214

5.5.1. Penetration resistance 214

5.5.2. Moisture content, bulk density and WFPS 219

5.5.3. Infiltration 219

5.5.4. Crop yield 220

5.5.5. Tracks versus wheels 221
5.6. ASSESSMENT OF OBJECTIVE OUTCOMES 222
5.7. CONCLUSIONS 224
CHAPTER 6 226
6. A study of CTF systems and their economics 226
6.1. Introduction 226
6.2. Controlled traffic systems 230
6.3. Aims and objectives 230
6.4. Methodology 231
6.5. Results and discussion 235
6.6. Conclusions 239
CHAPTER 7 240
7. Discussion 240
7.1. The effect of field traffic on soil structure and workability 241
7.1.1. Soil bulk density and cone penetration resistance 242
7.1.2. Greenhouse gases 244
7.1.3. Soil workability 244
7.1.4. Pore space, water holding capacity and drainage 245
7.2. The management of permanent traffic lanes 245
7.3. Yield responses to soil compaction 246
7.5. Economics of conversion to and maintenance of a CTF system 247
7.6. Practical challenges associated with CTF 249
CHAPTER 8 251
8. Conclusions 251
References 254
A 254
B 255
C 257

D-E 259
F-G 260
H-I 262
J- K 263
L 264
M 265
N-O-P-Q 267
R 267
S 269
T-U 271
V 272
W-Z 273
Further reading 274
A-fr 274
B-fr 274
C-fr 276
D-E-fr 276
F-G-fr 276
H-I-fr 277
J –K-fr 277
L-fr 278
M-fr 278
N-O-P-Q-fr 280
R-fr 281
S-fr 281
T-U-fr 282
V-fr 282
W-Z-fr 283

APPENDIX A 284

Summary of research data listing different soil and crop responses to wheel loads 284

Tables 1A – 3A 284

APPENDIX B... 288

Tables 1B – 3B 288

Figures

Fig. 1.1. Change in predicted stress at 0.4 m depth in the profile due to wheel loads imposed at the surface assuming a stress concentration factor of 4 (after Koolen et al., 1992) 3

Fig. 1.2. Relative speed and uptake of new technologies for agricultural enterprises compared with the best that other industries tend to achieve (Moody, 2005) 5

Fig. 2.1. Mean crop yield relative to no treatment compaction (100) from a series of 21 long-term trials in Sweden. 16

Fig. 2.2. Relative number of trials on different crops with estimated yield reductions (%) relative to the yield maximum in the individual trial with varying degrees of compactness in the plough layer (after Håkansson, 2005). 17

Fig. 2.3. Change (%) in bulk density with different wheel loads across different cropping systems and soils in the depth range 0 – 0.2 m. 30

Fig. 2.4. Change (%) in bulk density with different wheel loads across different cropping systems and soils in the depth range 20-60 cm. 30

Fig. 2.5. Change (%) in penetration resistance with different wheel loads across different cropping systems and soils in the depth range 0.2 – 0.5 m. 31

Fig. 2.6. Average performance of sugar beet harvested in 2004, 2005 and 2006 from three fields growing a rotation of sugar beet and winter cereals. 43

Fig. 2.7. The "Kensington Steam Cultivator" designed, built and operated by Alexander Halkett in the 1850s. This is the first known mechanised controlled traffic farming system in operation (after Halkett, 1858) 56

Fig. 2.8. The straddle frame proposed by Hood et al. (1985) at Clemson University 57

Fig. 2.9. A three drum and concave threshing and initial separation unit (Metianu, et al., 1990) were the basis of grain harvesting with this 12 m experimental gantry at Silsoe in the early 1990s. 57

Fig. 2.10. A controlled traffic farming system commonly adopted in Europe known as OutTrac. The system has two track gauges with a common centre line. The harvester tracks “outwith” the narrower track of all the other machines. 59

Fig. 2.11. The “TwinTrac” controlled traffic system which uses only the grain harvester wheel tracks by ensuring tractor passes straddle adjacent passes of the harvester........... 60

Fig. 3.1. Establishment of spring oats on an Evesham series calcareous clay in spring 1988 to which Table 6 of the paper relates. 93

Fig. 4.1. The controlled traffic field (28) and its position in relation to the three trafficked fields at the same point in the rotation (22, non-inversion tillage; 23, no-till; 15, ploughed) 142

Fig. 4.2. Double ring infiltrometer used in December 2005 at Colworth on each of the fields shown in Fig. 4.1.. 142

Fig. 4.3. The tracking configuration at Colworth from 2008 onwards resulting in an overlap between the narrower track gauge of the tractor (2.2 m) and the wider track gauge of the harvester (2.7 m).. 144

Fig.4.4. Penetration resistance versus depth for the four adjacent blocks of differently managed land on 30 Jan 06. Numbers are coincident soil moisture contents in same order as traces left to right (excluding tramlines). 147

Fig. 4.5. Penetration resistance on 25 April 2008 on three of the fields shown in Fig. 4.1. Numbers are coincident moisture contents, colours as per PR traces. 148

Fig. 4.6. Typical topsoil structure in 2005 following different tillage and traffic. 150

Fig 4.7. Typical topsoil aggregates taken from the 28, CTF no-till (left) and 23, RTF no-till (right) in August 2006.. 150

Fig.4.8. Large block of soil removed from 2-year old CTF permanent wheelway (left) and a similar block from a wheelway with a natural fracture (right). 151

Fig. 4.9. Typical soil condition on a randomly trafficked non-inversion system in autumn 2008 showing a highly compacted zone below the surface tilth...................................... 153

Fig. 4.10. Soil conditions in May 2009 under CTF (left) and RTF (right) no-till 153

Fig. 4.11. Soil condition in June 2009 under CTF no-till (left) and RTF non-inversion (right) 154

Fig. 4.12. Before and after trimming the lateral roots away from an OSR root 154

Fig. 4.13. Ratio of root weight to weight of whole OSR plant, 5th April 2006 155

Fig. 4.14. Ratio of root laterals and fibrous roots to total root weight, 5th April 2006 155

Fig. 4.15. Ratio of root weight to weight of whole OSR plant, 26th April 2006 156

Fig. 4.16. Ratio of root laterals and fibrous roots to total root weight, 26th April 2006 156

Fig. 4.17. Growth of OSR on 7 December 2005 158

Fig. 4.18. Volunteer OSR plants 26 days after harvest of the differently managed blocks of land. Left, RTF no-till, right, CTF no-till. 159

Fig. 4.18. Rutted CTF traffic lane in Australia. Such rutting is likely to be a problem in European conditions and should be avoided by careful management 163

Fig. 4.19. Tramline (left) and intermediate traffic lane (right) on a clay soil at Colworth three years after the field had been converted to CTF. 163

Fig. 4.20. Soil picked up by wheels when running on cultivated soil (left) within a random traffic system compared with spraying on the same day on a CTF no-till field. 164

Fig. 4.21. Condition of large aggregate from Normanton Lodge following 90 minutes immersed in water 166

Fig. 4.22. Series of photos (left to right) taken on 29th June, 2nd July and 9th July 2006 during which there were four wetting and drying cycles of the soil from Normanton Lodge. 167

Fig. 4.23. Flower pot filled with air-dried sieved (5 mm) soil from Normanton Lodge and sown with winter wheat on 7/10/06 showing surface conditions before sowing (left) and change in soil conditions with growth stages. 167

Fig 4.24. Examples of the results of subjecting aggregates to the soil structure and consistency drop test that forms part of the VSA. Left: field soil, right: pot soil. 168

Fig 4.25. Examples of field aggregates (left) and soil from the test pot (right) taken from Normanton Lodge 168

Figs 4.25. Field conditions following harvest of the sugar beet crop and example of difficulty in finding a non-tracked but cropped area at the edge of the field (right) 169

Fig. 4.26. Soil from the field condition (left) and from the edge of the field 170

Fig. 4.27. Sandy loam soil showing sampling positions and trafficked (bottom inset) and “non” trafficked soil (top inset) 171

Fig. 5.1. Tracks made by a combine harvester with conventional tyres (left) compared with the same harvester used on the same day with dual wheels front and rear at lowered inflation pressures (right) (after Chamen, 1997). 177

Fig. 5.2. Example of the manner of application of the compaction treatments (Chicksands site). 178

Fig. 5.3. Plot layout at Chicksands illustrating the fact that the treatment areas consisted of a number of rectangles along the plot length. 182

Fig. 5.4. Penetration resistance at Morley on 18 Nov. 2008. Treatment LSD = 0.102 MPa. 186

Fig. 5.5. Number of winter wheat ears at Morley prior to harvest in 2008. Columns with dissimilar letters are different at $p < 0.05$. 186

Fig. 5.6. Yield of winter wheat at Morley in 2008. LSD = 1.04 Mg ha^{-1}. Columns with dissimilar letters are different at $p < 0.05$. 187

Fig. 5.7. Yield of spring barley at Morley in 2009. Differences only significant at $p= 0.107$ 187

Fig. 5.8. Cone penetration resistance at Chicksands on 5/9/09 showing the results of tracking with the tracked and wheeled harvesters and the tractor and trailer combination compared with the “as found” condition. 188

Fig. 5.9. Cone penetration resistance at Chicksands on 22/9/09 showing the effect of subsoiling to around 35 cm depth and the effect of loads imposed subsequently. 189

Fig. 5.10. Cone penetration resistance under the rubber belts of the tracked tractor at Chicksands measured under the track idlers and beneath the unsupported belt. 190

Fig. 5.11. Change in gravimetric soil moisture content with depth at Chicksands on 26/01/10 coincident with penetrometer measurements. 191

Fig. 5.12. Cone penetration resistance on 26/01/10 at Chicksands showing results from all treatments. Treatment LSD = 0.031 MPa. 192

Fig. 5.13. Penetration resistance on 23 April 2010 at Chicksands. LSD: Treatment = 0.066 MPa, Tr x D = 0.474 MPa 194

Fig. 5.14. Change in soil moisture content with depth coincident with the penetrometer measurements at Chicksands on 24 April 2010. Treatment LSD = 0.70% w w^{-1}. 194

Fig. 5.15a. Volumetric moisture content on 2 March 2010 at Chicksands measured at 12 cm deep in the profile. Treatment 8 < all others at $p = 0.076$ 196

Fig. 5.15b Gravimetric moisture content (MC) on 2 March 2010 at Chicksands measured at 12 cm deep in the profile. (No significant difference between treatments) 196

Fig. 5.16. Bulk density at Chicksands on 2 March 2010 measured at 12 cm deep in the profile. Treatment 8 < all others at $p < 0.05$ 197

Fig. 5.17. Hydraulic conductivity at Chicksands measured at 12 cm depth on 12 April with the mini disc infiltrometer set at a suction of 1 cm. LSD 5.28 mm h^{-1}. 198

Fig. 5.18. Yields of winter wheat at Chicksands converted from sampled areas to Mg ha^{-1}. Differences in yield were not significant. 199

Fig. 5.19. Cone penetration resistance at Colworth on 6/9/09 showing the initial condition on the site (CTF, non-trafficked for 5 years) and the conditions following the compaction treatments. 200

Fig 5.20. Cone penetration resistance at Colworth on 28/12/09. Treatment LSD = 0.041; Tr x Depth LSD = 0.290 MPa 201

Fig. 5.21. Variation in soil moisture content with depth at the time of penetrometer measurements on 28/12/09 at Colworth. There was no significant difference in moisture content between treatments ($p = 0.172$, LSD = 1.37%). 202

Fig. 5.22. Cone penetration resistance at Colworth on 24 April 2010. 203

Fig. 5.23. Moisture profiles on 24 April 2010 coincident with the penetration resistance measurements depicted in Fig 4.3.1.4 at Colworth. LSD = 1.83%. 204

Fig. 5.24. Cone penetration resistance on the different plots at Colworth on 25 August 2010, measured using a hydraulically inserted probe. Treatment LSD = 0.120 MPa 205

Fig. 5.25. Cone penetration resistance in two adjacent fields at Colworth which were converted to CTF in 2006, one of which was subsoiled (CTF-sub) to 35 cm depth, the other not (CTF-no sub). 206

Fig. 5.26. Soil bulk density in the top 6 cm of the profile measured on 1/3/10 at Colworth on a selection of treatments including CTF no-till in the same field (LSD = 0.102 Mg m^{-3}). Columns with dissimilar letters are different at $p < 0.05$ 208

Fig. 5.27. Soil water filled pore space in the top 6 cm of the profile measured on 1/3/10 at Colworth on a selection of treatments including CTF no-till in the same field (LSD = 7.3%). No significant differences. 209

Fig. 5.28. Bulk density at 15 cm depth calculated from volumetric and gravimetric moisture measurements taken on 24 March 2010 at Colworth. 209

Fig. 5.29. Water filled pore space at 15 cm depth calculated from volumetric and gravimetric moisture measurements taken on 24 March 2010 at Colworth. No significant differences. 210

Fig. 5.30. Steady state infiltration measured with a double ring infiltrometer at Colworth on 11 March 2010 including results from adjacent trafficked (RTF) and non-trafficked (CTF) no-till areas. Treatment 6 > all others at $p = 0.10$ 211

Fig. 5.31. Steady state infiltration on selected treatments at Colworth on 23 March 2010 using three replications per plot plus results from adjacent trafficked (RTF) and non-trafficked (CTF) no-till areas. 211

Fig. 5.32. Crop yield from the different treatments at Colworth sampled on 29 July 2010. Columns with dissimilar letters are different at $p < 0.05$. LSD = 0.619 Mg ha^{-1} 213

Fig. 5.32. Comparison of penetration resistance on the six treatments which were measured on all four measurement dates at Colworth 217

Fig. 5.33. Penetration resistance for treatments which contrasted the effects of subsoiling at Colworth 218

Fig. 5.34. Relationship between crop yield and the maximum individual wheel or track loads multiplied by the number of occasions they were applied (left Chicksands, right Colworth) 221

Fig. 5.35. The different track designs involved in the compaction treatments. 222

Fig. 5.36. Example of a more favourable design of rubber belt track with many idlers but still with a significant element of the belt unsupported at the extremity of its width. 222

Fig. 6.1. Percent loss in crop yield of different crops grown on soil with traditional traffic management compared with non-trafficked soil. (see Literature Review) 227

Fig. 6.2. A CTF system where tractors straddle adjacent passes of the harvester 231

Fig. 6.2. Scaled illustration of the type of controlled traffic system adopted by Farmeco. The tracked area of the system is around 25%, of which the wider track of the harvester contributes 10%. 234

Fig. 7.1. Vertical force distribution under two types of rigid tracks with the same load and drawbar pull on loose sand (after Tijink, 1994) 243

Fig. 7.2. Retarded crop growth in an intermediate traffic lane when cropped with spring barley on a Hanslope clay soil 246

Fig. 7.3a. Reduction in yields (%) of combinable crops grown with varying degrees of controlled traffic compared with crops grown with varying amounts of soil compaction. 248

Fig. 7.3b. Reduction in yields (%) of a further range of crops grown with varying degrees of controlled traffic compared with crops grown with varying amounts of soil compaction. 248

Fig. 1A. The effect of different wheel loads applied to different soils in different parts of the world as part of research assessing their impact on bulk density and penetration resistance. The blocks in blue and yellow reflect graphed data appearing in Figs 2.3-2.5 285

Fig. 2A. The effect of different wheel loads applied to different soils in different parts of the world as part of research assessing their impact on crop yields displayed by soil type. 286

Fig. 3A. The effect of different wheel loads applied to different soils in different parts of the world as part of research assessing their impact on pore volume and saturated hydraulic conductivity (Ksat) 287

CHAPTER 1

1.1. INTRODUCTION

It could be said that in terms of population growth modern agriculture is the underlying cause of global warming because of its success in moving us from a subsistence agriculture to one in which thousands are fed through the efforts of very few. As a result, populations have risen year on year at an increasing rate in line with the teachings of Malthus (1798) who stated that “population does invariably increase when the means of subsistence increase”. What Malthus almost certainly didn’t anticipate was the massive effect of fossil fuels on our means of subsistence increase. It has meant that many more people can now be supported by the efforts of relatively few, mainly through the high energy density of oil used in our primary production systems. One could also argue that proving the main hypothesis of this research will add to the problem of over-population by improving production efficiency but it will not change the truism which Malthus identified and which is already impinging on our consciousnesses, as evidenced by the recent conference on greenhouse gas emissions and food security (The Royal Society, 2011). Equally, improved production efficiency will use finite resources more sustainably and with reduced environmental impact but a range of measures will be needed to address the 70% shortfall in food supply predicted by 2050 (Conway, 2011).

Improving production efficiency has not always been at the forefront of agricultural development, particularly when crop returns have been high. Practical issues and reliability are frequently the underlying drivers for change and this has applied equally to the effects of soil compaction due to field traffic, which only get addressed if work cannot proceed. These effects will almost certainly have been noted by our ancestors as they strove to till the soil by hand. Extensive foot traffic will have made digging more arduous and the results less satisfactory. However, as soon as fossil fuels became widely available at a low cost and were applied to this onerous task, these effects escaped our consciousness. Steam power soon became more sophisticated and the machines larger, (Haining & Tyler, 1970; Spence, 1960) so large in fact that sinkage often precluded their travel across the land. This practical issue brought about the introduction of winching systems, meaning that these large machines only needed to traverse the field headlands. A change to the more efficient internal combustion engine powered by high energy density oil enabled lighter machines to be designed, particularly when the Ferguson three-point hitch system was introduced (Ferguson, 1933). A further significant development was the pneumatic cross-ply tyre, enabling loads to be spread more widely and at lower pressure. It wasn’t long however before the negative impacts of soil compaction were noticed again, but in this instance by the levels of energy required and the poor workability of the soil. Arndt and Rose in their publication of 1966 made the classic observation that “excessive traffic necessitates excessive tillage “, a negative outcome for both soils and the farmer. It was from this point on that research on soil compaction and its effects on production efficiency became extensive, as evidenced by the Strutt Report (Strutt, 1970) and the literature review forming part of this thesis. Practically all data indicated negative outcomes, resulting in production losses, high energy demands, poor seedbeds and loss in soil physical function, but varying enormously according to cropping systems, soils and climates. Research further identified the processes and mechanics involved, allowing the industry to take counter measures, mostly in the form of improved running gear such as radial ply tyres and rubber tracks to reduce contact pressures. Unfortunately, these advances were offset almost equally by an increase in vehicle mass despite significant advances in tyre and track designs to reduce soil contact pressures (Fig. 1.1). These predictions are in line with the results obtained by Dresser et al. (2006) who measured average pressures of around 2 bar at 0.25 m depth with agricultural tyres inflated to a maximum of 2 bar. On their prepared soil, inflation pressure was the dominating influence on peak pressures in the soil. In contrast, Botta et al. (2008) found that it was load rather than contact pressure that had an effect on subsoil compaction. Subsoil compaction was also identified as a concern as early as the 1990s when a working group was set up by the International Soil and Tillage Research Organisation (ISTRO) leading to publications in a special issue of Soil and Tillage Research (Håkansson, 1994). This was followed by a European Union Concerted Action (Van den Akker et al., 2003) and an initiative was called for but there is little evidence of any practical action being taken. Van den Akker further explored the problem on Dutch soils (Van den Akker, 2006) and concluded that half of the sandy and sandy loam soils in the Netherlands with clay contents less than 17.5% exhibit over compaction in the top 0.2 m of the subsoil.

Not only is it evident that stresses greater than historic values are now being exerted at 0.4 m depth or more, the area extent of compaction at the surface through greater tyre volume (other than where track systems are being used) has also increased. With this has come greater potential for seedbed effects, most of which increase tillage energy requirements while negatively influencing quality (Chamen et al., 1990; Chamen et al., 1992a & b). It is evident from the literature that practically any vehicle-related compaction of cropped areas has a deleterious effect, whether this is upon crop yield, energy inputs for crop establishment or soil function in terms of the soil's ability to allow free access of air and water and to nurture macro fauna. A number of attempts to address this problem through field traffic management and vehicle design has been made over the generations, the most innovative by Halkett in the 1850s with his "Guidway Agriculture" (Halkett, 1858).

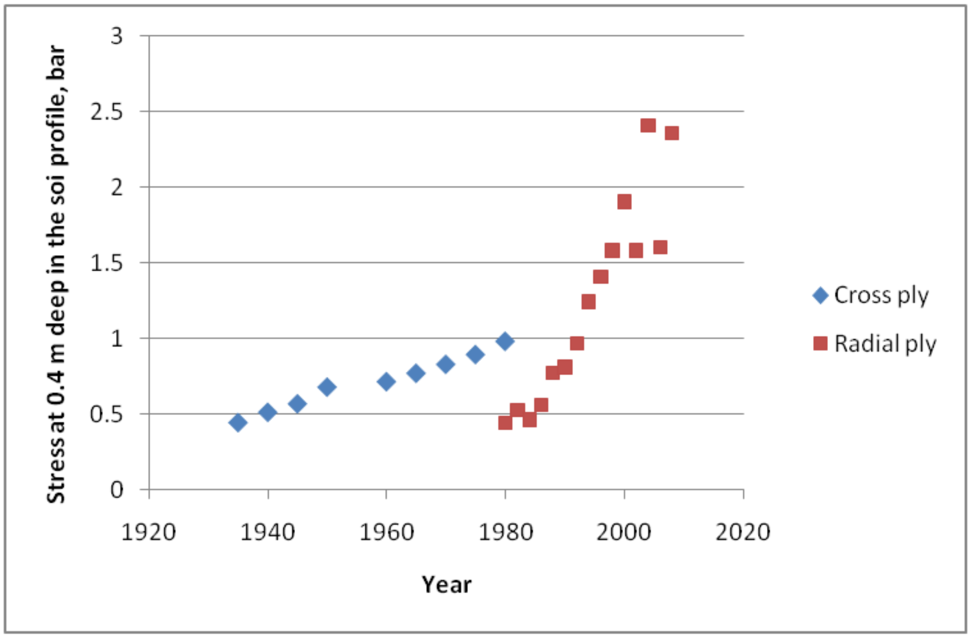


Fig. 1.1. Change in predicted stress at 0.4 m depth in the profile due to wheel loads imposed at the surface assuming a stress concentration factor of 4 (after Koolen et al., 1992)

This concept was revisited in the 1970s by Dowler (1980) and by research workers in the 1980s (Carter et al., 1988; Taylor, 1991; Chamen et al., 1992a; Chamen et al., 1994; Chamen & Longstaff, 1995). However, it is only in the early 21st century that the technology needed to realise "traffic free" zones with existing machines has become widely available, reliable and affordable in the form of Global Navigation Satellite Systems (GNSS), the most sophisticated of which provide repeatable dynamic tracking to within ± 20 mm. GNSS technology was first put to use for traffic management in Australia, where the established term "controlled traffic farming" was applied, the aim being to confine vehicle tracking to the least possible area of permanent traffic lanes (Tullberg et al., 2003). In Australia it is now used on around 15% of the cropped area where inputs have been reduced and cropping reliability increased through better interception and more efficient use of water (Radford & Yule, 1996). Minimising the area of permanent traffic lanes is governed by:

- the width and number of tyres or rubber tracks used per unit width of operation;
- the degree to which the tracking of this running gear is coincident.

The first of these two aspects relates directly to the vehicles involved in field operations and the working width of the equipment being used while the second is determined by vehicle track gauges (the centre distance between tyres or tracks on a single axle) and the commonality of operation width. If all track gauges are the same, tracked areas tend to zero with reduction in tyre width and increase in common operating width. Historically there has been little incentive for machinery manufacturers to consider common track gauges other than for high value crops whose row spacing led to two common imperial standards of 60 inches and 72 inches. These are now tending towards their nearest metric equivalents (1.5 m and 1.8 m) and have been augmented by 2 m, which is now often found on grain trailers as well as tractors and self-propelled sprayers. The limit on a track gauge of 2 m, particularly enforced in Germany, is an overall road width of 2.55 m to comply with The Road Vehicles Construction and Use Regulations (The Stationary Office, 1986). Equally, most countries have flexibility around this legislation, allowing vehicles up to 3 m wide to travel on roads with only minor constraints. Above this width, stricter limits are applied but these are accepted by farmers if they are associated with machines used only for a short season, such as combine harvesters. It is around the issues concerning combine harvesters however that controlled traffic systems meet one of their biggest challenges. Most combines now have a track gauges in excess of 2.55 m, often making these vehicles with 800 mm wide tyres close to 4 m wide on the road. Although matching this track gauge in Australia is feasible because of lower traffic density and dirt strips on the edges of most rural roads, it is either unattractive or impractical in Europe.

Controlled traffic systems therefore tend to be compromised or at least burdened by the additional tracked area of the combine harvester. Vegetable and root crop harvesters introduce slightly different problems in that their wheel positions are often perverse, with none of them lining up with each other or being designed to cover the whole area between the outer extremities of the machine. It can be seen therefore that although the technology in the form of GNSS is now available, achieving large non-trafficked areas of soil is not straightforward. For this reason, alternatives to a strict controlled traffic system have either been sought or used. In the Netherlands and Denmark for example, farmers do accept wider track gauges for their crop establishment and husbandry (Vermeulen et al., 2010) but still find it difficult to maintain the system at harvest.

It is evident that the widespread adoption of more efficient traffic management systems is not guaranteed or experiencing uptake at the speed or on the scale which might have been anticipated. Lorimer (2011) suggests that the adoption of new technologies in agriculture is more protracted than in other industries (Fig. 1.2) reflecting less competition between growers and their individualistic nature. To gain acceptance, new technologies and ideas not only need well documented and robust economics analyses that show improved profitability but they also require the support of widespread demonstration of success and reliability.

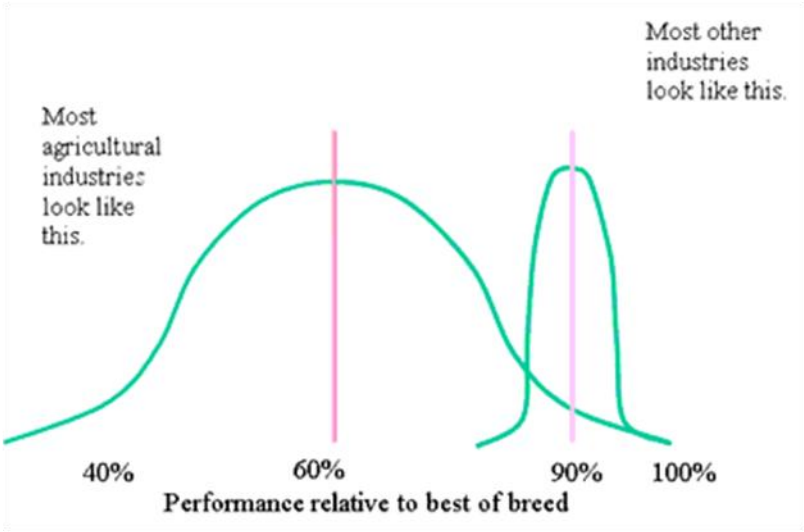


Fig. 1.2. Relative speed and uptake of new technologies for agricultural enterprises compared with the best that other industries tend to achieve (Moody, 2005)

1.2. AIM

The rationale for this thesis is to test whether non-trafficked soils develop better soil structure, require lower energy inputs and deliver more efficient and environmentally benign crop production systems than those where soil is trafficked randomly. Traditional farming systems regularly track up to 80% of field areas each season (Kroulík et al., 2009) and as natural repair of soil structure takes up to five years at 20 cm depth (McHugh et al., 2009), there is likely to be little or no arable land that has not been affected by traffic at any point in time. The aim of the research is to show that low traffic and traffic management systems can be devised and engineered to deliver practical, cost-effective and sustainable means of creating improvements compared with existing practice. Such systems may use a combination of approaches that achieve non-trafficked areas of 80% or more within any given field but work in harmony with LGP systems and judicious loosening of the soil. A single hypothesis, with supporting hypotheses was therefore developed, namely:

Avoiding most vehicle-related compaction on cropped areas is practical and improves soil structure and crop production efficiency.

The associated hypotheses are:

a. Yields from non-trafficked soils are different compared with those that have a high element of arbitrary or random traffic.

b. Yields from cropped traffic lanes are consistently lower than from traditionally trafficked non-inversion or direct drill[1] systems.

c. Most soils maintain a healthy structure in the absence of traffic and the intense tillage associated with it.

d. A calcareous clay soil relieved of all traffic and with little or no tillage acquires a more favourable structure than near identical surrounding soils managed traditionally.

e. Permanent traffic lanes acting as tramlines for chemical applications can perform at least as well as those created annually.

f. Controlled traffic systems or close equivalents achieving non-tracked areas of approximately 75-80% can be attained at zero net cost and are more profitable than traditional practice.

g. The damage done by grain harvesters running outside controlled traffic lanes can be minimised by fitting them with rubber tracks or with targeted soil loosening.

1.3. SPECIFIC OBJECTIVES RELATED TO THE HYPOTHESES

a. To examine the literature as a means of establishing differences in crop yields from non-trafficked compared with trafficked soils and to supplement these data with results from both field scale studies and replicated trials.
b. To contrast yields from cropped traffic lanes, non-trafficked and traditionally trafficked soils using field scale studies in parallel with a search of the literature.
c. To supplement the literature on soils vulnerable to compaction by targeted inspection and sampling at well established conventionally trafficked compared with potentially non-trafficked areas.
d. To make quantitative and qualitative assessments of the structure on a trafficked and non-trafficked calcareous clay soil.
e. To observe and revue the performance and stability of permanent traffic lanes over a number of years on nine fields within a five year crop rotation on a calcareous clay soil with supplementary evidence from commercial farms.
f. To assess, using a whole farm model, the net cost and profitability of a commercial farm conversion to CTF.

---

[1] No-till is used as a generic term throughout the thesis to indicate systems that do not employ a specific tillage pass before crop sowing. It therefore includes systems where there is little or no soil movement as well as those where considerable soil disruption occurs during the sowing process.

g. To test and contrast, using the literature and replicated trials, the effect of wheeled compared with tracked harvesters on soil conditions and crop responses on differing soils.

1.4. OUTLINE METHODOLOGY

The goal of this thesis is to test these hypotheses through a number of approaches. Firstly through a literature review that divides soil compaction-related effects into a number of primary aspects impacting soil structure and crop production. The review is supported by research published by the author starting in the 1980s as well as new work on both a plot and a field scale. The field scale studies, in the absence of appropriate replicated field trials, acquired data on soil structure, practicality and traffic lane management from conventionally farmed fields on contrasting soil types. The plot scale work was funded by three charitable trusts and investigated an alternative to full traffic management as well as targeted loosening of the additional tracking caused by combine harvesters on a wider track gauge and some on rubber tracks. The goal of demonstrating practicality and improved profitability was to complement the field scale studies with a whole farm economics study to assess the relative profitability of farms before and after conversion to a traffic management system.

CHAPTER 2

2. Literature review

2.1. INTRODUCTION

The aim of this review is to identify and assess the factors that deliver to the principal hypothesis of the thesis, namely that avoiding most vehicle-related compaction on cropped areas is practical and where it is avoided altogether, improves soil structure and crop production efficiency. The review therefore has three main themes in the context of avoiding soil compaction, namely:

- Soil structure and its interaction with the environment
- Crop production efficiency
- Practicality

The overarching focus however is on soil and its management within a highly mechanised agriculture. The aim is to bring together and draw conclusions from research targeted at understanding the impact of field traffic on soils and cropping systems. Soils and their management are therefore a major backdrop to this review and as such, the first section looks at them in more detail. As a global resource, their potential in supporting a spiralling population will be assessed as well as the extent to which “Conservation Agriculture” can act as a means of addressing soil degradation.

The review will also discuss the likely outcome of avoiding all traffic-induced soil compaction and its implications in terms of soil health and function. The initial approach was to study published reviews whose role would be to identify those areas of importance within cropping systems and cereal crops in particular. These areas were then investigated in more detail by focussing on key papers to provide a more comprehensive quantification of the effects. Unfortunately, during this process it soon became evident that there is little or no standardization in research, either in the manner in which it is performed or reported. This creates enormous difficulty in interpretation and comparison. For example, some of the work reporting zero traffic was after annual ploughing, and often this could only be gleaned by inference rather than direct description. Equally, many papers do not mention site preparation or recent history leaving the reader uncertain whether the effects or lack of them are due to the treatments applied or to the initial soil condition. Equally, treatments and their manner of application are often poorly described, again making interpretation difficult. As a result and where possible only papers with clearly defined treatments and site conditions were used as a basis for comment and discussion and particularly relevant reviews. In addition, the results from these and other papers were entered into a spreadsheet so that trends might be established by graphing data.

2.2. THE GLOBAL SOIL RESOURCE

The majority of crops produced worldwide are grown on naturally occurring soils and it is generally recognised that good soil health is a key requirement for optimum crop growth and environmental well-being, particularly in areas where excess or scarcity of water is commonplace. So, what are the rudiments of “good soil health or structure”? In reality, it is the perception of what functions soils should perform and their relative importance. Primarily it is the wish to maximise production efficiency – producing the most from the least, both now and in the future. But, soils also have a major impact on the environment, providing for example, a buffer for rainfall, a source and sink for atmospheric gases, home for a multitude of animals, bacteria and fungi and as a physical environment to support crops and our above ground activities.

2.2.1. Global Agro-eco Zones study

Fischer et al. (2002) in their study of Global Agro-eco Zones (GAEZ) used a wide range of resources to predict the agro-climatic yield potential of crops. Climatic resource data such as temperature, water and solar radiation were integrated with soil characteristics that include moisture storage capacity and reference evapotranspiration. For rain-fed productivity, a water-balance model was used to quantify the beginning and duration of the period when sufficient water is available to sustain crop growth. Calculated potential yields were subsequently combined in a semi-quantitative manner with other constraints to include factors such as pests and diseases related to climate.

The aim of the GAEZ methodology was to assess all feasible agricultural land use for specific management conditions and levels of inputs, and to quantify the expected production of relevant cropping activities. Although soil degradation in terms of compaction was not considered, it should be possible to infer the influence of soil over-compaction by looking more closely at the factors used for determining the land productivity potentials. Grower-reported results from Australia for example would suggest a significant impact of improved structure in terms of water availability in an area designated primarily as “moderate” in terms of suitability for rain-fed cereals. FAO has developed procedures for estimating Smax, the soil moisture storage capacity of soils, and these are an integral part of the Digital Soil Map of the World (DSMW) (FAO, 2001).

The more precise management of soils enabled through systems that avoid traffic on a large proportion of the cropped area (CTF) may alter the traditionally accepted constraints mentioned earlier, particularly those of soil depth, fertility, drainage and texture and in addition, the workability of the soil (Fischer et al., 2002). Thus, the GAEZ model could be a valuable tool to identify the worth (benefit) of reducing soil compaction, either regionally or on a global scale. This could be achieved by either modifying the soil moisture storage classes, or more specifically, by amending the storage capacity (in mm) of the individual soils listed in Appendix XIII of the report.

2.2.2. Soil degradation and threats to the environment

In 2006 the European Commission published a communication to other European Institutions entitled “The Thematic Strategy for Soil Protection” which was a proposal for action to ensure a high level of protection for soils. As part of its ten year programme there have been a number of scientific and technical reports and Houšková and Montanarella (2008) quote from the strategy in identifying soil compaction as one of the five most frequent threats to soils in Europe. They suggest that compaction disrupts the soil balance with other parts of the environment and accelerates threats such as erosion from both wind and water. To determine the problem on a European level they assessed the soil’s susceptibility to compaction and created a “new actualized version of the Map of Soil Susceptibility to Compaction in Europe”. Jones et al. (2003) also identify the extent of risk, dividing this into “susceptibility” based on relatively stable soil properties such as texture, and on “vulnerability”, based on likely wetness when field operations might be in progress. Tables 2.1 & 2.2 provide an overview of some of their data, which confirm that a large number of soils are both susceptible and vulnerable but equally that more work is needed to identify subsoils in Europe that are actually vulnerable to compaction. Table 2.2 reveals that Hanslope Association (Hodge et al., 1984, page 209) soils are amongst the “not particularly” vulnerable class but “moderately vulnerable” at field capacity.

Sustainable management is a key aspect that impacts on “soil health” and research over the past forty or more years has gradually become more focused on the soil degradation caused by increasingly heavy machinery being used to manage the land. Arndt and Rose (1966) made a crucial connection between traffic and tillage that was embraced in their observation that “excessive traffic necessitates excessive tillage”. Further concern about possible soil degradation due to machinery has been reflected in the studies by Jones et al. (2003) and Canarache & Van den Akker (2003). These databases concentrate particularly on the effects of traffic degradation or compaction of subsoils, raising concerns that wheel loads in excess of 6 Mg are now in danger of causing degradation deeper in the profile. Canarache & Van den Akker’s paper provides links to two European databases. The first, SOCOLIT, is a literature database on soil compaction and particularly that relating to subsoil compaction, while the second, SOCODB, is a specialist database providing details of over 600 field and laboratory experiments on the subject.

Table 2.1. Susceptibility and vulnerability of subsoils to compaction in different climatic zones (after Jones et al., 2003)

Class	Climate zone (subsoil state)	Perhumid (usually wet, always moist)	Humid		Sub-humid (seasonally moist and dry)	Dry (mostly dry)
			A (often wet, usually moist, rarely dry)	B (usually moist, seasonally dry		
Soil	PSMD, mm	≤50	51–125	126–200	201–300	>300
Susceptibility	Field capacity, days	>250	150–250	100–149	<100	≤40
Very high		E[a] (E)[b]	E (E)	V (E)	V (V)	M
High		V (E)	V (E)	M (V)	M (M)	N
Moderate		V (E)	M (V)	N (M)	N (N)	N
Low		M (V)	N (M)	N (N)	N (N)	N

[a] Vulnerability: E = extremely, M = moderately, N = not particularly, V = very.

[b] Classes within brackets refer to loose/weak topsoil conditions, those outside brackets to firm topsoil conditions

Potential Soil Moisture Deficit (PSMD)

Table 2.2. Susceptibility and vulnerability of some British subsoils to compaction

UK soil series	World Reference Base	Subsoil texture class	Clay content, % by weight	Subsoil bulk density, Mg m^{-3}	Subsoil particle density, Mg m^{-3}	Subsoil susceptibility class	Vulnerability class at FC[a] (firm)	Vulnerability class at PWP[b] (firm)
Naburn	Haplic Arenosol	Coarse	6	1.23	1.32	VH	E	V
Newport	Haplic Arenosol	Coarse	5	1.43	1.47	H	V	M
Wisbech	Calcaric Fluvisol	Medium	6	1.35	1.40	M	V	N
Wick	Eutric Cambisol	Medium	11	1.36	1.46	M	V	N
Romney	Calcaric Fluvisol	Medium fine	15	1.33	1.47	M	V	N
Agney	Eutri-gleyic Fluvisol	Medium fine	30	1.32	1.59	M	V	N
Hanslope	Calcari-stagnic Cambisol	Fine	35	1.43	1.83	L	M	N
Fladbury	Eutri-gleyic Fluvisol	Very fine	45	1.04	1.67	H	M	N
Evesham	Calcari-stagnic Cambisol	Very fine	60	1.41	1.92	L	M	N

[a] Field capacity (5 kPa): [b] Permanent wilting point (1500 kPa)

[a] Vulnerability: E = extremely, H = high, L = low, M = moderately, N = not particularly, V = very.

2.3. CONSERVATION AGRICULTURE

Although there are known and accepted links between heavy traffic and increased cultivations, many farmers are being urged by science to adopt reduced or no till systems to conserve organic matter and thereby improve soil health (Komatsuzaki & Ohta, 2007). The extent of adoption of these techniques was investigated by Benites et al. (2003). They found that the bulk of the 72 million ha under conservation agriculture (no-till, cover crops, retention of residues) worldwide is in Latin America, USA, Canada and Australia. The rest of the world constitutes only 3% of the total. There is also considerable extra potential in the US, where currently it represents only 20% of the area, and only 25% is practised on a permanent basis.

A number of authors have studied the effectiveness of these techniques in restoring soil health. Mullins et al. (1983) concluded that minimal soil disturbance on hard setting soils (mineralogy dominated by kaolinite clay) can reverse the degradation that causes this problem. However, Munkholm et al. (2003) in a 3 year study found that a sandy loam soil converted from mouldboard ploughing to no-till quickly exhibited a higher bulk density and penetration resistance that perpetuated throughout the trial. The authors concluded that periodic non-inversion loosening of the lower part of the arable layer on this soil would be needed to sustain a no-till production system. In complete contrast, Dao (1996) working on a silt loam concluded that reduced traffic intensity and lack of tillage were the reasons for both lower surface and sub-surface density of no-till compared with ploughing. Unger (1996) also identified traffic as the main contributor to differences in soil conditions after six years under no-till growing wheat and sorghum. Penetration resistance was 1.23 MPa under the trafficked furrow but only 1.13 MPa in the non-trafficked. However, these differences were only significant to 150 mm depth and the trafficked and non-trafficked furrows could not be differentiated in terms of bulk density. Botta et al. (2008) in their study of cross and radial ply tyre effects under long term no-till (9 years) and mouldboard plough tillage found increased penetration resistance in no-till to 150 mm depth but lower resistance in the 150-300 mm profile compared with resistance in the ploughed profile. Below 300 mm there were no differences between treatments but at all depths and with both soil management options, resistance was always lower in the traffic free areas.

Tebrügge & Düring, (1999) concluded that no-till had some beneficial effects on porosity, but although apparent at 120 mm depth, significant increases in percentage of pores >50 µm were confined to around 350 mm depth. Grabski et al. (1995) compared conventional tillage (chisel ploughing to 20 cm) and no-till for 14 years in a rotation of soybean and cereals. Although there were few differences in the early years of the trial, by its completion, soil macroporosity, saturated hydraulic conductivity, plant available water and water use efficiency were all greater under no-till. Similar changes were found by Czyz & Dexter (2009) on a silt soil in Poland. After six years of growing wheat with no-till, soil stability and an "*S index*" of soil quality had improved after an initial deterioration.

Bell et al. (2003) studying the soils that support the Australian grains and sugarcane industries determined that although nutrients and organic matter became stratified into surface layers the overwhelming effect of traffic with little tillage was increased soil strength and retarded early growth of crops. Although there was no evidence of reduced yields there was an increased susceptibility of cereal crops to deleterious soil organisms. Culik et al. (2002) recorded a change in the density of collembola, with no-till retaining larger densities than conventional tillage and mulch greater than no mulch. Deen & Kataki (2003) undertook a 25 year study to determine the differences in carbon sequestration with different tillage systems. Growing maize continuously for 14 years and soybean/maize in alternate years for 11 years they determined that soil bulk density was greater in the 50-200 mm profile under no-till and spring ploughing with cultivation, compared with spring mouldboard ploughing without cultivation and autumn ploughing with cultivation. In contrast, soil organic carbon (SOC) storage in the 0-600 mm profile was greatest under the treatments with the highest soil density. SOC in the 0-50 mm profile was around 12% higher for no-till, but when this was calculated on an equivalent mass basis, storage in the 0-400 mm layer was unaffected by time or tillage method. In reality, most of these differences would have been highly influenced by traffic intensity. Angers (1997) found that carbon and nitrogen storage in the 0-600 mm depth profile were unaffected by no-till, chisel ploughing or mouldboard ploughing provided these treatments did not affect crop production levels, but the distribution of C and N were significantly affected by tillage method. Bessam & Mrabet (2003) concluded that particulate organic matter (POM) in the 0-200 mm profile was significantly greater after 13 years of no-till compared with disc tillage, but differences only became apparent after 5 years. Mrabet's review (2003) concluded that no-till was a very beneficial system for the Mediterranean region as it increased soil organic matter, but there were some socio-economic, weed and other constraints to its adoption. Karunatilake et al. (2000) concluded that no-till was an economically viable system provided adequate consideration is given to maintaining soil structure.

Smith in his review (Smith, 2004) of soils as carbon sinks concluded that sequestering carbon in soil organic matter has a role to play in mitigating its build up in the atmosphere, but the accumulation is finite. Because historically soils globally have lost 40-90 Pg[2] of carbon through cultivation and disturbance, there is good potential for some restorative sequestration amounting to around 0.9 ± 0.3 Pg C yr^{-1}.

Drawing overall conclusions from these disparate lines of research is difficult, but there is an underlying trend that mirrors the fundamental physics of soils, albeit with some modification due to their high biological content. As with any material, soil responds to imposed stresses and it is evident that initially loose soils quickly compact when traffic is applied in the absence of remedial tillage. It is also logical and demonstrated from the research, that when the soil remains undisturbed, even under high loads, some porosity (and therefore reduction in density) is gained through rooting, biological and fauna activity. Almost certainly this increased porosity will be dominated by vertical pores, particularly closer to the surface. Horizontal pores will tend to be closed due to vertical loads, but even these will increase with time as the structure becomes stronger and more stable. Slipping wheels and trafficking in moist conditions will have a deleterious effect on both these and vertical pores, even if they normally withstand high loads. Of particular interest would be research that documented the relative abundance of horizontal and vertical pores under different management regimes and this now looks possible (Mooney & Korošak, 2009). In this methodology, soil is removed undisturbed in cores of up to 100 mm diameter and 200 mm in depth and are scanned with a three-dimensional x-ray micro-CT system that shows the distribution of pores and their quantification on a micron scale.

So, conservation agriculture may have a period of deterioration in soil structure which is followed by a gradual improvement that leads to a stable condition supporting good crop growth. Whether this is optimal is uncertain but this aspect will be reviewed in more detail in the section on crop performance.

2.4. REVIEWS ON THE EFFECTS OF SOIL COMPACTION IN AGRICULTURE

Reviews have been dealt with separately from the rest of the literature in recognition of their value in identifying many of the key issues related to soil compaction. Although the reviews cover many different aspects of the soil system, it is possible to divide them very broadly into physical aspects, crop nutrients and soil biology. Most consider the effect of these different aspects on crop yield.

---

[2] 1 Pg = 1 Gt = 10^{15} g

2.4.1. Soil physical aspects

Soane et al., 1980-1982
This review was divided into three separate parts of which the third (1982) is of greatest relevance. Their review must also be considered in its context of machinery induced stresses on soils that were significantly lower than they are today. The average mass of tractors in 1968 was reported to be 4.5 Mg, whereas 20 Mg is not uncommon for a fully ballasted tractor today (http://www.deere.co.uk/en_GB/products/agriculture/tractors/9030/9030.html, accessed June 2011). Of concern in 1968 was the compaction occurring on soils loosened by cultivation and the associated rutting and need for more intense and costly tillage. Traffic distribution and coverage was also seen as a key factor and percentage cover from 100 to 400% was not uncommon often as a result of limited widths of operation. In terms of crop responses, their focus was on seedbed compaction because it remained for the life of the crop. Effects on yields were variable however, reflecting either the different soil moisture conditions when the compaction was applied or through improving the pore continuity in a loose seedbed. Crop responses from regions of higher soil moisture provided evidence of up to 15% reduction in yields from wheel traffic. Quoting from Eriksson et al. (1974) there was an estimate that cereal yields in Sweden would be increased by 6% in the absence of compaction, although research from elsewhere (Koch et al., 2008) reported no response in wheat yield following sugar beet harvesting and ploughing. This raises the issue of comparing like with like. Comparing the outcome of compaction with different traffic intensities without taking previous tillage into consideration (e.g. shallow, deep or no cultivation) is almost meaningless (Botta et al., in press). Different depths and intensities of cultivation will also have different cost and timeliness aspects associated with them and in terms of crop production efficiency and environmental effects, cannot be ignored. This is where a standard is needed so that experimental outcomes can be compared on a more rational basis.

Mention is also made of an equation to relate yield responses to compaction inputs and this was developed further by Håkansson in relation to subsoil compaction (Håkansson et al., 1987). Effects of compaction on soil hydrology concentrated on water table effects and thus drainage systems. Keeping water tables below 500 mm was seen as a key requirement for reducing compaction risk, which if it were created would reduce permeability of the soil and increase the risk further. Persistence of compaction was also a cause for concern, particularly when it occurred within the subsoil because most research suggested little or no recovery, even after as long as nine years and with annual cycles of freezing to 1 m depth.

Soane et al. (1982) also devoted a lengthy section of their review to methods of reducing wheel compaction under wheels. They divided these methods into controlled traffic, traffic reduction and four categories of uncontrolled traffic including a high mass category whose access to the field would be restricted or even prohibited. Within the latter were proposals for reducing vehicle mass but as we have seen from commercial development of production systems, exactly the opposite has occurred.

Håkansson, 2005

Håkansson carried out extensive work on the effects of high axle load on subsoil compaction (Håkansson & Reeder, 1994) and edited a Special Journal Issue on the subject (Håkansson, 1994). Subsequently he published a book (Håkansson, 2005) bringing this and more extensive information together on the effects of compaction on arable soils from which the following information is drawn. Assessing particularly the effects on soil structure, he concluded that compaction implies a decrease in total pore volume and particularly affects the larger pores and voids between aggregates. The continuity of the macropore system is also impaired, leading to poor aeration, infiltration and transport of water. Resultant tighter bonding between soil particles and aggregates increases soil strength and this together with poor soil aeration leads to reduced crop root growth and poorer uptake of water and nutrients. Greater soil strength also negatively affects seedbed quality and crop establishment. Table 2.3 shows results taken from Arvidsson (2001) following an extreme case where a sugar beet harvester with around 10 Mg wheel loads had been driven track by track across the plots four times.

Table 2.3. Dry bulk density and saturated hydraulic conductivity following four passes of a sugar beet harvester with 10 Mg wheel loads on a loam soil (after Arvidsson, 2001).

Treatment	Bulk density, Mg m^{-3}				Hydraulic conductivity, mm h^{-1}			
	0.3-0.35 m		0.5-0.55 m		0.3-0.35 m		0.5-0.55 m	
	1996	1999	1996	1999	1996	1999	1996	1999
Without traffic	1.68	1.76	1.60	1.66	7.4	2.3	80.6	23.8
With traffic	1.74	1.78	1.69	1.70	0.8	0.33	5.7	4.7
Significance[1]	1%	ns	ns	10%	ns	5%	10%	5%

[1] 1%, p<0.01; 5%, p<0.05; 10%, p=<0.1

Considering the effects of compaction in the plough layer, Håkansson draws on results from 21 trials in Sweden carried out between 1963 and 1992 representing 259 location years. Modest wheel loads (by today's standards) of around 2 Mg were applied just before autumn ploughing but the intensity of traffic was high (350 Mg km ha^{-1}) compared with conventional practice largely because the traffic was applied uniformly across the whole plot width. Following the ploughing operation only light vehicles with low ground pressure tyres were used consistently across all the regional sites, the bulked results of which are shown in Fig. 2.1. These clearly show that traffic effects were not mediated by the ploughing operation and that yields took nearly 4 years to restore to the non-treatment level. In parallel with these trials were others imposing a lower intensity (120 Mg km ha^{-1}), where the yield losses were about one third of those from the higher intensity trial, suggesting that the effect was influenced by traffic intensity. Associated with these negative consequences comes a reduction in aeration of the soil and this can constrain crop growth due to lack of oxygen at the roots as well as promoting undesirable gaseous exchanges (see section 2.5.1.2). Equally, an elevation in penetration resistance can constrain root growth and critical values of anything between 1.5 and 3.0 MPa have been identified. There is no one constraining value however, as the level of resistance is affected by a range of variables, including soil texture, moisture and organic matter content and the particular soil structure present. Håkansson also recognises that too loose a soil can lead to poorer crop performance and identifies the concept of "degree of compactness". This is defined as the bulk density in the field as a percentage of the bulk density of the same soil after a standardised compaction treatment in the laboratory using a uniaxial stress of 200 kPa.

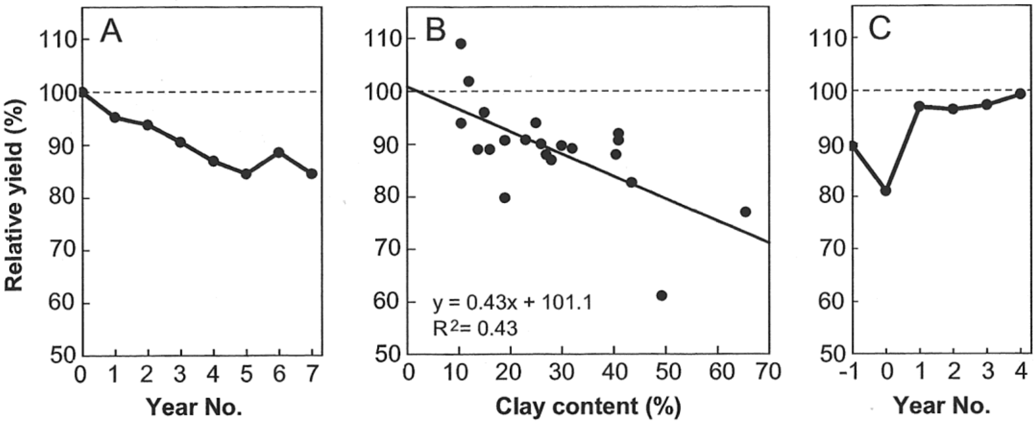


Fig. 2.1. Mean crop yield relative to no treatment compaction (100) from a series of 21 long-term trials in Sweden.

Treatment compaction consisted of annually and evenly applied traffic intensity of 350 Mgkm ha^{-1} (after Håkansson, 2005).

A. Mean relative yield in the compacted plots
B. Yields from year 4 to year 8 as a function of soil clay content
C. Yields following termination of treatment traffic (Year 0 last treatment)

Maximum crop yields have been shown to occur when the degree of compactness in the 50 – 250 mm depth layer is 87% with some deviation around this value. Håkansson quoting from Eriksson et al. (1974) provides data relating to the plough layer for spring barley, winter wheat and oilseed rape, as shown in Fig. 2.2. These show a relatively higher degree of compactness being optimum for cereal crops but a lower level for oilseed rape. Håkansson also quotes from several authors on a reduced uptake of plant nutrients in compacted soils and as a result, an increase in the risk of leaching, supported by data from an experiment in Germany suggesting a 50% increase in nitrogen leachate.

Also impacting on nutrient availability is biological activity and number and diversity of soil fauna. Micro-organisms in particular affect the decomposition of organic matter and their activity has been shown to decrease with increasing compaction, thus perhaps enhancing sequestration. If however the lack of nutrients released by organic matter mineralization reduces plant growth, the net outcome is less certain. More predictable are the effects of compaction on earthworms which have been widely studied. Results from Sweden suggested just a quarter of the biomass compared with non-trafficked soils and a reduction of 83% in their number. Micro-organisms are also involved in the fluxes of greenhouse gases and it has been widely shown that soil compaction can negatively influence emissions of nitrous oxide or the soil's ability to act as a sink for methane and these aspects are more widely covered in section 2.5.1.2.

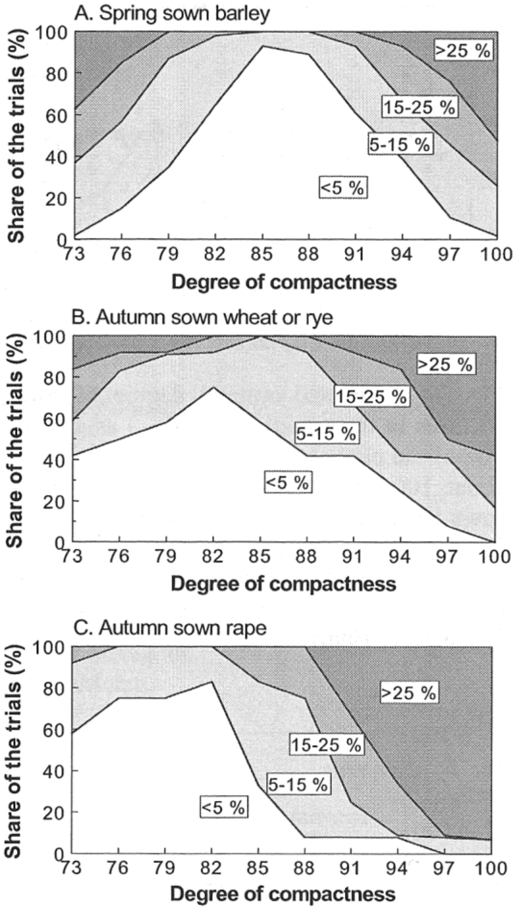


Fig. 2.2. Relative number of trials on different crops with estimated yield reductions (%) relative to the yield maximum in the individual trial with varying degrees of compactness in the plough layer (after Håkansson, 2005).

In terms of subsoil compaction, mention has already been made about the dominating influence of wheel load rather than contact pressure at the soil surface. Håkansson provides an equation relating depth of effect (z, cm) and axle load (x, Mg) in the form:

$$z = 22\ x^{0.5}\ \text{cm} \qquad \textit{Equation 2.1}$$

in other words subsoil compaction increases with the square root of the wheel load. This is only provided as an indicator, because there are many instances when compaction will not occur, such as when the pre-consolidation stress already exceeds the stress applied or when a pan layer protects the subsoil, as may happen in dry conditions (Spoor et al., 2003). Equally, subsoil compaction has been reported from relatively light vehicles but with repetitive passes (Botta et al., 2004) and in dry conditions (Trautner & Arvidsson, 2003).

Hamza and Anderson, 2005

Hamza and Anderson in their review of the nature and causes of soil compaction confirmed its main sources as overuse of machinery, intensive cropping and inappropriate soil management. It is also exacerbated by low soil organic matter and working in moist conditions. Depths of compaction from the surface to 0.6 m were recorded and the distinction was drawn between the effects of contact pressure, acting near the surface and wheel load acting deeper in the profile. They also quoted Jansson & Johansson (1998) whose research showed that wheeled machines left deeper ruts than vehicles fitted with tracks. There was however little difference in dry bulk density, penetration resistance, saturated hydraulic conductivity and porosity of the soil, except in the top 50-100 mm; here tracks caused an increase in bulk density whereas the wheels caused a decrease largely due to lateral soil flow. They also drew attention to the fact that although low ground pressure tyres allow larger loads to be carried before surface deformation occurs, a greater area of the field is trafficked. Quoting Chygorev & Lodyata (2000, but not listed) they concluded that any machine passage across the soil makes all soil parameters less favourable. Repeated passes, even with light vehicles can eventually have damaging effects on the subsoil, as also found by Zhang et al. (2006) who were only imposing wheel loads of 270 kg. Although Hamza & Anderson's review did not attempt to quantify the outcome of soil compaction, they did report increases in plant available water, reduced run-off, improved water infiltration and reduced emissions of nitrous oxide when all traffic was removed. Equally they quote Braunack et al. (1995) reporting no increase in the yield of sugar cane from non-trafficked soil as was also the case in their study reported in 2006 (Braunack & McGarry, 2006). However, lodging of the crop may have been a factor in this neutral or even negative response.

Batey, 2009

Batey in his review raises some rather different and more practical issues, such as effects on crop uniformity. As a precursor however, he relates data regarding the extent of human-induced soil compaction. This is considered to be widespread, affecting some 33 million hectares in Europe, 54 million hectares in countries in Eastern Europe and 18 million hectares in Africa. Within the detail, it is estimated that two thirds of over 600 commercial potato fields in the UK between 1992 and 2004 had a soil resistance sufficient to limit root growth. Equally however, research in Scotland has suggested that many lowland soils have some resilience to compression and there is no clear evidence of a threat. Batey (2009) also makes the point that the effects of a given level of compaction (or rather over-compaction) are related to both weather and climate. Irrigation or adequate rainfall can often mask the effects of compaction when they might be severe at high moisture deficits. Reporting from a farmer's perspective one of the main issues with compaction is the variation in growth, particularly for high value crops such as potatoes, beetroot, leeks and carrots. The outcome may be a lower value or even rejection in what is now a highly demanding market. Batey (2009) also reiterates the concern about subsoil compaction, quoting data from Sweden showing adverse effects on yields 11 years after the compaction was applied in soils experiencing deep over-winter frosts (to below the plough layer (Håkansson, 2005)). These data repudiate often heard claims that freezing and thawing will repair the damage.

2.4.2. Crop nutrients

Wolkowski, 1990

In his review of wheel traffic compaction effects on nutrient availability and crop growth, Wolkowski looked separately at the three principal nutrients involved. He concluded that loss of nitrogen through denitrification tended to increase with reduced tillage and was exacerbated by compaction that caused anaerobic conditions when soils are moist. This was also true of legumes that respond positively to compaction in dry conditions but negatively when wet. The relative uptake of phosphorous by plants is reduced as the bulk density of a given soil is increased. In fertilized soil this ranged from a control of 100% in soil at a bulk density of 1.4 Mg m^{-3}, to 62% at 1.7 Mg m^{-3} and in non-fertilized in the same range, to around 90%. The effect is not due to compaction per se, but to the reduced rooting associated with restricted pore space. Roots that can grow into a non-restricted layer are able to compensate for their lower intake elsewhere. With potassium there was evidence to suggest that uptake is reduced when oxygen concentration is reduced below 10%. Wolkowski commented that the uptake of potassium is reduced by compaction, but whether the mechanism is poor diffusion in the soil, low uptake or root growth limitations is difficult to determine. Plant roots for example can compensate for lack of available potassium or restricted root growth by increasing their root absorbing power. However, if increases in bulk density restrict root growth significantly, such compensation may be inadequate to maintain the uptake of potassium needed. Wolkowski concludes that where aeration is significantly reduced, nitrogen availability may decrease because of denitrification while potassium uptake may be constrained if respiration within the root is reduced. Plant growth is probably adversely affected because of a combination of these effects. Fertilization may compensate partially for a yield limitation (Marks & Soane, 1987) but subsoiling is generally unsuccessful.

2.4.3. Soil biology

Beylich et al., 2010

This review on soil biota and biological processes is important because the living part of the soil contains the drivers of change and usually improvement in soil structure; it is also critical for the release and cycling of nutrients from soil organic matter. There are occasions however when an alteration in relative species populations can have deleterious effects, such as enhanced emissions of nitrous oxide. Soil biota exist on many scales and Russell (1988) classifies micro-organisms into major divisions, the microflora, consisting of bacteria, fungi and algae and the microfauna and fauna, including protozoa, worms and arthropods. However, there are organisms that cross these boundaries and the classification is not therefore clear cut, but this detail is probably of little consequence in this context. Importantly however, the fertility of a soil is dependent upon either an adequate supply of plant food in an available form, or a microbial population which is releasing nutrients fast enough to maintain rapid plant growth. As the micro-organisms in turn need a food supply in the form of organic matter, soil fertility relies on added nutrients or a healthy population of micro-organisms and adequate organic material. Any management system that has a negative effect on these microbes fundamentally undermines the good health of a soil and it is in this context that the effects of soil compaction on the numbers and distribution of a range of soil biota are explored.

Beylich et al. (2010) conclude that, "due to the high variability of experimental situations and conditions in the evaluated papers, especially in papers describing field investigations, no general effect of soil compaction (on soil biota and biological processes) was found". They do however confirm that soil bulk densities of over 1.7 Mg m^{-3} always led to deleterious effects on microbial biomass and C-mineralization, but only the soils capable of reaching this density, which precludes most clays. To better understand these conclusions it is useful to explore their review in detail. In terms of earthworms for example, the authors report that burrowing can be impeded by soil compaction even if their abundance remains unchanged. In a separate paper, Söchtig & Larink, (1992) found that numbers were reduced in the bulk density range 1.32–1.49 Mg m^{-3} but both biomass and numbers were reduced drastically when bulk density reached 1.52 Mg m^{-3}. The argument against compaction causing a decline is that within a certain density range, earthworms are able to counteract the effects of compaction by increasing their burrowing activity, including in wheel tracks and through plough pans, as is evidential from observation in the field. It is also the case that due to the randomness of the traffic applied to fields, areas of severe compaction will only occur across a proportion of any given field, thus allowing populations to survive and increase in other areas. A further impact on the diversity of results, are the measurement methods discussed by the authors. Soil microbial biomass for example, measured by the fumigation method was found to decrease with increasing soil moisture, whereas by the substrate method, there was no change. Beylich et al. (2010) in their review did, however, take a very rigorous approach to setting the threshold values. Of 240 peer reviewed papers on the subject published between 1963 and 2007, 640 data records on micro-organisms and microbial activity and 332 records on soil fauna were evaluated. Through a process of rigour that eliminated papers for example because they did not quote relevant density data or these could not be derived, or there was no control treatment, the original papers were reduced to 54, of which 22 dealt with soil fauna and 32 with micro-organisms. In analysing their results on soil fauna, the authors conclude that heterogeneity might not be the only factor involved in the lack of a detectable correlation between compaction and abundance or biomass. Bulk density was the most commonly measured parameter to identify compaction effects but several authors considered this to be inadequate or inappropriate as a parameter that would influence soil fauna. Other parameters such as macropore volume might be more appropriate, but were rarely measured. In terms of microbial assessments, the authors point out that the threshold values for air capacity of 5% and 7% by volume was only reached by two and eight experiments respectively, whereas bulk density was greater than the threshold value in 15 out of the 23 compacted soils. The authors considered that future studies should include “a more functional characterisation of the soil pore system”, such as pore size distribution, connectivity and tortuosity. The technique being evolved by Mooney & Korošak (2009) would appear to be eminently suitable.

2.4.4. Discussion of reviews on the effects of soil compaction in agriculture

A wealth of evidence has been presented on what are almost universally negative outcomes from vehicle induced soil compaction. Where they are not negative, the compaction applied has often positively modified limiting conditions, by for example consolidating too loose a soil condition for trace element uptake or soil/seed contact for germination in dry conditions. Although yields may not always be negatively affected by compaction, restorative measures to avoid a reduction have often been time consuming and expensive.

The reviews have delivered a broad and sometimes detailed assessment of the past and sometimes current situation relating to traffic compaction in the field. Inevitably however, most will be at least five years behind today’s commercial practice in terms of imposed loads and traffic intensity. A visit to any major agricultural machinery show will demonstrate just how much vehicle mass is increasing, with cereal harvesters now offering 12 m cutting tables and planned further increases in size that will almost certainly take individual wheel loads to around 15 Mg.

The review by Beylich et al., (2010) is both recent and seems to be definitive in terms of soil biota. Their in-depth assessment would need considerable expertise and knowledge to counter and this review will therefore accept their evidence which found that “due to the high variability in experimental situations and conditions in the evaluated papers, especially in the papers describing field investigations, no general effect of soil compaction (on soil biota and biological processes) was found”. It must be stressed however that this does not dismiss what are widely recognised and mostly negative effects of compaction on soil biota and biological processes, only that experimental constraints have precluded verifiable proof of their existence.

The reviews have provided a valuable overview but some further detail is of interest and may deliver to some of the sub-hypotheses of the thesis listed in Chapter 1. Further investigation of research papers was therefore focussed on the three main themes related to compaction and its avoidance with sub-topics as listed below:

- Soil structure
    - organic matter and nitrous oxide
    - soil strength and bulk density
    - soil pore space, water infiltration and drainage
- Crop production efficiency
    - crop responses to compaction

  - fertilizer and water use efficiency
  - vehicle and implement performance
  - economics
- Practicality of compaction avoidance
  - machinery and farming systems
  - wheel tracks and erosion

2.5. SOIL STRUCTURE

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., 2008). 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, as well as many other aspects that will be covered in the following sections.

2.5.1. Soil organic matter and nitrous oxide

2.5.1.1. Soil organic matter (SOM)

Independent of soil texture, SOM 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, in 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 is the soil structure. In the case of soil compaction therefore, there is a need to know whether it has positive or negative effects on the amount of organic matter contained in the soil.

Reicosky et al. (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, has no effect on organic matter. Jensen et al. (1996) however, working on a silty clay loam, 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 in line with the fertilizer effects discussed later in this document. However, there are specific conditions and instances, such as under trafficked no till, that soil temperature is reduced, water content is increased and aeration reduced (Balesdent et al., 2000). In cool, moist regions these conditions may lead to little difference in conservation, whereas in warm dry, and particularly in warm moist areas, they may lead to a greater loss of organic matter (Balesdent et al., 2000). No till combined with controlled traffic (CTF) improves the situation and thus the potential for conserving SOM (Balesdent et al., 2000). However, on fragile soils in cool, moist climates this may not be enough to prevent a rapid build up in soil strength (Munkholm et al., 2003) that would impact negatively on CO_2 fluxes.

In the review by Holland (2004), more intense cultivation was cited as one of the reasons for the decline in SOM. 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 reduced 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 a similar 13-year trial, but observe that no-till compared with tillage systems only conserves more organic matter when the cropping would result in a positive balance.

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 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.

2.5.1.2. Nitrous oxide

A number of papers deal quite specifically with the effect of soil compaction on nitrous oxide (N_2O) emissions (Sitaula et al., 2000; Ball et al., 1999a, 1999b, 2008; Vermeulen & Mosquera, 2008, Hansen, 2008). All identify poor aeration as the underlying cause of increased emissions from compacted soils. Vermeulen & Mosquera (2009) worked with seasonal controlled traffic systems in vegetable production. This system confined all field traffic to permanent traffic lanes except during harvesting and annual ploughing, the latter used to mitigate compaction in the topsoil. They measured a 20-50% reduction in N_2O emissions compared with conventional practice, all significant at the 5% level (Table 2.4).

Table 2.4. Accumulated N_2O (kg N ha^{-1}) within a seasonal controlled traffic system (sCTF) used for vegetable production compared with that arising from random traffic farming (RTF) (after Vermeulen & Mosquera, 2009)

Crop and year	Measuring period	N_2O	
		RTF	sCTF
Carrot, 2004	14 July – 17 August	1.41	0.86
Spinach, 2005	28 April – 22 June	3.96	2.17
Sown onions, 2004	12 July – 17 August	1.78	1.40
Planted onions, 2005	21 April – 15 July	1.85	1.41

Rochette (2008) reviewed 25 field studies comparing conventional and no-till in relation to N_2O emissions. He concluded that it was poorly aerated rather than well aerated no-till soils that increased emissions, but these conclusions were based on drainage class and precipitation rather than the actual state of soils. Ball et al. (2008) also came to this conclusion but from actual field conditions. They attributed increased and upward emissions to increased water filled pore space, which also impaired the downward movement of N_2O that would be more likely to be converted to N_2. CO_2 emissions were also increased in soils with a higher bulk density but only at low water tension (-1 kPa). Six et al. (2004) in their review recognised the need to improve nitrogen management in no-till systems. In the short term, no-till compared with conventional tillage increased the global warming potential (GWP) and this was only mitigated after ten or more years in humid climates and uncertainly in dry climates after twenty years. Smith et al. (2001) assessed the carbon mitigation potential of European arable land and also concluded that of the 40.4 Tg C y^{-1} that could be sequestered with no-till, there would be 20.5 Tg C y^{-1} equivalent in the form of N_2O emissions.

Summary: effects of compaction on SOM and N_2O emissions

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 occurs, such as with minimum or no till systems, associated compaction has the potential to increase 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.

Confining all wheels or tracks to the minimum area of permanent traffic lanes should help assuage the considerable concern that reduced and no-tillage systems will increase CO_2 equivalent emissions, particularly with respect to nitrous oxide. There may be an elevated risk of emissions from the relatively small area of permanent traffic lanes if these are not managed appropriately. Quantification of the benefits of reduced compaction in terms of nitrous oxide emissions may be possible through the use of well developed models, employed in conjunction with measured contrasts in water filled pore space between trafficked and non-trafficked soils.

2.5.2. Seedbed quality

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 soil 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. 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. Equally, 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.

Campbell et al. (1986) and Dickson & Ritchie (1996) 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. 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.

Summary – seedbed quality

Soil compaction was found to increase the tensile strength and size of individual aggregates and thus reduce the aggregate size distribution and ultimately the heterogeneity of the soil components. Compaction produced coarse platy aggregates and a massive structure (few fissures and inter-particulate pores). Different types of tillage in the presence of excessive compaction tend to result in a similar outcome. Greater cloddiness is an underlying feature of compacted soils and therefore seedbed and rootbed quality are more assured under a controlled traffic regime.

2.5.3. Soil strength and bulk density

Table 2.5 lists a cross section of results from the research investigating changes in soil physical properties due to different traffic loads and intensities. Most records showed an increase in strength-related properties due to traffic, but some were moderated by differences in initial conditions (e.g. bulk density), soil moisture content and to a lesser extent soil type. (Anticipated improvements from additional SOM were not well tested). Yavuzcan (2000) for example noted that the effects of traffic were less noticeable under a chisel plough, where strength was greater initially, compared with a plough regime. This is reflected by Hamlett et al. (1990) who introduced traffic following ploughing and although not using high wheel loads, found that repeated traffic increased bulk density by 27% and penetration resistance by 100% compared with the condition post ploughing. Horn et al. (2003) investigated the effect of repeated passes on a Stagnic Luvisol (FAO, 1988) in a bin at the NSDL in Auburn. Repeated loading with up to 5.5 Mg continued to increase bulk density in the 35-39 cm depth layer in the range 0 – 10 passes and increased the degree of saturation in this layer from 61% to 89%. Lamandé & Schjønning (2010a) compared the effects of two loads (30 and 60 kN) and 560 and 800 mm wide tyres inflated to rated pressure on a non-disturbed soil ploughed 18 months earlier. At field capacity, stresses were dominated by inflation pressure near the surface and by wheel load at 0.9 m depth.

Meek et al. (1992) working on a coarse loamy sand confirmed the vulnerability of deep loosened soil to compaction. They introduced simulated wheel loads of 2.7 Mg, which increased bulk density by 10.5% to 0.35 m depth and re-compacted the soil to at least 0.65 m, about 0.15 m below the original loosening (see also Chapter 5). In a similar vein, Meek et al. (1988) aimed to differentiate the effects of harvest wheel loads on no-till and soil cultivated to 150 mm depth. They found that soil bulk density to 150 mm depth increased with up to five passes but ten passes were needed to reach equilibrium at 250-500 mm depth. There was no detectable difference in effect with tillage treatment. Similarly, Unger (1996) noted that increases in bulk density and penetration resistance within no-till and conventional tillage (discing and disc bedding) production systems for wheat and grain sorghum on a clay loam, were confined to traffic zones, not tillage method. The author concludes that non-trafficked zones can reduce the potential for adverse physical conditions under irrigation and no-till. Botta et al. (2008) also considered the effects of different wheel loads and ground pressures within no-till and

Table 2.5. Summary of the effect of traffic on either bulk density (bd, % or Mg m-3), penetration resistance (pr, % or MPa) or vane shear (vs, %) for a range of soils, depths, wheel loads and the percentage area of the ground covered by wheelings.

Country	Soil	Depth, cm	Max. wheel load, Mg	Tillage type	% area covered by wheels	Parameter	Comparative values		Paper
							Trafficked	Non-trafficked	
Turkey	Unknown	0-5	1.1	MP[4]/CP[5]	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.	Conv/no-till	100	pr	1.23	1.13	Unger, 1996
USA	Clay loam	0-60	9.0	MP	na	bd	+0.15		Johnson et al. 1990
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.	MP	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	MP	115	pr	113%	100%	Blackwell et al. 1985
UK	Evesham clay	0-45[2]	3.25	CP	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	No-till/CP	Conv.	bd	0.782	0.722	Chamen et al., 1992a
		20+	3.25		Conv.	pr	182%	100%	
UK	Evesham clay	0-45	3.25	MP	Conv.	pr	135%	100%	Chamen et al., 1990
		0-40	3.25		Conv.	bd	106%	100%	
UK	Sandy loam	10-15	Vibratory roll	No-till	100	bd	1.78	1.34	Pollard & Elliott, 1978
		20	Vibratory roll		100	pr	2.5	1.75	
CA, USA	Sandy loam	15-45	2.7	Tine	100	bd	1.82	1.65	Meek et al., 1992
Australia	Vertisols/Red Earths	5-25	Conv.	MP	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	Tine	100	vs	170%	100%	Radford & Yule, 2003
			(1x5) then 3						
		18-33			100	vs	113%	100%	

[1] Loosened wheelway; [2] Date one; [3] Date two [4] MP – mouldboard plough; [5] CP – chisel plough

conventional tillage regimes on a silty clay loam soil. Other than a greater susceptibility to subsoil compaction within the conventional tillage regime, tillage had no effect, but they concluded that wheel load was the dominating factor in subsoil compaction and was independent of ground pressure. However, topsoil compaction in terms of bulk density, cone resistance and rut depth was directly related to ground pressure. Ansorge and Godwin (2007) also found a significant reduction in adverse effect as contact pressure was reduced and particularly if this was achieved with a larger diameter rather than a wider tyre. Jorajuria et al. (1997) compared two tractors having an equal contact pressure but one with a mass of 4.2 Mg and the other just 2.3 Mg. For a given number of passes, the heavier tractor always produced greater increases in bulk density, but the lighter tractor was capable of causing just as much compaction with additional 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.

Botta et al. (2006) also found that multiple passes with a lighter tractor (1 Mg maximum wheel load) had serious consequences in direct drilled topsoil, rendering it unsuitable for seedling emergence. With 10 – 12 passes of this tractor compaction effects (increases in penetration resistance and bulk density) reached to 600 mm depth in the same profile. Diaz-Zorita & Grosso (2000) also working in Argentina found that the susceptibility of soils to compaction was reduced when organic carbon levels were elevated, regardless of soil textural class in the range loamy sand and loam to silty loam. Carter et al. (1991) measured a significant increase in penetration resistance on a coarse loamy sand in California when traffic was applied. Working on fragile soils on flood irrigated land they measured reductions in bulk density and penetration resistance with controlled traffic and also observed that these soils did not consolidate when flood irrigated in the absence of traffic.

The persistence of soil compaction on sandy loam soils was demonstrated by Pollard and Webster (1978) using concrete tracks to support traffic loads. The soil was initially loosened to 250 mm depth (Pollard & Elliott, 1978) and then compacted in layers from 170 mm depth upwards by a vibratory roll at a moisture content appropriate for maximum compaction. Two years later the concrete tracks were again used to thoroughly loosen the soil to 250 mm depth, following which bulk density measurements were conducted. These showed a 10% greater density ($P<0.05$) on the compacted soil between 200 and 300 mm depth compared with the non-compacted control. Chamen & Cavalli (1994) working on an 80% clay soil to determine the cause of an 18% reduction in mole plough draught found large differences in penetration resistance on trafficked compared with non-trafficked soil in both moist and dry conditions, but differences in bulk density were only apparent in moist conditions (Table 4). This was almost certainly due to the high shrinkage coefficient on this Evesham clay soil.

Bennie & Botha (1986) studied the effect of introducing controlled traffic following deep loosening after plough and tine cultivation using random traffic. Penetration resistance was reduced by over 60% but bulk density by only 6%. Loosening of the controlled traffic lanes after planting resulted in an intermediate effect but was beneficial for crop rooting (see section on crop responses). Boydell and Boydell (2003) working on a commercial farm noted changes in bulk density after the farm had been in controlled traffic for four years and where the original traffic operations had compacted 40% of the area on an annual basis. The maximum reduction in bulk density (11%) was experienced at between 250 and 500 mm depth. McHugh et al. (2003) investigated how long it would take a Vertisol to recover from 50 years of conventional farming with random traffic. After three years with no traffic and a rotation of winter cereal, a legume and lablab, cone penetration resistance had fallen from greater than 2 MPa to between 0.2 and 1.0 MPa in the depth range 0-400 mm and at the same moisture content. Stewart and Vyn (1994) carried out some similar research on a London loam soil with a 60% silt content. The effect of zero tillage and autumn chisel and mouldboard ploughing (both to 18 cm depth), in conjunction with the annual post harvest application of 6 Mg wheel load to 100%, 25% & 0% of the plot area was investigated. Soil bulk density, penetration resistance and maize yields were studied for 3 years on a site where maize had been grown continuously with ploughing and annual manure application for the previous 7 years. Zero traffic was achieved with a wide span tractor (FPU) but a plot combine of less than 4 Mg axle load was used to harvest these and the other plots. The plots receiving the 6 Mg wheel loads received loads from other machines during normal cultural operations, but the axle load of these did not exceed 5 Mg. Surprisingly, only in the third year was there any consistent evidence that bulk density had been reduced by zero traffic and only in the 50-100 mm depth profile but little is reported about the extent of the harvest traffic. This suggests that unlike the Vertisol studied by McHugh et al. (2003) this silt soil had little natural ability to reduce its density when traffic was removed. Cone resistance, in contrast, was consistently and significantly lower under the zero traffic treatment in the 0-200 mm depth profile. This contrast in bulk density and cone resistance response to applied traffic was also seen in experiments by Taboada et al., (1999) where no-till was compared with conventional tillage. Cone resistance on a sandy loam and on a silt loam rose by factors of 5.5 and 1.7 respectively while there was no detectable difference in bulk density.

Graphing of research data from Table 1A of Appendix A

As mentioned in the Introduction, a large number of papers were investigated, particularly in terms of bulk density and penetration resistance and results were tabulated in a spreadsheet. This information is too extensive to be included here, but the relevant worksheets have been copied and are shown in the Appendix A, Tables 1A - 3A, while Figs 2.3-2.5 provide an overview. In terms of bulk density, there is a limited trend towards an increase with wheel load in the 0-0.2 m profile, suggesting many other factors that seem to have had a stronger influence, for example contact pressure and soil moisture content and unfortunately these data are not consistently provided. In addition for both the bulk density and the PR data, some include operations in moist conditions, on ploughed and non-ploughed soils and up to ten machinery passes, which gives some plausibility to the large percentage changes indicated with relatively low wheel loads. There is even less

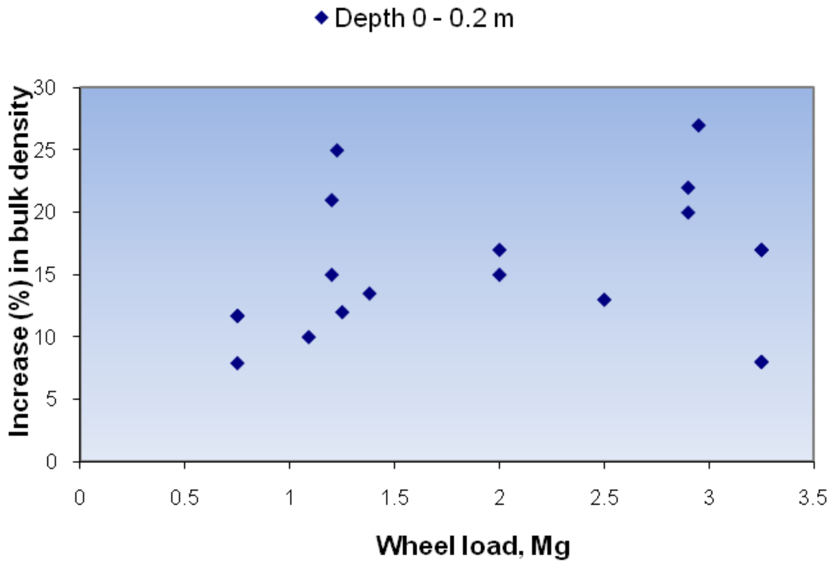


Fig. 2.3. Change (%) in bulk density with different wheel loads across different cropping systems and soils in the depth range 0 – 0.2 m.
(see Table 1A of the Appendix for sources)

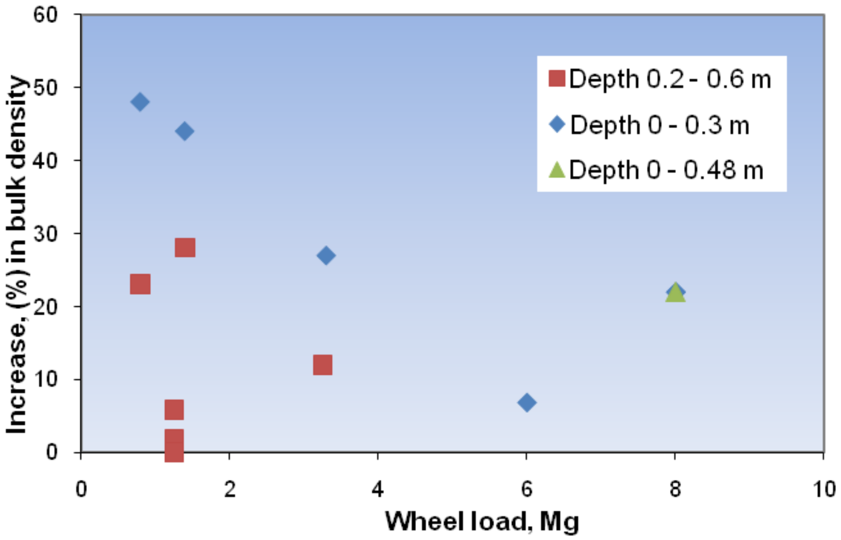


Fig. 2.4. Change (%) in bulk density with different wheel loads across different cropping systems and soils in the depth range 20-60 cm.
(see Table 1A of the Appendix for sources)

consistency as far as the penetration resistance data are concerned (Fig. 2.5), with responses being almost random when plotted against wheel load. As most of these data are derived from the same experiments as those for bulk density this is perhaps not surprising, particularly if one considers the close relationship between bulk density and penetration resistance afforded by Ghildyal and Tripathi (1987). They attribute soil strength (in the static sense) to the resistance to increase in bulk density and thus the force required to displace particles. The factors that affect the stress-density relationship are water content, particle size distribution, fluid polarity, cation species and its concentration and the clay mineral involved. Ghildyal and Tripathi (1987, page 134) show a clear linear relationship between the energy of penetration resistance and bulk density with strength increasing at a given moisture content in a given soil.

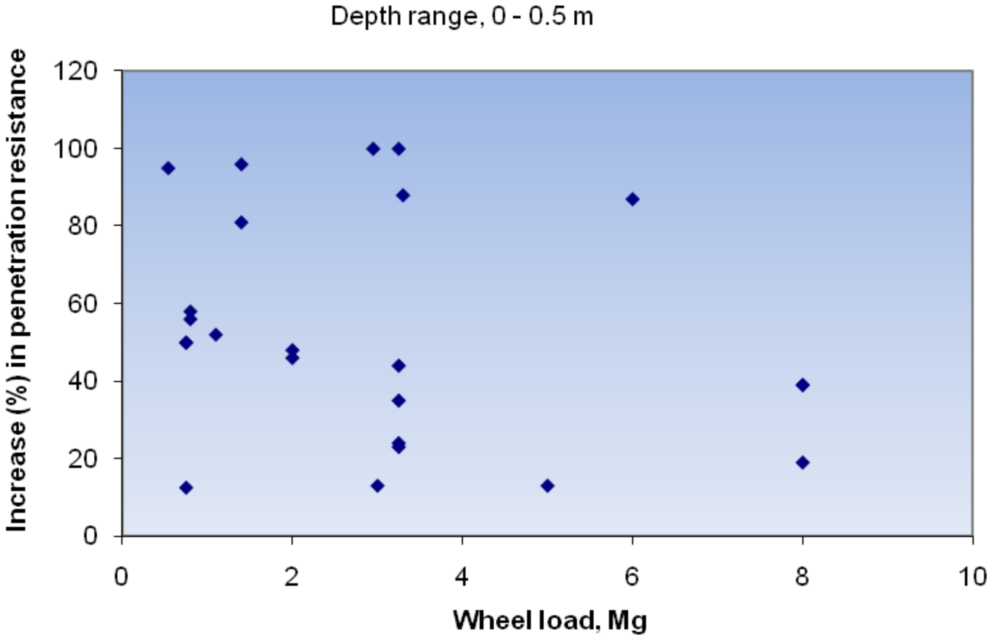


Fig. 2.5. Change (%) in penetration resistance with different wheel loads across different cropping systems and soils in the depth range 0.2 – 0.5 m.
(see Table 1A of the Appendix for sources)

Summary – soil strength and bulk density

Almost exclusively, research showed that bulk density increased as a result of imposed wheel loads rather than naturally, even when flood irrigation was involved. This suggests that susceptibility and vulnerability of soils are key factors that determine the level of damage rather than wheel loads per se. This is unsurprising given that responses rely on initial soil condition, the ground pressure of the applied loads and the soil water content, few of which were constant between soil types. Depth of effect is also determined by these factors and is particularly increased by subsoil loosening and by high wheel loads. Although heavier vehicles cause greater stresses in the soil per pass, lighter vehicles when used repeatedly can cause just as much damage. There was some evidence to suggest that high wheel loads can damage the subsoil even when this has a high pre-compression stress and the soil above it is dry.

2.5.4. Pore space, water holding capacity, infiltration and drainage characteristics

The size range, distribution and interconnectivity of pores within the soil are the basis for all water and air movements within the profile. There is probably no one ideal pore structure that is optimum for crop growth and soil function but rather a range outside which these aspects are negatively influenced. Of increasing importance across the globe is achieving a soil structure that maximises crop water use efficiency (see GAEZ study) and papers on this aspect will be explored in particular as well as those providing evidence or not of traffic effects on pore structure.

In terms of water use efficiency (WUE, defined as biomass or grain yield per unit of evapotranspiration), Radford et al. (2001) applied compaction annually over five seasons with treatments consisting of 10 and 6 Mg axle loads on a wet Vertisol following an initial compaction with a 10 Mg axle load. Compared with a control receiving neither the initial nor the annual loads, maize grown in the fifth year of the trial was most affected by the 10 Mg load with its WUE being reduced from 14.3 to 9.7 kg ha^{-1} compared with the control. Bennie and Botha (1986) carried out a more extensive trial with maize and wheat on an irrigated fine sandy soil in South Africa. Their treatments consisted of:

1. 250 mm deep mouldboard ploughing, harrowing and tine cultivation with random traffic.
2. was as 1, except that deep loosening to 400 mm followed the first harrowing and all subsequent operations were with controlled traffic.
3. was as 2, except that the compacted traffic lanes were deep ripped after planting.

Irrigation was applied with a high density micro-jet at 200 mm h^{-1} at 50% plant available water. Rooting depth was determined every 2 weeks by identifying the deepest visible root. Their results suggested that deep ripping and controlled traffic (treatments 2 & 3) led to a significant increase in total cumulative evapotranspiration (ET) and WUE for both crops compared with treatment 1. Table 2.6 provides an outline of their results. Interesting to note here were their data for the loosened wheel tracks, which were more in line with treatment 2 than treatment 1, suggesting that repair of the traffic lanes with no further compaction had been very beneficial.

Boydell & Boydell (2003) working on a vertisol compared a random traffic system (which tracked around 40% of the field area annually) with a controlled traffic system. Plant available water (a probable indicator of WUE) on the non-trafficked soil was around 6% greater while effective infiltration rose by 84% in the top 0.5 m of the soil profile.

Table 2.6. Cumulative evapotranspiration (ET) and water use efficiency of crops grown with random and controlled traffic following ploughing and deep loosening (after Bennie & Botha, 1986)

	Maize				Wheat			
Treatment	1[1]	2[2]	3[3]	LSD p=0.05	1	2	3	LSD p=0.05
Water applied, mm	781	845	839	50	694	724	721	ns
Total cumulative ET, mm	682	752	742	43	570	638	642	36
Water use, kg seed $ha^{-1}mm^{-1}$	9.4	11.4	10.8	1.1	6.8	8.7	8.4	0.9
Water use, kg seed $ha^{-1}mm^{-1}$ ET	10.8	12.8	12.2	1.1	8.3	9.9	9.5	0.8
Seed yield, Mg/ha	7.4	9.6	9.1	1.1	4.8	6.3	6.1	0.6

[1] 250 mm deep ploughing and cultivation with random traffic

[2] As 1, except 400 deep loosening followed the cultivation and all subsequent operations were with CTF

[3] As 2, except the traffic lanes were deep ripped after planting (see main text)

Sadras et al (2005) also working in Australia, but in a Mediterranean climate on a sandy loam soil, concluded that reduced growth of crops grown in compacted soil is related to a reduced ability to capture resources (particularly as a result of reduced rooting of the crop), rather than reduced efficiencies. Ishaq et al. (2001) measured the WUE of wheat on a sandy loam soil with compaction imposed at 150 mm depth to simulate subsoil compaction. In consecutive years efficiency was reduced by 22% and 14% with similar reductions in nutrient use efficiency but grain yield reductions of 38% and 8% respectively. Bai et al. (2009) reported on the same trial as Qingjie et al. (2009) after it had been in place for nine years. During this time water infiltration was around 67% greater on the no-till full residue controlled traffic system and this provided around 15% more water in the top 130 mm of the profile compared with the traditional random traffic and tillage system. Zhang et al. (2006) used a modelling approach to determine the effects of compaction, fallow length and mulching on the WUE of wheat grown on the Loess Plateau in China. Using an increase in bulk density of 20% in the 0-450 mm profile, they found that compaction resulted in the lowest WUE of all the treatments, largely as a result of increased evaporation of water from the soil surface. Conversely, mulching provided the highest WUE. Related to this were the results of Li et al. (2001) who found that residue cover greatly enhanced water infiltration, particularly in the presence of controlled traffic, which is a positive pre-cursor for improved WUE.

Although Blackwell et al. (1985) did not measure WUE per se, their well planned and documented study provides a wide range of detailed information about traffic effects on a clay soil of the Lawford series (Hodge et al., 1984 page 359). Following deep loosening to 350 mm depth and a crop of winter oats in which no wheelings were applied, winter crops were established by direct drilling. Compaction treatments were applied for the first two years of the four year trial using maximum wheel loads and tyre inflation pressures of 30.1 kN and 220 kPa respectively. Wheels were run side by side with an overlap of 15% in soil moisture conditions where the matric potentials varied between -16.1 and -3.0 kPa. Results showed that:

- Air filled porosity of the wheeled soil was 5% v/v less than the non-wheeled soil on all occasions of measurement. These differences were less below 200 mm depth.
- Overwinter, the wheeled soil had a tendency to become less dense, whereas the non-wheeled soil increased in density, but from a lower base level.
- The air permeability just below seed depth in the wheeled soil was about 3 times less than in the non-wheeled soil.
- There were around 3.5% & 4% more macropores (>60µm) in the non-wheeled soil at 150 & 250 mm depth respectively but 2% more in the wheeled soil at 50 mm, all deduced from water release characteristics.
- Free water was more commonly detected in the compacted soil, particularly in the depth range 50–250 mm.
- Differences in mean redox potential suggested the volume of poorly aerated soil was greater on the wheeled soil. At 150 mm depth, redox potential on the non-wheeled was around 300 mV greater than on the wheeled soil but these differences varied during the growing season.
- The thermal time above 0^0C was less for the compacted soil but this was not consistent with time. Wheeled soil tended to both cool and warm more rapidly than non-wheeled soil.
- The redox potentials were often low enough to permit denitrification, especially in the wheeled soil.
- Water release characteristics showed some advantage to the crops on the compacted soil (3% v/v more water available at 25 cm depth)

These data provide consistent evidence of greater aeration in the non-wheeled soil and importantly, less tendency for it to waterlog. The small increase in macropores at the surface on the wheeled soil may have been a fracturing effect of the lugs on the tyres. The thermal characteristics tend to support these data through the greater insulating properties of more air in the profile. Wagger and Denton (1989) found similar contrasts on a fine sandy loam soil growing maize, with total porosity in tracked areas being 21% less than non tracked and saturated conductivity some 90% less. These researchers were also some of the very few who recorded bulk densities greater than 1.7 Mg m^{-3}, which occurred in the trafficked inter-row. According to Beylich et al. (2010), discussed earlier, this is likely to impact negatively on soil biota. Meek et al. (1989) were also in this category on a coarse sandy loam, which even without traffic, reached a bulk density of around 1.7 Mg m^{-3}. With traffic, these values increased further, especially in the top 300 mm of the soil profile. Qingjie et al. (2009) compared controlled traffic using no-till and shallow tillage for wheat, both with full residue cover, with random traffic traditional tillage and partial residue cover. In addition to lowered bulk density in the 100-200 mm profiles of the controlled traffic systems, there was also an average 9.4% increase in soil water content in the 0-150 mm profile.

Chamen & Longstaff (1995) determined that hydraulic conductivity at 0.8 m depth was just 12 mm day^{-1} on a clay soil that had been regularly trafficked with 3 Mg wheel loads compared with 30 mm day^{-1} where all traffic had been avoided for four years. Alakukku (1996) also working on a clay soil found that passes with wheel loads of around 4.5 Mg could still be detected nine years after the event by up to 98% reduction in saturated hydraulic conductivity and 70% reduction in macroporosity (pores >300 µm) at 0.4-0.55 m depth.

An indication of improved drainage on non-trafficked beds was provided by Hamilton et al. (2003) who reported no waterlogging compared with trafficked soil alongside. Li et al. (2001) working within a typical grain production system, also in Australia on a similar soil, measured the impact of a 2 Mg wheel load on a soil that had been in no-till and no traffic for five years. This wheel traffic significantly reduced the time to ponding, the steady infiltration rate and the total infiltration compared with non-wheeled soil, regardless of residue cover. Non-wheeled soil had 4-5 times greater infiltration rate than wheeled soil and the residue cover had a greater and more positive influence on infiltration. Rohde and Yule (2003) show similar effects on a cracking clay but also record soil loss, which with repeated annual compaction and some tillage, was double that resulting from no-till and controlled traffic. McAfee working in Sweden on a clay applied 0.5 to 1 Mg wheel loads with a maximum inflation pressure of 200 kPa prior to sowing spring oats on soil ploughed the previous autumn. Total porosity of the soil was reduced by 6%, mostly through a loss of pores >60 µm, while water retention was increased and soil oxygen decreased, the latter to a level that was considered likely to reduce crop growth. Air permeability on the compacted plots was up to 190 times less in the 100-150 depth layer than that on the non-compacted plot. These conditions led to slower drying of the topsoil in the spring and quicker wetting up in the autumn.

Schäfer-Landefeld et al., (2004) compared the effect of high axle loads (15-25 Mg) applied to the soil surface on fields which exhibited severe plough pans from decades of ploughing. Covering 100% of the area or more, these loads reduced the air capacity in the 150-200 cm deep soil profile by an average of 57% in the range 17.5 to 2.8 m^3 100 m^{-3}. Air permeability was reduced significantly on seven out of the ten sites studied and by an average of 88%. On most sites the subsoils exhibited only minor changes but at one site which had been subsoiled a year earlier using rigid tines fixed beneath the plough shares, signs of severe compaction were evident. The author's conclusion that "this study produced little evidence of widespread and pronounced subsoil damage due to traffic with heavy farm machinery with axle loads up to 20 Mg" seems to have courted some controversy. In a letter to the Editor from Ehlers et al (Soil & Tillage Research, 80: 251-254) it is pointed out that although changes at subsoil depth (380-430 mm depth) were small, they were significantly detrimental in terms of air permeability (5 cases), bulk density (4 cases) and air capacity (2 cases). The correspondents suggest that in some important respects Schäfer-Landefeld et al.'s article is misleading and perpetuates the view that these types of machines uphold the standards related to soil quality, whereas they go against the innovative soil protection law enacted in Germany in 1998. This raises the issue of permanent traffic lanes which will be discussed in a later section in the thesis. Schäfer-Landefeld et al.’s study was followed by further work reported by Koch et al. (2008) in which sugar beet harvester wheel loads of around 10 Mg were applied side by side over three consecutive years in the presence of mouldboard plough and shallow mixing tillage. Incidental to the treatment compaction was other equipment with maximum wheel loads of 5 Mg which traversed the plots as required by cultural operations, including a combine harvester which travelled at right angles to the direction of the compaction traffic. As might be expected there was relatively little contrast in the penetration resistance between the treatment wheeled and non wheeled plots, except in the 150-250 mm profile when the wheeled plots exhibited a higher resistance. The largest contrast was between ploughing and shallow mixing tillage, with the ploughing exhibiting a low resistance to around 350 mm, below which there was no consistent difference between the force traces. Of the other measures, which included air filled pore volume and biopore numbers, only air permeability showed any consistent trend and this was elevated on the non-treatment wheeled plots at most depths in the profile, but particularly from 0.4 to 0.6 m under both tillage treatments.

Ankeny et al. (1990) provide a range of infiltration measurements on a silty clay loam in Iowa, taken within and without the trafficked inter-rows of a maize and soybean rotation (Table 2.7). These data are from quite extreme traffic conditions but of particular interest are the large contrasts even under no-till where the traffic intensity is likely to have been modest. The most significant data probably relate to zero tension which is likely to occur during prolonged rainfall and could mean the difference between severe run-off or none. However even the highest infiltration rates measured here equate to little more than 1 mm h^{-1} and are therefore unlikely to be able to withstand other than very low intensity rain before run-off occurs. Hamlett et al. (1990) also working in Iowa, but on a silt loam record greater infiltration on soil not trafficked after ploughing (870 mm h^{-1}) compared with 30 mm h^{-1} following compaction with a 5.9 Mg and a 2.7 Mg tractor.

Still on the theme of assessing the effects of traffic on ploughed soils, Campbell et al. (1986) considered both this condition and also the effects under direct drilling. Working in Scotland on an imperfectly drained sandy clay loam they found that wheel by wheel compaction (followed by light tillage, other than with the direct drilled treatment) with up to six passes of a relatively light tractor caused transient water-logging of the soil after just two passes of the tractor. This occurred on both the ploughed and direct drilled soil but the latter technique was found to be suitable in the absence of traffic despite this soil being classified as unsuitable for direct drilling.

Lamers et al. (1986) in their classic experiment on controlled traffic farming in the Netherlands, measured saturated water permeability in their light clay soil. Permeability on the non-trafficked soil was 3 m day^{-1} compared with 1.5 m day^{-1} on the trafficked soil with similar contrasts in the oxygen diffusion rate at 120-170 mm depth. Pore space was also around 7% greater on the non-trafficked soil, a slightly greater contrast than the 4% increase with a similar experiment on a loam. Vermeulen & Perdok (1994) report an average 35% increase in topsoil air-filled porosity in non-trafficked compared with conventionally trafficked soil. This compares with an average increase of just 3% with a low ground pressure system imposing surface pressures averaging less than half those imposed by the conventional system. Vermeulen & Perdok's inflation pressure limit for low pressure traction tyres was 80 kPa, which would allow around 5 Mg to be carried on a 900 mm wide tyre (Michelin, 2007).

In a synthesis of research reported by Chamen et al. (1992b) which involved a range of tillage and traffic treatments from four sites across Europe, there was an almost universal increase in pore space on the non-trafficked soils which ranged from sandy loam to clay (Table 2.8).

Table 2.7. Unconfined infiltration on a silty clay loam from trafficked and non-trafficked inter-rows within a maize and soybean rotation (after Ankeny et al., 1990).

Treatment	Tension, mm H_2O	Infiltration µm s^{-1}	CV rate, %
Non-trafficked, no-till	0	232.5	47
	30	53.2	46
	60	31.5	35
	150	9.6	35
Trafficked, no-till	0	22.5	53
	30	6.7	35
	60	4.7	37
	150	3.1	31
Non-trafficked, chisel	0	292.6	44
	30	53.8	21
	60	34.4	16
	150	12.5	28
Trafficked, chisel	0	9.8	65
	30	4.4	46
	60	2.9	37
	150	2.2	32

Table 2.8. Summary of the range of differences in pore space in non-trafficked soil relative to conventional traffic and tillage (100%) (after Chamen et al., 1992b)

Crop	% soil pore space, v v^{-1}
Cereals	98–116
Sugar beet	105–110
Potatoes	107
Ryegrass	112

McHugh et al. (2009) working on a vertosol (vertisol) studied its natural amelioration after conversion to a no-till controlled traffic system following over 50 years using traditional traffic and tillage. Within four years, available water capacity rose from 10.2 mm to 15.4 mm per 100 mm depth, bulk density decreased from around 1.40 to 1.25 g cm^{-3} at 100 mm depth while macropore density improved by up to 50% from marginal values. This natural amelioration of swelling/shrinking clay soils was also experienced on a Hanslope clay, results of which are reported elsewhere in this thesis. However, the timescale for amelioration at depths greater than 200 mm were likely to take at least five years as also reported by McHugh et al. (2003).

Of particular interest is the paper by Pagliai et al. (2003) who compared the effect of one and four passes of a rubber tracked and a four wheel-drive tractor on soil which had been mouldboard ploughed to 400 mm depth (this is Italy!) and lightly harrowed three months prior to the treatments being applied. Moisture content at the time of compaction was 30% (dry basis) on a clay soil classified as a Vertic Cambisol. The maximum load on the wheels was 765 kg with a corresponding contact pressure of 60 kPa. The tracked vehicle weighed 3.08 Mg total and exerted an average pressure of 35 kPa. Macroporosity in the 0–100 mm layer decreased from around 36% under the control to 16% following one pass of the 4-wd and to around 7% following one pass of the tracked vehicle. Four passes reduced each of these values by around one third. In the 10–20 cm profile, porosity was not decreased significantly by one pass of the wheeled tractor from the 13% of the control, but was significantly reduced by a single pass of the tracked vehicle and by four passes of both vehicles.

Summary – soil pore space, water holding capacity, infiltration and drainage characteristics

On all soils compaction had a detrimental effect on the infiltration of water. Without wheel compaction, infiltration increased by 84 to 400% alongside increases in plant available water. In greater weather uncertainty, this not only reduces the risk of flooding, but also enhances rainfall interception where the risk of drought is high.

The most important and generally deleterious effect of subsoil compaction is a reduction in hydraulic conductivity. On clays, loams and organic soils, wheel loads of 4 to 5 Mg can reduce saturated hydraulic conductivity in the 0.4–0.5 m profile by as much as 98%. On sandy loams, these detrimental effects can by induced by much lower axle loads. Heavily compacted topsoils can experience a 4-5-fold decrease in saturated hydraulic conductivity. Raised beds with controlled traffic have overcome winter waterlogging problems and significantly improved access and timing for spring cropping.

Decreased infiltration and conductivity lead to increased rainfall and irrigation runoff (44% greater) from both surface and subsurface flow. The further consequence, and as reported by a number of studies, is an increase in soil erosion, soil loss and transport of nutrients and applied chemicals (40% less with zero traffic & soil cover). Off-farm and catchment level consequences of these pollutants, whose concentration with controlled traffic were also up to 30% less, are increased costs of potable water supplies and danger to health.

Water use efficiency by crops may be reduced by compaction as a result of impaired rooting, both in extent and depth.

Excessive traffic necessitates excessive tillage, and tillage is the main cause of water loss from seedbeds. Dry seedbeds delay crop germination and growth and as a result, reduce crop yields. Excessive tillage can also exacerbate infiltration problems due to a higher percentage of fine aggregates.

Vehicle-induced compaction universally reduced the porosity of soils. This occurred particularly in moist conditions and through a reduction in macropores (up to 70% at 0.5 m depth). Typically the reduction in pore space 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 for crop growth largely as a result of reduced oxygen diffusion and relative diffusivity. Controlled traffic can therefore provide more favourable conditions for no till.

2.6. CROP PRODUCTION EFFICIENCY

2.6.1. Crop responses

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 will be considered elsewhere, but the energy (including time) factor will be addressed under the section on machinery.

The reviews considered earlier provided extensive evidence of the almost universal negative influence of compaction on crop yields but also suggested a relationship between soil compaction and crop yield that may be described by an optimum curve (Boone & Veen, 1994). Many of the papers on the subject were cited in those reviews, but further have been published in the intervening years, some of which are considered here.

Of particular importance when assessing yield responses to CTF systems is the comparison when conducted in the presence of no-till because many farmers adopting controlled traffic systems also adopt no-till, or something very close to it. Unfortunately there is a dearth of literature that addresses this very particular comparison, so to gain some insight into the effect of no-till, literature including trafficked situations has been included separately in this section.

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 Tables 2.9a&b summarise the relevant yield data in as simple a form as possible. More detail is given in Tables 2A and 3A of Appendix A.

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., 2002a; 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. Alakukku & Elonen (1995) carried out a trial of this nature comparing the effect of a tandem axle load of 19 Mg in year 1 on a clay soil (Vertic Cambisol, FAO, 1988) with no treatment traffic. Effects on spring cereal yields averaged over the following nine years was a 1% reduction following a single pass of the load in year 1 to a 4% reduction due to four passes. These reductions were attributed to subsoil damage. Some mitigation of these wheel load effects was possible by reducing ground pressures, as reported by Vermeulen & Perdok (1994). Crops showed yield increases of between 1% and 6% compared with conventional practice but not as great as zero traffic, which, other than for wheat, increased yields by between 8% & 10%. For wheat, a reduction of 3% was recorded suggesting that the soil condition was sub-optimal. In contrast, Graham et al. (1986) recorded a 6-7% increase in wheat yield due to low ground pressure traffic compared with conventional and zero traffic on a silt loam soil.

Li et al. (2007) working in Australia on a vertosol (vertisol) that had not been trafficked for twelve months, assessed the effect of a single annual pass of a 100 kW working tractor imposing a wheel load across the entire plot of around 2.2 Mg with tyres at an inflation pressure of 100 kPa. Yield of summer crops (sorghum, maize and sunflower) averaged 7.3% more where there had been no wheelings. A similar comparison with winter crops returned an average yield increase of 12.2%.

Table 2.9a. 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[2], loam[2], sandy loam[3], loam[3]	UK, NL, Scot., D	Chamen et al., 1992b
Wheat	119	Profile: fine sand of Annandale series	South Africa	Bennie & Botha, 1986
Wheat	118	Profile: clay[2]	UK	Chamen et al., 1992a
S. Barley	116	Profile: clay[2]	UK	Chamen et al., 1994
Wheat	126	Profile: clay[2]	UK	Chamen & Longstaff, 1995
Wheat	100	Profile: silt loam[4]	UK	Graham et al., 1986
Wheat	136	Raised beds: sands, loams[5]	Australia	Hamilton et al. 2003
Barley	144			
Oilseed rape	133			as above
Wheat	120	Profile: clay loams[2]	USA	Voorhees et al., 1984
Maize	127			
Soybean	119			as above
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[5]	Australia	Radford & Yule, 2003
	125	Subsoil: clay[5]		as above
Cereals & grain legumes	112	Profile: Red Brown earth[5]	Australia	Sedaghatpour et al., 1995
Wheat	100	Profile: clay[5]	Australia	Radford et al., 2000
Barley	124–162	Subsoil: sandy loam[4]	UK	Pollard & Elliott, 1978
Cereals	105–115	Profile: various	Ukraine	Medvedev et al., 2002a
Cereals	82–130	Profile: various	Poland	Lipiec, 2002
Oats	141	Profile: clay	Sweden	McAfee et al., 1989

[1] See text: [2] Soil Survey Staff, 1999: [3] FAO, 1988: [4] SSLRC, 1997 [5] Stephens, 1953:

Table 2.9b. 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
Oilseed rape	190	Profile: sodic clay[5]	Australia	Chan et al., 2006
Spring cereals	120–126	Profile: clays	Sweden	Håkansson et al., 1985
Spring barley	119	Profile: gley[6]	Scotland	Dickson & Ritchie,
Spring osr	125	Profile: gley[6]		1996b
Winter barley	115	Profile: gley[6]		ditto
Cereals	114	Profile: clay[5]	Australia	Tullberg et al., 2001
Spring cereals	105	Subsoil: clay[3]	Finland	Alakukku & Elonen, 1995
Average from Tables 2.9a and 2.9b	**122**			

[1] See text: [2] Soil Survey Staff, 1999: [3] FAO, 1988: [4] SSLRC, 1997 [5] Stephens, 1953: [6]gley, a waterlogged grey colour soil lacking in oxygen

In a seven year trial in China, Qingjie et al. (2009) compared controlled traffic using no-till and shallow tillage for wheat, both with full residue cover, with random traffic traditional tillage and partial residue cover. In addition to improved soil properties they measured a 6.9% increase in wheat yield compared with the traditional system. Bai et al. (2009) reported on the same trial as Qingjie et al. (2009) after it had been in place for nine years. During this time the mean yield of wheat was around 11% lower from the traditional system. It is possible to assess the effects of no-till and shallow tillage in the presence and absence of traffic from the work of Chamen et al. (1990). In their Table 7, no-till yields in the presence of normal and low ground pressure traffic were reduced by an average of 2% compared with shallow tillage whereas in the absence of traffic they increased by just over 1%. These differences were not significant but could indicate a trend over four years. Reintam et al. (2009) assessing the effects of soil compaction on spring barley used a 4.84 Mg tractor to apply one, three and six passes track by track across each plot. Most effects were experienced with six passes, resulting in an 80% reduction in barley yield in the first year after the single compaction events, around 60% in the second year and no detectable difference by year three. Recent work by Whalley et al. (2008) and Whitmore et al. (2010) suggested a negative trend in wheat yield as soil strength increases, regardless of whether the increased strength arises from compaction or drying.

Koch (2009) reports on a long term experiment with sugar beet looking at the effects of harvester wheel loads of 11.7 Mg on subsoil compaction while other loads were applied during normal cultural operations, including mouldboard ploughing to 300 mm depth.

The loads were applied in a sequence of three years and Fig. 2.6 shows the results from four measurement dates on each of the artificially created “fields”.

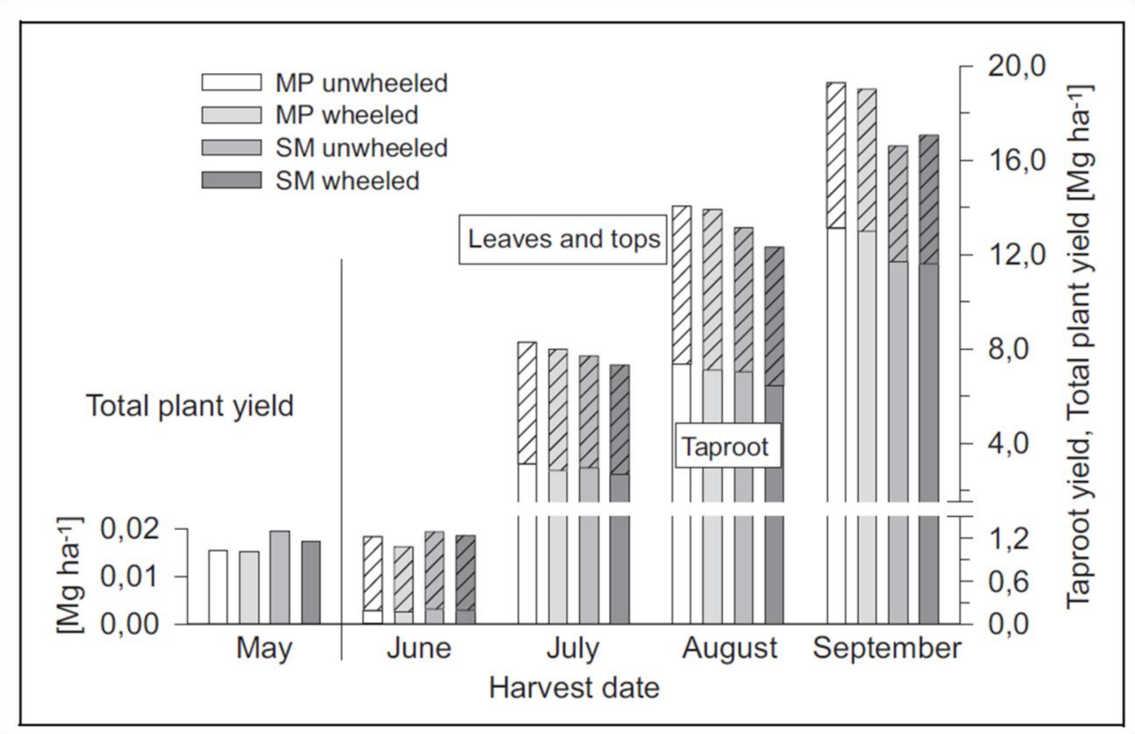


Fig. 2.6. Average performance of sugar beet harvested in 2004, 2005 and 2006 from three fields growing a rotation of sugar beet and winter cereals.
The three fields had a preceding history of mouldboard plough (MP) and shallow mixing tillage (SM). Maximum treatment wheel loads of 11.7 Mg and non-treatment loads of 5 Mg. See text for further details. (after Koch, 2009).

Taproot yields all tended to be higher on the “non-wheeled” treatments, but differences were only significant in June, July and August. However, what seems to have been completely ignored in this work is the cumulative effect of 5 Mg loads applied at the surface and unknown weights applied by tractor ploughing in the furrow at 300 mm depth. As the latter had been conducted for many years, it’s likely that the subsoil would have been severely compacted but there is no mention of deep loosening to alleviate this. Below 350 mm, penetrometer traces for the different treatments merge, suggesting that the subsoil had indeed reached a maximum strength.

Sheesley (1978) questioned whether controlled traffic could boost alfalfa yields in California, and concluded that if tracked areas could be reduced from their present 70% to 20%, forage yields could be increased by 20%. Głąb and Kopeć (2009) studied the effect of repeated compaction on the yield of meadow fescue on a silty loam soil in Poland. Only after six passes of a tractor weighing a total of 2 Mg was there any consistent reduction in yield, averaging 1 Mg in 20 Mg over three years and some of which was attributed to physical damage to the crop. This small difference almost certainly reflects the light wheeling compared with the weights that are now applied between grass cuts within a season (slurry application in Denmark for example with 59 Mg distributed across five axles, see http://www.controlledtrafficfarming.com/downloadssecure/Denmark%20CTF%20in%20Forage%20Grass%20Workshop%20Report.pdf, accessed March 2011).

Stalham et al. (2007) in their study of commercial potato production surveyed over 600 fields, in two thirds of which they found soil conditions with a penetration resistance greater than 3 MPa in the top 0.55 m. This compaction, largely associated with spring planting operations, was predicted to constrain root growth to <2 mm day^{-1} and cause problems with nutrient uptake and water utilization. The practice of stone separation increased the risk of compaction and is considered both time and energy inefficient. Delaying planting to allow soils to dry would, they considered, be a more cost-effective approach.

2.6.1.1. No-till crop responses in the presence of traffic

The most extensive data set was one from Scandinavia provided by Rasmussen (1994) who concluded that reduced tillage was most successful when growing winter wheat. Also tabulated in this work were data from 129 crop harvests where the average grain yields from no-till compared with plough tillage were 6.4% less. Results were also quoted from 20 harvests of oilseed rape and differentiated between those from coarse sands and from sandy loams. On the coarse sand, yields were 11.1% less for no-till compared with ploughing and 4.1% less on the sandy loams. A study in the UK quoted in a recent report to the Government Chief Scientific Adviser (Spink et al., 2009) suggests that in the case of OSR, direct sowing led to a 13% reduction in yields compared with mouldboard ploughing. In Australia Grabski et al. (1995) reported from replicated trials growing soybean and oats with chisel tillage to 200 mm or no-till for a period of 14 years. Soybean yields were significantly lower under no-till in the first two years but by year four were equal and by year six were consistently and mostly significantly greater than those from chisel ploughing. In complete contrast are their data for a single oat crop where yield increased by over 100% for no-till compared with chisel tillage.

Surprisingly, the work of Baker & Saxton (2007) does not mention any yield benefits, only improved production efficiency. Košutic et al. (2007) demonstrated an increase in wheat yield with no-till while Akbarnia et al. (2010) showed a significant reduction. Similarly in the research by Yalcin & Cakir (2006) they found that the yield of no-till corn (*Zea mays* L.) for silage was reduced in the first two years by 10-40%. Variation in no-till yields is also evident from the work of Patterson et al. (1980) whose long term experiments at three sites reported both a significant increase with no-till but equally, significant reductions compared with plough based tillage but often comparable yields with non-inversion tillage. Evident from the research was rather better performance of the no-till system on heavy soils in the dry UK season of 1975/76 and this is reflected in research by DeFelice et al. (http://www.notill.org/LE_Articles/V5N2A3_defelice.pdf accessed, March 2011) who found improved performance in drought stress areas of the US but rather poorer yields than conventional practice in areas of cold and wet. These latter data align with anecdotal evidence from farms converting to no-till in the cooler climate of the UK (Reynolds and Buckingham, personal communication, 2011) and a widely held view that yields are depressed in the first few years of conversion to no-till. Carter (1990) working with spring crops in Canada on a fine sandy loam found that although yields of no-till spring barley were not reduced compared with traditional systems of establishment, including mouldboard ploughing, deep loosening the soil prior to direct sowing raised the yield above that of ploughing. He concluded that the key to no-till yield increases would be if the system allowed earlier drilling in the spring.

Summary – crop responses

Soil compaction by vehicles had a significantly negative outcome on crop yields. These negative outcomes were not confined to specific crops, soils, climates or farming systems. Negative responses to compaction for 15 different crops ranged from 2–81% with wheel loads from 1 to 10 Mg. There were only 3 instances in a total of 79 when a positive response to compaction was recorded, and this ranged from 8–15%. There was evidence that firming the seedbed with a roll or equivalent had a positive effect on crop establishment and yield.

Deep loosening prior to the introduction of controlled traffic was generally beneficial and reduced the timescale for and increased the level of benefits. Equally, some soils classified as unsuitable for direct seeding can sustain this technique in the absence of traffic provided some very shallow loosening is periodically applied.

A number of East European countries have developed equations that relate crop yield to, for example, traffic intensity, soil clay content and time since a compaction event. Ranges of optimum bulk density have been specified from 1.1 to 1.5 Mg m^{-3}.

The factors associated with compaction that reduce the growth potential of crops include oxygen supply, volumetric water content and vulnerability to denitrification. Poor rooting of the crop due to excessive soil strength may exacerbate these influences.

It is unlikely that additional fertilizer will overcome the negative effects of soil compaction on yield.

Yields after converting to no-till in the presence of traffic tend to fall in the first few years, sometimes by as much as 40% but generally in the range 4-10%. In the long term, yields recover and can exceed those associated with tillage.

2.6.2. Fertiliser use efficiency

Clarkson (1981) questioned whether the large amounts of energy consumed in fertilizer production could be economically sustained. In 2006 the implications of water pollution caused by the movement of fertilizers into ground and other waters and the likely implementation of legislation around the EU Water Framework Directive (http://www.environment-agency.gov.uk/research/planning/33106.aspx accessed on 11

Jan 2011) became very apparent. In 2011, the rapidly rising cost of fertilizers also put the subject of fertilizer use efficiency firmly in the minds of growers.

In response to 1981 concerns about energy use in fertilizer production, Clarkson (1981) asked whether crop species could be better adapted for the efficient exploitation of nutrients in the soil and what is meant by efficiency in this context? He also stated "species which produce roots that are coarse, unbranched or which lack root hairs exploit soil phosphate ineffectively. Quoting from Bayliss (1972) he also reported that phosphate extraction from phosphate deficient soil with a variety of species was directly related to the size of their root/soil interface. The roots of oilseed rape (*Brassica napus* L.) for example were found by Bole (1973) to have few root hairs and experiments showed that plants compensate for this by taking up relatively more phosphorus per unit length for example, than roots with root hairs. In effect, the presence or absence of root hairs has little effect on phosphorus uptake and this does not conflict with the statement of Clarkson, but it does have implications in terms of availability within the profile. Forbes and Watson (1992) shed more light on phosphorus uptake, suggesting that because of its relative scarcity, immobility and poor diffusion, plants access phosphorus through root growth and a symbiotic association with *mycorrhizas*. The importance of root growth in the process of phosphate uptake is therefore firmly established and is constrained by poor root proliferation. Access to potassium is mostly through diffusion, so lack of root proliferation will constrain uptake.

Accepting that root proliferation and fertilizer use efficiency are closely related, a more fundamental approach to root response to differences in soil structure was taken by Goss & Reid (1981). Firstly they confirmed earlier research showing that roots cannot reduce their diameter to enter smaller spaces; they rely on expanding existing pores. They also found that the volume of root axes was little affected by a reduction in intercellular space (as a result of compaction), as was also the total root volume. However, longitudinal extension was severely curtailed, meaning that overall there were more short fat roots in response to a reduction in pore space. Depending on pore diameters, only root axes might be affected, for example in barley, pore diameters of between 150 and 450 µm would not restrict root laterals and these would compensate for a reduction in growth of the axes. It is also apparent that plants develop internal compensation for restricted root growth by increasing the rate of nutrient uptake per unit of root, but this compensation is limited by the supply of nutrients from the restricted volume of soil that can be explored. Overall they concluded that roots need a soil structure with adequate vertical and continuous pores that are just larger than their diameter or that will readily expand. Forbes and Watson (1992) graphically display evidence of the ability of plants to explore volumes of soil that are accessible and contain more nutrients and/or water. They draw on the work of Weaver (1926) who showed the roots of sugar beet responding to clay layers in a sandy soil by significant extra lateral branching and growth in these layers.

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, 1991 & 1990; Torbert & Reeves, 1995). Wolkowski (1990) concluded that the smaller uptake of N, P & K was the result of poor crop rooting and lack of oxygen (see Reviews section), 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., 2002a; Wolkowski, 1990). Medvedev et al. (2002b) concentrate on the effects of different levels of soil compaction at different depths in relation to nutrient uptake (N, P & K) in a “heavy loam soil”. Specifically they relate efficiency of uptake to differences in depth of placement of fertilizers as a means of compensating for soil over-compaction. In terms of compaction, the greatest effect on nutrient uptake and yield were when density exceeded 1.4 g cm^{-3}. This differential in uptake was more consistent in the 15 - 30 cm depth layer for all the nutrients but depth of placement did not appear to effect final yield. 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 (see Section 2.5.1.2). 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. Subsoil compaction seems to have been the catalyst for the reduced nitrogen intake reported by Alakukku & Elonen (1995). Their work (see section 2.6.1) suggested that nitrogen uptake (determined from dry matter yield x nitrogen content of seeds) was reduced by 9% and 4% on clay and organic soils respectively. This was in the nine year period following a single application of four passes of a 19 Mg tandem axle load. Other work (Ball et al., 1999b) showed evidence of increased carbon dioxide (CO_2) and methane (CH_4) losses from compacted soils.

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).

Given these data suggesting constraints on rooting and fertilizer use efficiency with increase in soil compaction, the manner of crop rooting under controlled compared with traditionally trafficked plots is of considerable interest. Changes in root growth in response to soil compaction also prompt the question, “what price has the plant paid in terms of final yield for compensatory or retarded root growth?”

Summary – fertiliser use efficiency

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%.

2.6.3. Vehicle and implement performance

As reported in the section on seedbed quality, compaction tends to increase the strength of a given soil at any given moisture and SOM 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.

Arndt & Rose (1966) 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. 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. Tullberg et al.'s (2003) research supported the findings of Dickson & Campbell (1990) who compared conventional and zero traffic systems over a period of four years on a clay loam in Scotland. They 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. Tullberg (2000) also 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. In contrast, draught differences in dry conditions were not detectable.

Chamen et al. (1990, 1992a) working on an Evesham series clay soil in England (Hodge et al., 1984, page 186) 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. Also recorded was an 84% reduction in the energy needed to establish wheat, both as a result of changing from traffic to no traffic and shallow tillage to no tillage and without loss in yield. 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. However, they also reported one instance when the draught requirement for shallow tillage was higher on the non-trafficked compared with the trafficked plots. This was with a tine cultivator and may possibly be explained by fundamentally different processes in soil failure. On the non-trafficked soil the implement was working in a moist fine tilth where the tines were causing a stirring action, whereas on the trafficked soil, the operation was dominated by fracture of aggregates from within the soil mass. Mouazen (2002) provided a possible explanation for this, albeit in a sandy loam rather than a clay soil. Cohesion was found to increase in loose soil when the samples underwent contraction due to shearing forces and conditions in the friable clay may have been similar. Working deeper in the profile on the same soil, Chamen and Cavalli (1994) reported an 18% reduction in the draught of a mole plough working at 0.55 m depth.

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 in their sustainability, whose repair costs were high.

There is a dearth of literature on the specific effect of soil compaction on the wear of soil engaging implements. However, it is well-known that “points” behind implement or tractor wheels wear out more rapidly because they need replacing far more frequently in this position. This is confirmed by Owsiak (1999) who 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. Fielke et al. (1993) reported 55-73% reduction in wear rate when bulk density had been reduced by a previous pass but also by 40-50% just due to a change in bulk density from one year to the next. Richardson (1967) also suggests that wear on a particular implement is subject to the <u>strength</u> of the abrasive material, as also found by Ferguson et al. (1998).

Table 2.10 summarises the draught and energy data from the principal references consulted.

In the 1980s, Chamen et al. (1990) compared a low ground pressure (LGP) system with conventional practice and with a “zero” traffic regime. The LGP system employed tyres inflated to around one third of the pressure of conventional practice but after four years there was no conclusive evidence that the lower pressures had either increased yields or reduced tillage inputs, the latter despite the soil having a lower bulk density than conventional practice to around 0.4 m depth. In more extensive trials during the same period (Chamen et al., 1992a) using reduced ground pressure systems, more favourable results were reported but the systems were only considered practicable for wheel loads of up to 5 Mg.

Table 2.10. Draught and energy requirements for trafficked and non-trafficked soil.

Description	Depth of operation, mm	% reduction, zero compared random		Author(s)
		Draught	Energy	
Tine cultivation	100		51	Chamen et al., 1990
Shallow ploughing	100	60		Chamen et al., 1992a
Ploughing	200			
Cereal rotations	various	20	29-87	Chamen et al., 1992b
Ploughing	200	37		Chamen & Longstaff, 1995
Mole ploughing	550	18		Chamen & Cavalli, 1994
Ploughing	200[1]	25		Lamers et al., 1986
Rolling resistance	surface		48	
Direct drilling	40	c. 15		Dickson & Campbell, 1990
Chisel ploughing	not stated	44		Dickson & Ritchie, 1996

[1] Depth reduced by 20% compared with conventional practice

Pagliai (2003) compared rubber tracks with tyres using modest loads (c. 1 Mg) and concluded that the tracks tended to confine compaction to the surface layers as did Blunden et al. (1994). Ansorge and Godwin (2007) working with much higher loads (12 Mg) came to a similar conclusion. The research around rubber track systems suggests that they can at least protect subsoils and may therefore have a part to play in overcoming some of the practical constraints (matching harvester track widths) associated with controlled traffic systems (see Chapter 5).

Summary: vehicle and implement performance

Removing vehicle-induced compaction from the cropped area reduces tillage energy requirements as well as the need for tillage *per se*. Zero traffic reduced the draught requirements for shallow (10 cm) primary tillage by up to 60% with an average of around 37%. The draught for mole ploughing (at 55 cm) fell by 18% and energy demands for seedbed preparation by up to 87%. At intermediate depth (20–25 cm), zero traffic reduced implement draught by up to 44%, while power requirements for primary and secondary tillage were reduced by 45% and 47% respectively. Energy savings of 29-87% have been recorded within particular cropping systems. Energy savings include the savings from fewer operations, shallower depths of operation and lower draught requirements of the implements involved. With energy savings there are also savings in implement wear due to less abrasion from lower density soils. Within a controlled traffic regime, there are also around 13% savings from the improved tractive efficiency and 30% lower towing forces when running on compacted traffic lanes. Practitioners of controlled traffic in Australia have responded to these reduced energy demands by selecting smaller rather than larger replacement tractors.

2.7. CONTROLLED TRAFFIC FARMING SYSTEMS

2.7.1. Economics of conversion to and maintenance of controlled traffic farming systems

Regardless of the benefits of managing the compaction from field traffic to the least possible area of permanent traffic lanes, farmers will not adopt the system if the conversion is too costly or it is not economically viable once established. An integral element of addressing the hypothesis that managing compaction will improve crop production efficiency must therefore revolve around the return on investment and profitability of any new system. Most studies to assess the economics have been undertaken in Australia, where controlled traffic systems have been adopted on around 15% of the grains cropping area. One such study was undertaken by Bowman (2008) who assessed the change in profitability of 16 farming businesses moving from fairly rigorous tillage practices to no fallow tillage and to direct drilling of crops with traffic control. The latter was an integral part of a change to direct drilling as it was seen as the means of improving water infiltration and increasing cropping frequency. Also included in the change was the implementation of high precision guidance to maximise the benefits of the controlled traffic systems. Although environmental benefits were identified as part of the change, these were not considered to bring any monetary value to the transition. A 60% reduction in fuel use was predicted on a per hectare basis across the 6500 ha owned by the farmers involved, not including the savings from improved tractive efficiency. The analysis included benefits from reduced overlaps (15%), greater cropped area per season (20%) and savings on maintenance and labour. Machinery was upgraded at the time of the transitions and 44% of this cost was attributed to the conversion to controlled traffic, meaning that there was a net cost involved. Results suggested a 17% return on capital investment with a payback period of 5.9 years and the potential to nearly double the annual profit for each of the farms converting. A similar study by Strahan and Hoffman (2009) in Queensland based on two farms also indicated significant improvements with an average 2.4% increase in return on investment and a 141% boost in profits.

Gaffney and Wilson (2003) carried out an extensive desk top study based on field data from a number of Australian farms and on research results. Using a steady state analysis technique they calculated the long-term average costs and returns for four different tillage systems based on a 5-year rotation of wheat and sorghum with six month fallows. Two of the four tillage scenarios were different designs of CTF systems, one of which delivered a tracked area presently closer to those likely to be achieved in Europe. These are depicted in Table 2.11 alongside trafficked conventional and zero tillage (no-till) systems. The 2 m CTF system maintained all traffic in the permanent traffic lanes other than the grain harvester.

Table 2.11. Three of the four crop establishment systems used in the desk top study of costs and returns by Gaffney and Wilson (2003)

Conventional	***Zero tillage***	***Zero till plus 2 m CTF***
164 kW tractor 8 m chisel plough 10 m scarifier 12 m cultivator	164 kW tractor	164 kW tractor
12 m airseeder	10 m chisel plough/airseeder	9 m chisel plough/airseeder
80 hp tractor	4 wd utility	80 hp tractor
18 m simple boom	18 m boom	18 m boom

The cost of implementing the CTF system, including marking out and reshaping contour banks plus interest was a one-off charge of £10.40 ha^{-1}. In terms of yields the assumed net benefits compared with conventional practice were:

Zero till	+5%
Zero till plus 2 m CTF	+7.5%

Their cautious net benefit of changing from conventional practice to controlled traffic was £10.2 ha^{-1} which assumed:

- a reduction in field efficiency from 90% to 85%;
- field level savings of only 5% compared with 10%;
- CTF yield benefits reduced by 15%.

With a full controlled traffic system based on a common 3 m track gauge, the increase in profit was £20.4 ha^{-1} which allowed for a 15% increase in tractor cost and a 10% rise in capital invested in implements. These improvements did not allow for any increase in cropping frequency or improved timeliness. The reduction in field efficiency was in line with data from Bochtis et al. (2010) who assessed differences between an uncontrolled and a controlled traffic system applying slurry with an applicator and a support unit, both with a capacity of around 14 m^3. The reduction in field efficiency for two machinery systems and two fields averaged around 5%.

Mason et al. (1995) also working in Australia conducted a case study based on a farm property of around 550 ha growing wheat, maize, millet, soybeans and sorghum, of which around 50% are direct sown each season. They assumed three scenarios, namely:

1. Controlled traffic with no change to existing cropping. Yields would increase by 40% in the worst seasons, by 10% in the average and no change in the best.
2. Change existing system to all direct sowing. Yields, worst seasons +10%, average, no change, best -10%.
3. Combination of controlled traffic and direct sowing. Yields, worst seasons +40%, average +10%, best, no change.

Results predicted the net farm margins would be as follows:

Existing system	£141 ha^{-1}
Existing cropping but with CTF	£163 ha^{-1}
Change existing system to direct sowing	£186 ha^{-1}
Combined CTF and direct sowing	£246 ha^{-1}

Based on these results the authors considered that the extra complexity of changing to controlled traffic only would not be worthwhile but equally, neither would changing the farm to all direct sowing with random traffic. The most profitable change was to controlled traffic and direct sowing which represented a 74% increase in net margin.

McPhee et al. (1995a) considered the relative capital costs of a conventional production system on a cracking clay soil with irrigated double cropping compared with two controlled traffic scenarios. Conventional practice involved chisel ploughing, discing and rotary hoeing, while the controlled traffic system adopted either direct sowing following bed forming or a modest level of tillage. Table 2.12 provides an outline of their results.

Table 2.12. Relative capital and operating costs for conventional practice and two alternatives based on controlled traffic. (after McPhee et al., 1995a)

Cost element	CTF direct sowing	CTF with light tillage	Conventional with tillage
Capital, £	24,320	36,100	77,760
Operating cost, £ ha^{-1} $crop^{-1}$	18	40	62
Total cost, £ ha^{-1} $crop^{-1}$	51	127	187

The change to controlled traffic represented around 70% reduction in capital cost and a 73% reduction in total costs.

Chamen and Audsley (1993) working in the England used a whole farm arable model to compare the profitability of a number of controlled traffic systems, including a number of wide span gantry tractor systems while growing wheat, barley, beans and oilseed rape. Research data were used to make estimations of yield responses, wheeling losses, energy requirements and work rates as a function of the systems. A maximum yield response of 7% was assumed for systems with no compaction on the cropped area, with yield losses due to wheelways assumed equivalent to half the area lost.

The main systems investigated were:

1. Conventional. Tractor-based plough system with temporary tramlines at 24 m.
2. 6 m tractor. Tractor-based controlled traffic system using tine cultivation for straw incorporation. All implements in multiples of 6 m.
3. Gantry system with all operations, including a specialist harvesting unit, with 6 m four-wheel drive gantries. (Harvesting workrate 2 Mg ha^{-1} less than the other systems)

- The 6 m tractor system, which was penalised by £57 ha^{-1} due to an assumed increase in chemical costs in the absence of ploughing, was £18 ha^{-1} less profitable than the conventional system on medium soil but £18 ha^{-1} more profitable than conventional practice on heavy land.

- The full gantry system was just as profitable as the conventional system on medium soil and £25 ha^{-1} more profitable on heavy soil.
- In these comparisons, the zero (controlled) traffic systems rely on a positive crop yield response to be competitive with conventional practice.
- Removing the harvesting workrate constraint imposed on the gantry system raised its profitability by between £6 & £8 ha^{-1}.

There were two constraints placed on the controlled traffic systems when this work was undertaken, namely the relatively large proportion of non-cropped wheel tracks which reduced overall yield by 10.6% and the additional chemical costs for non-inversion tillage of £57 ha^{-1}. The 10.6% reduction in yield resulted in an overall lower yield compared with conventional practice despite an assumed 7% increase in yield on the non-trafficked beds. The disparity in chemical costs is now less obvious and the work by Chamen and Audsley (1993) did not consider how vehicles could return to the same traffic lanes year in year out. The use of satellite guidance and auto-steer is now common practice, but it comes at a cost. As will be seen from Chapter 6, these guidance systems bring many other benefits but with an investment of £10,000-£15,000 per vehicle, they need to be considered carefully.

In terms of vegetable production, only the paper by Vermeulen & Mosquera (2009) considered the economics of conversion to controlled traffic, but only in the form of a seasonal system. Quoting from Vermeulen et al. (2007) they considered that machinery costs would be greater for sCTF systems but that only a 1.6% increase in yield would be needed to cover this extra cost and this was set against a predicted 6-10% increase in yield with sCTF.

Summary of economics

The economics of changing from a conventional random traffic system to controlled traffic depends to a large extent on the cost outlay, savings in inputs and the level of increased returns. In the large body of economics research emanating from Australia, the following factors were the key elements resulting in increased profitability through a change to controlled traffic:

- up to 60% reduction in fuel use
- reduced overlaps as a result of high precision satellite guidance;
- greater cropping frequency achieved by improved water infiltration rates;
- a significant reduction in tillage inputs, often to no-till;
- often a net cost of conversion but a high return on capital investment.

Profitability increases ranged from modest (£10 ha^{-1} at 2003 prices) to substantial (£105 ha^{-1} at 1995 prices). More recent research suggested that making full use of all the benefits associated with a change to controlled traffic would increase farm profit by up to 200% (Bowman, 2008).

In England, a 6 m tractor-based controlled traffic non-inversion tillage system was more profitable than conventional plough based tillage on heavy land (£25 ha^{-1} at 1993 prices) but £18 ha^{-1} less profitable than the conventional system on medium soil. Applied constraints to the CTF systems may have been excessive but a reduction in field efficiency may be required based on the work of Bochtis et al. (2010). A 6 m gantry tractor system was at least as profitable as conventional practice on medium soil but £25 ha^{-1} more profitable on heavy land. The greatest benefits were associated with controlled traffic and no till, where machinery costs were reduced by up to 73% and profit improved by 75%. Although growers changing to CTF find that their investment in machinery is significantly reduced, future investment in precisely guided implements to maximise the potential of controlled traffic systems is predicted. These factors are discussed and assessed in Chapter 6.

2.7.2. Practical aspects of CTF systems

2.7.2.1. CTF machinery and system designs

The literature reported so far has suggested that there are few if any negative outcomes from avoiding vehicle compaction on cropped areas. Avoiding this type of compaction altogether in the field is not a practical option, but controlling traffic to the least possible area of permanent traffic lanes would appear to be a sensible approach, given that recent developments in guidance technology make this feasible. One of the main questions therefore is, can this be achieved on a practical scale and can it be sustained? This section investigates relevant research but also explores documentation about practical experiences and potential means of achieving controlled traffic systems.

Probably the very earliest literature on this subject is the treatise given by Halkett in the 1850s (Halkett, 1858). Halkett recognised the difficulty of getting the heavy machines of his day across the field and turned to the rapidly developing "permanent way" technology in the form of steel rails. These supported a steam driven spanning beam across which many different operations were performed, as illustrated in Fig. 2.7. He also recognised the precision and flexibility which a machine of this nature could bring, using in his treatise texts such as:

- "the implements and their operation are always kept at a regulated height"
- "it enables ploughing, cultivating, sowing, hoeing, watering and reaping all capable of being performed"
- "as the seeds are sown with mechanical precision in lines, hoeing, trimming or watering can be carried out in between"

This is the first example of what are known today as gantry tractors and a history of these vehicles is given by Taylor (Taylor, 1994). This includes proposals by Henry Grafton (from Spence, 1960) to build a machine on tracks and there were many other proposals of this nature around at that time. However, there is little further mention of them in the literature until 1977 when Dowler applied for a patent for the "Monotrail" (Dowler, 1977), which was the first of a number he filed.

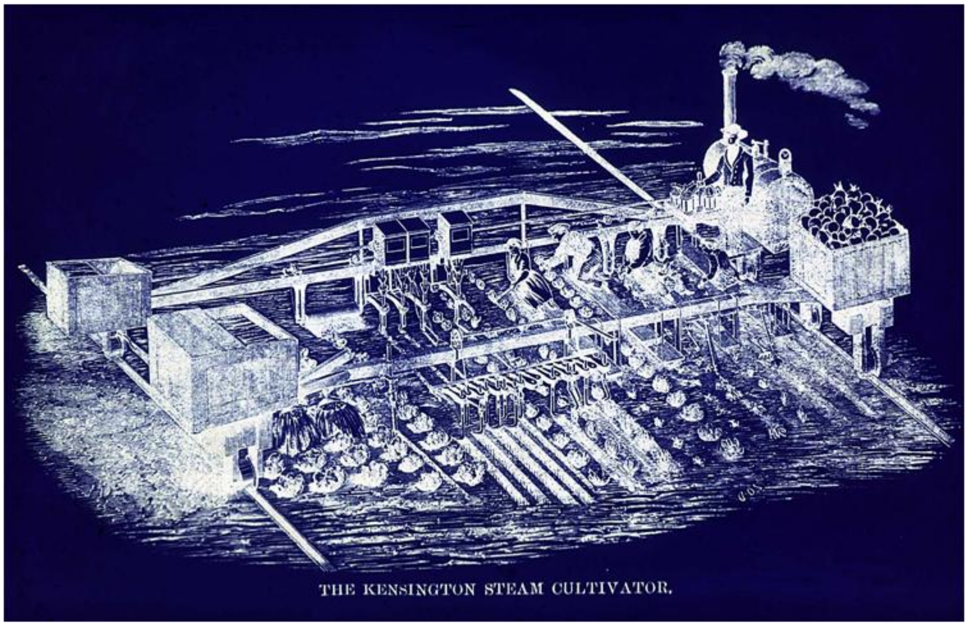


Fig. 2.7. The "Kensington Steam Cultivator" designed, built and operated by Alexander Halkett in the 1850s. This is the first known mechanised controlled traffic farming system in operation (after Halkett, 1858)

Hood et al. (1985) also proposed a "straddle frame" spanning around 10 m as an attachment to a standard tractor (Fig. 2.8). Taylor (1994) also mentions developments in the former U.S.S.R. in the late 1970s and early 1980s, driven not so much by soil compaction, whose damaging effects were well documented in the form of yield losses and aggravated erosion, but from anticipated shortages of labour and energy. Their aim was a machine capable of ensuring use of electrical energy, non-injury of plants, the minimum of hand labour and simultaneous operations, much along the lines proposed and illustrated by Halkett (Fig. 2.7). Similar goals were proposed by Japanese scientists who built a gantry system operating on concrete rails spaced at 12 m (Miyazawa et al., 1987, from Taylor 1994). Investigations were also being carried out in the UK at that time (Tillett and Holt, 1987; Chamen et al., 1992a) and a commercial 5.8 m spanning unit (the Field Power Unit, FPU) went into small scale production in Israel in the early 1980s (Ashot Ashkelon Industries Ltd); an FPU has been used for all but harvesting operations on a farm in Bedfordshire since 1996. Many of the units were built as harvesting aids for high value vegetable crops (Tillett and Holt, 1987) but few addressed the challenge of small grains harvesting. The exceptions were Taylor (1989) and Chamen & Longstaff (1995). Taylor also introduced the concept of "zone management" which recognised three soil-tyre relationships, one of which stressed the fact that 75% of compaction occurs at the first pass, so reducing number of passes was not recognised as a benefit.

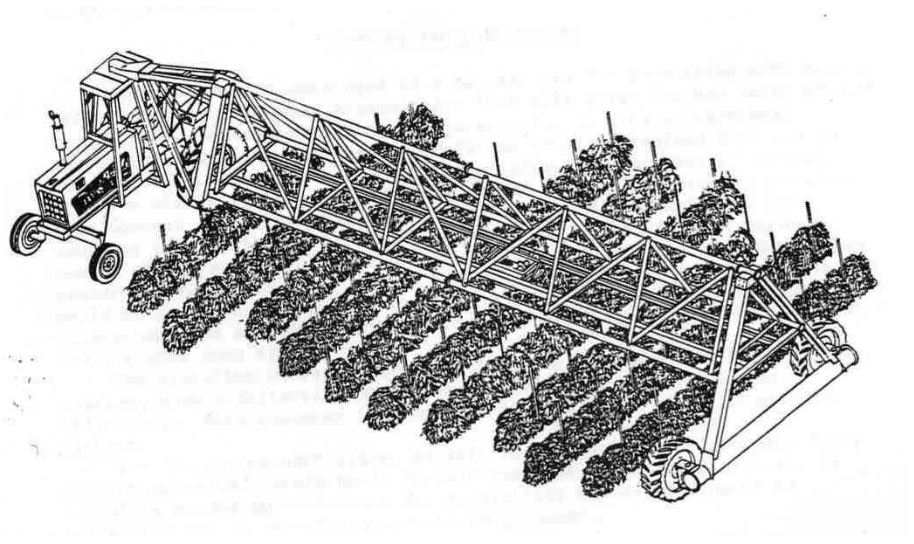


Fig. 2.8. The straddle frame proposed by Hood et al. (1985) at Clemson University

Also, and of particular interest was a proposed change in the profile of traction tyres from what are now basically convex, to concave. This makes them more stable on permanent traffic lanes, which as a result could be designed to take high loads and was the means by which small grains harvesting was addressed – they simply picked up a small harvester and used it as an attachment. Chamen et al. (1994), over a period of about five years, developed a fully functional grain cutting and separation unit which was able to cut the 12 m bed width by having two positions on the gantry frame (Fig. 2.9). Further work on the design of a grain harvesting unit was undertaken as part of a commercial contract (Chamen, 2002), but development was not carried forward.

Fig. 2.9. A three drum and concave threshing and initial separation unit (Metianu, et al., 1990) were the basis of grain harvesting with this 12 m experimental gantry at Silsoe in the early 1990s.

Development of controlled traffic systems based on traditional tractors is first mentioned in the literature by Cooper et al. (1969; 1983). Williford (1985) reported on work in cotton production which accommodated a six-row system where all wheel traffic was restricted to the outside 250 mm of a 2.5 m wide bed. Research reports including “controlled traffic” in the title are absent in the 1960s, but 25 papers figure in the 1970s, rising to around 170 in the 1980s but fall to less than 30 in the 1990s and post 2000. It was in the 1990s however that the first farm-based systems are reported by Tullberg (1997) in Australia. These used conventional tractors but with their track gauge extended to 3 m to match that of grain harvesters. McPhee et al. (1995b) considered the machinery required for an irrigated double cropping system in Australia, concluding that “planting machinery not usually associated with the conventional systems in the area” would be needed. Although the first adopters used mechanical marking systems for pass to pass accuracy, maintaining the wheel tracks in the same place from year to year was a major challenge (Tullberg & Yule, personal communication). The advent of satellite guidance and particularly the land-based Real Time Kinematic (RTK) correction signal seems to have been the key enabling technology that made controlled traffic possible and even easy, with tractor-based systems. The RTK correction is now an almost essential element, not only delivering a high level of accuracy (± 20 mm) but also non-time-dependent repeatable positioning, as described by Larsen et al. (1994).

Tullberg et al. (2006) provided an overview of what is now common practice for controlled traffic systems in Australia, which have been adopted on around 15% of the grain production area. Most use a 3 m track gauge on their vehicles to match the grain harvester but a track gauge of 2 m is also common to match existing equipment. In this situation, the track gauge on the grain harvester is frequently extended to 4 m to fit into the system. Implements are often multiples of the track gauge but this is not essential. Most common is a 9 m operating width for tillage, planting and harvesting and 27 m for chemical applications. Greater widths are also now becoming commonplace with 12 m and 36 m. An odd multiple is most often used for chemical applications as this avoids an extra set of wheelings on the headland. Harvester cutting platforms are also invariably slightly wider than their operating width, to ensure there are no crop misses. Of particular importance in Australia are field layouts for the controlled traffic systems (Tullberg et al., 2006), these being designed to ensure efficient disposal of water on soils that rarely incorporate the underground drainage schemes that are common across Europe. But, the direction of traffic lanes is important, both from the standpoint of field efficiency but also in relation to potential erosion and this aspect is dealt with in the next section.

Outside Australia, uptake of controlled traffic systems has been sporadic. They were constrained initially by poor availability and the high price of satellite guidance systems, and presently by practical issues as described by Chamen (2005). The latter include matching the track gauge of all vehicles to the grain harvester because this makes them impractically wide. There is also an enormous range of implement widths making matching difficult and in some cases the length of the unloading augers on grain harvesters will not reach trailers in the adjoining wheel tracks. Most of these issues are proving surmountable, even if it is at the cost of a slightly greater tracked area, as illustrated by one of the most common systems to be employed in the UK (Fig. 2.10). With this system, the compaction imposed by the harvester can be removed if required by a two leg subsoiler of an appropriate design.

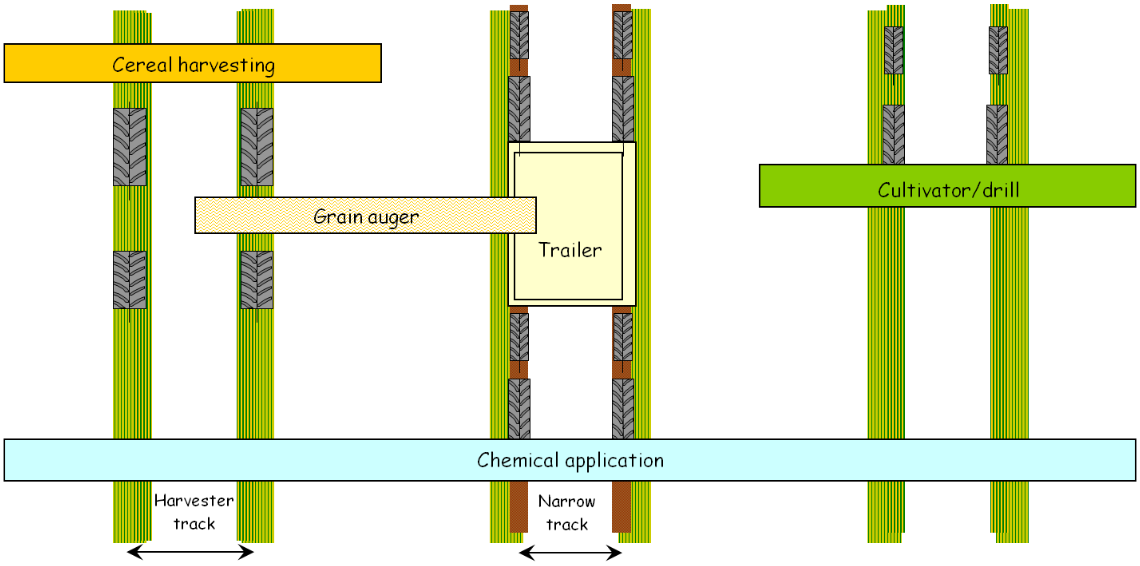


Fig. 2.10. A controlled traffic farming system commonly adopted in Europe known as OutTrac. The system has two track gauges with a common centre line. The harvester tracks "outwith" the narrower track of all the other machines.

Another system being employed is known as TwinTrac and was proposed in 2005 by a UK grower (Shaw, personal communication). This cleverly uses the grain harvester wheel tracks for all operations but the base implement width is the addition of the two track gauges, meaning it is limited to around 6 m (Fig. 2.11). A grower in Yorkshire has optimised this system for growing both grain and potato crops by widening the track gauge of his grain harvester to 3.86 m. This is exactly double the track gauge used by his tractors to accommodate potatoes, but it did require small modifications to equipment because his base implement width is 1.93 + 3.86 = 5.79 m. Most commercial equipment in this size region is 6 m, so narrowing of implements was required. In terms of the grain harvester, the most common cutting platform width at this scale is 6.1 m, so it just requires the guidance system to steer the vehicle at 5.79 m centres. The system is described by Vermeulen et al. (2010). Included in this case study is anecdotal evidence of a 50% reduction in fuel use resulting from conversion to CTF and no-till. No-till was not considered an option without also adopting traffic management in the form of CTF. This farmer has also confronted the issue of straw baling and with the help of a local engineering company, now has a pick up system for 0.5 Mg bales which is fitted to the three-point linkage of a tractor with a reverse drive conversion. Bales are "chased" to the end of the field with only minor diversions from the permanent traffic lane. Further development will allow these "diversions" to be precluded, confirming the fact that most systems can be engineered to deliver what is required.

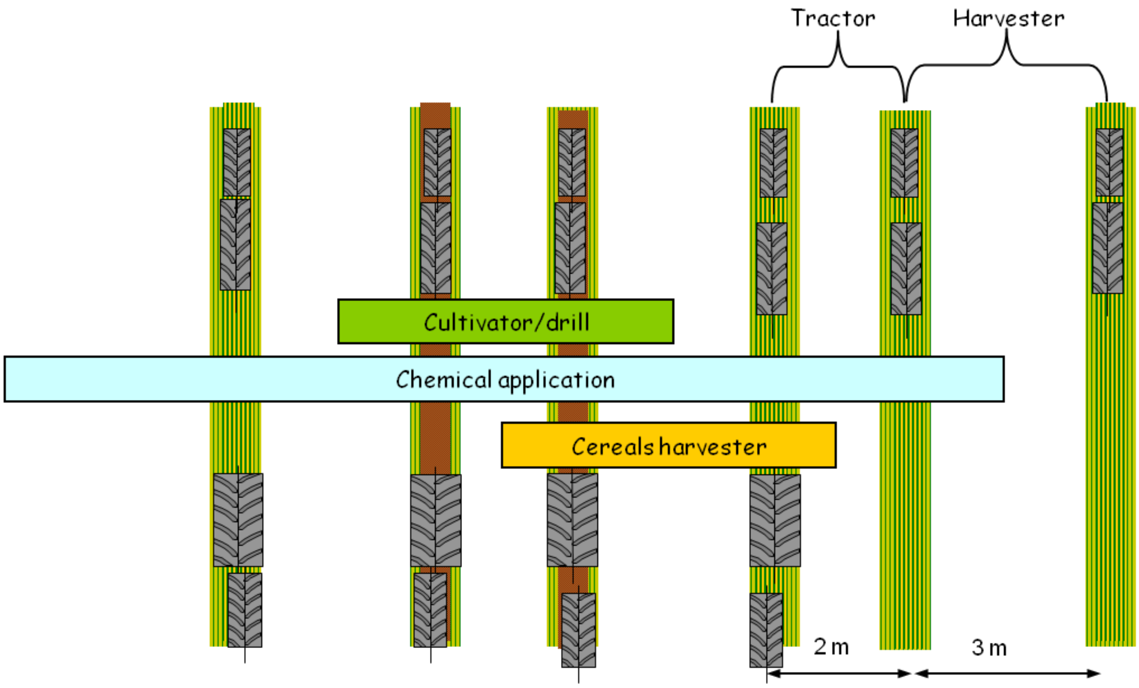


Fig. 2.11. The "TwinTrac" controlled traffic system which uses only the grain harvester wheel tracks by ensuring tractor passes straddle adjacent passes of the harvester.

Implement width is the addition of the two track gauges, which for practical reasons limits implements to around 6 m wide (after Shaw, personal communication, 2005).
Further confirmation of fuel savings is provided in another case study available at: http://controlledtrafficfarming.com/downloads/CTF%20Case%20study%205.pdf (accessed April 2011) where tractor power on the farm has dropped by 16%, but this includes the power needed for some contracting operations which they were not doing before. This conversion to CTF and the running costs are the basis for the economics study undertaken in Chapter 6. Neither of these systems raised major practical issues but equally, neither converted without some modification of equipment. A farm that still has a practical problem to overcome is one operating with a nominal 12 m controlled traffic system. Minor modifications were needed initially, primarily because the 12 m cutting platform of the harvester actually cut only 11.96 m, meaning the final implement width selected was 11.66 m to be in harmony with the drill row spacing. The unresolved issue is the length of the grain unloading auger which does not reach to the centre of the next wheel track. The manufacturer is unable to address this problem so an extension tube will be fabricated and trialled by the farmer in 2011.

2.7.2.2. Wheel tracks and erosion

The permanent traffic lanes are an integral part of avoiding compaction on most of the cropped area and their installation and management are crucial to the success of any controlled traffic system. Most research does not consider this aspect but some information can be gleaned and anecdotal evidence is also reported. Also considered here will be research addressed at the specific issue of erosion, particularly that initiated by wheel tracks. It will also assess the impact of recognized differences in infiltration between trafficked and non-trafficked soil in an attempt to predict likely outcomes of adopting controlled traffic compared with current practice.

Taylor (1983) was probably the first researcher to recognize the additional benefits brought to a controlled traffic system by optimising the design of the permanent traffic lanes. It was well known that the first pass across a relatively soft soil brought with it high rolling resistance and poor tractive efficiency. However, by the fourth pass, efficiency had risen from less than 50% to close to 75% on a Decatur silty loam with very similar results for a sandy loam and a clay soil. At the same time, bulk density under the traffic lanes had increased by an average of 9% with around 20 mm sinkage. Taylor concludes that permanent traffic lanes improve tractive efficiency and flotation together with timeliness. Lamers et al. (1986) also draw this conclusion and quote from Perdok and Lamers (1985), who reported a 13% increase in the relative tractive efficiency of permanent traffic lanes brought about by a reduction in rolling resistance and increased coefficient of traction. They estimated an overall 48% saving in energy from better trafficability and less tillage demand from the non-trafficked beds. In practical terms the lanes were highly trafficable, except in very wet conditions, when they became very slippery. The latter problem has also been reported by farmers using a “seasonal” controlled traffic system where annual ploughing restores the damage caused by the harvesting of high value vegetable or root crops (http://www.controlledtrafficfarming.com/downloadssecure/NL%20CTF%20Workshop%20Report.pdf, accessed February 2011).

Permanent traffic lanes have also been used as drainage channels in the form of “raised bed farming”, primarily in the southern states of Australia. Here laser levelling provides a means of quickly disposing of overwinter rainfall to establish crops more quickly and reliably in the spring. Hamilton et al. (1998) and Thompson (1995) describe the systems in some detail and the advantages gained but neither these authors nor several others writing on the subject (Maynard, 1995, Bakker et al., 1995, Bakker et al., 1998) mention performance of what are in effect sunken traffic lanes. One can only presume that they were not a problem either in terms of erosion or trafficability. Erosion would not be a problem because although these sites are often on quite undulating ground the traffic lanes and cross drains are on modest grades designed to avoid erosive velocities (Hamilton et al. 1998). Also to be presumed is that although access would have been limited to when water ceased to flow, this was ahead of when it would be possible without the raised bed design.

Webb et al. (2004, pp. 35-40) propose a number of management options for surface traffic lanes often left without crop that form the basis of a guidance system for chemical applications. If erosion or weeds are a problem they suggest “fuzzy, sown or furry” tramlines, these ranging from crop established by broadcasting (fuzzy) or shallow sowing (sown) to diverting of chaff during harvesting (furry).

The issue of erosion in traffic lanes was addressed by Titmarsh et al. (2003) working in central Queensland. Their comprehensive study on a range of soils was carried out in cooperation with commercial growers and compared up and down slope with across slope orientation of controlled traffic wheelways. Table 2.13 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 at least are generally small (Evans, 2002). Table 2.14 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. 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. A tentative conclusion 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 but 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 data 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 there is no direct comparison with a conventionally trafficked situation.

Table 2.13. Runoff and suspended sediment loss on three farm sites in central Queensland for across slope and up/down slope orientation of controlled traffic wheelways (after 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 2.14. 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 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 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. The paper by Evans & Brazier (2005) shows just how difficult it is to predict erosion with any degree of certainty, despite robust field data.

Table 2.15 provides a summary of the literature in relation to surface infiltration rates. As far as rainfall intensity is concerned, the most dramatic events in the UK 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. Most erosion is confined to silts, sands or loams. The South Downs for example has Lithomorphic soils with up to 80% silt. Ankeny’s figures (Table 2.15) suggest a 36–200-fold increase in infiltration with CTF 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.

Table 2.15. Infiltration data for the top 50 mm of soil taken from literature and from recently recorded but non-verified field measurements (see Chapter 4)

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

[1] 5–25 cm depth

Summary of practical aspects and erosion

Many different means of achieving substantial areas of non-trafficked soil have been proposed, researched and used over the past 160 years, but only in the late 20th and early 21st century has there been widespread adoption of tractor-based systems by farmers. Key to this adoption has been satellite guidance and auto-steer capable of delivering repeatable positioning to vehicles with an accuracy of ± 20 mm. Initial adoption occurred in Australia where practical constraints were less obvious but it is now gaining ground in Europe where alternative approaches are being developed. These tend to track a larger area but still deliver key benefits. Although machine modification is often required, this can frequently be carried out on farms or by local engineering companies. Those who have converted are reporting investment, fuel and labour savings.

Trials with across-slope compared with down-slope orientation of controlled traffic wheelways provided no clear distinction of erosion benefits between directions but rills were more common with across-slope orientation and suspended sediment loss greater with the down-slope orientation. There were no comparisons with conventional traffic systems which precluded quantification of the effect of predicted greater infiltration on the controlled traffic beds.

2.8. CONCLUSIONS TO THE LITERATURE REVIEW

- In a study of the soil as a global resource it was recognised that it is as vital to our wellbeing as it is to that of the planet, but it is being degraded. Some of this degradation is due to over-compaction by machinery and this has a fundamental effect on models that predict water holding capacity from which global production potential is calculated. Of particular concern are wheel loads in excess of 6 Mg, together with high tyre inflation pressures, which are having a negative impact on subsoils.
- Although conservation agriculture has been shown to have many benefits such as reducing tillage and therefore energy inputs to the soil, there is concern that the

lack of tillage in the presence of random traffic is having a deleterious effect. Retaining residues at the surface helps to protect the soil from raindrop impact and erosion but dense layers with an elevated organic matter content can cause increased emissions of nitrous oxide. The case for additional sequestration of carbon as a result of conservation tillage systems has not been well proven but the finite potential exists. The dominating influence on the amount of organic carbon in the soil at any given point on the globe remains cropping.

- Reviews on the effects of soil compaction imposed by field vehicles concluded that it had overwhelmingly negative effects. These effects, outcomes and implications included:
    - Poorer water infiltration, drainage and aeration
    - Negative influences on crop yields and greenhouse gases as well as crop rooting, energy inputs and nutrient uptake by crops.
    - Of particular concern was the threat of high wheel loads on subsoil layers whose condition may already be beyond economic repair. This damage may already be permanent and having a negative effect on yields and soil hydraulic properties.
    - Restorative measures for soil compaction are expensive and quickly compromised by subsequent non-controlled traffic. Methods for reducing these effects were limited within a commercial environment that seems intent on increasing loads still further.
    - Avoidance of soil conditions that are too loose can also have a negative influence and reveal an optimum that is around 85% of the maximum compaction level for any given soil.
    - Low ground pressure tyres can improve soil conditions (increased porosity and lowered soil strength) and yields, but their benefits are constrained, largely due to the greater area they compact on each pass. Equally, due to their greater width, they are only a practical solution for wheel loads of up to 5 Mg.
    - Crop uniformity can be compromised by the random nature in which compaction is applied in the field, resulting in either crop rejection or lower value.
    - The effect of soil compaction on soil biota and biological processes is almost certainly negative, but its significance is uncertain largely as a result of the high variability in experimental conditions and recording methods.
- Soil structure determines the nature of physical processes that occur within soils and for a given soil texture, is largely driven by soil organic matter. Sequestration or oxidation of organic matter is itself driven by many different factors but the direct effect of compaction by vehicles appears to be neutral.
    - seedbed quality is negatively affected by compaction which reduces its required heterogeneity leading to poorer outcomes. The absence of compaction has exactly the opposite effects.

- Vehicle compaction increases the strength and density of soils whose vulnerability is the key factor that determines the level of damage rather than wheel or track loads per se. Subsoil loosening makes soils particularly vulnerable and susceptible to all levels of load, particularly with repeated passes and in moist conditions.
- Beneficial air and water movement into and out of the soil is compromised by vehicle compaction and can lead to water run-off, soil erosion, flooding and chemical pollution while creating poor water uptake and water use efficiency by plants whose rooting may be impaired.
- Crop yields are almost universally compromised by vehicle compaction but responses are strongly influenced by prevailing conditions and crop resilience. Principally the effects are associated with restricted rooting due to poor soil conditions that constrain their access to water and/or air and nutrients. Too loose soil conditions such as those experienced after ploughing, can reduce yields and are associated with a degree of compactness lower than about 85%.
- Vehicle compaction increases the energy and need for tillage which when avoided can reduce inputs by up to 80%. When confined to permanent traffic lanes further savings are achieved through improved tractive efficiency. These savings manifest themselves on farms by selection of smaller rather than larger tractor replacements.
- Lower or more cost effective investment in machinery is a manifestation of controlled traffic systems that consistently deliver more profitable farming businesses, often by a magnitude or more. Simultaneously, these systems deliver environmental benefits that reduce the negative impact of farming operations.
- High precision and repeatable positioning of satellite guidance systems have been the enabling technology for controlled traffic systems. Uptake of controlled traffic in Australia was enhanced by acute inefficiencies, poor water infiltration and a favourable infrastructure. Uptake in Europe faces greater challenges that initially require a change in the mindset of primary producers but can be engineered, as have many other developments in the past.
- There is little or no evidence to suggest that erosion in wheel tracks will be enhanced by the establishment of permanent traffic lanes, largely due to several magnitudes of increase in infiltration in surrounding soils through improved structure from compaction avoidance.
- The literature elicited a list of topics for further investigation that confirmed the validity of attempting to prove the overarching hypothesis of this thesis.

2.9. GAPS IN RESEARCH

The review has identified a number of gaps in research or areas that need further study to provide guidelines for practitioners of CTF systems, namely:

1. Creation and maintenance of permanent wheel tracks.

The permanent wheel tracks are a central element of any controlled traffic system which succeeds or fails depending on their condition. Particular aspects that need to be considered are:

   a. Rutting and traffickability – how can these be avoided and maintained respectively?
   b. Erosion – what are the main drivers for this and how can it be minimised?
   c. Yield from cropped traffic lanes. Many CTF systems will be operating with tracked areas of 20-30% and to lose this cropped area would be unacceptable, so optimising the yield of crops sown in these tracks is essential.

2. Persistence of deep soil loosening in the absence of traffic and tillage.

To what extent will different soils maintain a good structure when both tillage and traffic are removed? Although the literature has provided some evidence there has been rather limited work in the UK.

3. The degree to which soil compaction can explain crop yield variability in commercial farming.

Many farmers now practise “precision farming”, a term used to describe the management needed to counter variability within fields, particularly in terms of crop yield. Research has shown a clear negative effect of soil compaction on yield but can this be modelled through knowledge of the trafficking applied?

CHAPTER 3

3. Papers published by the author addressing the principal hypothesis

3.1. INTRODUCTION

The earliest of the literature reports on work that started in 1982 and this was a first exploration of the then AFRC Institute of Engineering Research at Silsoe into the subject of soil compaction. Being an engineering institute, a clear objective outlined in the first paper was to use the results for “the development and assessment of alternative machinery systems to improve crop production efficiency”. This theme continued throughout the other papers and manifests itself in the form of engineering the development of a wide span vehicle system, which was seen as the most practical and cost-effective technology to achieve non-trafficked areas of at least 90%. The engineering development will not be focused on here (see Chamen et al., 1994) but the system did provide large areas of non-trafficked soil upon which extensive research could be conducted, including implement draught and energy measurements. There is a dearth of measurements of this nature in the literature reflecting the difficulty of acquisition. The other key objective of the research contained in the papers was “to quantify soil and crop responses to different levels of tyre/soil contact pressure”. This objective immediately reveals a lack of awareness of the role of wheel load which became so evident in the literature review but this did not constrain the research, which ran with little or no interruption on the same site from 1982 until 1994. In the first four years the experiment formed a series across Europe that were part funded by the European Union and whose results are synthesised by Chamen et al. (1992a). The particular papers selected for review are listed below:

1. Chamen et al., 1990. Journal of Agricultural Engineering Research 47: 1-21.
2. Chamen et al., 1992b. Soil & Tillage Research, 24: 359-380.
3. Chamen & Cavalli, 1994. Soil & Tillage Research, 32: 303-311.
4. Chamen & Longstaff, 1995. Soil Use & Management 11: 168-176.

Although the literature review dealt in some detail with some of the work presented here, there were many other aspects to these papers that support the main hypothesis and these will be explored with the aim of eliciting information that might deliver to the associated hypotheses listed in Chapter 1.

3.2. METHODOLOGIES

Some of the information and methodologies are common to all of the research reported and principal among these was the experimental site and its preparation. Key to this was the initial soil condition that had been “restored” to a depth of 400 mm using simultaneous topsoil cultivation and subsoiling in the form of a rotary digger with integral subsoiling tines (Chamen et al., 1979). This condition was presented to each of the experiments with only treatment traffic on the replicated plots. One exception was a preparatory cultivation in 1982, following which the soil was loosened again to 400 mm depth. The plots were 24 m wide by 35 m long and had four replications from 1982-1986 and three in the years thereafter. One of the aims of the experiment was to impose vehicle compaction in a manner which reflected common practice on farms, i.e. a high element of randomness, with some areas being trafficked several times while others not at all for the first year or two. Within the constraint of plots which could only be accessed along their length, this proved difficult to achieve but was approached by recording the starting point of every operation and using markers on all machines. This allowed a plot to be made of all wheel traverses and for subsequent operations to be moved slightly to spread the traffic evenly across the main plot area. This was assisted by having a cultivator with two “wings” that could be removed to alter its working width but also by having narrow discard areas at the join between plots where some overlap of operations could be accommodated.

The soil was an Evesham Series calcareous clay whose mineral properties are outlined in Table 1 of the first paper (Chamen et al., 1990, page 2).

3.3. DISCUSSION OF PAPERS

3.3.1. Chamen et al., 1990. The effect of tyre soil contact pressure and zero traffic on soil and crop responses when growing winter wheat

Several figures are of note in this paper because they address the gap in research relating to the persistence of deep loosening effects in the absence of traffic. Figs 1 & 2 confirm the longevity of the loosening effect (4 years) in the absence of vehicle traffic and little difference between the shallow cultivated (to around 100 mm depth) plots and those that were direct sown with a disc drill. Also of interest here is the consistently lower penetration resistance under the low ground pressure system (maximum inflation pressure 50 kPa) below 100 mm depth. The fact of equal strength and density in the top 100 mm tends to confirm other research that highlights the area effect of low ground pressure systems based on wheels. These track a much larger area on each pass and therefore build up compaction in the topsoil more rapidly, confirming the advantage of tracks that lay down area in length rather than width. Essentially, the significantly improved conditions maintained under zero traffic deliver positively to the main hypothesis.

The hydrology of the site was also of interest with the non-trafficked soil consistently exhibiting lower volumetric water content for a given negative matric potential (Figs 6 & 7), which has been maintained throughout the period of the experiment. This coincided with greater water extraction on the non-trafficked plots suggesting greater plant available water (Table 5).

The paper also demonstrates the danger of having too loose a soil profile in which to grow crops, which in this case triggered a deficiency of manganese in the wheat. This particular soil was prone to the problem which could only be effectively countered by the application of manganese sulphate and this was common practice in the area, even without traffic control. Yields, particularly in the first year were negatively affected by this deficiency and this situation persisted for the duration of the experiment and therefore cannot be considered to support the hypothesis. Lower yields from non-trafficked soil reflect our inability to achieve the right conditions because they can almost certainly be compressed to the right degree, if only that degree were known. This compaction may or may not have an impact on the draught requirement of the tillage operations, which as will be seen from Table 9 exposed the difficulty of creating consistency and being able to compare like with like. The significantly different soil conditions on the zero traffic plots meant that little or no tillage was required to create a seedbed. A Dutch harrow was therefore used in place of the heavy duty spring tine, which as will be seen from the text (page 16 of the paper) could not be constrained to the depth required. Although draught data were acquired, these were not always directly comparable, except in 1985 when conditions were such that the same cultivator was used across all the plots. Here draught on the non-trafficked soil averaged 42% less than on the trafficked and the total energy for crop establishment was reduced by over 70% (Table 10), again delivering positively to the central hypothesis. Another interesting phenomenon was apparent in 1983, when very dry conditions leading up to and following harvest created severe shrinkage and cracking of the soil (Fig. 9). This was recognisably different between the treatments, with the least cracking occurring on the non-trafficked plots. The reason is almost certainly associated with the lack of heterogeneity of compacted soil and less variation in soil strength leading to fewer but larger cracks. The contrast in conditions was exacerbated by a tendency for friable soil on the non-trafficked plots to fill the cracks which did appear.

Full paper, Chamen et al., 1990

J. agric. Engng Res. (1990) **47,** 1–21

The Effect of Tyre/Soil Contact Pressure and Zero Traffic on Soil and Crop Responses when Growing Winter Wheat

W. C. T. Chamen;* E. T. Chittey;* P. R. Leede;* M. J. Goss;† K. R. Howse‡

* Soil Science Group, AFRC Engineering, Silsoe, Bedford MK45, UK.

† Plant Science Division, Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen AB9 2QT, UK.

‡ Soils and Agronomy Department, Rothamsted Experimental Station, Harpenden, Herts AL5 2JQ, UK.

(Received 6 August 1989; accepted in revised form 21 December 1989)

Winter wheat was grown for 4 years on a clay soil subjected to three levels of tyre/soil contact pressure, in conjunction with direct drilling and shallow tine cultivation. Zero, low and conventional tyre related stresses were applied to the soil in the course of normal cultural operations and measurements were made of soil, crop and machinery responses.

Under zero traffic, a deep friable tilth was retained from one season to the next. Cone resistance and soil density generally increased with tyre contact pressure, but the greatest difference was between soil stressed by tyres compared with that which remained traffic free. Porosity was reduced by conventional traffic but saturated hydraulic conductivity at and below 0·5 m depth was unaffected by treatment.

There was no conclusive evidence to suggest a difference in yield related to the traffic treatments but total yield from the zero traffic plots was lower than from the other treatments because of manganese deficiency.

Compared with zero traffic, conventional and low ground pressure systems increased shallow tine cultivator draught by 60% and the energy for cultivations and drilling by up to 250%. Standard traction tyres were effective for low ground pressure operation, but safety during road use needs consideration. Zero traffic improved soil conditions and a cost effective means of achieving such a system should be explored.

1. Introduction

Over the past few decades, soil compaction in the topsoil has been identified as one factor limiting further increases in cropping efficiency.[1] This compaction impedes the movement of liquids and gases within the rooting zone, through a reduction in soil porosity, and its alleviation requires a regular, energy-intensive, deep-loosening operation to sustain crop yield. It has also been recognized that a complete absence of soil firming may lead to a reduction in crop performance due to nutrient deficiencies[2] and that a certain degree of soil compactness is required for maximum crop yield.[3] This "degree of compactness" (defined[4] as the relative bulk density of a field soil compared with the density acquired by a prepared unconfined field sample of the soil subjected to a static pressure of 200 kPA) has been shown by Håkansson[5] to be a more useful measure than bulk density or porosity in relation to crop performance, because the maximum yield is obtained at a very similar degree of compactness, regardless of soil type. For a particular soil however, density, cone resistance, hydraulic conductivity and water content provide a more precise measure of soil physical conditions that can be related to cultivation requirements and water movement.

Other factors, including advances in plant breeding, the chemical control of weeds, pests and diseases, and the introduction of improved mechanization systems have led to significant increases in the yield of many crops. In contrast, the widespread adoption of high output reduced cultivation systems for winter cereals has, in the U.K., contributed to a build up of soil compaction and to the limitation of full crop potential.

The aim of this research, was to quantify soil and crop responses to different levels of tyre/soil contact pressure at one site in England and in particular, to assess the effect of soil changes on cultivation requirements and machinery performance. These results could then be used in subsequent research, as a basis for operational and economics research studies and for the development and assessment of alternative machinery systems, to improve crop production efficiency.

2. Description of experiment

2.1. *The site*

A specific site was selected on the Institute farm at Silsoe, Bedfordshire because it exhibited the following features; (1) a clay soil typical of those used for cereal growing in eastern England, (2) homogeneity of the soil throughout the site, and (3) the absence of abrupt textural changes in the soil vertical profile. The properties and classification of the soil on the site selected are shown in Table 1.

The site was prepared with the aim of eliminating all traffic-induced compaction to a depth of 400 mm. The site was mole-ploughed in autumn 1981 at 2 m centres and at 560 mm depth (new main drains were introduced on the plot headlands in November 1983). This was followed in summer 1982 by combined rotary digging and subsoiling at depths of 140 mm and 400 mm, respectively and by rotary cultivation to 100 mm depth. A further subsoiling operation, to relieve the compaction caused by the tractor during rotary cultivation, was carried out at 400 mm depth using a tracklaying tractor. Prior to 1976 the cropping was predominantly grass, but this changed to cereals in 1977 and the first experimental crop was preceded by spring barley. Although some plots were on level ground, the site generally sloped downwards by about 3° from North-East to South-West. Plots 24 m wide by 35 m long were arranged in a randomized block design with four replications.

Table 1

Soil description and textural analysis of the site

Soil: Typical calcareous pelosol of the Evesham Series (Hodge *et al.*)[6]
Description: Clayey, calcareous, impermeable subsoil over gault clay

Soil constituents	(% by weight [USDA classification])
Clay	59·5
Silt	23·5
Sand (fine)	14·9
Sand (coarse)	2·1
Texture	Clay
Organic matter[7]	5·4
Calcium carbonate	7·7
Lower plastic limit (% m.c.d.b.)	47·3
pH	8·1

2.2. *Treatments*

Six treatments, consisting of three tyre/soil contact pressures and two methods of crop establishment, were applied in the experiment for the 4 crop years 1982/1983 to 1985/1986. The three tyre/soil contact pressures were provided by the following means.

1. (1) Tractors and equipment which ran at random over the plots using conventional tyres at between 100 and 250 kPa inflation pressure ("normal" treatment, designed to reflect current farming practice).
2. (2) Tractor and machines which ran at random over the plots, but which were modified to accept sufficient additional conventional wheels and tyres, so that all tyre inflation pressures could remain at or below 50 kPa ("low ground pressure" (LGP) treatment). A pressure of 50 kPa is less than that generally recommended for vehicle speeds above 10 km/h.
3. (3) A system where the wheels of tractors and equipment were confined to permanent wheelways (2·4 m apart) and no tyre-related stress was applied to the cropped area ("zero" treatment).

Winter wheat was established by each of these traffic systems using commercial farm practice of reduced and zero tillage operations, as follows.

(1) Shallow tine cultivation followed by drilling with a single disc soil opener.
(2) Direct drilling with a triple disc soil opener.

The treatments and their abbreviations are listed in Table 2.

Table 2
Treatments and their abbreviations

Traffic	*Cultivation*	
Normal	Direct drilled	(NDD)
LGP	Direct drilled	(LDD)
Zero	Direct drilled	(ZDD)
Normal	Shallow cultivated	(NSC)
LGP	Shallow cultivated	(LSC)
Zero	Shallow cultivated	(ZSC)

Cultivation equipment consisted of a heavy-duty spring-tine (HDST) cultivator, a dutch and a seed harrow. Sowing was done with a 4 m trailed grain and fertilizer drill equipped with either the triple or single disc openers and with "single" or "dual wheels". Agricultural chemicals and granular fertilizer were applied from 12 m booms on three-point linkage mounted machines; and metering of fertilizer was from a ground-driven metering wheel. To facilitate the necessary tractor changes when operating these applicators, they were mounted on a specially designed, wheeled carriage. This was equipped with its own power take-off train and the primary wheels (fixed at 2·4 m track) could be "dualled" when necessary.

Harvesting was with a conventional, self-propelled, combine harvester having a wheel track of 2·4 m. Provision was made to dual all wheels. The harvester was equipped with a small temporary holding tank for grain weighing and sampling, and with a 1·2 m or a 4 m wide cutting table. A straw spreader was fitted to the rear of the combine.

3. Crop and soil management

Following harvest of the previous wheat crop, straw spread by the combine harvester on the experimental area was burned and soil measurements made from the bare surface. Cultivations for the next wheat crop then began with the aim of sowing during the first week of October. Agricultural chemicals and granular fertilizer were applied to the crop at the appropriate growth stages and in line with good commercial practice using annual/permanent tramlines.

On the normal and LGP treatment plots, the only wheelings applied were those required for normal cultural operations and as these were constrained to run parallel to the length of the plots, steps were taken to ensure their even build up across the plot width. These steps consisted of recording the position of all wheel passes and planning subsequent operations, so that wheels were positioned in those areas which either had, in the early stages of the experiment, been left uncovered or as the experiment progressed, been less intensively stressed by tyres. Typically, random wheelings from tractors amounted to five passes in the shallow cultivation system and two passes in the direct drilled system. These were followed by about six tractor passes using tramlines and one set of random wheelings from the combine harvester (using the 4 m wide cutting table). No trailer wheelings were imposed on the plots but by the time the second crop was established, no significant area remained unstressed by tyres.

On the zero traffic plots each pair of 2·4 m tracks (was permanent, uncropped wheelways spaced at 4 m centres) was established using the appropriate tractor. All subsequent traffic used either all six pairs of wheelways (4 m implements) or just two pairs (12 m implements).

During cultivation, soil engaging tines, which would otherwise have cultivated the wheelways, were removed. Drill coulters were left in place in the wheelway positions but no grain was metered to them. Harvesting was with both the 1·2 m and 4 m wide tables. (See Section 4.2). This system was devised purely as a means of establishing experimental unwheeled beds and was not considered a practical farm system.

4. Measurements and records

4.1. *Weather and soil*

Meterological records from the Silsoe station situated 2 km from the site, were used to calculate potential evapo-transpiration of the crop using the method of Penman.[8]

Cone resistance was recorded at random on each plot using a Findlay Irvine "Bush Penetrometer" having a 30° cone of 127 mm^2 base area; soil bulk density was measured in a similar manner with a twin probe, nucleonic, density meter.[9] Differences in surface topography resulting from the treatments were recorded using a profile gauge. This was placed at right angles to the direction of wheelings and its 46 × 20 mm diameter probes, spaced 50 mm apart, were lowered on to the soil surface.

Measurement of soil water content was made to 2 m depth, using a calibrated neutron moisture meter (Wallingford type). Surface corrections were made following the procedure outlined by Harris.[10] Matric and hydraulic potential measurements, were made with tensiometers installed through the walls of permanent access pits, established on the site in September 1982 using the method described by Howse and Goss.[11] Similarly, piezometers were also installed at between 0·5 m and 2 m depth. These were used to measure saturated hydraulic conductivity, using the method described by Youngs and Goss,[12] in which the level of water in the manometers was lowered and the rate of return rise observed. The sites of the 0·8 m diameter × 2m deep access pits on single replicates of four treatments (NDD, NSC, ZDD, ZSC), ensured that mole drain channels were not interrupted and were centrally placed between the permanent wheelways on the zero traffic plots. As data from the neutron moisture meter were to be used to establish water release characteristics (soil matric potential versus water content), a number of preliminary measurements were made on this soil. These were used to check the values of water content indicated by the calibration curve provided with the meter, against those derived on a volume basis using gravimetric readings. Good correlation was achieved and the need for recalibration of the meter was therefore deemed unnecessary.

4.2. *Crop*

It was the intention during drilling that the depth of sowing and number of seeds sown should be eliminated as variables in this experiment. Since a common depth of seed placement could be achieved only by appropriate adjustment of the drill coulters, any differences in sowing depth which were recorded, reflect an inability to achieve this aim, rather than a treatment effect. On the other hand, the number of seeds sown per unit area on each treatment, remained constant by using the same drill metering device on all plots, and differences in population were therefore likely to be a depth or treatment effect. The prewinter plant populations established on each treatment were estimated from 10 counts per plot, each covering an area of 0·21 m^2. Similarly, sowing depth was recorded by measuring the distance between the seed coat and the point of transition between the white and green stem of 20 plants selected at random on each plot. Dry matter production was determined, during the most active growth period of the crop, on the replicates being monitored for soil water use. These data were collected by trimming sample areas ($5 \times 0{\cdot}2$ m^2) of the crop to ground level at the start and the end of the growth period. On each of the normal and LGP plots, grain yield was determined from a single, randomly positioned, full length cut, from cropped areas exclusive of any tramlines or wheelways, using the 4 m cutting table of the combine harvester. On the zero traffic plots, a similar cut was made using the 1·2 m wide table, placed centrally over one of the 2 m wide unwheeled beds. The remainder of the crop on these plots was then harvested using the 4 m table. Sample weights from each treatment were multiplied by an appropriate factor to give an overall yield per hectare.

4.3. *Machinery*

During cultivation and crop sowing, measurements were made of tractor forward speed, wheel slip and fuel consumption and the depth of work of the implement. Where possible direct measurements were made of implement draught. The aim during each machinery operation was to maximize output whilst maintaining work quality, subject to some constraints imposed by measuring procedures and plot working. Tractor speed was recorded either manually in conjunction with wheel slip or by a chronometer and radar distance meter mounted on the tractor. Fuel use was measured with a positive displacement type liquid meter, installed permanently in the fuel lines of each of the tractors. Implement working depth was monitored on each plot by measurements from the undisturbed soil surface. The draught of mounted implements was measured using a three-point linkage dynamometer.[13] Information from these transducers was coded on the tractor and transmitted via a radio link to a receiving vehicle on the field headland. The signals were then decoded, digitized and analysed by an LSI 11/2 computer following each run. A minimum of four runs of 10 s duration were normally made on each plot. Following each operation on a given treatment, the measuring equipment and implement were transferred to the tractor required for the next treatment.

Fuel use data were converted to equivalent power at the tractor power take-off (pto), using no-load engine speed and fuel consumption versus power curves established for each tractor. These curves were produced from readings taken at different engine no-load governor settings, with the tractor connected to a dynamometer via the pto shaft. This technique provides a quick and simple method of comparing the power requirements of different operations on the same tractor, on a particular day, under similar field conditions and when wheel slip and travel speed can be recorded. As a measure of absolute power, however, it is accurate only when account can be taken of differences in air temperature, relative humidity and fuel temperature between field and calibration conditions.

It is also subject to a number of errors when operations are compared using different tractors, as was the case in this experiment. These include different transmission and rolling resistance losses and relative differences in fuel temperature on each tractor, between field and calibration test conditions. Differences in transmission and rolling resistance losses, can be allowed for by measuring the power required to propel the tractors across the field unloaded. Differences in temperature on the other hand can only be corrected for by measurement. The errors from this source are likely to be minimal however, since a change in temperature of 13°C (fuel specific gravity 0·837 at 15·6°C and coefficient of expansion = 0·000666) is required before power availability is altered by just 1%. Where implement energy requirements were compared therefore, this was determined by subtracting the unloaded power and the percentage of wheel-slip loss from the gross power. This figure was then used together with the implement work rate to compute energy requirements, and was considered to be accurate to within ±5%.

5. Results and discussion

5.1. *Weather*

Records (Table 3) showed the rainfall, compared with the 30 year mean, was above average in the autumns of 1982 and 1984 and consistently greater than average in May of all years. Except in 1984, February was a month of below average rainfall, as were the months of September and October 1985. Individual monthly mean soil temperatures at 100 mm depth, varied by a maximum of 3·8°C from the 30 year mean (July 1983) and by 4·1°C between years (January 1983 and January 1985). In general February was significantly cooler and July significantly warmer than average.

5.2. *Cone penetration resistance*

Differences in cone resistance between treatments became less variable with time, as would be expected from the way the treatments were applied. In 1985, it was apparent that the main contrast (significant at the 5% level) was between trafficked and untrafficked soil[14] where, although the difference varied with depth, the average increase in resistance due to traffic was 35%. An additional set of measurements, taken in March 1986 (*Fig. 1*) indicated that on average over the depth range measured, the trafficked

Table 3

Rainfall and soil temperature at Silsoe, 1982–1986

	Monthly rainfall, mm (mean soil temperature, °C at 100 mm depth)					
	1982–83	*1983–84*	*1984–85*	*1985–86*	*Mean*	*30 year mean*
Sept.	47·2 (13·9)	63·4 (13·3)	99·5 (12·9)	17·4 (14·2)	56·9 (13·6)	44·8 (13·6)
Oct.	110·5 (9.3)	37·7 (9·8)	41·1 (9·7)	16·1 (10·4)	51·3 (9·8)	46·8 (9·5)
Nov.	69·3 (6·8)	37·5 (6·3)	89·7 (7·0)	44·3 (3·4)	60·2 (5·9)	50·7 (5·3)
Dec.	43·9 (2·6)	38·3 (3·5)	35·7 (4·0)	86·9 (5·8)	51·2 (4·0)	51·2 (3·4)
Jan.	34·7 (4·7)	63·6 (2·1)	37·7 (0·6)	57·4 (2·1)	48·3 (2·4)	45·7 (2·5)
Feb.	26·1 (1·1)	34·7 (2·1)	16·5 (–)	9·5 (0·2)	21·7 (1·1)	35·8 (2·6)
Mar.	29·6 (4·4)	37·5 (3·4)	33·0 (3·2)	51·7 (3·3)	37·9 (3·6)	39·4 (4·1)
Apr.	94·7 (6·3)	8·9 (6·9)	13·3 (8·1)	60·9 (5·6)	44·4 (6·7)	38·5 (7·5)
May	99·9 (10·7)	81·2 (10·3)	46·4 (11·3)	56·2 (11·9)	70·9 (11·1)	40·0 (12·0)
June	11·4 (16·6)	45·4 (16·3)	107·6 (14·4)	13·4 (16·5)	44·4 (16·0)	47·9 (16·0)
July	31·5 (21·3)	8·5 (18·6)	51·2 (18·2)	38·9 (18·5)	32·5 (19·2)	48·8 (17·5)
Aug.	32·3 (18·4)	42·2 (17·8)	32·7 (14·8)	76·4 (14·9)	45·9 (16·5)	59·8 (16·4)
Total	631	499	604	529	566	549

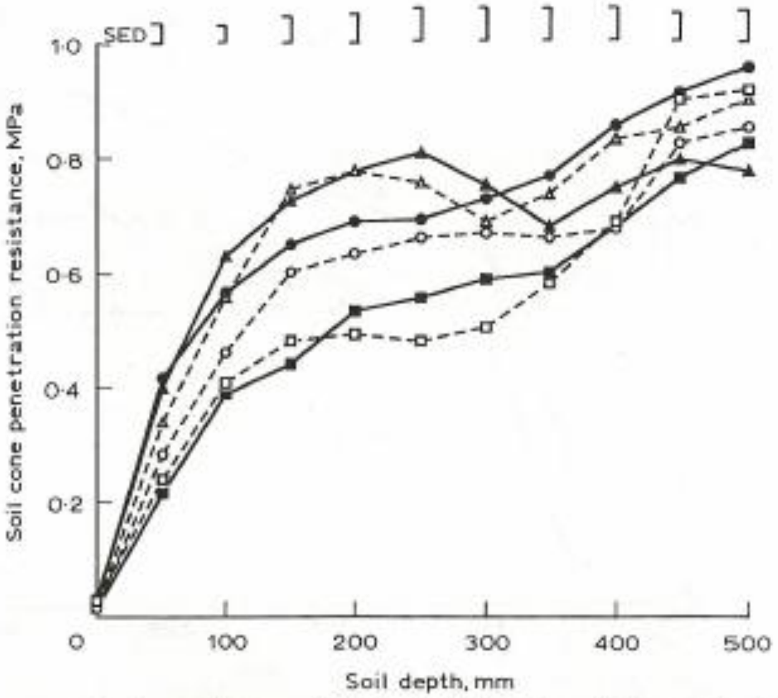


Fig. 1. Soil cone penetration resistance on 24 March 1986. —▲—, *NDD;* —●—, *LDD;* —■—, *ZDD;* – –△– –, *NSC;* – –○– –, *LSC;* – –□– –, *ZSC*

(including LGP) soil had a 26% greater resistance than the untrafficked soil (significant at the 0·1% level) and a range of differences between treatments from 0 to 62%. However, in general, cone resistance on the LGP plots was intermediate between that recorded on the normal and zero treatment areas. On the LGP plots there was evidence (significant at the 5% level) to suggest, that resistance was greater following direct drilling than after shallow cultivation.

5.3. *Bulk density*

Changes in soil dry density over the period of the experiment reflected not only the tyre/soil contact pressures applied but also the area trafficked for a given load. Hence in the first 2 years of the trial,[15,16] density tended to be greatest on the LGP plots, but by 1984 this trend, except in the top 100 mm of the soil profile, was less obvious and density on the normal plots became greater.[14] In 1985, although there was no significant difference in density following shallow cultivation or direct drilling, the mean values for normal traffic were significantly higher[17] (at the 5% level) than for LGP. In addition, both the normal and LGP trafficked soils were significantly higher in density, (at the 0·1% level) than those remaining untrafficked.

In 1986, additional density measurements were made with a high resolution meter[18] to a depth of 400 mm. These showed a very similar trend (*Fig. 2*), with average differences between all three traffic treatments, over the whole depth range, being significant at the 5% level. Although there was no difference in soil response to shallow cultivation or direct drilling, average differences in density due to normal and zero traffic, were 13% under shallow cultivation and 6% meaned for both methods of cultivation. More recent

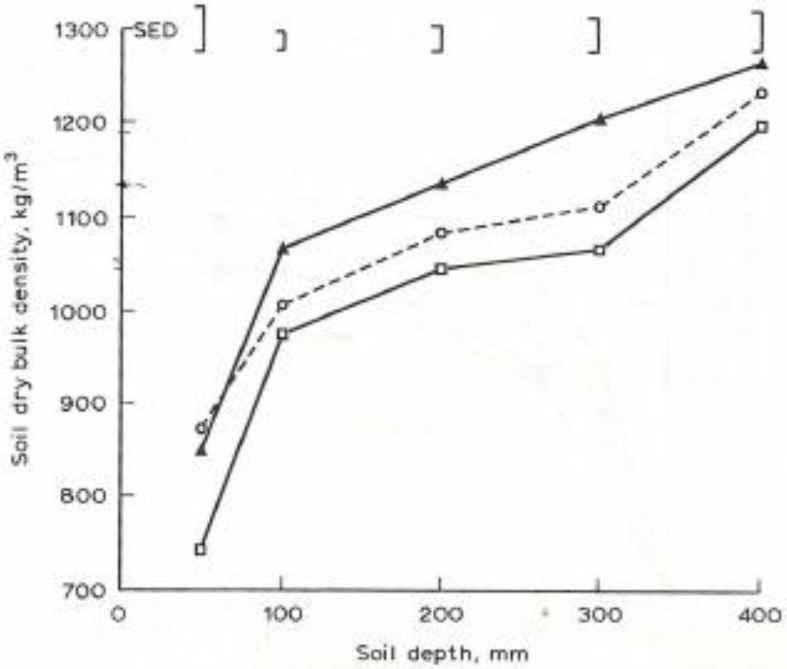


Fig. 2. Soil dry bulk density meaned for shallow cultivated and direct drilled soil, March 1986. —▲—, normal; – –○– –, LGP; – –□– –, zero

work by Douglas[19] growing ryegrass for silage, showed similar trends in soil density, despite being on a different soil and under dissimilar climatic conditions.

Interpretation of these and the cone penetrometer results, were also considered, taking account of the displacement of the original soil surface caused by wheel sinkage and as discussed by Henshall and Smith.[20] However, even if this difference in surface level is taken into account (approximately 70 mm, based on density measurements) an effect of traffic is still apparent at 0·4 m depth.

Table 4 gives measurements of the soil surface profile on single replicates of the normal and LGP treatments taken in autumn 1985. Some difference between the LGP and normal plot surfaces was indicated and histograms of surface depression below an arbitrary minimum (*Fig. 3*), confirmed that the normal treatments resulted in a greater number of larger surface depressions. These measurements, compared with those from

Table 4
Summary of surface depression data relating to a 4·55 m length of surface profile taken from four plots

	Depression below arbitrary minimum, mm		
Treatment	*Mean*	*Maximum*	*Standard deviation*
NDD	49·9	104	26·1
LDD	38·7	78	18·5
NSC	40·0	74	19·2
LSC	30·8	65	16·9

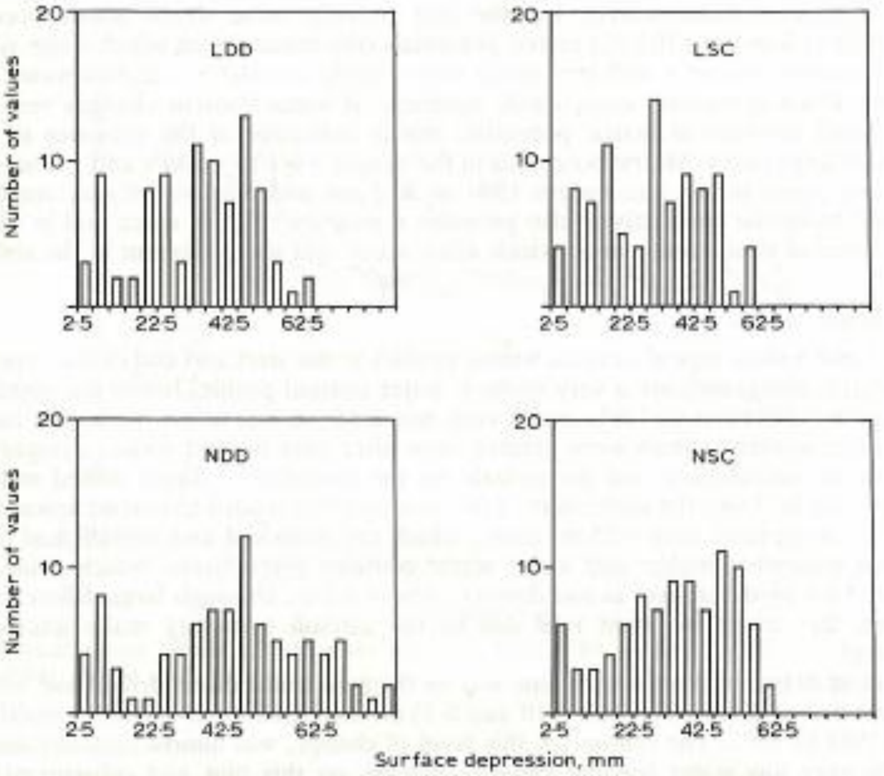


Fig. 3. Histograms of surface depressions below an arbitrary minimum from normal and LGP soil surface profiles measured in autumn 1985

earlier years,[14–16] suggested that as the whole plot area of both traffic systems became more evenly compacted, less differential sinkage of the wheels occurred, and differences between treatments became less noticeable.

5.4. *Soil water*

The soil water measurements were used to provide further information on soil compaction and its effect on root growth and function. Thus, differences in the drained water content and of the water table level of the upper profile, provide an indication of drainage characteristics, i.e. a lower water content and a more rapid fall in water table, would be compatible with a greater number of larger pores and/or pores of a more continuous nature. Differences in water table level below the drains and in the depth of water extraction by the crop, as indicated by the tensiometers, provides information about crop rooting depth. Very shallow rooting could indicate a physical barrier to roots, such as a compacted layer, or conversely an adequate supply of water and nutrients in the topsoil. Interpretation of the data therefore needs to be considered carefully in relation to the season, to crop growth and to water supply. It should also be noted that errors in neutron count created by differences in soil density and considered by Holmes[21] and by Cannell and Asbell,[22] were only of the order of 4%. Similarly, any error due to scattering of neutrons by the hydrogen content of the soil's organic matter, was unlikely to have affected treatments differentially and will therefore only have caused an error in absolute values.

The moisture release curves for the soil provide more detail about pore sizes, particularly at low (0 to 10 kPa) matric potentials (the tension with which water is held in the soil matrix), where a well-structured soil is likely to exhibit a higher water content than one which is severely compacted. Similarly, if water content changes very rapidly with a small increase in matric potential, this is indicative of the presence of a large number of large pores. Matric potentials in the ranges −0·1 to −5 kPa and −5 to −20 kPa will empty pores in the size ranges 1500 to 30·5 μm and 30·5 to 7·6 μm, respectively. Saturated hydraulic conductivity also provides a measure of pore space and in particular the presence of continuous pores, which allow water and air movement in the soil.

5.4.1. *Water content*

Figs 4 and *5* show typical drained winter profiles at the start and end of the experiment. The initial readings indicate a very uniform water content profile, below the depth of site preparation cultivation (0·4 m), and a very non-uniform one above it. In the cultivated layer, water content values were greater even after very limited traffic, compared with those on the untrafficked and particularly on the untrafficked direct drilled soil. *Fig. 5* indicates that by 1986, the uniformity of the readings had tended to extend upwards in the profile, to a depth of only 0.25 m, above which the trafficked and untrafficked soils still exhibited somewhat higher and lower water contents respectively, which could not be accounted for by differences in soil density. Above 0·1 m, although large differences were apparent, the errors in count rate due to the air/soil boundary make interpretation uncertain.

The most dramatic change with time was on the zero traffic direct drilled soil, where the water content at depths between 0·10 and 0·35 m, increased by about 10%, mostly in the period 1984 to 1985. The reason for this level of change, was almost certainly associated with the very low water holding capacity initially on this plot and subsequent natural settling, rather than a treatment effect, since, of all the treatments, this soil had the lowest number of mechanical forces applied to it.

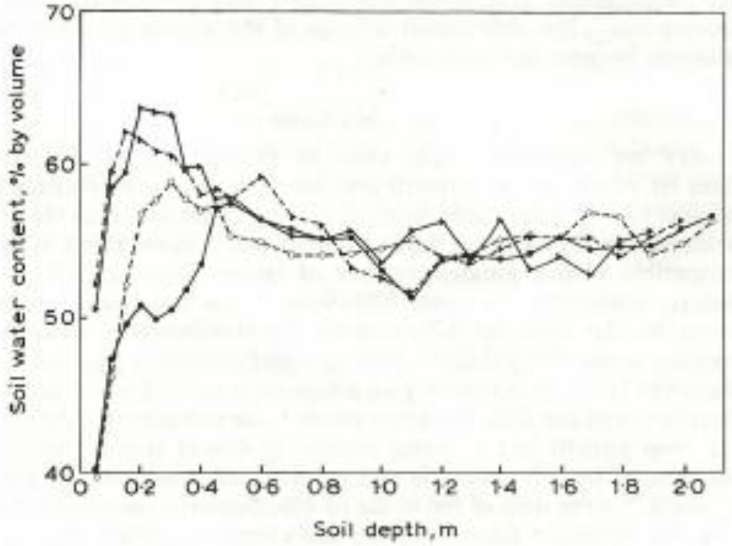


Fig. 4. Typical winter profile of soil water content, January 1983. —▲—, *NDD*; --▲--, *NSC*; —●—, *ZDD*; --○--, *ZSC*

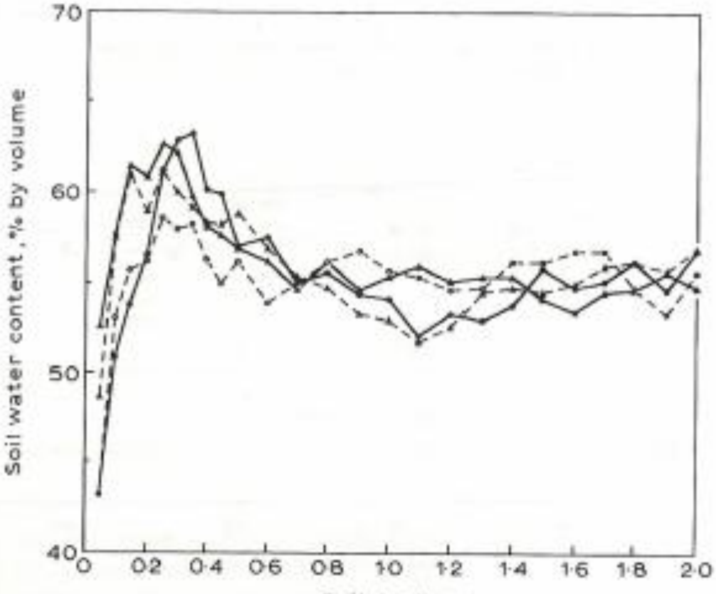


Fig. 5 Typical winter profile of soil water content, April 1986. —▲—, *NDD;* – –▲– –, *NSC;* —●—, *ZDD;* – –○– –, *ZSC*

5.4.2. *Water table*

The location of the water tables in the midline between mole channels, indicated from hydraulic potential profiles, generally dropped to about 1·8 m below the soil surface from day 200 (July 19), until about day 325 (November 21), then rose rapidly to remain at between 0·2 and 0·6 m depth over the winter period. Only during short periods after rain, did the level rise to within 0·1 m of the surface. Under the ZSC treatment, the water table was consistently nearer the soil surface by between 0·1 and 0·2 m than on the other monitored plots. To some extent, this was considered to be a siting problem caused by disruption of the mole channels, which were both coincident and parallel to the permanent wheelways over this section of the plot; crop performance as discussed later, may also have accounted for some of this difference in the water table level. On the ZDD plot the soil exhibited a tendency to drain more quickly and to a lower level, but this characteristic became less noticeable with time. The maximum depth of water extraction by the crop ranged from 1·4 to 2·0 m (depending on season) on three of the monitored plots (NDD, NSC, ZDD) with no evidence of a significant difference between treatments. On the ZSC treatment plot, the higher water table mentioned above, limited this range to 1·0 to 1·8 m.

5.4.3. *Soil moisture characteristic curves*

Volumetric water content was plotted against matric potential at 0·15 m depth (just below maximum cultivation depth) for both 1983 and 1986 (*Figs 6* and *7*). In general these show that on any given treatment, the number of relatively larger pores decreased with time. However, the volume of water extracted over the two ranges of matric potential (Table 5), was nearly always greater on the untrafficked plots, indicating a greater number of relatively larger pores remaining under these treatments. At 0·3 m depth, considerable extremes seemed to exist in 1983. On the untrafficked soil, a large

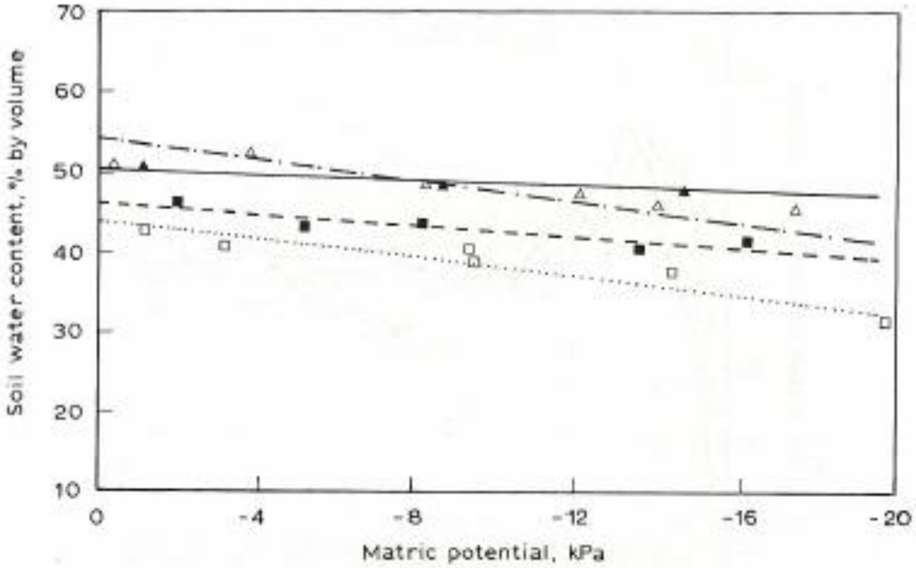


Fig. 6. Water release characteristics on the direct drilled plots at 0·15 m depth. ······□, *1983 ZDD;* —·—·△, *1983 NDD;* – – – –■, *1986 ZDD;* ——▲, *1986 NDD*

percentage of the water was extracted at matric potentials below −10 kPa. However, on the trafficked plots, there was only a steady decline, or as in the case of the direct drilled soil, very little water extraction until a potential of −8 kPa was reached, following which there was an extremely rapid decline. By 1986, these differences at 0·3 m depth were much less extreme, indicating that pore sizes equivalent to this range of suctions, were generally similar on all treatments.

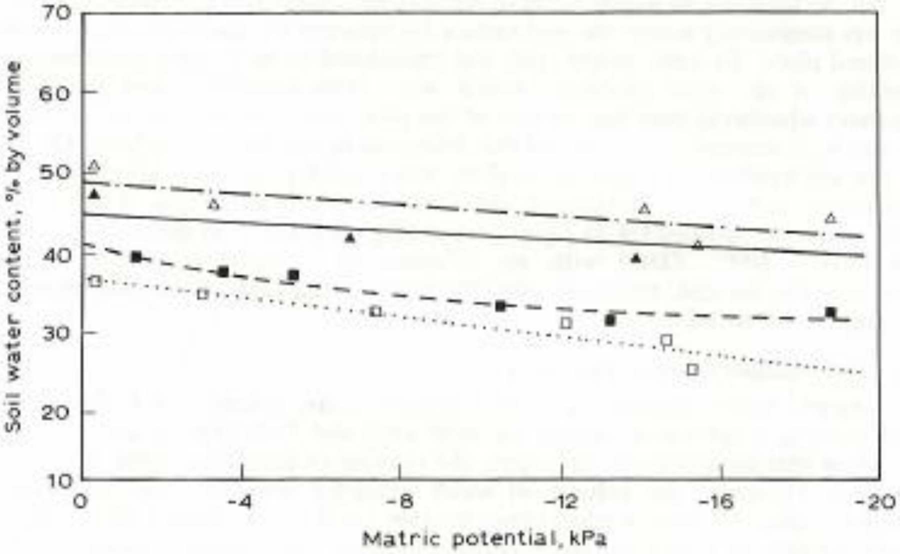


Fig. 7. Water release characteristics on the shallow cultivated plots at 0·15 m depth. ······□, *1983 ZSC;* —·—·△, *1983 NSC;* – – – –■, *1986 ZSC;* ——▲, *1986 NSC*

Table 5

Change in volumetric water content (% by volume) with decrease in matric potential (kPa) at 0·15 m depth

Year	*Treatment*	*Matric potential, kPa* *0 to −5*	*−5 to −20*
1983	NDD	−3·15	−9·43
1986	NDD	−0.69	−2·07
1983	ZDD	−2·82	−8·45
1986	ZDD	−1·60	−4·78
1983	NSC	−1·03	−3·11
1986	NSC	−0·65	−1·09
1983	ZSC	−1·80	−5·39
1986	ZSC	−2·90	−2·26

At 0·4 m depth, more data were available, but only on the direct drilled plots was there any evidence to suggest a greater number of large pores in an untrafficked regime.[17]

5.4.4. *Saturated hydraulic conductivity*

Fig. 8 shows the saturated hydraulic conductivity profile established from measurements made on 10 January and 8 April 1986. Observations of values from trafficked and untrafficked soil gave no indication of a treatment effect. The limited range of variability in the data confirms the homogeneous nature of the soil on this site.

5.5. *Crop performance*

Depth of seed placement varied between treatments by no more than 20 mm in any one year and similarly plant populations differed by a maximum of only 70 plants/m^2 (Table 6). Yields (Table 7), which in the first year on the trafficked plots, also included crop from

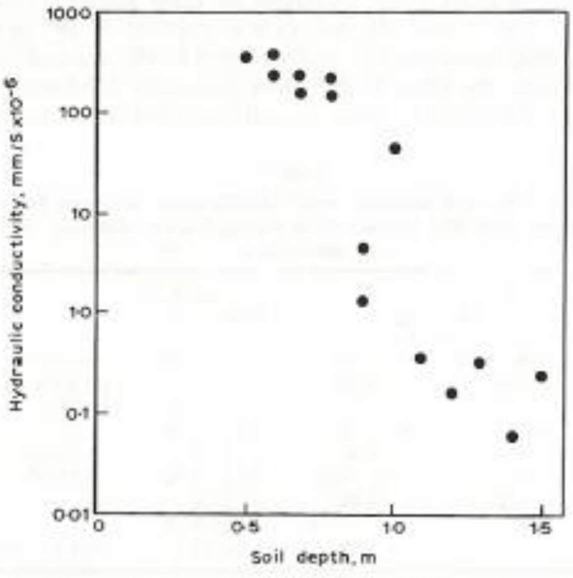


Fig. 8. Saturated hydraulic conductivity profile established from the four monitored plots in spring 1986

Table 6

Depth of seed placement and prewinter plant populations

Traffic	*Depth of sowing, mm (plant population, plants/m²)*					
	N		*L*		*Z*	
cultivation	*DD*	*SC*	*DD*	*SC*	*DD*	*SC*
1982–83	45(341)	43(328)	34(375)	36(375)	39(358)	41(343)
1983–84	36(290)	35(280)	39(276)	45(286)	46(264)	46(285)
1984–85	50(323)	47(315)	39(350)	47(322)	56(325)	50(336)
1985–86	33(249)	29(275)	39(242)	34(256)	36(269)	32(312)

soil as yet unstressed by tyres (3% of the surface area on the LGP plots and 22% on the normal plots) were unaffected by cultivation treatment when meaned over the 4 years. However, in 1985, there was an unexplained reduction due to shallow cultivation on the zero traffic plots and in 1986 a small overall loss in yield following direct drilling, which was attributed to an observed greater incidence of blackgrass.[17] No specific factor other than treatment could explain the slightly improved yield following the LGP treatment in 1986.

In 1985 and 1986, the pattern of water use by the crop on the four monitored plots (NDD, NSC, ZDD, ZSC), was characterized by an early period when it was below the use predicted from calculations of potential evapo-transpiration,[8] followed by a similar period when the estimated potential was exceeded. During the latter period in 1985, crop on both the direct drilled plots, appeared to use relatively more water than the wheat established by shallow cultivation. These differences were not reflected by grain and dry matter yield, the latter of which ranged from 10·1 to 11·3 t/ha in 1985 and 12·5 to 14·6 t/ha in 1986. Differences between treatments were not significant.

The reduction in yield on the zero traffic plots in 1983 was almost certainly promoted by manganese deficiency in the crop. Paling and limpness of the wheat were observed in April, particularly on the untrafficked beds but the problem was also apparent in narrow strips on some of the normal plots. Analysis of crop samples from all treatments,[15] revealed evidence to suggest that the manganese content of the peduncle and ear was proportional to crop yield and inversely proportional to the amount of mildew on the flag leaf and ear. Crop from the zero traffic plots generally exhibited a lower manganese content than that from the other treatments, although this difference was not found to be

Table 7

Mean crop yields (t/ha) and standard errors of differences of means for each treatment (yield corrected to 85% dry matter, from cropped areas exclusive of tramlines and wheelways)

Traffic	*N*		*L*		*Z*		
cultivation	*DD*	*SC*	~~*SS*~~ DD	*SC*	*DD*	*SC*	
1983	8·85	8·91	8·67	8·74	7·48	7·29	
	8·88		8·70		7·39		(N-Z) = 1·49 ± 0·30***
							(L-Z) = 1·32 ± 0·30***
1984	8·05	7·99	8·37	8·59	7·67	7·66	
	8·02		8·48		7·67		(L-Z) = 0·81 ± 0·22**
1985	5·48	5·56	5·41	5·47	5·63	4·94	(All-ZSC)*
	5·52		5·44		5·28		
1986	6·46	6·61	6·91	7·54	6·58	7·17	
	6·54		7·22		6·87		(N-L) = −0·68 ± 0·25*

* (*P* = 0·05), ** (*P* = 0·01), *** (*P* = 0·001)

significant statistically. In 1985 and 1986 the crop was treated with manganese sulphate before any deficiency symptoms appeared.

Manganese deficiency in cereal crops is most often caused by poor uptake at the plant roots, rather than from a deficiency in the soil. There are a number of explanations for this problem, but two are commonly quoted. The generally accepted explanation considers that if soil is compacted in the rooting zone, more carbon dioxide accumulates, and this lowers soil pH and reduces the amount of oxygen available for microbial oxidation, a mechanism which converts available manganese into an unavailable form of MnO_2. This explanation is disputed however by Passioura and Leeper,[23] who suggest that insoluble MnO_2 is made soluble by a contact reduction mechanism of the roots. This requires intimate soil/root contact, and hence the need for soil consolidation. In general, high pH and soil organic matter levels exacerbate the problem.

In view of the fact that in 1983, 22% of the surface area of the normal plots was as yet unstressed by tyres, it was surprising that this treatment did not also suffer a significant loss in yield. This may have been associated with the fact that tyres cause more extensive sub-surface firming of the soil, than is evident from the footprint. The narrow strips of manganese deficient crop on the normal plots were certainly observed to be of less significance than was suggested by the surface areas which remained unstressed.

To investigate the effect on crop yield of firming the soil by rolling, a supplementary trial was conducted in spring 1986 on a number of the unwheeled beds, in conjunction with the application of manganese sulphate. Analysis of crop yield data showed that the application of manganese sulphate increased yield significantly, but that no other effect was apparent.[16] Table 8 provides a summary of these data.

The susceptibility of the crop to manganese deficiency on this soil obviously confounded treatment differences, particularly when manganese applications were delayed or were with less effective materials (chelates). The poor yield in 1985, which in itself masked differences between treatments, was a combined effect of take-all and foliar disease, the latter appearing suddenly in late May and persisting despite the application of sprays.

Although the trial with rolling failed to identify a beneficial yield effect from this treatment, many other experiments[2,3] have suggested that some degree of soil firming is necessary. If this is the case, then further work is necessary to determine the optimum economic level of soil compactness. This should take account of both the degree of

Table 8

Effect of manganese sulphate application and rolling on crop yield of the zero traffic plots

	Crop yield, t/ha (corrected to 85% dry matter)				
	Manganese		*No manganese*		
Treatment	*Roll*	*No roll*	*Roll*	*No roll*	*Means*
ZDD	7·03	6·58	6·10	6·40	6·53
ZSC	7·00	7·17	6·68	7·08	6·98
Means	7·01	6.87	6.39	6.74	
	6·94		6·56		

Standard error of the difference of means; vertical comparisons ±0·329, horizontal ±0·329, interactions ±0·323 compactness identified by Håkansson[3] for maximum crop yield, and of the energy requirements for subsequent cultivations, following the appropriately timed consolidation.

5.6. *Machinery performance*

5.6.1. *Draught and cultivation*

Table 9 shows data relating to draught measurements taken during primary cultivations. In all years, the HDST was found to be inappropriate on the zero traffic plots, because of its wide tine spacing (220–280 mm). The deep friable tilth retained on untrafficked soil was only stirred locally and was formed into ridges needing subsequent levelling. This implement was therefore replaced by a dutch harrow (*c.*, 250 kg/m width), whose narrowly spaced (50 mm) vertical tines formed a good seedbed in one pass.

Results showed that implement draught was not reduced by LGP operations compared with normal traffic, and indeed on some occasions it was increased. This was probably associated with the greater area stressed by tyres with the LGP system. In just two passes with an implement 4 m wide, tyres on the LGP tractor covered an area equivalent to 100% of the soil surface, whereas for the normal system the corresponding figure was only 43%. Additional measurements were made in 1985 to provide a direct comparison between the draught of the HDST under all traffic regimes (Table 9). In particular, it will be seen that on the ZSC plots, draught was reduced by 37% (including an additional draught component for the two tines removed in the wheelways) compared with that required on the normal plots. Draught of the dutch harrow on the ZSC plots was relatively high, largely arising from an inability to control its depth of work. If the crumble roller was adjusted to support all the weight of the machine, it rapidly became blocked by moist fine soil. The roller was therefore used in a "float" position which gave some firming to the soil, but allowed the tines to find their own depth of work. In 1985, because of these problems, the dutch harrow was replaced by a medium weight seed harrow (100 kg/m width) having similarly spaced tines but no crumble roller. Although this performed satisfactorily, its depth of penetration was limited to about 40 mm and was close to being inadequate. An intermediate weight of harrow would obviously have been ideal.

Table 9

Implement draught requirement during shallow cultivation

		1983		*1984*		*1985*	
Treatment and pass	*Implement*	*Depth of work, mm*	*Draught, kN*	*Depth of work, mm*	*Draught, kN*	*Depth of work, mm*	*Draught, kN*
NSC, 1st	HDST	60	7·9 (14)	85	22·8 (18)	95	18·3 (14)
LSC, 1st	HDST	60	8·1 (14)	85	19·8 (18)	95	21·1 (14)
ZSC, 1st	HDST	—	—	—	—	95	11·5* (14)
ZSC, 1st	DH	100	13·0	120	17·3	40†	7·3†
NSC, 2nd	HDST	80	14·3 (18)	90	nr	100	10·3 (18)
LSC, 2nd	HDST	80	13·6 (18)	90	6·4 (14)	100	12·2 (18)

In parentheses = number of tines in 4 m width.
HDST = heavy-duty spring-tine; DH = dutch harrow.
* draught for 12 tines multiplied by 14/12.
† medium weight harrow.
nr not recorded

In autumn 1983, low rainfall resulted in the precultivation soil conditions shown in *Fig. 9*. The pattern of soil shrinkage cracking varied noticeably between treatments. On the normal plots it tended to be parallel to the wheelings, whereas a more random and extensive pattern was apparent on the LGP plots. On the unwheeled soil, the cracks tended again to be parallel to the wheelings (permanent wheelways), but had been filled to a large extent by the friable top soil. Cultivation on the NSC and LSC plots was difficult in these conditions. Use of the HDST was impracticable, because this either just scratched the surface or pulled out very large clods. Several alternative implements were tested for effectiveness, including a soil-driven rotary cultivator, a power harrow, a dutch harrow and chisel discs. Of these, only the latter could withstand the conditions and

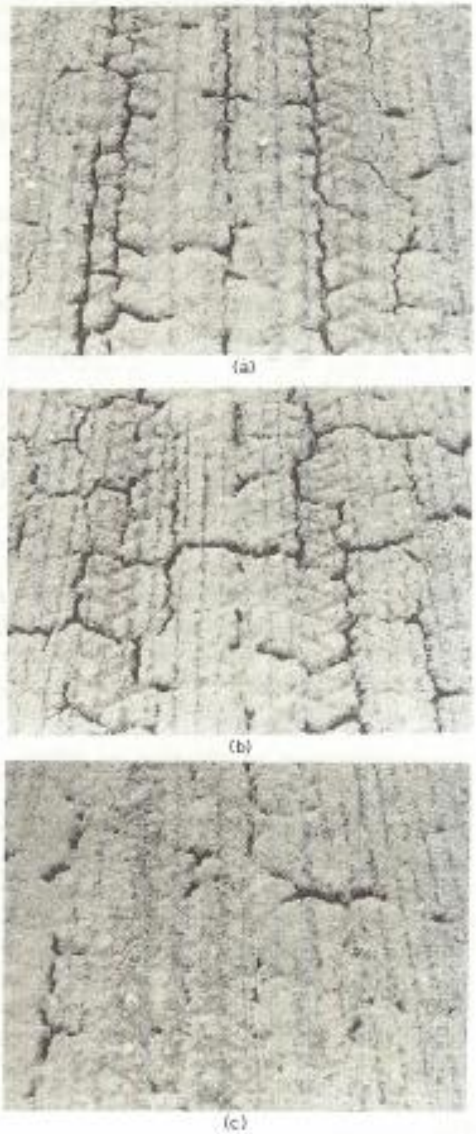


Fig. 9. Soil conditions prior to cultivation in autumn 1983. a, normal; b, LGP; c, zero

provide any measure of tilth, albeit with two passes. In contrast, conditions on the ZSC plots were such that a seedbed was produced by just one pass of the dutch harrow. Significant rainfall immediately following these trials however, resulted in a complete change in soil conditions, and the HDST and dutch harrow were both subsequently used to good effect, on the trafficked and untrafficked soils, respectively. On the direct drilled plots, large fissures were still present when drilling was due to commence. To prevent loss of seed down these cracks, all plots were cultivated initially with the dutch harrow.

It is evident that from what appear to be relatively small (albeit statistically significant) differences in cone resistance and bulk density between treatments, that marked contrasts in soil workability can occur. Similarly, small changes in soil water content with matric potential, may have a considerable effect on days available for cultivation, particularly when extremes of rainfall occur. Although workability was assessed only in the top 100 mm of soil, it is interesting to note that, even though quite extreme levels of trafficking were imposed, the differences in soil water content between treatments existed only in the top 0·3 m. It was also noticeable that these contrasts became apparent early in the experiment and persisted, indicating that trafficking, following deep loosening, very quickly returned the soil to a "trafficked" condition.

In the absence of traffic, although the relatively low initial water content of the drained profile increased with time, it remained below that of the trafficked soil. This was confirmed by the water release characteristics, the combined implications of which were that in the absence of traffic, this clay soil drained more readily and to a greater extent than where traffic was present. The potential negative effect that this may appear to have on seed germination in the untrafficked beds, was not realized. Indeed, the fine tilth observed in the top 100 mm of soil and the very limited cultivations needed to produce a seedbed, ensured minimum moisture loss and intimate contact between seed and soil. Although no shallow cultivation advantage was gained with the LGP system, the relative absence of soil rutting, particularly following initial trafficking after loosening, may in practice allow slightly shallower cultivation operations, and reduce the likelihood of restrictions on travel speed owing to driver discomfort.

5.6.2. *Energy requirements and costs*

Energy requirements for cultivations were very similar on the normal and LGP plots and on average were 95% greater than those required on untrafficked soil (Table 10). When the medium weight, rather than the heavy dutch harrow was used on the zero traffic plots, this figure rose to more than 500%. Total energy for the shallow cultivation

Table 10

Net energy requirement for cultivation and drilling

	Energy, MJ/ha								
	1983			*1984*			*1985*		
Treatment	*Cults*	*Drilling*	*Total*	*Cults*	*Drilling*	*Total*	*Cults*	*Drilling**	*Total*
NDD	85	33 (36)	118	29	45 (50)	74	—	47 (50)	47
LDD	74	27 (39)	101	22	34 (39)	56	—	40 (39)	40
ZDD	91	23 (46)	114	33	39 (56)	72	—	35 (56)	35
NSC	187	34 (35)	221	175	32 (47)	207	145	33 (47)	178
LSC	160	33 (44)	193	165	28 (47)	193	151	31 (47)	182
ZSC	91	25 (46)	116	85	26 (50)	111	24	27 (50)	51

In parentheses = depth of seed placement, mm.
*drill plus seed harrow

system was, on average, increased by 80% when normal and LGP traffic were used, compared with zero traffic, and similarly by 253% when the medium weight harrow was introduced in 1985. Table 10 also shows that the differences in energy for drilling, including direct drilling, were to some extent confounded by differences in sowing depth, but that the energy requirements were generally lower on the zero, compared with the normal plots. A similar, but less significant increase in energy, was also apparent for the LGP system compared with the zero system. Total energy requirements for direct drilling were similar on all treatments and where small differences occurred, these were generally attributable to changes in drilling depth. Difficulty of coulter penetration, often apparent with triple disc coulters, was significantly absent on the unwheeled soil, and indeed some problems were experienced in preventing the drill from sowing too deeply. These lower coulter penetration forces could enable lighter and less expensive drills to be used under this regime and allow the direct drilling technique to be adopted in a wider range of soil and climatic conditions.

Hietbrink and Chamen,[24] using results from this work showed that a system based on a 12 m gantry for maintaining unwheeled beds, was significantly more profitable than a conventional traffic system. Savings in fixed and cultivation costs were the main reason for increased profitability, as well as the low predicted yield losses from land lost to wheelways. A 6 m tractor-based bed system had the lowest costs, but was the least profitable system because of the larger area, and therefore higher predicted yield losses, due to the traffic lanes.

7. Conclusions

The following conclusions can be drawn from this 4 year trial on a 60% clay content Evesham series soil.

(1) Cone penetration resistance in the top 250 mm of soil, increases with the tyre/soil contact pressure indicated by inflation pressure, but the greatest contrast in resistance is between soil which is stressed or unstressed by tyres.

(2) Soil dry bulk density in the top 400 mm, increases with the tyre/soil contact pressure indicated by inflation pressure. Differences in density between soils stressed by tyres at conventional pressures and those remaining traffic-free, can average 10%.

(3) Because tyres in a LGP machinery system stress a larger area of soil during each operation, density and resistance of a loosened soil, tend to increase more rapidly under this regime, compared with conventional practice. However, under a LGP system, these properties ultimately stabilize at a lower level than those under a conventional system.

(4) Soil cone resistance and bulk density are not differentially affected by light and medium intensities of traffic (direct drill and shallow cultivation systems, respectively), when subjected to conventional or LGP regimes.

(5) The number of relatively larger pores in a loosened soil profile, as indicated by water release curves, decreases with time as a result of cultivation and weathering. At 0·15 m depth, conventional traffic further reduces these numbers; at 0·3 and 0·4 m depth, and where shallow cultivation is practised, the difference between trafficked and untrafficked soil cannot be differentiated. Under a direct drilling regime, the effect of traffic on the number of larger pores is still evident at 0·4 m depth.

(6) At 0·5 m depth, traffic has no effect on saturated hydraulic conductivity.

(7) The yield of wheat is not differentially affected by shallow cultivation or direct drilling, but the loose seedbed conditions under a zero traffic regime, tend to

trigger manganese deficiency in the crop and lead to a loss in yield. Prophylactic applications of manganese sulphate can overcome this problem.

(8) Trafficking the soil increases the draught requirement of a shallow tine cultivator by up to 60% and the energy requirements for shallow cultivation and drilling by up to *c.*, 250%. In the absence of traffic, soil tilth is maintained from one year to the next and very little cultivation is needed to establish a seedbed.

(9) Increasing the number of standard tyres on machinery, combined with a reduction in their inflation pressure, is a practical method of reducing soil rutting. A rapid cost effective method of changing tyre inflation pressures, while on the move, is necessary to allow safe operation on the road.

(10) The potential of a zero traffic system, to provide widespread savings in cultivation inputs and an improvement in soil structure, is considerable. A cost effective method of providing such a system should be explored.

Acknowledgements

The authors are indebted to colleagues at AFRC, IER and IACR and at the former AFRC Letcombe Laboratory for their support. We thank staff from the Soil Survey and Land Research Centre for their assistance. This work was funded by the Ministry of Agriculture, Fisheries and Food, the Department of Education and Science and the European Commission.

References

[1] **Davies, D. B.** Reduced cultivations for cereals. Home Grown Cereals Authority Review Article. Hamlyn House, Highgate Hill, London: HGCA, 1988

[2] **Soane, B. D.** Compaction by agricultural vehicles: a review. SIAE Technical Report No. 5 (reprinted from Soil and Tillage Research 1 and 2, 1980–1982)

[3] **Håkansson, I.; Voorhees, W. B.; Riley, H.** Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. Soil and Tillage Research 1988, **11:** 239–282

[4] **Eriksson, J.; Håkansson, I.; Danfors, B.** The effect of soil compaction on soil structure and crop yields. Swedish Institute of Agricultural Engineering, Bulletin 354, 1974

[5] **Håkansson, I.** A method for characterising the state of compactness of an arable soil. In: Impact of Water and External Forces on Soil Structure (Drescher, J., Horn, R., de Boodt, M., Eds). Catena Supplement II, Catena Verlag, Cremlingen, FRG

[6] **Hodge, C. A. H.; Burton, R. G. O.; Corbett, W. M.; Evans, R.; Seale, R. S.** Soils and their use in eastern England, Bulletin No. 13. Harpenden: Soil Survey of England and Wales, 1984

[7] **MAFF/ADAS**. Analysis of agricultural materials: method reference; organic matter in soil. Her Majestey's Stationary Office reference book 427, 1986

[8] **Penman, H. L.** Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society 1948, **(A) 193:** 120–146

[9] **Soane, B. D.; Campbell, D. J.; Herkes, S. M.** Hand-held gamma-ray transmission equipment for the measurement of bulk density of field soils. Journal of Agricultural Engineering Research 1971, **16:** 146–156

[10] **Harris, W.** A method for improving the accuracy of measuring soil moisture near the soil surface with a neutron meter. ARC Letcombe Laboratory Report for 1973, 1974, pp. 56

[11] **Howse, K. R.; Goss, M. J.** Installation and evaluation of permanent access pits which permit continuity of measurement in cultivated soils. Experimental Agriculture 1982, **18:** 267–276

[12] **Youngs, E. G.; Goss, M. J.** Hydraulic conductivity profiles of two clay soils. Journal of Soil Science 1988, **39:** 341–345

[13] **Scholtz, D. C.** A three point linkage dynamometer for restrained linkages. Journal of Agricultural Engineering Research 1966, **11:** 33–47

[14] **Chamen, W. C. T.; Chittey, E. T.; Howse, K. R.** The effects of different tyre/soil contact pressures on soil and crop responses when growing winter wheat: Year 3—1984–85. Divisional Note DN 1432, AFRC Institute of Engineering Research, Silsoe, 1986

[15] **Chamen, W. C. T.; Cope, R. E.; Geikie, A.; Stafford, J. V.** A long-term experiment to compare the effect of different tyre/soil contact pressures on soil and crop responses when growing winter wheat: Year 1—1982–83. Divisional Note DN 1263, AFRC Institute of Engineering Research, Silsoe, 1985

[16] **Chamen, W. C. T.; Chittey, E. T.; Geikie, A.; Howse, K. R.** The effect of different tyre/soil contact pressures on soil and crop responses when growing winter wheat: Year 2—1983–84. Divisional Note DN 1296, AFRC Institute of Engineering Research, Silsoe, 1985

[17] **Chamen, W. C. T.; Leede, P. R.; Howse, K. R.; Goss, M. J.** The effect of different tyre/soil contact pressures on soil and crop responses when growing winter wheat: Year 4—1985–86. Divisional Note DN 1489, AFRC Institute of Engineering Research, Silsoe, 1988

[18] **Henshall, J. K.: Campbell, D. J.** The calibration of a high resolution gamma-ray transmission system for measuring soil bulk density and an assessment of its field performance. Journal of Soil Science 1983, **34:** 453–463

[19] **Douglas, J. T.** Conventional, reduced ground pressure and zero traffic systems in ryegrass grown for silage. Departmental Note 18, Scottish Centre of Agricultural Engineering, Penicuik, 1987

[20] **Henshall, J. K.; Smith, D. L. O.** An improved method of presenting comparisons of soil compaction effects below wheel ruts. Journal of Agricultural Engineering Research 1989, **42:** 1–13

[21] **Holmes, J. W.** Influence of bulk density of the soil on Neutron Moisture Meter calibration. Soil Science 1966, **102:** 355–360

[22] **Cannell, G. H.; Asbell, C. W.** The effects of soil-profile variations and related factors on neutron-moderation measurements. Soil Science 1974, **117:** 124–127

[23] **Passioura, J. B.; Leeper, G. W.** Soil compaction and manganese deficiency. Nature 1963, **200:** 29–30

[24] **Hietbrink, O.; Chamen, W. C. T.** An economic comparison of gantry and tractor-based zero traffic systems used for growing a rotation of crops on a cereals farm. Divisional Note DN 1487, AFRC Institute of Engineering Research, Silsoe, 1988

3.3.2. Chamen et al., 1992a. Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime

This paper was selected because the work involved many different techniques and measurements to determine structural differences between trafficked and non trafficked soils as well as including an assessment of permanent wheelways. It also assessed the impact of a controlled traffic system in which the harvester and plough tractor were not included (described in the paper as a partial system). This addresses an identified gap in research by studying an alternative to a full CTF system and also provides information for at least one of the sub-hypotheses.

One of the first points to note from the research is the comment about ploughing this non-trafficked soil. Unlike traditional practice when the plough is required to break up the soil, it was found that the plough actually created compaction in moist conditions by lifting the soil too abruptly. A less abrupt lift to the mouldboards may well be more appropriate much along the lines of the old Lea type bodies (Fream, 1962, page 120) employed for turning long unbroken furrow slices. It was also recognised that there were opportunities for a wider range of cultivators to be used, particularly for weed control where soil conditions were more amenable to the use of sweeps for example. Differences in tilth due to wheel compaction were very evident on this soil as illustrated in Fig. 5 of the paper but other substantiation of the effects were only in tabulated form relating to the sowing of spring oats (Table 6 of the paper). Fig. 3.1 provides an illustration of the effect of these differences in the field, albeit at an earlier stage in crop establishment than when data in the table were recorded.

Fig. 3.1. Establishment of spring oats on an Evesham series calcareous clay in spring 1988 to which Table 6 of the paper relates.

Sown on the same day, photographed on the same day and sown to the same depth. Left: non-trafficked. Right: conventionally trafficked

Although the permanent wheel tracks were used excessively due to the repeated passes required by the relatively narrow experimental equipment fitted to the 12 m gantry, there were only short periods when these could not be used and mostly because appropriate equipment was not available to manage them. The most difficult regions were low lying areas of the field or any points into which water tended to run. The main way of circumventing this was to avoid rutting of more than around 50 mm, but this was difficult if the areas were already wet. Careful layout of the wheel tracks could help to avoid this but drainage of the tracks was also recommended. Less aggressive traction tyres were also tried to reduce break up of the wheel tracks in dry conditions (Michelin “sand tyres”) and avoid deep lug marks when the soil was wet. However, the sand tyre was found to have insufficient traction. The worst scenario was to have powdered soil in the base of over-deep wheel tracks and significant rainfall. This occurred in one field and could only be solved in the short term by ploughing out the wheel tracks.

Cultivation energy benefits were identified for the partially controlled traffic system compared with conventional practice. Approximately 10% was saved for ploughing while the overall energy required to produce a seedbed was reduced by up to 44%. Where a completely controlled traffic system was employed, energy savings of 60% were recorded for ploughing while the energy required to prepare a spring seedbed were reduced by 69%. Fig. 5 of the paper also shows a remarkably different soil condition after ploughing trafficked compared with non-trafficked soil, the latter being much closer to a seedbed. This observation was supported by measurements of mean weight diameter (MWD, cumulative percentage of soil aggregates passing through sieves of different diameters) of the aggregates at different stages of seedbed preparation, all of which showed a significantly improved tilth on the non-trafficked soil, mostly represented by MWD values of just 50% of those on the trafficked plots (Fig. 6). Although bulk density was consistently lower on the non-trafficked soil, these differences were not significant and were both low as revealed by results of the degree of compactness test (Håkansson, 2005) listed in Table 11. These results highlight what are often large variations in differences between trafficked and non-trafficked soil, the reasons for which are often the variability of the trafficked condition. In dry seasons, much less damage may be incurred by trafficking and the non-trafficked condition may therefore be indistinguishable, but this is the exception rather than the rule.

Full paper, Chamen et al., 1992a

Soil & Tillage Research, 24 (1992) 359–380 359
Elsevier Science Publishers B.V., Amsterdam

Assessment of a wide span vehicle (gantry), and soil and cereal crop responses to its use in a zero traffic regime

W.C.T. Chamen, C.W. Watts, P.R. Leede and D.J. Longstaff
Soil Science Department, Silsoe Research Institute, Wrest Park, Silsoe, MK45 4HS, UK

(Accepted 10 June 1991)

ABSTRACT

Chamen, W.C.T., Watts, C.W., Leede, P.R. and Longstaff, D.J., 1992. Assessment of a wide span vehicle (gantry), and soil and cereal crop responses to its use in a zero traffic regime. *Soil Tillage Res.*, 24: 359–380.

The adverse effect of soil over-compaction on crop production efficiency was the basis for a programme to assess soil and crop responses to a zero traffic regime based on a 12 m gantry. The vehicle and its operating system, together with tasks ranging from fertilizer and spray application to draught and powered cultivations and cereals harvesting, are described. Results indicated that the gantry was a practical means of separating the cropped and wheeled (zero traffic) areas of a field. Cultivation draught and energy savings of up to 50% and 70%, respectively, were identified on a clay soil where traffic was eliminated from the cropped area. There was also evidence that this regime resulted in significant improvements to soil structure and crop establishment. The average yield of wheat from the zero traffic plots in 1989 was 6.8 t ha^{-1}, compared with 5.7 t ha^{-1} from the conventionally managed soil. In the dry season of 1989–1990, the yield of oats was not differentially affected by treatment.

INTRODUCTION

Over the last few decades, advances in agricultural mechanisation and the increased cost of labour throughout Europe have led to the widespread use of tractors and machinery of increasing weight and power. In the Strutt report (Ministry of Agriculture, Fisheries and Food (MAFF), 1970), it was concluded that a whole range of soils was suffering from the effects of the passage of heavy machinery over them in unsuitable conditions. Dwyer (1970) also concluded that it was important to quantify, by experiment, the economic losses resulting from soil over-compaction. Little has changed over the intervening years other than a greater awareness of the problems and some limited modifications to machinery practice. Meanwhile agricultural vehicles of steadily increasing weight and power are being used. In his introduction to the published proceedings of the Workshop on Soil Compaction (Monnier

---

Correspondence to: W.C.T. Chamen, Soil Science Department, Silsoe Research Institute, Wrest Park, Silsoe, MK45 4HS, UK.

and Goss, 1987) organised by the European Commission in 1985, Monnier stated that soil compaction resulting from vehicles remained a major contributor to waterlogging, reduced gas diffusivity, restricted root growth and an inefficient use of fertiliser. Davies, in his review of 1988 (Davies, 1988), identified the soil compaction which occurred during wet seasons to be a reason for increased costs. The inflexible use of reduced tillage systems in the UK in the 1970s exacerbated the compaction problem, and Davies recommended that zero traffic systems should continue to be investigated. In the recent Priorities Board report (MAFF, 1990), recommendations were made for research into methods for conserving soil structure and understanding the processes affecting movement of water through soils.

In response to these problems, experiments were set up nationally and within Europe (Blackwell et al., 1986; Campbell et al., 1986; Graham et al., 1986; Lamers et al., 1986; Chamen et al., 1990a,c). Results indicated that considerable improvements to current practice could be achieved by reducing tyre/soil contact pressures, or by permanently excluding wheels from the cropping area (zero traffic). Yield responses of up to 7% were recorded for low ground pressure traffic (Graham et al., 1986) and, in separate experiments in Sweden, yield differentials between zero and conventional traffic exceeded 10% (Håkansson et al., 1988). Substantial savings in cultivation inputs (20–50%) and improvement in soil structure were also identified with zero traffic (Chamen et al., 1990c), and this prompted the Institute at Silsoe, UK, to investigate a practical means of achieving such a system. A tractor-based arrangement to establish zero traffic for all operations was considered, but because of the large area lost to wheelways created by the relatively narrow span needed for harvesting and primary cultivation, this system was not considered practical for European conditions. In this paper, an alternative in the form of a wide span tractor (gantry) is described, and soil and cereal crop responses to its use are reported.

MACHINERY AND METHODS

Machinery

The experimental gantry system

Gantries are machines whose implements normally work within the span of their widely spaced pairs of wheels (Fig. 1). They generally operate by running backwards and forwards parallel to the longest side of a field, moving sideways by one means or another after each pass to the adjacent strip of land. In this way they create single wheelways at a centre distance equal to their span. Compared with a tractor system, only half the number of wheel tracks are produced for a given implement width. If these wheelways are used for every operation, the controlled or zero traffic concept described by Taylor

Fig. 1. Illustration of the basic features of a wide-span tractor or gantry, shown with the drive wheels in their road mode position.

(1989) is introduced and the wheeled and cropped areas are permanently separated, allowing optimisation of soil conditions for both crops and tyres.

Extensive development of the Institute's research vehicle has continued since the purchase of a prototype in 1983. The gantry has a 12-m-wide track and is powered by a 74 kW engine which drives two wheels through variable-displacement, axial piston, hydraulic pumps and radial piston motors. The driven wheels, one at each end of the gantry, can be steered through 120° and are paired with castor wheels which allow virtually unlimited directional movement of the machine. In the field, the drive wheels are positioned at right angles to the lateral axis of the frame, and the vehicle is steered by the differential speed of the wheel motors. On the road, the drive wheels are steered in a conventional manner. The driver is positioned on a rotatable seat at one end of the gantry frame over a line between one of the paired drive and castor wheels. Implements are attached either on under-frame linkages, or on a cross-slide three-point linkage capable of operating at any position along the frame. The under-frame linkages are four separate units which can be raised and lowered independently or in unison, and they follow changes in ground contour when operating. A spring-tine cultivator and a set of rolls were designed specifically to operate across the full width of the gantry using these linkages. The spring-tine cultivator consists of four frames, each 2.8 m wide, with tines mounted in four rows with an individual spacing of 110 m. The 0.6-m-diameter flat rolls used for firming the seedbed are fully mounted and

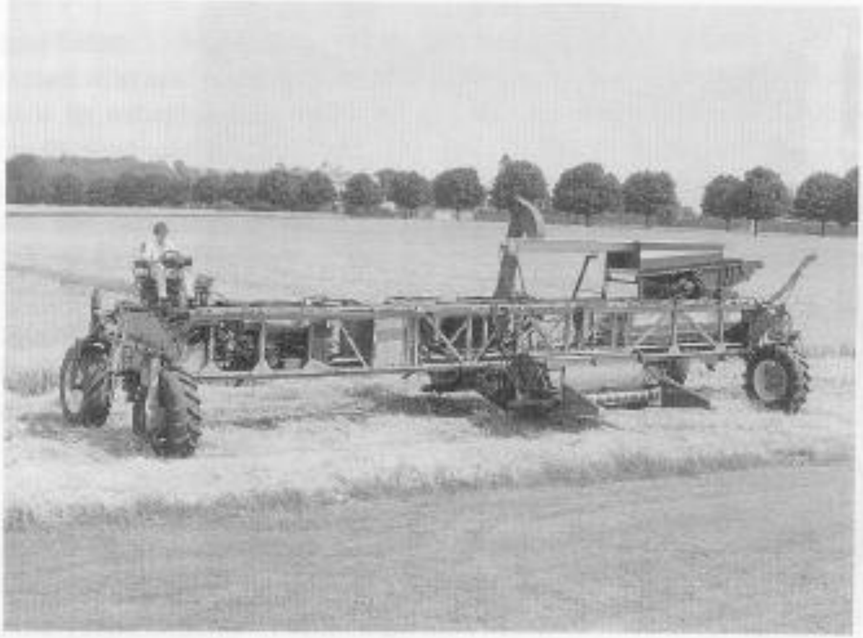


Fig. 2. The experimental gantry with the harvesting unit attached.

allow up to 500 kg m^{-1} to be applied to them hydraulically. They consist of four units mounted via a single rose bearing positioned close to the soil surface. This allows just four hydraulic rams to be used for their operation and ensures that undesirable loads created by the draught forces are avoided. The three-point linkage has a 30 kW power take-off (pto) drive and a lift capacity of 30 kN at the end of the lift arms. The vehicle is more fully described by Chamen et al. (1990b).

For cereal crop harvesting, a 2-m-wide grain-stripping rotor (Klinner et al., 1987) was mounted on the rails used for the three-point linkage (Fig. 2). Material from this was passed to a threshing and straw separation system consisting of three lightweight drums and concaves and a cleaning shoe (Metianu et al., 1990). Grain was stored in a bin within the gantry frame. The stripped straw left by this unit was chopped by a system mounted on the gantry. This employed a conventional combine harvester cutting table and a straw chopper mounted one behind the other.

Methods

Assessment of vehicle performance

Performance of the gantry was measured by a range of on-board transducers. The power developed by the engine while operating in the field was determined from fuel consumption versus power curves. These were established with a dynamometer and fuel meter at a range of no-load governor settings before the engine was installed in the gantry (see Chamen et al., 1990c, pp.5–6 for further information). Flow, pressure and temperature transducers were installed in the hydrostatic drives to measure the tractive effort of the gantry. A flow transducer was fitted at each wheel, together with a temperature sensor, while pressure sensors were installed in both flow and return lines at each wheel. These transducers, together with overall motor efficiency curves, allowed a measure of motor torque and power to be established to within an accuracy of ±4%. A check on flow losses at the motor could also be made by reference to rotational speed monitors installed at each wheel. The true ground speed of the gantry was established from a radar distance meter (mounted centre span) and a chronometer. All data from these transducers were either taped by an analogue recorder on the gantry, or transmitted via a telemetry link to a vehicle on the headland which was equipped with a data processing system (Watts and Longstaff, 1989).

To assess the practical performance of a gantry, the operation of such a vehicle was observed on a 90 ha arable farm, where a 12-m-wide 49 kW vehicle had been in use for applying spray and fertiliser for a number of years (Dowler, 1980). Measurements were made during the application, by one operator, of 125 kg ha^{-1} of granular fertiliser with a 12-m-wide pneumatic spreader mounted as an integral unit on the gantry. The fertiliser (in 50 kg bags) was transported and loaded by hand with the aid of a tractor and fork-lift attachment.

Effectiveness of implements used on the gantry

A number of subjective assessments were made of the performance of a range of implements when used on the gantry. These included a 2-m-wide six-furrow shallow plough (100 mm depth), a 1.1-m-wide three-furrow conventional plough (200 mm depth), and a 2.2-m-wide rotary digger (Chamen et al., 1979). Other implements investigated for primary cultivation were of the rolling cultivator design and included conventional discs, 'Dyna-Drive', 'Spintiller' and 'Turbotiller' (Fig. 3). A rod weeder and sweeps were also used so that their effectiveness in controlling weeds on untrafficked soil could be considered.

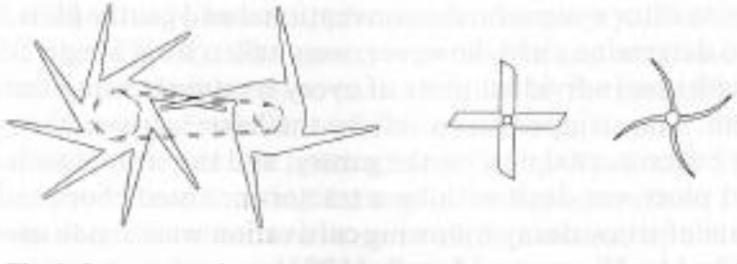


Fig. 3. Schematic of the 'Dyna Drive' (left), 'Turbotiller' (middle) and 'Spintiller' (right). All were soil driven, and rotors of the latter two were normally angled to the direction of travel.

Soil and crop responses

In addition to the assessments relating to engineering aspects of the gantry, a number of field trials were conducted with the aim of monitoring soil and crop responses to limited or zero traffic systems.

In one study, measurements were made on the performance of a system which confined the use of conventional equipment to primary cultivation and harvesting, whilst a 12-m-span, 67 kW gantry (Dowler, 1989) was used for secondary cultivation, sowing and chemicals application. Two sites, both on clay soil, were used to compare this partial gantry system with conventional practice during the cultivation and sowing of spring barley. At both sites, conventional practice was simulated by introducing the wheeling intensity reported by Soane et al. (1975) on soil within existing partial gantry beds. A 65 kW tractor was run over 90% of the area, and tramlines were introduced by running a 38 kW tractor up and down the 12-m-wide beds four consecutive times in the same position. On the gantry beds, traffic history was limited to the annual use of a combine harvester and a small or tracked tractor for primary cultivation. Both areas for these assessments were ploughed to about 200 mm depth using the 65 kW tractor. At one site a three-point linkage dynamometer (Scholtz, 1966) was used to measure the draught of the plough, and its specific resistance was calculated from the mean of a number of spot measurements of depth. In the following spring the plots were cultivated and sown using the Dowler gantry in one treatment, and a conventional tractor system in the other. Because no drill was available to fit the gantry, the seed was broadcast and cultivated into the soil.

The site used for the study of a complete gantry system, in which no traffic was imposed on the cropped area, was one used for an earlier traffic trial which had been completed in 1986 (Chamen et al., 1990c). The Evesham series clay soil was re-prepared in autumn 1986 with the aim of eliminating all traffic-induced soil compaction to a depth of 0.4 m. Thereafter, 24-m-wide × 35-m-long plots were established using a randomised block design with three replications. These plots were sown with cereals using conventional or gantry traffic in conjunction with differing tillage practices, but no crops were harvested from them until the gantry-mounted harvester became available in 1989. In that year winter wheat was harvested either with a combine harvester or with the stripping rotor system on the conventional and gantry plots, respectively. Samples to determine yield, however, were taken from single 2-m-wide × 35-m-long swaths on individual plots of every treatment using the gantry harvesting system. The stripped straw left by the harvester was then cut and chopped by the experimental unit on the gantry, and the straw swath left on the conventional plots was dealt with by a tractor-mounted chopper. Measurements of the rate of straw decay following cultivation were made using the technique described by Harper and Lynch (1981).

A few comparative draught measurements were made in 1988, but more extensive assessments were possible in 1989, and particularly those relating to the ploughing operation. Bulk density of the ploughed layer was measured using the technique described by Andersson and Håkansson (1963). This method involves sinking a bottomless metal box, measuring 0.7 m × 0.7 m, to the base of the plough layer and measuring the surface profile of the soil within the box. The ploughed soil is then removed, weighed and sampled for moisture, and a measure is also made of the profile of the exposed surface.

RESULTS AND DISCUSSION

Machinery

Vehicle performance

The general configuration of the vehicle and the hydrostatic drive, with its associated electrical and mechanical control systems, made the gantry highly manoeuvrable, both in the field and on the road. In the field, part-width implements could be employed at one end of the vehicle without control problems, providing sufficient drive torque and traction were available from the adjacent wheel. In general, the spring-tine cultivator could be used full width, but peak loads at each wheel were limited to about 20 kN, and these were sometimes exceeded when the implement was used directly into stubble. Ploughing in very dry soil with the implement at one end of the vehicle also created this problem, which was exacerbated by the lack of an adequate depth-control system. Although mean draught loads in these conditions were only of the order of 13 kN, peak forces exceeded 20 kN at one wheel. In this situation, directional stability was impaired by oil by-pass flow and loss of wheel speed. This problem could be overcome by introducing a four-wheel drive system, but more sophisticated steering control would be necessary to maintain the flexibility of movement provided by the castor wheel arrangement on the existing vehicle.

Gantry field operating system

Figure 4 shows how the 12-m-wide gantry was used to mark out a field. In this instance a double headland was created to allow for the subsequent use of a 24-m-wide boom applicator on the gantry. The field was completed at '22' (see Fig. 4). The gantry was easy to use and automatically provided a mark for each successive pass, or bout, in the form of a new wheelway. The system avoided gaps between bouts and overlapping of bouts except adjacent to headlands (see the hatched area in Fig. 4). Small field size and awkward shape were not limiting factors in gantry operation. Proximity to the field boundary was restricted in some circumstances by the height of the driver's position (i.e. by overhanging branches), and by any physical protrusion of the machine outside the line of the wheels. LePori and Chamen (1989) used

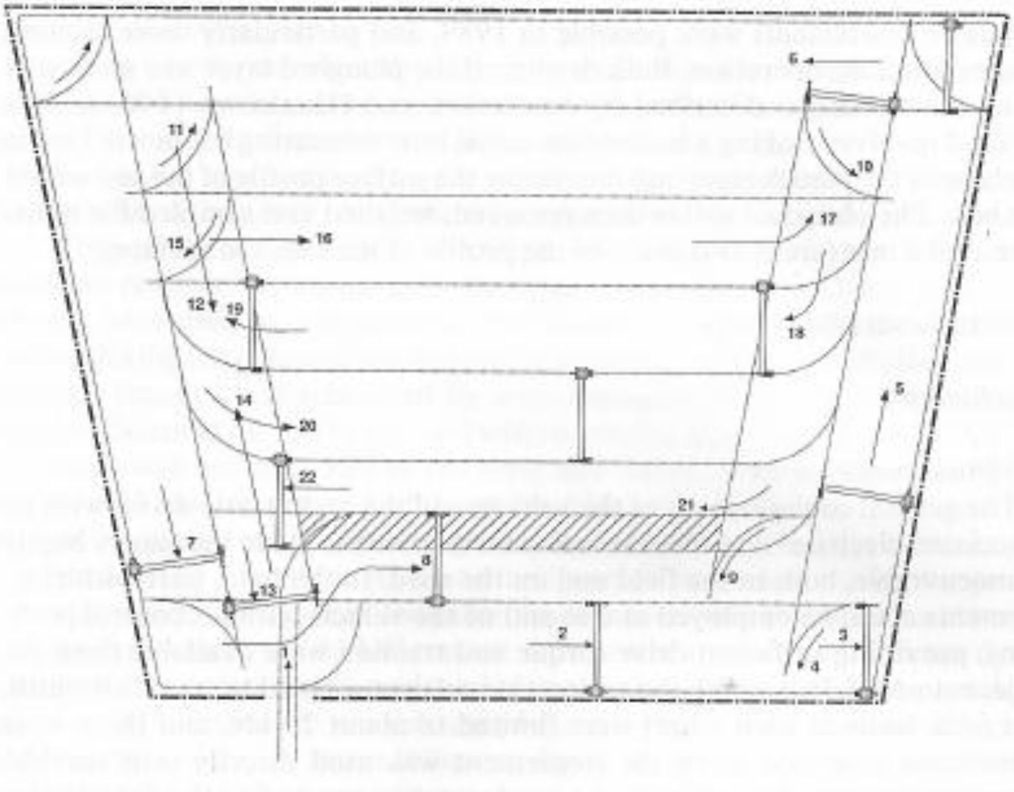


Fig. 4. Schematic of a typical sequence of operations required to set out a field with a 12-m-wide gantry system. The inner headland was set up on the assumption that a 24-m-wide application boom would be used subsequently (sequence in numbered order).

a computer model to investigate the work rate and field efficiency of a gantry system. In general, working width and operating speed had far greater influences on work rate than did field size or working pattern, but efficiency was mostly influenced by speed, width and field size.

Table 1 shows a breakdown of the activities for the operator and the gantry while spreading fertiliser in one of the two fields in the farm study. An overall rate (including time spent travelling to and from the fields which were both about 500 m from the farm) of 6 ha h^{-1} was recorded for the total 21.9 ha covered. Forward speed when spreading was approximately 13 km h^{-1}. These figures may be compared with those for conventionally mounted spreaders using recognised formulae. The Agricultural Development and Advisory Service formula (MAFF, 1984) suggested that, for a similar tractor system, an output of 6.7 ha h^{-1} should be possible, but this did not include the time taken to travel to and from the field. Another formula (Operational Research Group, 1989), which took account of this travelling time and used a similar means of hopper filling, suggested an overall output of 5.2 ha h^{-1}. It would seem therefore that although the gantry is an unconventional vehicle there is little or no penalty associated with its manoeuvrability during these opera-

TABLE 1

Breakdown of activities for the gantry and the operator when spreading fertiliser

Activity	Number	Total time (min)	Proportion of time (%)	Mean time (min)	Standard deviation ($n-1$)
Gantry activity					
Travel to field	1	3.2	2.6	3.2	0
Travel in field	5	9.1	7.3	1.8	0.99
Working	29	53.5	42.7	1.8	0.35
Headland turning	27	9.9	7.9	0.4	0.13
Filling up	3	20.9	16.7	7.0	3.29
Travel from field	1	4.5	3.6	4.5	0
Waiting	2	14.6	11.7	7.3	1.30
Miscellaneous	1	0.7	0.5	0.7	0
Headland working	1	8.7	7.0	8.7	0
Operator activity					
Drive to field	1	2.4	2.0	2.4	0
Walk to field	1	3.0	2.4	3.0	0
Walk from field	1	3.9	3.1	3.9	0
Gantry operations	3	110.6	88.3	36.9	51.36
Loading pallet	1	2.5	2.0	2.5	0
Drive from field	1	2.7	2.2	2.7	0

tions, and the key factor in comparing gantry and conventional system work rates is the ground speed when spreading. This speed will, to a large extent, be affected by the prime mover's influence on the stability and performance of the spreader. The gantry is likely to be able to work at greater forward speeds than a tractor system but with similar accuracy because its wide track reduces roll accelerations and the yaw movements caused by steering corrections (Chamen et al., 1986).

Effectiveness of implements used on the gantry

The abrupt lifting action of the shallow plough worked well, except in moist clay soils where the furrow slice was compacted and smeared. A similar situation occurred with the deeper-working plough, and it was apparent that, if ploughing is necessary in a zero traffic regime, consideration should be given to re-designing the plough share and mouldboard. On compacted soils existing designs of plough perform a loosening operation, but on a well-structured clay, for example, exactly the opposite may occur. On untrafficked soils which do not recompact under the influence of wetting and drying cycles, the need is to plough to the minimum depth necessary for inversion and weed control, and to do this without damaging the existing soil structure.

The rotary digger performed well, although the limited pto power available on the gantry restricted forward speed to about 3 km h^{-1}. Its inherent low draught requirement and ability to mix straw into the profile made it ideal for gantry operation.

Of the other implements used for primary cultivation, the discs and Turbotiller showed the greatest promise for the incorporation of crop residue. If they were designed with the correct configuration and weight (assuming downward pressure could be applied by the gantry), a working width of up to 12 m could be anticipated. The Spintiller showed promise in burnt stubble, particularly with respect to its low draught and high speed capability, but again downward pressure would be needed to maintain penetration.

For mechanical weed control, the sweeps were simple and effective in a wider range of conditions than was the rod weeder, but both machines, as in normal practice, needed periods of dry weather for weed control to be effective. Working at a maximum depth of 50 mm, the draught requirement of the sweeps was observed to be minimal. There appears to be potential for the automatic control of inter-row cultivators of this nature when mounted on the gantry. Accuracy to within a few millimetres has been shown to be possible by R. van Zuydam (personal communication, 1990).

For secondary cultivation, where few surface residues were present and the tilth was not too intractable, the spring-tine cultivator or a medium-weight (100 kg m^{-1} width) straight-tooth harrow worked well. A heavier straight-tooth harrow (180 kg m^{-1}) also proved satisfactory for producing a seedbed on untrafficked clay soil following stubble burning. Where more vigorous secondary cultivation was required and there was little surface residue present, a reciprocating harrow was effective. A rotary harrow, although somewhat over-vigorous in its action, performed well in all conditions. The rolls were used to firm the seedbed. In general these were effective, but considerable sinkage occurred in particularly soft conditions and they then ceased to rotate. This could be overcome by increasing their diameter or by modifying the flat surface of the rolls. The variable-pressure control worked well and allowed easy adjustment of the amount of firming applied. Care had to be taken, however, not to transfer too much pressure to the rolls, or the weight on the drive wheels became inadequate for traction.

Although all sowing and fertiliser spreading was done with conventional pneumatic machines mounted on the three-point linkage, the performance of the 4-m-wide seed drill confirmed that the gantry was capable of operating hoe-type coulters across its full span.

The harvester (Fig. 2) was used in barley, oats and wheat, and provided an acceptably clean sample with few losses in the good harvest seasons of 1989 and 1990. Tailings, in the form of partly threshed heads containing small seeds, were sometimes a problem, and the introduction of a re-thresher may need to be considered. Output, at about 6 t h^{-1}, could be improved if the quantity of chaff reaching the cleaning shoe were reduced.

The performance of the union of combine harvester table and straw chopper with stripped straw varied according to the crop condition. Where a stiff-strawed crop was encountered, the straws did not feed evenly from the cutter-bar onto the cross-auger because they had no ears to weigh them down. As a result, the straw bunched on the cutter-bar until it was forced into the auger by more crop, and this often caused an overload or blockage. This, and the fact that some of the material was aligned with the chopping blades, reduced chopping effectiveness considerably. The straw was also initially less fractured, because it had not passed through the drum and concave of a harvester.

Wheelway design and maintenance

Experience to date suggests that the semi-permanent, soil-based wheelways should be at a slightly lower level than the surrounding soil (maximum 50 mm) and, where necessary, they should be drained into the adjacent beds. The wheelways should be established in relatively dry conditions (particularly if the soil has been deep-loosened just prior to their establishment) and preferably at the soil moisture content equivalent to maximum compactability. Maintenance of the wheelways can be achieved by spilling soil into them during cultivation of the bed. Rounding off the edge of a bed should be avoided because this leads to poor crop establishment by the drill, and reduced performance with implements such as rolls which cannot respond adequately to hollows. The angled tines used by Spoor and Miller (1989) were also investigated as a means of maintaining the wheelways, but these imposed quite high loads on the gantry, and required an additional control system and linkage in an area of the machine where there was little space available.

In low areas of a field, water tended to stand in the wheelways. The extent of this problem is difficult to assess because, in our experiments, part-width implements were widely employed and the wheelways were used far more extensively than would normally occur. Where a gantry system had been in operation for over 10 years (Dowler, 1989) there appeared to be little difficulty, confirming our observations that the wheelways tended to improve with time if they were under normal use.

The design of the traction tyres on a gantry has a very significant effect on the durability of the wheelways. Contemporary designs have evolved against a background of widely varying conditions, but where a deeply lugged tyre is essential for work on cultivated or soft soil. On properly maintained semi-permanent wheelways, this design breaks up the surface and creates a powdery layer which, if it is a clay soil, turns into a slurry when wetted. The treads of conventional tyres can also leave deep lug marks in the wheelway which trap water and lead to further softening of the surface. A less aggressive tyre lug design may therefore be more appropriate and could have the added advantage of being non-directional, i.e. it would allow the gantry to have equal traction performance in both directions of travel.

Loss in cereal crop yield from the area lost to permanent wheelways is a critical factor in the determination of farm profit. If the loss is only equivalent to a small proportion of the area, or if there is a critical width of wheelways above which losses rise rapidly, a tractor-based system with narrow tyres or tracks could be a viable alternative to a gantry. Alternatively, if the wheelway losses are small, gantry span could be reduced (providing the machine's stability for spray and fertiliser application was not compromised) and this could allow all full- or half-width implements to be employed (e.g. for harvesting and primary cultivation); something which cannot be anticipated with a 12-m-wide machine. Data from Austin and Blackwell (1980); Darwinkel (1984), Lamers et al. (1986) and current work at the Silsoe Research Institute (authors' unpublished data, 1990) suggest that the loss in cereal yields from wheelways about 0.5 m wide may only be equivalent to about half the area lost.

Soil and crop responses

Partial gantry system

Compared with conventional practice, the partial gantry system reduced plough specific resistance by 16% (Table 2). Similarly, this system reduced the fuel used per hectare ploughed by about 10%. Further savings were identified for the partial gantry system in the spring. Although three passes with a spring-tine cultivator were required to form a tilth (compared with one pass of a power harrow on the conventional plots), overall savings in specific fuel use ranged from 19% to 44% (Chamen and Leede, 1989).

Complete gantry system

Table 3 provides details of some physical and mechanical properties of the soil on the site used for these trials, and Table 4 shows data collected during shallow ploughing in autumn 1988. Draught and energy on the conventionally trafficked plots was more than double that required on the untrafficked soil, and a coarser tilth was produced (Fig. 5). Measurements during the previous spring (following a similar ploughing operation in autumn 1987) also showed that fewer and less intensive cultivations were required to produce a seedbed on the untrafficked soil (Table 5), and this treatment also led to the establishment of a significantly greater number of plants more rapidly (Table 6).

Analysis of the 1989 yield data showed that differences between individual treatments were not significant at the 5% level. However, when the treatments were grouped into gantry and conventional traffic, mean yields from the gantry plots were greater by 1 Mg ha^{-1} (Table 7).

Assessments on two adjacent plots of gantry and conventional plough treatments showed that there was a slightly greater quantity of straw on the untrafficked plot. In addition, because control problems prevented the gantry-

TABLE 2

Specific draught and fuel requirements and rates of work on conventional and partial gantry plots

System	Operation	Rate of work ($ha\ h^{-1}$)	Specific fuel use ($l\ ha^{-1}$)
Site 1[a]			
Conventional	Ploughing	0.8	27.4
	Power harrowing	0.6	16.2
	Drilling	2.3	3.1
	Total		46.7
	Specific plough draught = 117.5 kN m^{-2}		
Partial gantry	Ploughing	0.8	25.7
	Spring tining	5.5	2.4
	Broadcasting	10.6	1.3
	Spring tining (×2)	3.2	4.0
	Total		34.2
	Specific plough draught = 101.3 kN m^{-2}		
Site 2[b]			
Conventional	Ploughing[c]	0.6	28.9
	Power harrowing	0.8	16.0
	Drilling	2.9	4.7
	Total		49.6
Partial gantry	Ploughing[c]	0.7	25.7
	Spring tining	1.6	8.0
	Broadcasting	15.6	0.9
	Spring tining (×2)	3.6	4.5
	Total		40.3

[a] Site 1: Clay 42.8%; silt 25.6%; sand 32.7%; moisture content at: primary cultivation, 30.4%; lower plastic limit, 26.0%.

[b] Site 2: Clay 60.0%; silt 28.6%; sand 9.4%; moisture content at: primary cultivation, 38.1%; lower plastic limit, 35.2%.

[c] No direct measurement of plough draught was possible.

mounted cutter-bar from being lowered sufficiently, stubble length was also greater (Table 8). However, the chopped length of straw was similar on both plots despite the different methods of chopping employed. Results of soil measurements taken before ploughing (Table 9) reflected the atypical conditions which prevailed in autumn 1989. Summer rainfall had been very low and soil strength (as indicated by the cone resistance readings) was, as a result, very high. Ploughing with a four-furrow conventional plough was difficult in these conditions. On the conventional plots, additional weight (100 kg per furrow) had to be added to the plough to aid penetration. Although no weights were needed on the gantry, the relatively high draught and absence of an adequate depth-control system created problems of wheel slip. These were exacerbated by insufficient torque, particularly when the plough was immediately adjacent to one of the drive wheels. Table 10 shows that the depth of

TABLE 3

Physical and mechanical properties of the site where trafficked and untrafficked soil was maintained (soil series: Evesham)

	Single adjacent ploughed plots	Whole site (mean)
Constituents (% by weight)		
Clay	68.8	59.5
Silt	22.6	23.5
Sand	8.6	17.0
Texture (USDA classification)	Clay	Clay
Moisture content (% dry basis)		
Liquid limit	84.5	
Plastic limit (Casegrande)	45.4	47.3
Plastic limit (drop cone)	42.3	
Plastic index	39.1	
Linear shrinkage (%)	21	
Organic matter (%)	5.3	5.4
Particle density (Mg m^{-3})	2.46	
Reference density (Mg m^{-3}) (Eriksson et al., 1974)	1.185	

TABLE 4

Draught and energy requirement of a 2-m-wide six-furrow shallow plough on trafficked and untrafficked soil in 1988

System	Depth of work (mm)	Forward speed (km h^{-1})	Draught (kN)	Specific draught (kN m^2)$^{-1}$	Implement energy (kJ ha^{-1})
Conventional	95	3.2	23.4***	107	117
Gantry	98	3.8	9.4	42	47

***Difference in draught significant at the 0.1% level.
Least significant difference (LSD) in draught ($P \leq 0.05$) = 3.1 kN.

ploughing was limited, and was 17 mm less with the gantry than with the conventional system. Specific draught, however, was 20% less on the untrafficked soil. (Data from Patterson et al. (1980) suggests that specific draught varies very little with depth over this depth range.) In addition, the mean weight diameter of aggregates (a value calculated by summing the products of the proportions by weight of clods of different mean sizes within a sample and the respective clod sizes, see Gardner, 1956) collected from the trafficked plot was 114 mm, and these aggregates were of a very blocky nature compared with the friable 56-mm-diameter aggregates from the untrafficked

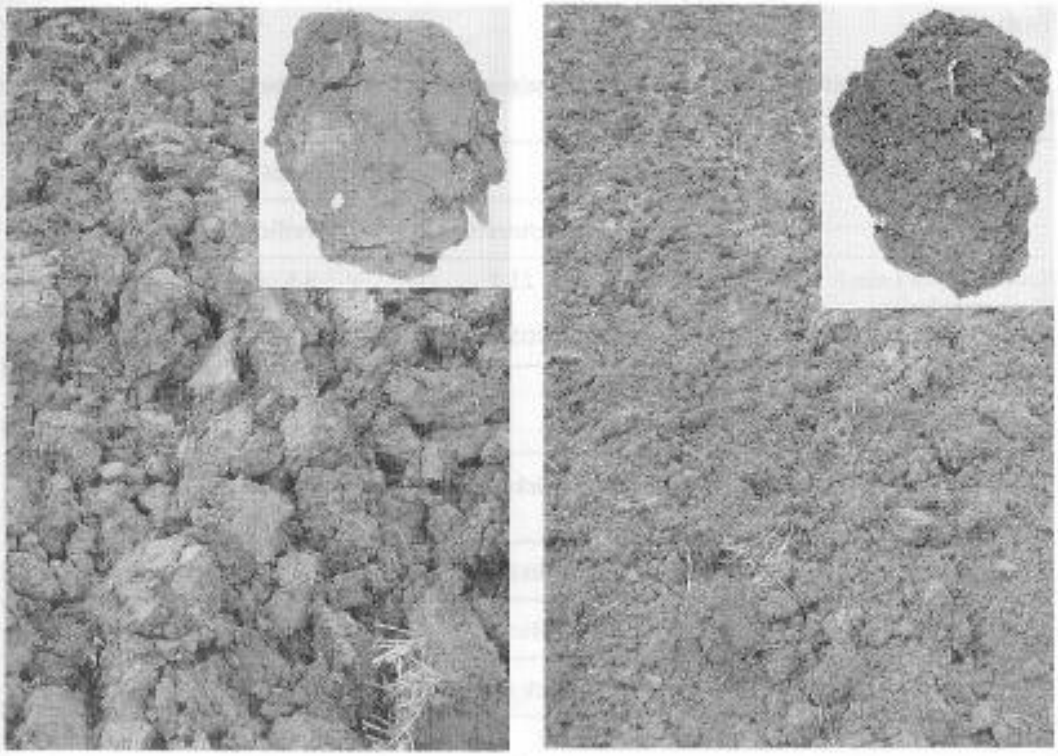


Fig. 5. Soil tilth and aggregate structure following ploughing on trafficked (left) and untrafficked (right) soil.

TABLE 5

Energy requirements for spring cultivation and sowing following autumn ploughing on trafficked and untrafficked soil in 1988

System	Fuel energy (MJ ha^{-1})					
	Cultivation spring-tine	Harrowing		Drilling	Rolling	Total
		Power	Seedbed			
Trafficked (conventional)	57.1	108.0	29.1	30.7	29.8	254.7
Untrafficked (gantry)	–	–	25.2	26.6	27.2	79.0

soil (Fig. 6). However, no significant differences could be detected in the clod strength or density of these aggregates. A further indication of the superior tilth after ploughing on the untrafficked plot was provided by a lower surface roughness value (76 compared with 99, Table 10).

TABLE 6

Sowing depth and plant population of spring oats (var. Dula) sown on trafficked and untrafficked soil in spring 1988

	System		Sample standard deviations	
	Trafficked	Untrafficked	Trafficked	Untrafficked
Sowing depth (mm)	24.2	25.2	9.6	8.4
Plant population (plants m^{-2})	581	707	22.9	25.2

TABLE 7

Yield of winter wheat from trafficked and untrafficked soil in conjunction with different tillage/straw disposal methods in 1989

Treatment	Yield ($t\ ha^{-1}$) corrected to 85% dry matter			
	Replicates			Means
	Block I	Block II	Block III	
Gantry, straw burnt, cultivated	7.38	5.80	6.53	6.57
Gantry, straw cultivated	6.19	6.49	6.96	6.55
Gantry, straw ploughed	6.84	7.59	7.18	7.20
Conventional, straw burnt, cultivated	4.70	6.57	6.04	5.77
Conventional, straw cultivated	5.01	5.73	5.55	5.43
Conventional, straw ploughed	5.46	6.72	5.69	5.96
Trafficked (conventional)				5.72
Untrafficked (gantry)				6.77**
LSD ($P \leqslant 0.05$)				0.54

Mean yields from individual treatments were not significantly different.

**Yield significantly greater at the 1% level.

Degree of straw burial was less on the untrafficked soil. The straw cover index (Chittey et al., 1986) was 38 compared to a value of 22 for the trafficked soil, but this probably reflected the slightly shallower depth of ploughing and longer stubble, rather than a system effect.

Secondary cultivation on these ploughed plots for both systems was with a 3-m-wide rotary harrow. However, two passes of the machine were required on the trafficked plot to produce the same tilth made by one pass on the untrafficked soil (Fig. 6). The two passes required 23.8 kW and 20.1 kW at the pto; 26.4 kW was needed for the single pass on the gantry. This represented an energy saving of 32% on the untrafficked soil. Because of the shallow depth of ploughing, the secondary cultivations increased the amount of straw on the surface. This rose to an index of 44 on the gantry plots and 27 on the conventional plots. In practice, a deeper ploughing operation will be required to en-

TABLE 8

Straw quantity and physical characteristics on single adjacent plots of the trafficked and untrafficked plough treatments, 1989

	Trafficked (conventional)	Untrafficked (gantry)
Total weight ($\mathrm{t\,ha^{-1}}$)	7.7	8.2
Mean stubble length (mm)	124	207
Chop length analysis (%)		
<50 mm	21	12
50–120 mm	27	33
>120 mm	52	55
Median length (mm)	127	130

TABLE 9

Soil conditions before ploughing in autumn 1989 on single adjacent plots of the ploughed treatments

	Trafficked (conventional)	Untrafficked (gantry)	Standard error
Soil dry bulk density ($\mathrm{Mg\,m^{-3}}$)	0.952	0.916	
Moisture content (% dry basis)	26.1	24.1	
Cone penetration resistance (MPa) at			
50 mm	1.481	1.017	0.214*
100 mm	1.753	1.492	0.114**
150 mm	2.240	2.026	0.116*
200 mm	2.981	2.620	0.189*
250 mm	3.490	2.940	0.229**
300 mm	O/L	3.411	
350 mm	O/L	O/L	

O/L, overload of instrument.
*$P \leq 0.05$; **$P \leq 0.01$.

sure adequate burial of straw and to control volunteer cereals and weeds reliably.

Observations following sowing of winter oats at the end of October 1989 indicated very little difference in the rate of crop emergence, and measurements showed that there was no significant difference in plant populations, which established at about 320 $\mathrm{m^{-2}}$. Bulk density of the ploughed layer, measured in January 1990, indicated that the untrafficked soil was about 8% less dense than the trafficked soil (Table 11). However, in the particular conditions encountered, inserting the 0.5 $\mathrm{m^2}$ sampling frame could have had some influence on the sample soil density, and some modification to this technique may be required if it is to be used in the future. Table 11 shows the data derived from the samples, and these indicate that both treatments gave low density and high porosity values. This was not unexpected because the unu-

TABLE 10

Plough draught requirements and subsequent soil conditions on trafficked and untrafficked soil in 1989

	Trafficked (conventional)	Untrafficked (gantry)	LSD ($P \leq 0.05$)
Depth of ploughing (mm)	130	113	
Plough draught (kN)	18.9	12.9**	1.3
Specific draught (kN m^{-2})	122	97**	13.6
Energy required for ploughing (MJ ha^{-1})	155	106**	8.0
Depth of ploughed soil (mm)	169	137	
Increase in volume of ploughed layer (%)	130	121	
Surface roughness of ploughed layer (mm)	99	76	
Dry bulk density of ploughed soil (Mg m^{-3})	0.732	0.757	
Dry weight of soil moved (kg m^{-3})	124	104	

**$P \leq 0.01$)

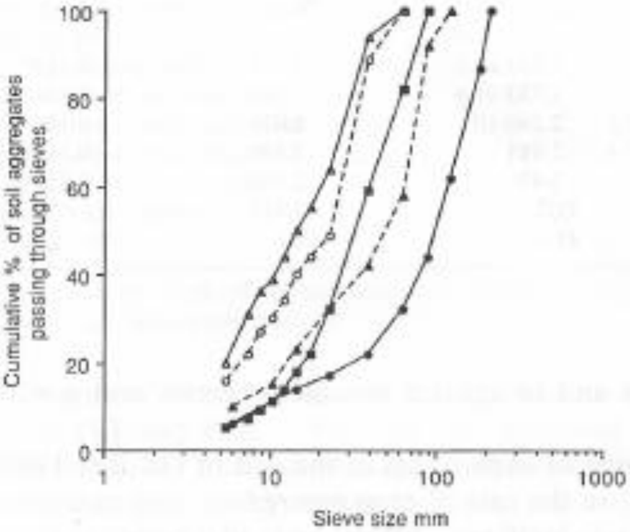


Fig. 6. Soil tilth following ploughing and secondary cultivation on trafficked and untrafficked soil. (The aggregate mean weight diameter (mm) are given in brackets) ● trafficked, ploughed (114); ▲ untrafficked, ploughed (56); ■ trafficked, rotary harrow (45); ○ untrafficked rotary harrow (27); △ trafficked, rotary harrow second pass (29).

sually dry autumn conditions meant that there was little likelihood of soil compaction occurring on the trafficked plots.

An analysis of variance of the yield from all plots in 1990 indicated that there were no significant differences between treatments. However, the slightly lower yield on the untrafficked ploughed soil (Table 11) may have been the result of loose topsoil conditions. Measurements showed that, despite au-

TABLE 11

Physical properties of the ploughed layer (25–125 mm) determined in January 1990, using the technique of Andersson and Håkansson (1963), and crop yield on single adjacent ploughed plots

	Trafficked (conventional)	Untrafficked (gantry)
Soil dry bulk density (Mg m^{-3})	0.782	0.722
Moisture content (% dry basis)	51.6	52.3
Porosity (%)	68	71
Degree of compactness	0.66	0.61
Yield of oats (t ha^{-1} at 85% dry matter)	5.20	5.03

TABLE 12

Soil cone resistance on single adjacent plots of the ploughed treatments in March 1990

	Trafficked (conventional)	Untrafficked (gantry)	Standard error
Soil moisture content at 150 mm depth (% dry basis)	52.3	48.0	
Cone penetration resistance (MPa) at			
50 mm	0.695	0.686	0.166
100 mm	0.928	0.705	0.164
150 mm	1.352	0.838	0.181
200 mm	1.352	1.114	0.127*
250 mm	1.753	1.105	0.178**
300 mm	1.667	1.067	0.170**
350 mm	1.692	1.198	0.185*

*$P \leq 0.05$; **$P \leq 0.01$.

tumn rolling, the degrees of compaction on both this and the trafficked plot were very low, at 0.61 and 0.66, respectively. This compares with the optimum of 0.85 for maximum yield suggested by Eriksson et al. (1974). Table 12 indicates that cone resistance within the ploughed layer of the two plots was similar, but below this resistance on the untrafficked soil was significantly less.

Measurements of the rate of straw decay suggested that there was no significant difference in weight loss between treatments, which was 30% in December 1989 and increased to 45% by mid-March 1990. Further measurements over a number of seasons will be necessary.

CONCLUSIONS

A 74 kW, two-wheel drive, 12-m-span gantry can be used for full-width light cultivation, sowing and chemicals application. Ease and speed of operation are similar to tractor-based systems carrying out equivalent tasks. If higher draught operations are required (greater than 20 kN at one wheel), it may be necessary to employ a four-wheel drive narrower-span gantry.

If a gantry is only able to replace conventional equipment for operations other than harvesting and primary cultivation, crop establishment fuel savings of up to about 40% may still be possible. Where a gantry is used for all operations on a clay soil, plough draught is reduced by between 20 and 50%, and its energy requirement by up to 60%. The energy required to produce a seedbed is reduced by between 30% and 70%. If wheels are excluded from the cultivated area in this way, the strength and density of a clay soil are reduced significantly in comparison with conventional practice, and the structure of the soil is visibly improved. Soil tilth tends to be retained from one season to the next, and the better seedbed conditions resulting from this can improve crop establishment.

The yield response of wheat and oats to zero traffic, compared with conventional traffic, is variable. In a dry season when little damage from compaction occurs, there may be no yield response from the untrafficked soil compared with conventional practice. In wetter seasons, a zero traffic system can improve yield by up to 1 Mg ha^{-1}. An anticipated improvement in the timeliness of sowing, resulting from fewer and less intensive seedbed operations with zero traffic, is more likely to provide a consistent yield response than the different levels of compaction considered here.

ACKNOWLEDGEMENTS

The authors are indebted to colleagues at the Silsoe Research Institute and in particular to G. Govorusa, D. Pack and T. Walker. This work was funded by the Ministry of Agriculture, Fisheries and Food, the European Commission and the Department of Education and Science.

REFERENCES

Andersson, S. and Håkansson, I., 1963. Mark fysikaliska undersökingar i odlad jord. XIV. Om ett par nya metoder att bestämmer markytans mikrotopografi, dess höjdförändringar och matjordens porositet. (Soil physical studies in cultivated soil. XIV. New methods of determining the micro-topography of the soil surface, its height variations and porosity of the topsoil.) Grundförbättring, 16: 1–26.

Austin, R.B. and Blackwell, R.D., 1980. Edge and neighbour effects in cereal yield trials. J. Agric. Sci., 94: 731–734.

Blackwell, P.S., Graham, J.P., Armstrong, J.V., Ward, M.A., Howse, K.R., Dawson, C.J. and Butler, A.R., 1986. Compaction of a silt loam soil by agricultural vehicles. I. Effects upon soil conditions. Soil Tillage Res., 7: 97–116.

Campbell, D.J., Dickson, J.W., Ball, B.C. and Hunter, R., 1986. Controlled seedbed traffic after ploughing or direct drilling under winter barley in Scotland, 1980–84. Soil Tillage Res., 8: 3–28.

Chamen, W.C.T. and Leede, P.R., 1989. Dowler field gantry project. AFRC Inst. Eng. Res., Contract Rep., CR/349/89/8647, 26 pp.

Chamen, W.C.T., Cope, R.E. and Patterson, D.E., 1979. Development and performance of a high output rotary digger. J. Agric. Eng. Res., 24: 301–318.

Chamen, W.C.T., Chittey, E.T. and Armstrong, M.C., 1986. Development and assessment of a wide-span vehicle for arable crops. Nat. Inst. Agric. Eng., Silsoe Divisional Note DN 1357, 43 pp.

Chamen, W.C.T., Vermeulen, G.D., Campbell, D.J. and Sommer, C., 1990a. EEC Cooperative project on reduction of soil compaction. Paper No. 90-1073. Am. Soc. Agric. Eng., St. Joseph, 28 pp.

Chamen, W.C.T., Watts, C.W., Leede, P.R. and Longstaff, D.J., 1990b. Development and assessment of a wide span tractor (gantry) for arable crops. AFRC Inst. Eng. Res., Silsoe Divisional Note DN 1587, 64 pp.

Chamen, W.C.T., Chittey, E.T., Leede, P.R., Goss, M.J. and Howse, K.R., 1990c. The effect of tyre/soil contact pressure and zero traffic on soil and crop responses when growing winter wheat. J. Agric. Eng. Res., 47: 1–21.

Chittey, E.T., Chamen, W.C.T. and Patterson, D.E., 1986. Cultivation systems for straw incorporation on clay soil, 1984–1985. AFRC Inst. Eng. Res., Divisional Note DN 1318, 23 pp.

Darwinkel, A., 1984. Yield responses of winter wheat to plant removal and to wheelings. Neth. J. Agric. Sci., 32: 293–300.

Davies, D.B., 1988. Reduced cultivations for cereals. Agricultural Development and Advisory Service, Home Grown Cereals Authority, London, 67 pp.

Dowler, D., 1980. Improvements in or relating to agricultural implements. The Patent Office, London, Patent specification 1578857, 12 November, 4 pp.

Dowler, D., 1989. Lift off for the gantry. Farm Contractor, ACP, Oxford, UK, July, p. 30.

Dwyer, M.J., 1970. Compaction problems on agricultural soils. Nat. Inst. Agric. Eng., Silsoe, Dept. Note DN/TE/011/1450, 28 pp.

Eriksson, J., Håkansson, I. and Danfors, B., 1974. The effect of soil compaction on soil structure and crop yields. Swedish Inst. Agric. Eng., Bull., 354: 101 pp.

Gardner, W.R., 1956. Representation of soil aggregate size distribution by a logarithmic-normal distribution. Soil Sci. Soc. Am., Proc., 20: 151–153.

Graham, J.P., Blackwell, P.S., Armstrong, J.V., Christian, D.G., Howse, K.R., Dawson, J.C. and Butler, A.R., 1986. Compaction of a silt loam by wheeled agricultural vehicles. II. Effects on growth and yield of direct drilled winter wheat. Soil Tillage Res., 7: 189–203.

Håkansson, I., Voorhees, W.B. and Riley, H., 1988. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. Soil Tillage Res., 11: 239–282.

Harper, S.H.T. and Lynch, J.M., 1981. The chemical components of decomposition of wheat straw leaves, internodes and nodes. J. Sci. Food Agric., 32: 1057–1062.

Klinner, W.E., Neale, M.A. and Arnold, R.E., 1987. A new stripping header for combine harvesters. Agric. Eng., 42: 9–14.

Lamers, J.G., Perdok, U.D., Lumkes, L.M. and Klooster, J.J., 1986. Controlled traffic farming systems in the Netherlands. Soil Tillage Res., 8: 65–76.

LePori, W.A. and Chamen, W.C.T., 1989. Analysis of gantry field operations. Am. Soc. Agric. Eng., St. Joseph, Paper No. 89-1620, 19 pp.

Metianu, A.A., Johnson, I.M. and Sewell, A.J., 1990. A whole crop harvester for the developing world. J. Agric. Eng. Res., 47: 187–195.

Ministry of Agriculture, Fisheries and Food, 1970. Modern farming and the soil. Agricultural Advisory Council on Soil Structure and Soil Fertility, London, Report, 119 pp.

Ministry of Agriculture, Fisheries and Food, 1984. Fertiliser handling and application. Mechanisation Leaflet No. 15.

Ministry of Agriculture, Fisheries and Food, 1990. Third report to the Agriculture Ministries and Chairman of the Agricultural and Food Research Council by the Priorities Board for

Research and Development in Agriculture and Food. Min. Agric., Fish. Food, London, 45 pp.

Monnier, G. and Goss, M.J. (Editors), 1987. Soil Compaction and Regeneration. AA Balkema, Rotterdam/Boston, 167 pp.

Operational Research Group, 1989. Spray logistics model. AFRC Inst. Eng. Res., Silsoe.

Patterson, D.E., Chamen, W.C.T. and Richardson, C.D., 1980. Long-term experiments with tillage systems to improve the economy of cultivations for cereals. J. Agric. Eng. Res., 25: 1–35.

Scholtz, D.C., 1966. A three point linkage dynamometer for restrained linkages. J. Agric. Eng. Res., 11: 33–47.

Soane, B.D., Butson, M.J. and Pidgeon, J.D., 1975. Soil/machine interactions in zero-tillage for cereals and raspberries in Scotland. Outlook Agric., 8: 221–226.

Spoor, G. and Miller, S.M., 1989. Investigations into improved soil management and traffic control practices in the sugar beet crop. Silsoe College, Bedford, 123 pp.

Taylor, J.H., 1989. Controlled traffic research: An international report. Int. Comm. Agric. Eng., Dublin, 8 pp.

Watts, C.W. and Longstaff, D.J., 1989. Mobile instrumentation and data processing system for testing field machinery. J. Agric. Eng. Res., 43: 67–76.

3.3.3. Chamen & Longstaff, 1995. Traffic and tillage effects on soil conditions and crop growth on a swelling clay soil

Of particular interest in this paper are further results from the study involving a controlled traffic system in which the harvester and plough tractor were excluded, which again addresses a gap in research as well as some of the hypotheses.

Surprisingly at this later stage of the experiment, the draught and energy requirement of the ploughing operation when only the harvester had run over the plots, was no less than for conventional practice and the resulting tilth was actually poorer (Table 2 of the paper). These measurements were taken in the final year of the experiment, when the trafficking applied during normal cultural operations would gradually have covered most of the plot areas. The reasons for the poorer tilth were considered to be, at least in part, due to the absence of wheels breaking up the soil during post ploughing operations. It was estimated that on average, wheels impart around 8 kW to the soil during operations of this nature, a proportion of which goes into compaction, the other into crushing of clods. It was concluded that there were few advantages to be gained from this system. Also of particular significance in this paper was the greater draught requirement of the tine cultivator on non-trafficked soil. This was thoroughly investigated at the time to determine if there was some anomaly in the measuring equipment or recordings, particularly as the plough and rotary digger measurements were at complete odds with these data. They showed for example a 31% reduction in plough draught and a 35% reduction in specific energy for rotary digging on non-trafficked compared with ploughing on trafficked soil. It was postulated at the time that it may have been due to differences in the type of soil failure but as no further evidence of an effect of this nature has been found in the literature, it can only remain conjecture.

In these experiments, considerable time and effort were concentrated on soil pore space and its associated water release characteristics. Figs 3-5 showed the effects at three depths under both tine and plough tillage and led to a number of conclusions. For example, the non-trafficked soil consistently exhibited a greater number of larger pores which would lead to a more rapid movement of water to the drains on the non-trafficked soil. By inference, this also means that the soil would have a greater water capacity at saturation and greater aeration at field capacity. What it doesn’t provide are data on water use efficiency by the crop, although yield results would suggest that this was certainly not impaired as yields from the non-trafficked soil were on average 28% higher than from the trafficked plots (Table 6 of the paper). However, this yield improvement was thought to have been caused by better over-winter drainage in a season when rainfall was 35% greater than the 30 year mean. Aerial photos had revealed a significant advance in crop growth on the non-trafficked compared with the trafficked plots in April. Further inspection of the rainfall data for 1994 reveals a very dry period during June and July (47% of 30 year average), which are critical months as far as crop yield is concerned (Kettlewell et al., 2003). Fig. 7 of the paper suggests that crop on the trafficked soil was not extracting water at the rate of the non-trafficked crop. It was also evident that the higher matric suction on the non-trafficked plots did not fall overnight, suggesting either continued demand or poorer re-supply from deeper in the profile. Suction on the trafficked plots fell dramatically overnight suggesting the opposite but only a greater range of measurements would have revealed the reasons behind these phenomena.

In terms of soil structure, this paper provides consistent evidence of improved conditions, with lower bulk density and penetration resistance together with more favourable drainage and aeration characteristics. Whether these are optimum for this particular soil is uncertain but they could certainly be termed “more healthy” in that they returned a higher yield and improved drainage, the latter perhaps of equal significance to cropping as discussed in the paper on nitrous oxide emissions later in this chapter.

Full paper, Chamen & Longstaff, 1995

Soil Use and Management (1995) 11, 168–176

Traffic and tillage effects on soil conditions and crop growth on a swelling clay soil

W.C.T. Chamen & D.J. Longstaff

Abstract. Trafficked and non-trafficked (12 m gantry) crop production systems, which had been maintained on an Evesham series 60% clay soil since 1986, were used again in 1993 during the cultivation and sowing of winter wheat. After a one year set-aside break, mouldboard ploughing, tine cultivation and rotary digging were compared. Measurements were made of tillage energy, soil tilth, cone penetration resistance, biological activity and crop performance, and on specific plots, soil density, seedbed tilth and water release characteristics.

Despite the one year's set-aside break, the effect of the previously applied traffic treatments remained and resulted in a smaller specific plough resistance and tillage energy on the non-trafficked soil. Tine cultivator draught however was greater on the non-trafficked compared with the trafficked plots. The specific energy required for rotary digging on non-trafficked soil was similar to that required during the ploughing of similar plots.

A measure of indefinite biotic activity indicated that this was apparently greater on the non-traffficked soil, while soil density was decreased by up to 18% in these conditions compared with the trafficked land. Average cone resistance over the depth range 0 to 0.5 m was 1.51 MPa on the trafficked, compared with 1.24 MPa on the non-trafficked soil. Cone resistance also tended to be greater after tine cultivation compared with that after ploughing. Water release curves were interpreted as showing more macropores within the topsoil of the non-trafficked compared with the trafficked plots. Tine cultivation on trafficked soil had more smaller pores than mouldboard plough cultivation. Winter wheat yield was increased by 25% (from 8 to 10 t/ha) on non-trafficked compared with trafficked soil.

Keywords: Soil compaction, no-tillage, ploughing, tines, energy, soil water retention, clay soils

INTRODUCTION

The increasing weight and power of agricultural tractors and machinery in response to increased labour costs, has led to concern about soil over-compaction. In Monnier's introduction to the proceedings of a 'Workshop on Soil Compaction' (Monnier & Goss, 1987) it was stated that 'soil compaction resulting from vehicles remained a major contributor to waterlogging, reduced gas diffusivity, restricted root growth and inefficient use of fertilizer'. It is also widely quoted as being of detriment to many aspects of crop production (Soane & Van Ouwerkerk, 1994). Davies (1988) in his review of reduced cultivation identified soil compaction in wet seasons as a reason for increased costs. In the UK, widespread and inflexible use of minimum tillage systems, made possible by crop residue burning, tended to exacerbate the problem, particularly in the topsoil. To assess the severity of these problems, experiments started at Silsoe in 1982. Results (Chamen *et al*., 1990) indicated that major benefits to soil conditions could only be achieved if wheels were completely eliminated from the cropped area. Further research was therefore invested in developing and assessing a gantry system as a means of providing 12 m wide beds of non-trafficked soil (Fig. 1). This paper brings together the results of the final two years (1992–1994) of this trial set up in 1986. Its aim was to compare soil and crop responses to trafficked and non-trafficked cereal crop production on an Evesham series clay (mesic Aquic Eutrochrept, (Soil Survey Staff, 1994)) (Table 1). Results from earlier years (Chamen *et al*., 1992; Chamen & Audsley, 1993; Chamen *et al*., 1994; Chamen & Cavalli, 1994) consistently revealed significant and substantial decreases in tillage energy and cone resistance, and improvements in soil tilth, crop establishment and yield on non-trafficked compared with trafficked soil. These results were similar to those obtained by Carter *et al*. (1988), who used a 10 m span gantry to produce non-trafficked conditions on a coarse-loamy, non-acid thermic Xeric Torriothent. In the irrigated production of alfalfa (*Medicago sativa*) and cotton on this soil, eliminat-

Table 1. Properties of the soil (0–200 mm) from the experimental site

Soil constituents	% by weight†
Clay	59.5
Silt	23.5
Sand (fine)	14.9
Sand (coarse)	2.1
Texture	Clay
Organic matter	5.4
Calcium carbonate	7.7
Lower plastic limit water content, % dry basis	47.3
pH (water)	8.1

† Soil Survey Staff, 1994.

Silsoe Research Institute, Soil Science Group, Wrest Park, Silsoe, Bedford MK45 4HS, UK.

Fig. 1. The 12 m wide 75 kW gantry, used for creating and maintaining non-trafficked beds of soil, operating with two 2-furrow ploughs on the experimental site.

ing traffic from the cropped area approximately doubled water infiltration rates and reduced soil cone resistance and bulk density by 40% and 8% respectively compared with random traffic. Tullberg & Lahey (1989) also demonstrated the dramatic increase in implement draught requirement brought about by wheel compaction. In typical soil conditions working 200 mm deep, this amounted to an increase of 28% compared with non-trafficked soil. Lamers *et al.* (1986) and Dickson *et al.* (1992) recorded energy savings of around 50% as a result of separating cropped and wheeled areas. They also concluded that yield responses to non-trafficked soil were likely to be greatest under wet conditions, mainly as a result of increased O_2 availability in the subsoil.

In the final two years of the trial reported here, the aim was to confirm some of the earlier results from both this and other experiments. Also significant to the experiment, was the setting up in 1991 of a Linked Research Group between Silsoe Research Institute and Silsoe College. The aim of the College work was to link the structural condition of the soil, as influenced by tillage and traffic, to physics-based descriptions of the processes of solute movement in macroporous soils. Results of this study are reported by Dougherty *et al.*, (1995). The Institute's part of the work centred around quantifying the energy inputs associated with the tillage and traffic treatments, and assessing differences in soil structure, as indicated by water release curves, soil bulk density and cone penetration resistance. These measurements were aimed at testing the hypothesis that removing wheel traffic from the cropped area would lead to greater air-filled porosity and lower soil strength and density.

The last two years of the trial, 1992 and 1993, were considerably wetter than average, particularly during the periods of the main machinery operations. The first of these wet periods, in autumn 1992, combined with soil damage associated with the headlands surrounding the experiment, led to abandonment of crop establishment on the trial for that season (annual set-aside was introduced).

TREATMENTS

The following treatments were applied in a cereal cropping regime using a three block randomized plot experiment. Plots were 35 m long by 24 m wide, with access for machinery from both ends.

(1) Tractor plough (TP, Trafficked). This system used a conventional three furrow mouldboard plough (200 mm depth) mounted on a 75 kW four wheel drive (4 wd) tractor. All secondary tillage and other operations were with conventional equipment and random trafficking of the plots.

(2) Tractor tine cultivated (TT, Trafficked). A heavy duty spring tine cultivator with 75 mm wide twisted shares spaced at 250 mm centres was used to a depth of around 125 mm. (14 tine implement mounted on a 75 kW 4 wd tractor). All secondary tillage and other operations were with conventional equipment as for (1).

(3) Gantry plough (GP, Non-trafficked). Ploughing as for (1) above, but this system used two identical 2 furrow left and right hand ploughs mounted on a 75 kW gantry (Fig. 1). All other operations were also carried out with gantry mounted equipment to avoid trafficking of the cropped area.

(4) Gantry tine cultivated (GT, non-trafficked). Cultivation as for (2) above, but the 14 tine implement was split into two 7 tine implements which were mounted separately on the gantry. All other operations were also with gantry mounted equipment.

(5) Partial gantry (PG, trafficked/non-trafficked). Ploughing and harvesting were carried out with conventional equipment as for (1) above, but all other operations were with gantry mounted equipment to avoid further trafficking of the cropped area.

(6) Gantry speculative (GS, non-trafficked). This treatment was based on the gantry, but with the idea that experimental equipment rather than commercially available implements could be used. In 1991 and 1993, primary tillage was with a power driven rotary digger. All other operations were with conventional but gantry mounted equipment.

The gantry used was an experimental two wheel-drive 12 m span machine (Fig. 1), more fully described by Chamen *et al.* (1994). This machine enabled 12 m wide beds of soil to be maintained free of wheel traffic for the duration of the experiment (1986–1994). Secondary tillage on both tractor and gantry plots consisted of a combination of discing and power harrowing depending on the conditions. In 1991, winter wheat was sown in mid October. Although this crop was harvested and yield assessments made, wet weather delayed harvest to such an extent that variable shedding losses (estimated to be around 2.5 t/ha) made these results unreliable. As the wet conditions continued, it proved impossible to carry out any cultivations, and the site was put into rotational set-aside. The over-winter regrowth was sprayed off with glyphosate in May 1993 and the plots primary cultivated with the different treatments in July, followed by secondary tillage and sowing of winter wheat in late September.

MEASUREMENTS

During primary tillage, measurements were made of the forces on the different implements as well as the speed of operation and depth of work. Data from these measurements were transmitted via a telemetry link as described by Chamen *et al.* (1994). Following seedbed preparation, samples of soil tilth were taken from the TP, GP and PG treatments to determine, by sieving, the mean weight diameter (MWD) of the aggregates. Soil cone resistance was measured with a Bush recording penetrometer (Anderson *et al.*, 1980) on all plots, to a depth of about 0.5 m in September 1992 and in April 1993. In March and April 1992, an evaluation was made of a technique (after Von Törne, 1990) for comparing the activity of indefinite biotic (microbial and zootic) processes within the soil on the treated plot areas. Ten 20 mm by 3 mm aluminium strips 400 mm long with five 8 mm diameter holes spaced at 50 mm intervals below a surface marker line were inserted at random positions on each plot. Each of the holes in the strips had been filled with pea flour mixed with a dilute agar solution. The strips were withdrawn after 14 days and the quantity of pea flour remaining was categorized as 0 if less than 25% of the flour remained, 0.5 if between 25% and 75% remained and 1 if more than 75% was judged to have remained intact. Profiles of soil water content to match the cone resistance and biological sampling data were established gravimetrically from samples extracted from appropriate areas in the field.

For the work on solute movement, the entire plot area was mole ploughed in April 1991 to a depth of 0.55 m at 2 m centres, using the winching technique described by Chamen & Cavalli (1994), but still in line with conventional practice on clay soils in the United Kingdom (Spoor *et al.*, 1990). Later in the spring, four adjacent plots were hydrologically isolated by inserting polythene sheeting vertically to a depth of 1 m. Trenches were dug at the lower end of the plots and pipes connected to the individual mole channels through the plastic sheeting. The discharges from each of the mole channels on a particular plot were then interconnected and piped to a lower area of the field. Here, they emptied into a ditch via water samplers and V-notched weirs, as described by Leeds-Harrison *et al.* (1992) and Dougherty *et al.*, (1995). In April 1994 bulk density of the topsoil was measured at two positions (2 replications) on each of these plots using the technique described by Andersson & Håkansson (1963). This involved sinking a bottomless metal box, measuring 0.7 m × 0.35 m, to approximately 200 mm depth. The surface profile of the soil within the box was defined using pins spaced at 50 mm on the square. A layer of soil about 170 mm deep was then removed and a similar profile of the exposed surface established to give volume by subtraction. Samples for gravimetric determination of water content were taken from the soil extracted. On the same four plots, change in water potential with time was monitored with porous cup tensiometers connected to pressure transducers and data loggers. Two sets of tensiometers were installed on each of the plots at depths of 100, 150 and 300 mm and gravimetric water content measurements at these depths were made daily during a drying phase of the soil. Subsequently, volumetric water content was calculated from the density measurements, but direct measurements of volumetric water content were also made daily with a neutron probe. This was inserted in permanently installed single tubes on each of the plots. During February 1993, saturated hydraulic conductivity of the soil was measured at between 0.8 m and 1.1 m depth with piezometers installed horizontally using the technique described by Howse & Goss (1982). Hydraulic conductivity and shape factors for the piezometers were taken from Youngs & Goss (1988). Crop yield was measured on all plots using the gantry equipped with its own harvesting unit. This consisted of a 3.6 m wide standard cutterbar feeding an experimental grain threshing and separating mechanism. Following a single full length cut on each plot, grain was unloaded into a sack which was weighed and sampled for moisture content in the field.

RESULTS AND DISCUSSION

Implement performance

Table 2 provides a summary of the implement performances measured during primary tillage following the set-aside

Table 2. Tillage implement performance, July 1993

Treatment & implement†	Forward speed, m/s	Depth, mm	Draught, kN	Pto power, kW	Specific energy, kJ/m	Tilth MWD, mm$^{N.S.}$	Labour^2, h/ha
TP/Plough	1.05	191	7.8^1	–	13.55^a	18.1	2.97
GP/Plough	0.96	207	5.4^1	–	8.55^b	16.7	2.37
PG/Plough	1.03	173	7.6^1	–	13.96^a	24.4	3.04
TT/Tines	1.26	112	1.88^1	–	nr	nr	0.63
GT/Tines	1.05	103	2.48^1	–	nr	nr	0.76
GS/Rotary digger	0.85	127^r 222^t	0.61	27.1	8.84^b	nr	1.75

^{1} Draught per furrow/tine.

^{2} Derived from spot rate of work.

^{a,b} Values of energy with different letters significantly different at $P < 0.001$.

$^{N.S.}$ Not significant at $P \leqslant 0.05$.

^{r} Rotor, ^{t}rear mounted tines.

nr not recorded.

† for key see 'Treatments' section.

period. The plough data, which reveal a similar trend to previous years, show a decrease both in tillage energy and the labour required for the non-trafficked compared with the trafficked soil. There was however no difference between the trafficked and partly trafficked treatments. Although there were differences in the MWD of the tilths recorded on the three plough treatments (Table 2), these were not statistically significant. Results for the PG treatment suggested that this had led to the coarsest tilth, which was in line with previous observations. The reason for this coarse tilth was considered to be the absence of the effect of tyres during secondary tillage. On average tractor tyres impart about 8 kW to the soil and in many instances help create a tilth in addition to causing soil compaction. Although secondary tillage was undertaken at higher than average soil water contents, (44% dry basis; plastic limit water content 47%, see Table 1) this was still in the friable consistency range with a moderate resistance to compaction.

Previously recorded decreases in draught from the tine cultivator on non-trafficked soil were absent, the reasons for which were not evident.

Cone resistance, water content and bulk density

The differences and change in cone resistance with depth in April 1993 were similar to those recorded in September 1992 (Fig. 2), revealing a generally lower strength following ploughing compared with tine cultivation and following non-trafficked compared with trafficked soil. Both of these differences were significant ($P \leqslant 0.05$) at each depth below 150 mm. The average of the autumn and spring resistance measurements over the full depth range for the trafficked (TT & TP) and the non-trafficked (GT & GP) treatments was 1.51 and 1.24 MPa respectively. Similarly, values for the PG and GS systems (see Treatments section) were 1.25 and 1.23 MPa respectively. Although the lower resistance under the gantry treatments would be expected, the lower resistance at and below 200 mm depth following ploughing, on both trafficked and non-trafficked plots, is surprising. Differences in soil water contents, which would have had a marked effect on these results, were measured on all of the plots at 150, 300 and 500 mm depths in September 1992 and April 1993 (Table 3). Results revealed no significant differences between either tillage or traffic treatments, but a decrease with depth. Further more extensive measurements in April 1994, (but restricted to the four hydrologically isolated plots) exhibited a consistent and quite large decrease of volumetric water content on the non-trafficked compared with the trafficked soil (Fig. 3) and a tendency for the tine

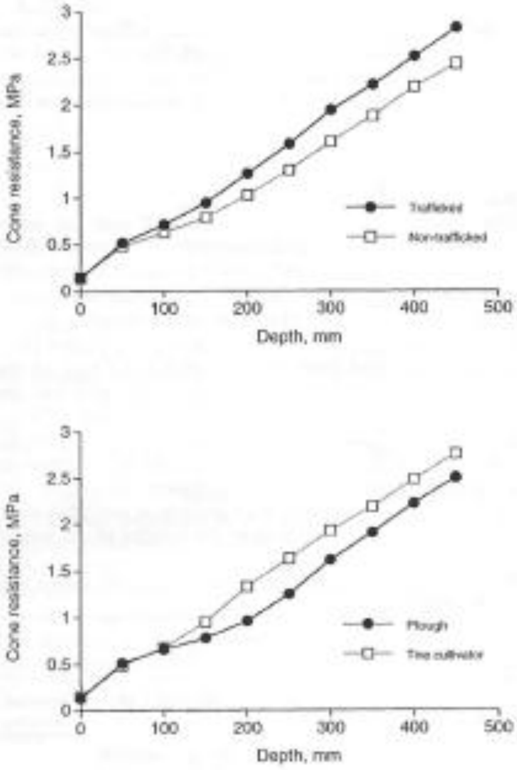


Fig. 2. The effect of traffic and tillage on soil cone penetration resistance, April 1993.

Table 3. Summary of soil water content data at different times during the trial

	Mean topsoil water content, g/100g						
	Treatment†						
Date¹	TP	TT	GP	GT	PG	GS	S.E.D.
1	50.1	47.7	48.4	50.2	nr	nr	1.5 (N.S.)
2	49.5	46.8	44.4	47.3	48.6	48.1	4.1 (N.S.)
3	48.1	47.6	49.0	48.9	48.7	51.6	2.4 (N.S.)
4	56.7	57.9	57.0	59.8	59.3	62.1	2.4 (N.S.)

	Mean soil water content at different depths (mm)								
	50	100	150	200	250	300	500	S.E.D	L.S.D.
1	48.3	49.7	50.5	49.3	47.7			0.74	1.5
2			52.0			48.1	42.2	1.3	2.7
3			54.1			50.2	42.6	0.58	1.2

¹Dates: 1 = 5 March 1992; 2 = 15 September 1992; 3 = 23 April 1993; 4 = 13-21 July 1993.
S.E.D. = standard error of difference of means.
nr = not recorded.
N.S. = not significant at $P \leq 0.05$.
L.S.D. = least significant difference at $P = 0.05$.
† for key see 'Treatments' section.

cultivated plots to be wetter. These contrasts would have tended to exacerbate rather than diminish the differences in cone resistance between the trafficking and tillage treatments, and certainly provide no explanation for the tillage effect.

Bulk density of the four hydrologically isolated plots was consistently lower on the non-trafficked soil (Table 4). However, under the ploughing regime where annual loosening to sampling depth had occurred, differences were less than the deviation of the results.

Water release characteristics

The volumetric water contents were used with soil water potential measurements to determine the *in situ* water release characteristics over a period of about 15 days. Unfortunately data from the neutron probe varied randomly and showed no evidence of a drying phase during the sampling period. Figures 4 and 5 show the mean water contents and daily potentials averaged from two tensiometers on each of the plots. On both the ploughed and tine cultivated soil the data showed marked evidence of a greater number of larger pores (smaller water contents at a given potential) on the non-trafficked plots, but the contrasts were less extreme on the ploughed soil. There was also evidence to suggest that the differences in this data were greatest at potentials close to zero, i.e. a greater contrast in the number of the largest pores. This difference is likely to have particular bearing on drainage characteristics, leading to a more rapid movement of water to the drains on the non-trafficked soil. Figure 6 shows evidence, on the trafficked plots, of larger pores on the ploughed compared with the tine cultivated soil. The results at 300 mm depth must however be treated with caution, since density measurements were extrapolated to this depth from the 0–200 mm profile. The third group of data show the effect of assuming a common density for the TT and TP plots at this depth. It is likely that the true picture lies somewhere between these two extremes. On the non-trafficked soil, differences between the tillage treatments were absent at 100 mm depth, but there was a tendency for the tine cultivated soil to have a greater water content at a given potential at 150 and 300 mm depth.

A further indicator of differences in soil structure between the trafficked and non-trafficked soil are differences in daily fluctuation of matric potential. Figure 7 provides a snapshot of this variation over a typical 48 hour period, together with soil and air temperatures measured on an immediately adjacent site under grass. These data largely rule out

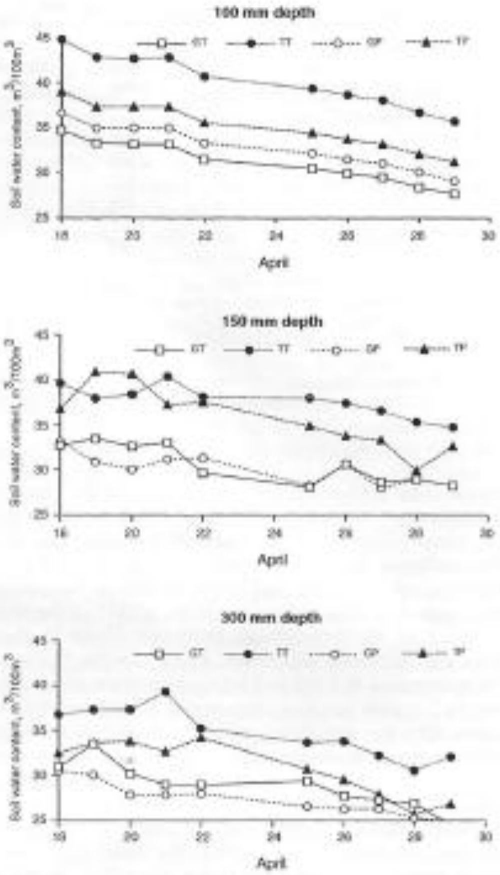


Fig. 3. Changes in volumetric water content with time and depth on the four hydrologically isolated plots in April 1994, GT = gantry/tine, TT = tractor/tine, GP = gantry/plough, TP = tractor/plough.

Table 4. Soil dry bulk density on the four hydrologically isolated plots (21–26 April 1994)

Plot no. and treatment†	Dry bulk density, kg/m³ (maximum depth of sampling, mm)				
	06 TT	07 GT	08 TP	09 GP	Standard deviation
	787(162)	608(154)	686(181)	642(114)	
	663(152)	572(181)	666(214)	667(192)	
Plot mean	725(157)	590(167)	676(197)	655(153)	55.7

† for key see 'Treatments' section.

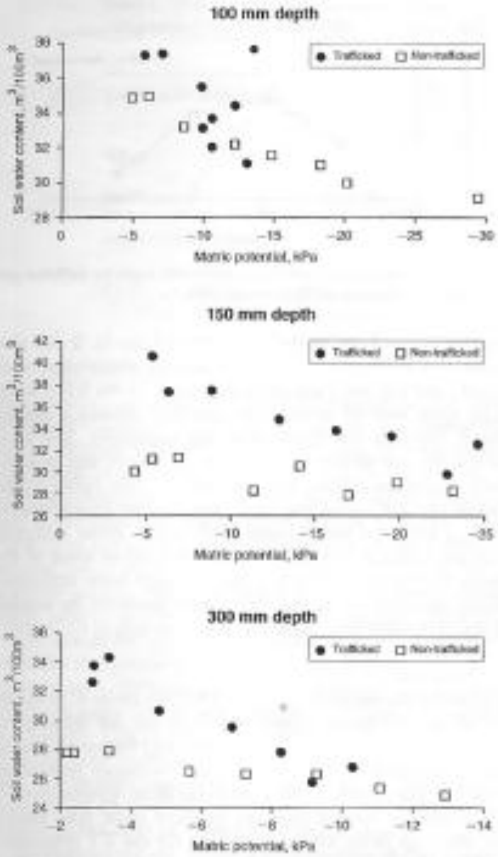


Fig. 4. Changes in matric potential at three depths on trafficked and non-trafficked ploughed soil in April 1994.

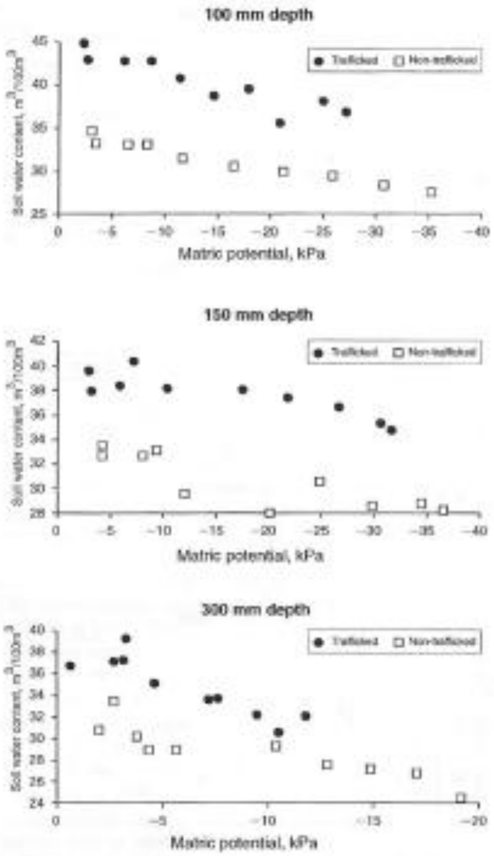


Fig. 5. Changes in matric potential at three depths on trafficked and non-trafficked tine cultivated soil in April 1994.

temperature effects on the tensiometers as a cause of the fluctuations, leading us to conclude that the differences are treatment related. These and the previous data show that either the water was able to move more readily on the non-trafficked soil (less fluctuation with diurnal variations in crop uptake), or that the crop was extracting water from greater depth on these plots. It would also suggest that despite a greater water content for a given matric potential on the trafficked soil, depletion of water by the crop could not be sustained from the surrounding soil.

Hydraulic conductivity

Figure 8 shows results of measurements at four depths on single plots of the trafficked and non-trafficked ploughed treatments taken in February 1993. At these considerable depths there was no consistent treatment effect, but the data confirm the magnitude of the conductivity as being similar to earlier measurements on this site by Youngs & Goss (1988). More extensive measurements were restricted by transient water tables and by a lack of response from the piezometers.

Biological activity

Analysis of the results was carried out taking each depth and location within a plot as a binomial trial with either no flour taken (0), all flour taken (1), or a condition half way between (0.5). Results from the ten strips from each plot were added giving a figure between 0 and 10 for each treatment. Examination of the results from the March sampling, using soil water content as a covariate, showed that the small differences in soil water content (Table 3) had no influence on the results. The effects of traffic and tillage were found to be statistically significant, but there were also other interactive effects which made interpretation difficult. The data were therefore scaled to a simple proportion and then transformed using Berkson's (1953) logistic curve or logit relationship of the form:

$$\mathrm{Logit}\ (p) = \ln\ (p/(1-p))$$

where

$$p = \text{biological activity}/10$$

The subsequent analysis of variance indicated no interactive effects, but the effect of traffic and method of cultivation

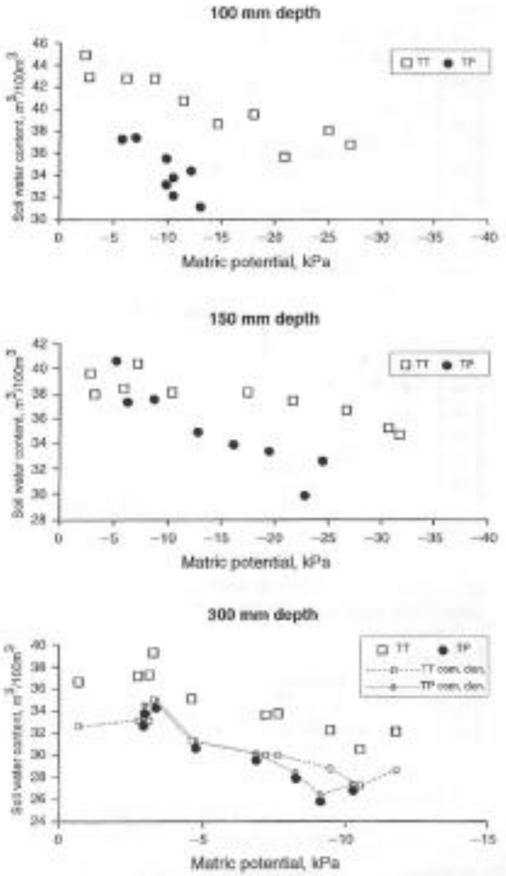


Fig. 6. The effect of tine cultivation and ploughing on matric potential at three depths on the trafficked soil. At 300 mm depth, the additional data show the effect of assuming a common soil density for the two types of cultivation, TT = tractor tine, TP = tractor/plough.

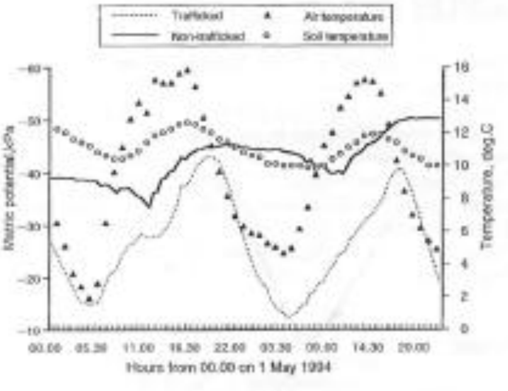


Fig. 7. Changes in matric potential at 150 mm depth on trafficked and non-trafficked soil, together with air and soil (at 50 mm depth) temperature fluctuations during a 48 hour period in May 1994.

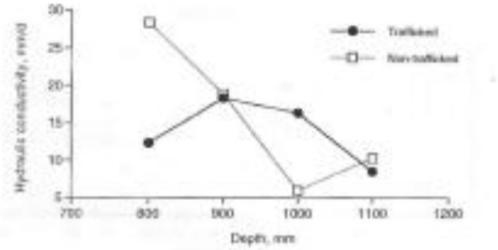


Fig. 8. Soil saturated hydraulic conductivity with depth on trafficked and non-trafficked ploughed soil in February 1993.

remained significant at the 0.1% level (Table 5). It was also evident that the level of animal activity diminished with depth, and the effect was again significant at the 0.1% level. The same analysis of the later sampling showed a similar trend, but only the depth effect was significant. The level of activity was greater in April than in March, and particularly nearer the soil surface. The only animals visible to the naked eye and taking the food, were worms approximately 30 mm long and about 1 mm in diameter. Some difficulty was experienced with flour being pulled out of some of the holes by the moist clay soil as the strips were extracted. Some modification of the strip might therefore be needed if this technique were to be used widely in soils of this nature.

Crop response

Following the set-aside period in 1992–93, there were found to be no significant treatment effects on the number of winter wheat plants which had established following sowing on 23 September 1993. The average November population was 198 plants/m^2. Table 6 provides more information on these data, in view of the large standard error. Also shown are the crop yields which, other than for the TT treatment, did not correlate with plant numbers. In this case the effect of traffic was significant at $P<0.01$ and the speculative treatment (GS) led to a significantly greater yield ($P<0.05$) than the PG system.

Rainfall over the 9 month period September to May was about 35% greater than the 30 year mean (58.7 mm compared with 43.6 mm) and the 25% increase in yield measured on the non-trafficked soil was almost certainly associated with better drainage on these plots. This is borne out by the water release curves which showed that less water was held in the profile at low matric potentials (Figs 4 and 5) on the non-trafficked plots. Similarly, an aerial colour photograph of the site in late April revealed more advanced crop growth on the non-trafficked compared with on the trafficked soil. The increase in yield, although considerably greater than in some of the drier years, compares with an average increase of 11% from three previous harvests.

Treatment trends

Results from these two years were broadly in line with earlier work. The main deviation was in the increased draught of the tine cultivator on the non-trafficked compared with the trafficked soil. Differences in soil structure and the pattern of soil failure observed with this implement and experiences from earlier years, would lead us to suggest that

Table 5. Mean values of the transformed biological activity data (using logit (p) = ln (p/1 − p)) and mean values on the scale recorded in the field (bracketed) for the March 1992 sampling

	Trafficked		Non-trafficked			S.E.D.
Traffic (mean of all depths)	-1.0^{a} (3.3)		0.3^{b} (5.4)			0.22
	Ploughed		Tine cultivated			
Tillage (mean of all depths)	0.0^{a} (5.1)		-0.7^{b} (3.6)			0.22
Depth, mm	50	100	150	200	250	
(mean of all treatments)	1.3^{a} (7.3)	0.0^{b} (5.0)	-0.7^{b} (3.7)	-0.7^{b} (3.5)	-1.6^{c} (2.3)	0.16

S.E.D = standard error of difference of means.

^{a,b,c} Values with different letters significantly different at $P \leq 0.01$.

this type of cultivator is not ideally suited to the non-trafficked condition of this soil. Overall, results showed the non-trafficking systems to have advantages in terms of less implement draught and soil resistance, improved tilth, better drainage characteristics, particularly at low matric potentials and a very significant improvement in yield, averaging about 15%. The speculative treatment which employed a draught neutral rotary digger on the gantry, and which returned the greatest yield in 1994, was ideally suited to this two wheel-drive gantry system with its limited draught capability. Work rate of the rotary digger, which was only slightly less than the two passes needed by the tine cultivator, was 26% greater than with the plough. An economics analysis of different controlled or non-trafficking systems by Chamen & Audsley (1993), showed a gantry system to be about £35/ha more profitable than conventional practice on heavy soil, and directly comparable on medium land. These results were based on a 7% increase in yield of combinable crops, which in the light of more recent work, must be seen as a conservative estimate. Where a 20% decrease in cereal prices was anticipated, the non-trafficking systems all improved their profitability compared with conventional practice. Environmental advantages of the non-trafficking system, in addition to smaller energy inputs, are the potential for applying liquid wastes to the soil during wet periods with less risk of surface runoff, less risk of nitrate loss through denitrification and more efficient use of nitrogen fertilizer. All plots had identical applications of fertilizer, and it must therefore be assumed that it was less available or used less efficiently by the crop on the trafficked soil, as found by Douglas *et al.* (1992, 1995) in their experiment on grass for silage production.

Table 6. Plant populations and winter wheat crop yield, 1993/94

	Treatment†							
Measurement	TP	TT	GP	GT	PG	GS	S.E.D.	L.S.D.
Plants/m^{2}	221	146	202	196	210	209	47.2 (N.S.)	
Yield, t/ha	8.55	7.39	10.10	10.01	9.49	10.49	0.62	1.44

N.S. = not significant at $P \leq 0.05$.

L.S.D. = least significant difference at $P = 0.05$.

† for key see 'Treatments' section.

CONCLUSIONS

Removing wheel-induced soil compaction on this site led to a substantial fall in primary tillage energy requirement (up to about 40%) and a decrease in both soil bulk density and cone penetration resistance compared with conventionally trafficked soil. These results are in line with those from a number of other researchers (Lamers *et al.*, 1986; Carter *et al.*, 1988; Tullberg & Lahey, 1989; Dickson *et al.*, 1992). The non-trafficked treatment also led to smaller soil water contents at low matric potentials, suggesting that heavy land under this regime would suffer less from waterlogging than if it were managed with conventional traffic. These conditions led to a 25% increase in winter wheat yield in 1994 compared with conventional practice, and an average increase of 15% over four harvests. In line with the increased yield and changes in soil structure, an assessment of soil living animal activity suggested that the conditions under a non-trafficking regime would favour an increase in the number and/or activity of these animals.

These results are favourable in terms of environmental factors. Fertilizer use efficiency was increased by around 15% and should, for a given fertilizer input, decrease the loss of nutrients in the drainage water. A more freely draining soil may also allow earlier access after wet spells and for an extended period during the winter. The application of slurries and sewage sludge may also be undertaken with less risk of surface runoff. Inter-row cultivation rather than chemical weed control may also be possible, both as a result of these drier conditions and due to the improved friability of the soil. The economics of gantry systems are likely to be further improved in view of the increased yield response compared with that anticipated in the study by Chamen & Audsley (1993). Overall, the benefits of eliminating wheel traffic from the cropped area would appear to be considerable.

ACKNOWLEDGEMENTS

This project was funded by the U.K. Ministry of Agriculture, Fisheries and Food and by the Biotechnology and Biological Sciences Research Council. Our thanks are also due to Silsoe College and Silsoe Research Institute staff who assisted with hydrological isolation of the plots, and to Rodger White at SRI for much of the statistical analysis of the data.

REFERENCES

Anderson, G., Pidgeon, J.D., Spencer, H.B. & Parks, R. 1980. A new hand-held recording penetrometer for soil studies. *Journal of Soil Science* **31**, 279–296.

Andersson, S. & Håkansson, I. 1963. Soil physical studies in cultivated soil XIV. New methods of determining the micro-topography of the soil surface, its height variations and porosity of the topsoil. *Grundförbättring* **16**, 1–26.

Berkson, J. 1953. On the subject of biological assays. *Journal of the American Statistical Association* **48**, 565.

Carter, L., Meek, B. & Rechel, E. 1988. Zone production research with wide tractive research vehicle. *Proceedings of the 11th Conference of the International Soil Tillage Research Organization, Penicuik, Edinburgh*. **1**, 221–225.

Chamen, W.C.T., Chittey, E.T., Leede, P.R., Goss, M.J. & Howse, K.R. 1990. The effect of tyre/soil contact pressure and zero traffic on soil and crop responses when growing winter wheat. *Journal of Agricultural Engineering Research* **47**, 1–21.

Chamen, W.C.T., Watts, C.W., Leede, P.R. & Longstaff, D.J. 1992. Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime. *Soil and Tillage Research* **24**, 359–380.

Chamen, W.C.T. & Audsley, E., 1993. A study of the comparative economics of conventional and zero traffic systems for arable crops. *Soil and Tillage Research* **25**, 369–390.

Chamen, W.C.T., Dowler, D., Leede. P.R. & Longstaff, D.J. 1994. Design, operation and performance of a gantry system: experience in arable cropping. *Journal of Agricultural Engineering Research* **59**, 45–60.

Chamen, W.C.T. & Cavalli, R. 1994. The effect of soil compaction on mole plough draught. *Soil and Tillage Research* **32**, 303–311.

Davies, D.B. 1988. *Reduced cultivations for cereals.* Research Review-Home Grown Cereals Authority, UK, 5 Hamylyn House, Highgate Hill, London.

Dickson, J.W., Campbell, D.J. & Ritchie, R.M. 1992. Zero and conventional traffic systems for potatoes in Scotland, 1987–1989. *Soil and Tillage Research* **24**, 397–419.

Dougherty, E., Leeds-Harrison, P.B., Youngs, E.G. & Chamen W.C.T. 1995. The influence of soil management on drainage hydrographs. *Soil Use & Management*, **11**, 177–182.

Douglas, J.T., Campbell D.J. & Crawford, C.E. 1992. Soil and crop responses to conventional, reduced ground pressure and zero traffic systems for grass silage production. *Soil and Tillage Research* **24**, 421-439.

Douglas, J.T., Crawford, C.E. & Campbell, D.J. 1995. Traffic systems and soil aerator effects on grassland for silage production. *Journal of Agricultural Engineering Research* **60**, 261–270.

Howse, K.R. & Goss, M.J. 1982. Installation and evaluation of permanent access pits which permit continuity of measurement in cultivated soils. *Experimental Agriculture* **18**, 267–276.

Lamers, J.G., Perdok, U.D., Lumkes, L.M. & Klooster, J.J. 1986. Controlled traffic farming systems in the Netherlands. *Soil and Tillage Research* **8**, 65–76.

Leeds-Harrison, P.B., Vivian. B.J. & Chamen, W.C.T. 1992. *Tillage effects in drained clay soils.* American Society of Agricultural Engineers, Paper 92–2648, St. Joseph, Michigan.

Monnier, G. & Goss, M.J. (Eds) 1987. *Soil Compaction and Regeneration.* AA Balkema, Rotterdam/Boston, 167 pp.

Soane, B.D. & Van Ouwerkerk, C. (Eds) 1994. *Soil Compaction in Crop Production.* Elsevier Science B.V., Amsterdam.

Soil Survey Staff. 1994. *Keys to Soil Taxonomy 6th Edition.* USDA Soil Conservation Service, Government Printing Office, Washington, D.C.

Spoor, G., Cronin, C.J. & Leeds-Harrison, P.B. 1990. Mole drain installation for leaching purposes. *Proceedings of the Symposium on Land Drainage for Salinity Control in Arid and Semi-arid Regions.* Drainage Research Institute, Cairo, **3**, 47–54.

Tullberg, J.N. & Lasey, G.V. 1989. Energy cost of wheeltrack tillage. *Agricultural Engineering Australia* **18**, 42-45.

Von Törne, E. 1990. Assessing feeding activities of soil-living animals. *Pedobiologia* **34**, 89–101.

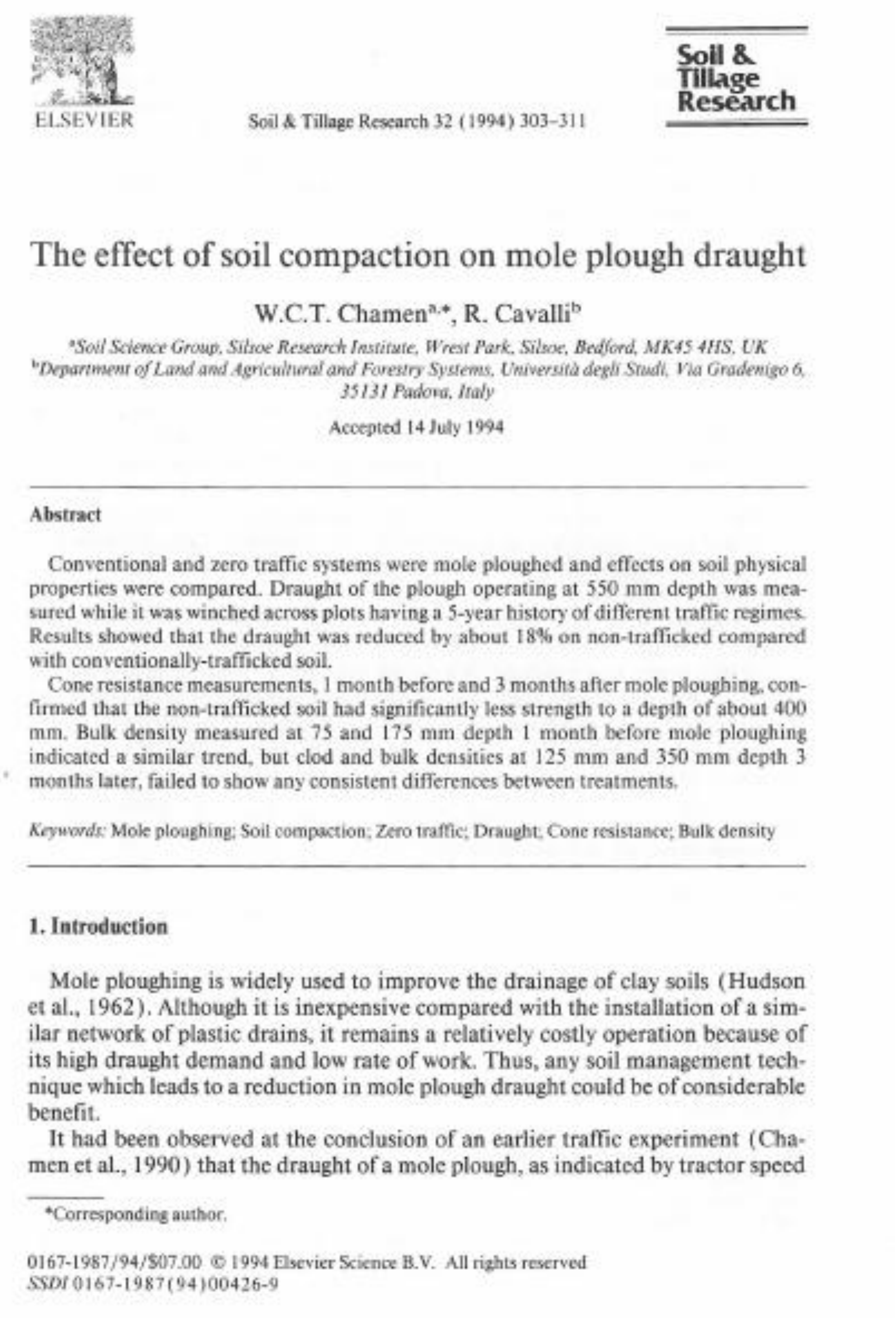
Youngs, E.G. & Goss, M.J. 1988. Hydraulic conductivity profiles of two clay soils. *Journal of Soil Science* **39**, 341–345.

3.3.4. Chamen & Cavalli, 1994. The effect of soil compaction on mole plough draught

This paper has been selected particularly because it reveals what appear to be traffic effects on draught forces in the subsoil created by a mole plough which may be an indication of subsoil compaction. It also provides some further evidence of the persistence of loosening effects that were largely absent in the literature. However, the original paper made no attempt to distinguish between the forces generated on the mole plough by the leg and the foot, including the expander. Godwin et al. (1981) in their extensive study of the forces on mole ploughs were able to distinguish clearly between forces on the leg and forces on the foot as illustrated in their Fig. 2. They determined that the major proportion of draught is generated by the leg of the mole plough and this proportion increases with depth. In an alluvial gley soil the leg accounted for around 70% of the total force when operating at 500 mm depth and this compares with data quoted from Wells (1951), which suggested around 66%. The depth of operation in the studies being discussed here was around 550 mm, so with a similar soil (albeit with weaker subsoil layers than the Evesham used by Chamen & Cavalli) and depth of operation, the data from Godwin et al. (1981) should provide a reasonable prediction. This is confirmed by their model studies where the shear force was more uniform with depth and predicted over 60% of the total force being generated by the leg. The sliding beam component did not need to be considered in Chamen & Cavalli's work because the trailed three-point linkage kept the beam clear of the ground (their Fig. 1).

The outcome of these considerations is that of the 18% reduction in draught of the mole plough determined by Chamen & Cavalli, only around 30% is likely to have emanated from the mole plough foot, i.e. around 5%. However, lower strength in the deeper layers above the mole plough foot, as indicated from penetration resistance data (Fig. 2, Chamen & Cavalli) of the non-trafficked soil would suggest that this is a conservative estimate, particularly as this phenomenon was apparent to around half the operating depth of the mole plough. A key aspect in assessing the overall efficiency of the mole plough operation includes not only the draught of the mole plough, but the resulting effects, such as mole channel stability and the soil structure delivering excess water to the these channels. According to Godwin et al. (1981), weaker soil layers above the mole should allow the foot to be used closer to the surface without the danger of generating a crescent failure and thus unstable condition. Reducing the depth of mole ploughing can have a substantial effect on the energy required, with forces reducing with depth at between 3 and 8 kN 100 mm^{-1} (from Godwin et al., 1981). Mole ploughing will still almost certainly be required on non-trafficked soils, but there is every indication that this will be a less costly and therefore more efficient operation.

Full paper, Chamen & Cavalli, 1994



ELSEVIER

Soil & Tillage Research 32 (1994) 303-311

Soil & Tillage Research

The effect of soil compaction on mole plough draught

W.C.T. Chamen[a,*], R. Cavalli[b]

[a]*Soil Science Group, Silsoe Research Institute, Wrest Park, Silsoe, Bedford, MK45 4HS, UK*
[b]*Department of Land and Agricultural and Forestry Systems, Università degli Studi, Via Gradenigo 6, 35131 Padova, Italy*

Accepted 14 July 1994

Abstract

Conventional and zero traffic systems were mole ploughed and effects on soil physical properties were compared. Draught of the plough operating at 550 mm depth was measured while it was winched across plots having a 5-year history of different traffic regimes. Results showed that the draught was reduced by about 18% on non-trafficked compared with conventionally-trafficked soil.

Cone resistance measurements, 1 month before and 3 months after mole ploughing, confirmed that the non-trafficked soil had significantly less strength to a depth of about 400 mm. Bulk density measured at 75 and 175 mm depth 1 month before mole ploughing indicated a similar trend, but clod and bulk densities at 125 mm and 350 mm depth 3 months later, failed to show any consistent differences between treatments.

Keywords: Mole ploughing; Soil compaction; Zero traffic; Draught; Cone resistance; Bulk density

---

1. Introduction

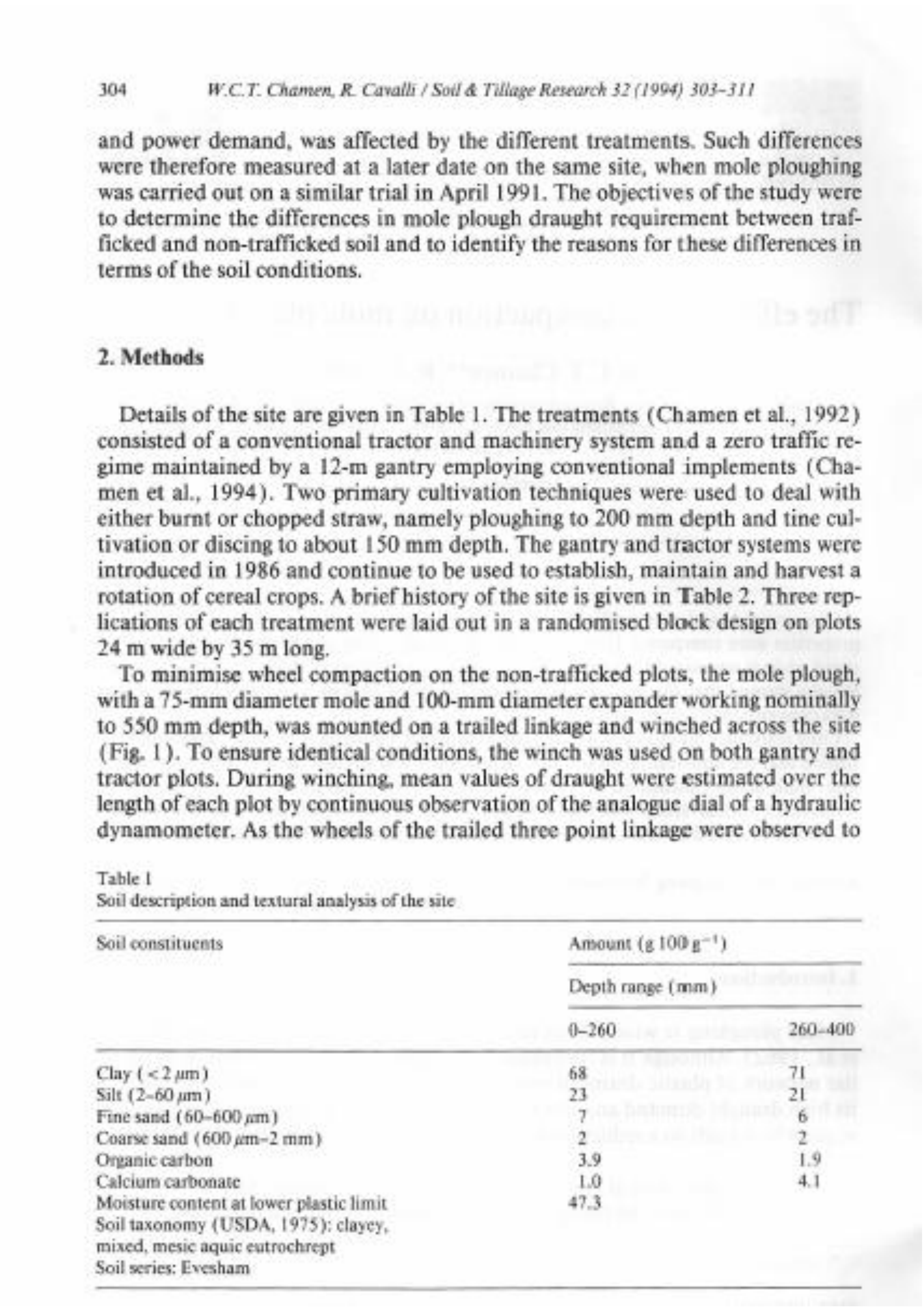
Mole ploughing is widely used to improve the drainage of clay soils (Hudson et al., 1962). Although it is inexpensive compared with the installation of a similar network of plastic drains, it remains a relatively costly operation because of its high draught demand and low rate of work. Thus, any soil management technique which leads to a reduction in mole plough draught could be of considerable benefit.

It had been observed at the conclusion of an earlier traffic experiment (Chamen et al., 1990) that the draught of a mole plough, as indicated by tractor speed

---

*Corresponding author.

0167-1987/94/$07.00
SSDI 0167-1987(94)00426-9



and power demand, was affected by the different treatments. Such differences were therefore measured at a later date on the same site, when mole ploughing was carried out on a similar trial in April 1991. The objectives of the study were to determine the differences in mole plough draught requirement between trafficked and non-trafficked soil and to identify the reasons for these differences in terms of the soil conditions.

2. Methods

Details of the site are given in Table 1. The treatments (Chamen et al., 1992) consisted of a conventional tractor and machinery system and a zero traffic regime maintained by a 12-m gantry employing conventional implements (Chamen et al., 1994). Two primary cultivation techniques were used to deal with either burnt or chopped straw, namely ploughing to 200 mm depth and tine cultivation or discing to about 150 mm depth. The gantry and tractor systems were introduced in 1986 and continue to be used to establish, maintain and harvest a rotation of cereal crops. A brief history of the site is given in Table 2. Three replications of each treatment were laid out in a randomised block design on plots 24 m wide by 35 m long.

To minimise wheel compaction on the non-trafficked plots, the mole plough, with a 75-mm diameter mole and 100-mm diameter expander working nominally to 550 mm depth, was mounted on a trailed linkage and winched across the site (Fig. 1). To ensure identical conditions, the winch was used on both gantry and tractor plots. During winching, mean values of draught were estimated over the length of each plot by continuous observation of the analogue dial of a hydraulic dynamometer. As the wheels of the trailed three point linkage were observed to

Table 1
Soil description and textural analysis of the site

Soil constituents	Amount (g 100 g^{-1})	
	Depth range (mm)	
	0–260	260–400
Clay (< 2 μm)	68	71
Silt (2–60 μm)	23	21
Fine sand (60–600 μm)	7	6
Coarse sand (600 μm–2 mm)	2	2
Organic carbon	3.9	1.9
Calcium carbonate	1.0	4.1
Moisture content at lower plastic limit	47.3	
Soil taxonomy (USDA, 1975): clayey, mixed, mesic aquic eutrochrept		
Soil series: Evesham		

Table 2
Recent history of the site

Year	Details of operations	Crop harvested
1986	Mole ploughed, subsoiled and rotary dug[a]	Winter wheat
1987	Straw on cultivated plots burnt	Spring barley
1988	Straw on cultivated plots burnt	Spring oats
1989	Straw on cultivated plots burnt	Winter wheat
1990	Straw on all plots chopped	Winter oats
1991	Straw on all plots chopped	Spring barley
1991	Mole ploughed in April	

[a] Chamen et al., 1979.

Fig. 1. Winching of the mole plough using a trailed three-point linkage as a stabilizing drawbar.

create different depths of rut on each of the treatments, a straight edge was used to measure the amount of wheel sinkage.

Just prior to mole ploughing, soil cone resistance and bulk density were measured on each of the plots. Cone resistance was measured to a depth of 350 mm at 12 positions on each plot, with a Bush recording penetrometer having a cone with a base diameter of 12.83 mm and semi-angle of 15°. Bulk density was measured using 75-mm diameter cores taken at three depths: 0–50, 50–100 and 150–200 mm at two randomly selected positions on each plot. Following harvest of the spring barley crop, which was accomplished using the traffic treatments already described, further soil measurements were taken, but to a greater depth than those recorded previously. The sampling strategy was designed specifically to investigate the reasons for the relatively large differences in mole plough draught observed between the different traffic treatments. Cone penetration resistance and clod and bulk density measurements were made on the tine cultivated plots of both traffic treatments. Clod density was determined from ten clods, each of about 0.2 dm^3 volume, extracted undisturbed from three positions (in the mid-line between mole channels) on each of the sampled plots at approximately 125 mm and 350 mm depth. The clods were coated in Saran resin to determine their density as described by Brasher et al. (1966) and Blake (1965). Clod volume was corrected, assuming normal shrinkage (McGarry and Malafant, 1987), to the value equivalent to the mean moisture content of the complete sample set, which was 275 $g\,kg^{-1}$. Bulk density was measured at depths of 125–175 and 325–375 mm.

Cone resistance was measured as before but 20 sets of readings were taken on each plot to a depth of 450 mm.

3. Results and discussion

3.1. Soil density

April 1991 measurements of dry bulk density and water content are presented in Table 3. The effects of traffic and depth were significant at $P<0.01$ for both density and water content, but there was an interaction ($P<0.01$) between cultivation and traffic as far as density was concerned. The differences in water con-

Table 3
(a) Soil dry bulk density water content in April 1991

Depth (mm)	Bulk density ($kg\,m^{-3}$): mean of all treatments	Water content ($g\,kg^{-1}$)		
		Gantry	Tractor	Mean
25	847	241	367	304
75	936	420	470	445
175	1005	432	483	457
LSD ($P<0.05$)	47	40		30

(b) Dry bulk density according to treatment ($kg\,m^{-3}$)

Traffic	Cultivation	
	Ploughed	Cultivated
Gantry	877	832
Tractor	966	1041
LSD ($P<0.05$)	46	

Table 4
Clod dry density and water content in September 1991

Depth (mm)	Density (kg m^{-3})	Water content (g kg^{-1})
125	1804	28.9
350	1625	26.1
LSD ($P<0.05$)	93	1.1

Table 5
Soil dry bulk density and water content in September 1991

Depth (mm)	Bulk density (kg m^{-3})	Water content (g kg^{-1})
150	1215	28.9
350	1300	25.8
LSD ($P<0.05$)	62	14.7

tent were confined to the change between 25 mm and 75 mm depth, with no further significant increase between 75 and 175 mm depth. However, bulk density increased significantly between all depths and between gantry and tractor traffic, but the limited depth of measurement meant that it was difficult to relate these data with the draught of the plough (see later section).

Differences in clod density and water content in September were confined to the effect of depth (Table 4). This was surprising and it was postulated that the earlier differences between the treatments were due to a dissimilarity in macroporosity or structural cracks between clods which would not have shown up in the clod analysis. To check this hypothesis, nine cores were taken from 100–200 mm and 300–400 mm depths on single plots of each of the two treatments. Results (Table 5) again showed that only the effect of depth was significant ($P<0.001$). It was concluded therefore that wetting and drying cycles of the soil, together with its drier state in September, largely masked the differences that had been found earlier in the year.

3.2. Soil cone resistance

Cone resistance data were analysed as a split plot design over all depths and treatments. In April (Fig. 2) resistance increased significantly ($P<0.001$) with depth and on average was significantly greater ($P<0.05$) over the whole depth range on the tractor compared with the gantry plots (1.22 compared with 1.03 MPa respectively, LSD = 0.01 MPa). There was no evidence to suggest that type of cultivation had an effect. As soil water content on the gantry plots was less than on the tractor plots (Table 3), this would have increased cone resistance on the non-trafficked soil. Therefore the contrast between trafficked and non-trafficked soil was likely to have been greater than was actually recorded.

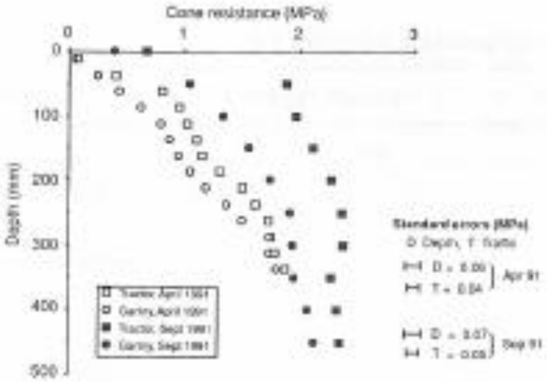


Fig. 2. Soil cone resistance for trafficked (tractor) and non-trafficked (gantry) plots in April and September 1991.

The September measurements of cone resistance (Fig. 2) exhibited a similar trend to those in April, but to a greater extent, with all differences being significant at $P<0.001$. The mean resistance on the tractor plots was 2.06 MPa compared with 1.60 MPa on the non-trafficked soil (LSD=0.20 MPa). On this occasion there was no significant difference in the soil water content between treatments but there was a significant change with depth (Table 5).

These results were in contrast to those of clod and bulk density taken in September, and it was postulated that differences in cone resistance could have been caused by the small but non-significant differences in soil water content. To test this hypothesis, the following relationship between cone resistance and soil water content derived by Utomo and Dexter (1981), was assumed:

$$\text{April} \quad \ln Q_1 = a + bw_1 \tag{1}$$

$$\text{September} \quad \ln Q_2 = a + bw_2 \tag{2}$$

where Q_1 and Q_2 are the mean cone resistances and w_1 and w_2 the mean water contents at 125 mm depth recorded on the different dates. Values of 1.474 and −3.181 were obtained for a and b respectively. These values were then used in the same equation with the cone resistances measured in September for trafficked and non-trafficked soil, to predict the soil water content. Taking cone resistances of 2.099 MPa for the trafficked and 1.491 MPa for the non-trafficked plots, the predicted water contents were 230 and 338 g kg^{-1} respectively. The mean difference in water content between traffic treatments was only 1 g kg^{-1}, showing that the differences in cone resistance could not have been accounted for by the variation in water contents that were observed.

3.3. Mole plough draught

Draught of the mole plough on the tractor plots was significantly greater than on the gantry plots ($P<0.01$, Table 6), but cultivation method (ploughing or tine

Table 6
Draught requirement and variation in nominal depth of a mole plough when operated on trafficked (tractor) and non-trafficked (gantry) soil at 550 mm depth

Traffic	Draught (kN)	Wheel sinkage (mm)
Gantry	25.3	44.7
Tractor	29.6	22.5
LSD ($P<0.05$)	2.1	7.7

cultivation) had no effect. The mean effect of traffic was a 14.5% reduction in draught for the non-trafficked compared with the trafficked soil. This is a conservative measure of the difference between the treatments, because the wheels of the carriage sank to a greater extent on the gantry plots (Table 6). This led to a 22.2-mm increase in depth of operation for the non-trafficked compared with the trafficked soil. According to Godwin et al. (1981), the draught of a mole plough tends to increase as the square of the depth of work. If the draught of the mole plough on the gantry plots is corrected to the equivalent depth on the tractor plots (550+22.2 mm), the value on the non-trafficked soil is reduced to 24.3 kN. This represents a 17.9% reduction in draught compared with the conventional treatment. If an allowance for the increased rolling resistance of the carriage on the zero traffic plots were to be included, a further reduction in draught for mole ploughing would result.

The relationship between both clod and bulk density and mole plough draught was inconsistent. In April, the bulk density of the non-trafficked soil was about 150 kg m^{-3} less than the trafficked soil, reflecting the differences in mole plough draught recorded, but in September bulk and clod densities for the different treatments were indistinguishable. It is apparent therefore that the density of the soil is not always a good indicator of soil strength. This is probably associated with changes in the structure of the soil, whereby a similar density can exist, but where the pore size distribution is very different. Watts and Dexter (1994), working on this site, found that the geometric mean diameter of aggregates on the gantry plots was smaller and the macro-porosity greater'than on the trafficked soil. However, these data only relate to the top 150 mm of soil, and the soil conditions which are likely to have had an effect on the mole plough would almost certainly have existed at a depth of at least 300 mm. It can only be postulated therefore that the dissimilar soil structural conditions near the surface persisted to this depth in the profile.

Below a moling depth of about 300 mm, the leg forces on a mole plough tend to predominate over those from the foot and expander and, in a cohesive soil, the resultant force tends to move up the leg with increasing depth of operation (Godwin et al., 1981). At 550 mm depth, it is estimated that the resultant force would have been approximately 350 mm deep. As the depth effects of compaction on this soil had in the past generally been confined to the top 300 mm, the magnitude of the differences in draught force between treatments was unexpected. However, the rigorous approach to the results of the cone resistance measurements confirmed that real differences in strength existed at the depth of the resultant draught force. It would appear, therefore, that cone resistance measurements provide a good indication of differences in draught force.

The draught data recorded in this experiment were very similar to that published by Godwin et al. (1981). In their work on an Evesham soil with similar properties, the total horizontal force recorded with a 100-mm expander operating at a comparable depth was 29.2 kN. No mention, however, was made of the effect of soil conditions on the total draught of the plough and there are few other published data relating to the soil resistance of mole ploughs.

The effect which differences in traffic compaction may have on the persistence of the mole channel is of considerable interest. Although no data have yet been recorded on this aspect, it is hoped that some measurements can be made within the expected life span of the mole system.

4. Conclusions

Zero compared with random traffic on the soil led to a reduction of about 18% in the draught requirement of a mole plough working at 550 mm depth. This reduction was associated with contrasts in soil strength of about 17% in the top 400 mm of the soil profile, as indicated by differences in cone resistance. Soil bulk or clod density was not found to be a reliable indicator for predicting differences in strength or draught requirement on this soil.

Acknowledgements

The authors are grateful to Dr W.R. Whalley of Silsoe Research Institute for making his data on cone resistance and bulk density from April 1991 available to the authors. This work was part of a programme funded by the Ministry of Agriculture, Fisheries and Food.

Prof. R. Cavalli was supported at Silsoe Research Institute by The British Council/National Research Council Scientific Co-operation Program—Italy.

References

Blake, G.R., 1965. Clod density. In: C.A. Black et al. (Editors), Methods of Soil Analysis. Part 1. American Society of Agronomy, Madison, WI, pp. 371–373.

Brasher, B.R., Franzmeier, D.P., Valassis, V. and Davidson, S.E., 1966. Use of Saran resin to coat natural soil clods for bulk-density and water-retention measurements. Soil Sci., 101: 108.

Chamen, W.C.T., Cope, R.E. and Patterson, D.E., 1979. Development and performance of a high output rotary digger. J. Agric. Eng. Res., 24: 301–318.

Chamen, W.C.T., Chittey, E.T., Leede, P.R., Goss, M.J. and Howse, K.R., 1990. The effect of tyre/

soil contact pressure and zero traffic on soil and crop responses when growing winter wheat. J. Agric. Eng. Res., 47: 1–21.

Chamen, W.C.T., Watts, C.W., Leede, P.R. and Longstaff, D.J., 1992. Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime. Soil Tillage Res., 24: 359–380.

Chamen, W.C.T., Dowler, D., Leede, P.R. and Longstaff, D.J., 1994. Design, operation and performance of a gantry system: experience in arable cropping. J. Agric. Eng. Res., in press.

Godwin, R.J., Spoor, G., and Leeds-Harrison, P., 1981. An experimental investigation into the force mechanics and resulting soil disturbance of mole ploughs. J. Agric. Eng. Res., 26: 477–497.

Hudson, A.W., Hopewell, H.G., Bowler, D.G. and Cross, M.W., 1962. The drainage of farm lands. Bulletin No. 18, Massey College, Palmerston North.

McGarry, D. and Malafant, K.W.J., 1987. The analysis of volume change in unconfined units of soil. Soil Sci. Soc. Am. J., 51: 290–297.

United States Department of Agriculture, 1975. Soil taxonomy—a basic system of soil classification for making and interpreting soil surveys. Agriculture handbook no. 436. USDA-SCS, US Government Printing Office, Washington, DC.

Utomo, W.H. and Dexter, A.R., 1981. Age hardening of agricultural top soils. J. Soil Sci., 32: 335–350.

Watts, C.W. and Dexter, A.R., 1994. Traffic and seasonal influences on the energy required for cultivation and on the subsequent tilth. Soil Tillage Res., 31: 303–322.

3.4. CONCLUSIONS

Considering a typical calcareous pelosol of the Evesham Series:

1. This soil maintains a more favourable structure for at least four years following deep loosening when not subjected to maximum conventional wheel loads of around 3 Mg which increase its strength and density while reducing its porosity. Tillage inputs can also be substantially less than when this soil is trafficked with also a more favourable outcome in terms of seedbed quality. The different nature of the soil structure may require a change to the type of tillage tool needed to produce a seedbed efficiently.
2. The calcareous nature of this soil means that crops can suffer a trace element deficiency if the degree of compactness is too low. Light surface firming in the form of rolls may not always overcome this problem.
3. When subjected to tyre contact pressures of 50 kPa or less the strength and density of the pelosol remains lower than the same soil subjected to similar loads but with tyres at 100-250 kPa pressure.
4. Although reducing the annually trafficked area can have benefits in the first one or two seasons, persistence of compaction and extension of the tracked area tends to build up with time and the poorer characteristics and extra energy associated with conventional practice return within three years.
5. Avoiding wheel loads of around 3 Mg on this soil for a period of four years seems to provide some relief to subsoil layers at around 0.5 m, as indicated by 18% lower draught loads on a mole plough.
6. Active management of some of the permanent wheel tracks is required, mostly in the form of infilling but there is scope for using less aggressive traction tyres that avoid break up of the running surface. Inappropriate management can compromise access to the wheel tracks in wet conditions.

CHAPTER 4

4. The effects of CTF systems on crop growth, yield, soil structure and infiltration in non-replicated field studies

4.1. INTRODUCTION

This chapter describes a number of disparate studies that were initiated with the aim of filling gaps in knowledge and to reinforce areas where knowledge was limited. The studies conducted at Colworth arose from the fact that in 2004, Unilever expressed interest in assessing Controlled Traffic Farming (CTF) on their Lee Farm, at Colworth in Bedfordshire, UK on a Hanslope Association clay soil. Initially CTF was adopted on one 8 ha field but in 2006, it was extended to a further eight fields covering a total of 73 ha. On these fields, opportunities were taken to assess performance of the permanent traffic lanes, to investigate cropping and to assess changes in soil structure with time. However, these assessments of soil structure were on a self-restructuring soil and one of the shortcomings of previous research on CTF in the UK is the limited number of soils on which studies have been undertaken, and in particular, those with poor self-restructuring characteristics. Sands and silts for example do not appear to restructure naturally with cycles of wetting and drying, freezing and thawing (Pollard and Webster, 1978) and there is only limited evidence to suggest that different crop rooting can achieve any improvement (Goss, 1987). It is important for farmers converting to CTF to understand what happens on these soils because deep loosening is expensive. They need to know whether deep loosening is necessary and indeed, whether in the absence of traffic, all soils will maintain an acceptable structure. One study carried out on a non-restructuring soil was that by Campbell et al. (1986) who worked on a Winton Series silty clay loam (Gleyic Luvisol, FAO, 1988). They showed that this soil, previously designated as unsuitable for no-till, was able to grow crops well with CTF and maintain good structure. In view of this positive outcome and need to know more about these soils, one part of the work described here concentrated on trying to assess the likely impact of CTF on soils that have little ability to restructure quickly without physical intervention (tillage). This work started with a pot study, but in view of shortcomings with this technique, extended to field assessments. The overall aim of these studies was therefore to investigate the practicalities, performance and sustainability of CTF not only through direct observation and measurement at Colworth but also through associated regional studies where CTF was not actually being employed. The specific objectives were:

1. At Colworth:
    a. to quantify the comparative yields from non-trafficked, randomly trafficked and intensely trafficked areas
    b. to gauge the impact of controlled traffic and no-till on soil strength, water infiltration and structure

   c. to quantify differences in crop root growth between trafficked and non-trafficked areas
   d. to draw up a management strategy for permanent traffic lanes
2. To determine the potential of different soils to restructure in the absence of machinery compaction

4.2. METHODS

4.2.1. Colworth

The CTF system adopted at Colworth was based on 20 m chemical applications whereby crop drilling and harvesting was with 6.66 m wide equipment. Crop sowing used a trailed drill with tine openers (John Dale Zero Till drill) and this and the tractor track gauge was matched to that of a John Deere harvester with an imported 3 m axle conversion supplied by John Deere for one of their 8530 tractors. This system resulted in two permanent tracks about 650 mm wide spaced 3 m apart repeated across the field every 6.66 m. The single field was on a Hanslope Association clay soil (Table 4.1) and was part of a block of four adjacent similarly textured fields that were at the same point in a five year rotation (Fig. 4.1). The permanent wheel tracks were set up while harvesting field beans in 2004 using a satellite based correction signal (John Deere Starfire 2) and an auto-steer system on the harvester. Where comparisons were made with traditional practice this consisted of identical harvesting machines (maximum 7.3 Mg per wheel), a rubber belted tractor with individual track loads of 7 Mg (also used for ploughing out of the furrow) plus other tractors with wheel loads of around 2 Mg. In particular, these treatments could be summarised as below with field numbers taken from Fig. 4. 1:

Field 28	CTF, no-till
Field 22	Random traffic (RTF), non-inversion tillage
Field 23	RTF, no-till
Field 15	RTF, plough

None of the fields were deep loosened in the years leading up to the introduction of CTF on field 28, which previously had been ploughed with the tracked tractor operating out of the furrow. The different tillage systems had been in place since 2002 except Field 23 which changed from ploughing to no-till in 2004.

4.2.1.1. Assessment of soil structure and water infiltration

The principal methodology was comparison of the trafficked and non-trafficked soils which formed the block shown in Fig. 4.1. Penetration resistance (PR) was measured on two occasions; the first with 30 replications on each treatment was with a hand-held recording Eijkelkamp Penetrologger with a 30 degree cone of base area 1.3 cm^3. The second set with 100 replications was with a speed regulated hydraulically pressurised probe (as per the hand-held device) operated from an “All Terrain Vehicle”. Water infiltration was also measured on two occasions. The first was at eight random points on

Table 4.1. Particle size analysis, organic carbon and pH of the clayey, mixed, mesic aquic eutrochrept soil (Soil Survey Staff, 1999) of the Hanslope Association (Hodge et al., 1984, page 209) at Colworth.

Soil property	Units	Depths, mm	
		0 - 100	250 - 300
Size, 0.063 – 2 mm, sand	%	20.05	20.12
Size, 0.002 – 0.063 mm, silt	%	33.34	33.03
Size, <0.002 mm, clay	%	46.62	46.86
pH		7.52	8.38
Organic carbon	%	2.68	1.00
Soil texture[1]		Clay	Clay

[1] Texture class as defined by Hodgson, 1976

each of the four fields shown in Fig. 4.1 over a period of two consecutive days in December 2005 using a double ring infiltrometer as shown in Fig.4.2. Equal numbers of measurements were taken on each day to minimise the time element between readings on one treatment compared with another. The second set of measurements were taken with a Decagon Mini Disk infiltrometer in early 2008 using suctions of 10 or 20 mm, but only on the no-till fields (28 and 23, Fig. 4.1). Infiltration with this instrument is determined from the slope of the quadratic equation computed from the cumulative infiltration plotted against the square root of time, as proposed by Zhang (1997) for dry soil and is stated as hydraulic conductivity rather than infiltration. Twenty one of these measurements were made on each of the two fields spread over two days but with an equal number of measurements from each of the fields on each day. In addition to these quantitative measures, subjective assessments were made of soil structure under the differently trafficked treatments through observation and photographic evidence.

4.2.1.2. Assessing the responses of oilseed rape (OSR) to different traffic and tillage

Roots of the OSR crop were examined by digging out individual plants at random from each of the four fields shown in Fig. 4.1 where the different crop establishment techniques had been employed. At the first sampling, ten plants were extracted per treatment and as a result of noticeable differences in rooting a more extensive sampling was made taking twenty plants from each treatment. The roots were severed at the transition between the green of the stem and the white of the root, washed and weighed. The lateral roots were then removed and the remainder of the root weighed again. As most comparisons were made on a ratio basis, differences in dry weight were not an issue. Weighing the root whole and then after removing the laterals achieved the ratio of root laterals to tap root weight, which formed the basis of the comparisons.

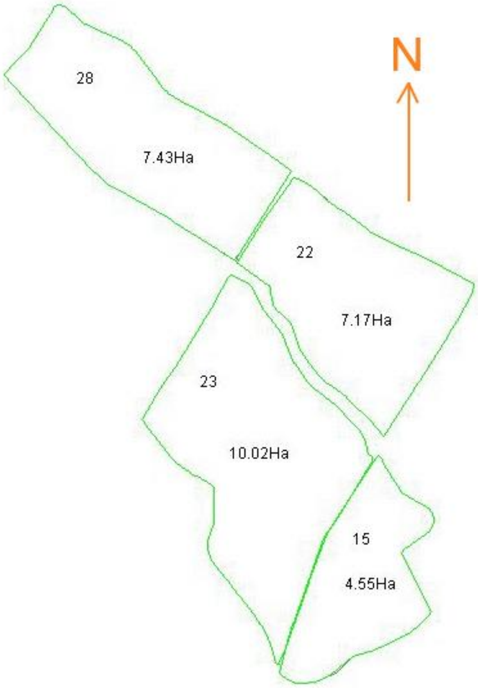


Fig. 4.1. The controlled traffic field (28) and its position in relation to the three trafficked fields at the same point in the rotation (22, non-inversion tillage; 23, no-till; 15, ploughed)

Fig. 4.2. Double ring infiltrometer used in December 2005 at Colworth on each of the fields shown in Fig. 4.1.

4.2.1.3. Measuring OSR yield

To ensure accuracy of yield comparisons, each of the field's cropped areas was mapped using the *John Deere Starfire* position receiver fitted on the JD 8530 tractor. The data were then verified by *Farmade* software that provided a field outline and confirmed the area indicated on the *Greenstar* display and displayed in Fig. 4.1.

4.2.1.4. Field and traffic lane comparisons of crop yields

To provide an overview of the field yields from those managed conventionally and those managed with CTF, the total yields from the differently managed areas were monitored each year from 2007 until 2010. During this time there were nine fields managed with CTF and seventeen with RTF. Yields were determined by weighing each trailer load from individual fields and then correcting the weights to a common moisture content. These yields are from fields with a very disparate history and management from year to year and with some variation in texture but all from the Hanslope Association. Averages for each crop also vary from year to year, with for example one from CTF, while the average for RTF might come from four fields

In a more detailed study, the relative yields in the CTF no-till beds and those from the direct sown cropped permanent tracks were compared with each other and with those from conventional practice. The variances of trial samples were calculated and used to determine the number and the size of hand collected samples needed to detect a 10% difference in yield. This analysis suggested that all the ears from ten, one metre random lengths of crop row within each treatment would be needed. In 2008 these were collected, bagged, weighed and then dried at 105 degrees centigrade for 40 hours before being weighed again. In 2009 the same procedure was adopted but the straw was also removed to ground level and weighed and dried in a similar manner when separated from the ear. The fields from which the samples were collected and details of their management are shown in Table 4.2.

Table 4.2. Fields from which crop ears were sampled for yield analysis

Field number	Management	Sampling date
37-40	CTF no-till since September 2006 after deep loosening to around 40 cm. **Wheat** after OSR /spring barley	11/8/ 2008 & 18/8/2009
34-38	Random traffic non inversion tillage (discs/power harrow). **Wheat** after OSR /spring barley	11/8/ 2008 & 18/8/2009
42	CTF no-till since September 2006. **Wheat** after wheat	11 August 2008
28	CTF no-till since September 2004. **Spring barley** after winter wheat.	17 August 2008
23	Random traffic (RTF) no-till since September 2004. **Spring barley** after winter wheat	17 August 2008

4.2.1.5. Assessment of permanent traffic lanes

In 2006 when the additional fields were brought under controlled traffic management, a change was made to 24 m chemical applications and an increase in the drill width to 8 m. In 2008 the principal CTF tractor was changed to a smaller machine (John Deere 7930) and the wheel track gauge was reduced to 2.2 m together with those of the trailed drill. The reason for this change was recognition that the 3 m axle tractor was not likely to be a commercial success in Europe and was dissuading farmers from considering the system on their own farms. This change increased tracked area to 24% and also meant that the traffic lanes now existed in three forms (Fig. 4.3), namely:

1. Tramlines – unsown traffic lanes used for crop establishment, harvesting and chemical applications
2. Intermediates – sown traffic lanes used for crop establishment and with a proportion of the width run over by the harvester
3. Harvester – section of sown traffic lanes run over only by the harvester

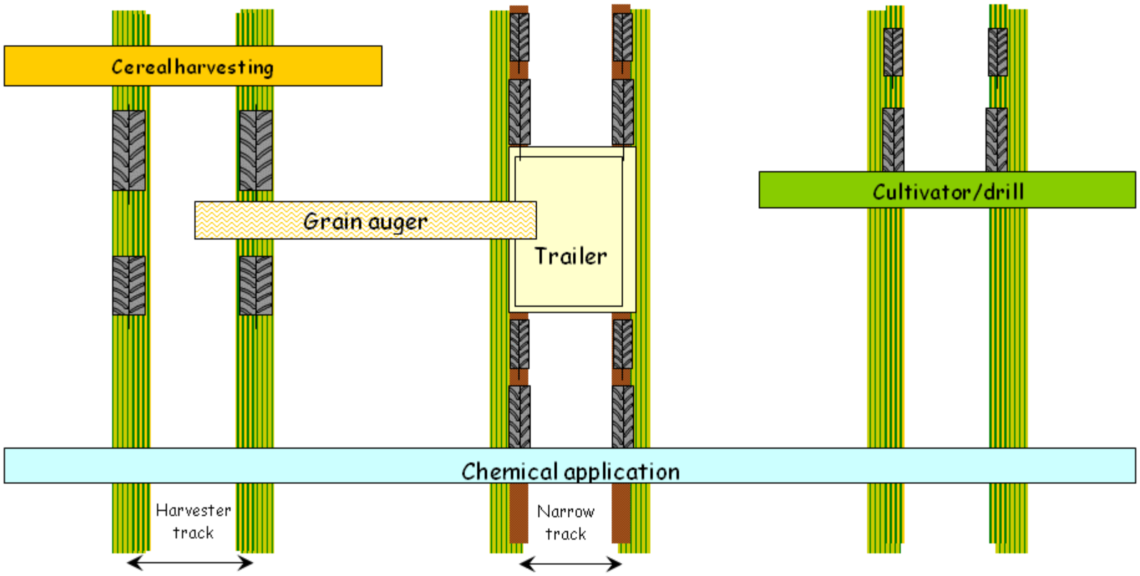


Fig. 4.3. The tracking configuration at Colworth from 2008 onwards resulting in an overlap between the narrower track gauge of the tractor (2.2 m) and the wider track gauge of the harvester (2.7 m).

4.2.2. REGIONAL STUDIES ON NON-RESTRUCTURING SOILS

4.2.2.1. Normanton Lodge Farm

Soil in the field selected for assessments on this farm was a clay loam of the Ashley Association, constituents of which were measured by the pipette method (BSI, 1990) and are listed in Table 4.3. Other physical parameters were measured with the Keen-Racjowski box. Observation and sampling of this soil started in June 2006 within the cropping sequence shown below:

2003	Sugar beet
2004	Spring beans
2005	Winter wheat

2006 Linseed/mustard

Table 4.3. Constituents of the Ashley Association soil (Hodge et al., 1984, page 96) at Normanton Lodge Farm

Parameter	Topsoil	Subsoil
% coarse sand	1.77	1.63
% sand	9.84	9.10
% fine sand	13.23	12.71
% total sand	24.84	23.44
% silt	46.76	56.73
% clay	28.40	19.84
Texture class[1]	Clay loam	Clay loam

[1] Hodgson, 1976

Samples of the soil in the form of large undisturbed aggregates were removed from the field for tests and observations. Bulk density was estimated by the immersion method whereby a container was filled to its neck with water and previously weighed aggregates completely immersed. The displaced water was weighed and wet and dry bulk densities calculated from this weight and the aggregate moisture contents determined from aggregate sub-samples taken before immersion. A study to assess the self-restructuring nature of this soil was commenced by wetting up a number of the aggregates and breaking them up by hand to a coarse tilth. This sample was then spread out and left on a free draining area to be subjected to a number of wetting and drying cycles, the results of which were photographed from a standard height and position. Following these wetting and drying cycles, the sample was broken down further and after air drying, passed through a 5 mm sieve. The sieved sample was then placed in a pot 300 mm deep and 300 mm in diameter which was buried to its rim in a cultivated plot of dissimilar soil. Winter wheat was sown in the pot (as it was in the field from which it was sampled) in October 2006 and growth and soil structure were observed until it was hand harvested in August 2007 as it was by machine on the field site. At this point the intact pot of soil was returned to Normanton Lodge and its structure visually compared with the field soil at a spot close to the original sampling point. Following this observation, both the pot soil and further field samples were subjected to the Visual Soil Assessment (VSA) procedure and the Soil Structure and Consistency test described by Shepherd (2009). In addition, five pits around 0.4 m deep were dug at random in the field and an average of four aggregates were extracted from each. These and the undisturbed profiles were photographed. Porosity, soil mottles and cultivation pan were assessed from these photos together with similar assessments of the pot soil, but necessarily with fewer samples. The consistency tests were carried out later following some drying of the soils.

4.2.2.2. Extensive field sampling

As a supplement to the pot study and in recognition of its limitations, an alternative methodology for assessing soil structure differences between trafficked and non-trafficked soil was developed that could be applied to most fields. The technique involved studying soil in the main body of the field through the use of soil pits and extracted aggregates and using a similar approach but with very selective sites at the cropped boundary. These boundary sites were chosen at positions within the cropped area but no further than a 1 m from the crop edge and in a position where wheel tracking was very unlikely to have occurred. Particular care had to be exercised where ploughing had been used as tractor wheels often come close to the field boundary during this operation; some fields had to be precluded on these grounds. Four fields were selected for assessments, three of which had been cropped with cereals and the fourth with sugar beet. Three pits were dug in each of the contrasting positions and soil condition was assessed using photographs and where possible, the VSA method described above. Other than the assessments carried out at Normanton Lodge, all other inspections were in Bedfordshire, UK.

4.3. RESULTS AND DISCUSSION

4.3.1. Colworth

4.3.1.1. Penetrometer resistance

Fig. 4.4 shows the mean values of 30 replications of PR measured on each of five differently managed areas on 30 January 06, together with respective soil moisture contents for all other than the tramlines. Below 35 cm, the relatively low resistance of the tramline wheelway could be a moisture effect for which there are no data. Even allowing for the relatively small contrasts in soil moisture there are marked differences in resistance with treatment and these follow a logical pattern which can be explained by the traffic and tillage and are fully supportive of the findings from the literature review. The second set of measurements was taken on 25 April 2008. Results (Fig. 4.5) show a similar trend to those taken in 2006 with the highest resistance under random traffic no-till and the lowest under the controlled traffic no-till. Differences in strength of the top 30 cm of soil on the RTF no-till compared with the CTF no-till were marked. Digging out a block of soil at field capacity on the RTF no-till with a fork proved impossible, despite digging around all four sides. In contrast, the non-trafficked soil could reliably be eased out by just one insertion of the fork demonstrating the significant change in structure on this soil following the removal of all field traffic.

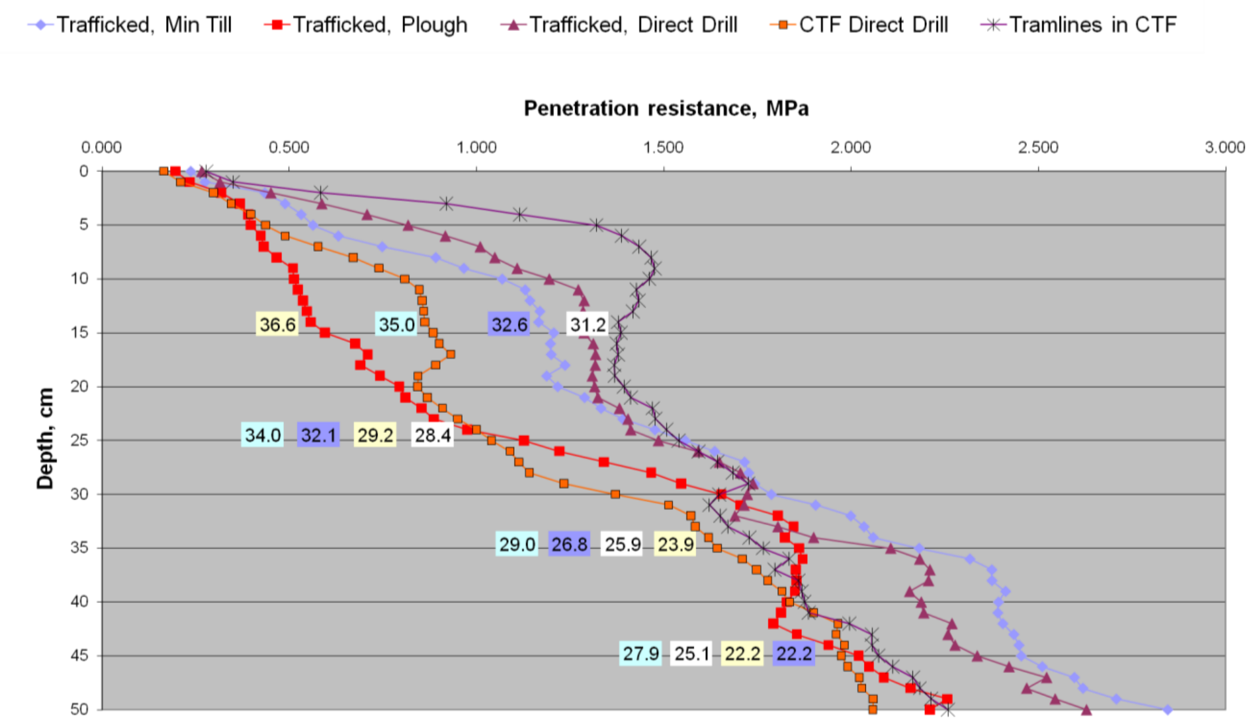


Fig.4.4. Penetration resistance versus depth for the four adjacent blocks of differently managed land on 30 Jan 06. Numbers are coincident soil moisture contents in same order as traces left to right (excluding tramlines).

4.3.1.2. Infiltration

Table 4.4 shows the averages of the data together with their standard deviations and errors. They are of particular interest in the UK (and probably across Europe) in terms of the relative potential for soil erosion as well as the efficient interception of water. Tramlines on fragile soils on slopes are a concern and it will be the aim of these and other measurements to confirm that controlled traffic systems do not constitute an additional threat.

Table 4.4. Average of eight infiltration measurements taken with a double ring infiltrometer (Fig. 4.2) on each of the fields shown in Fig. 4.1 in December 2005.

Treatment	Mean infiltration, mm/h	Standard deviation	Standard error
28, CTF no-till	904a	474	167
RTF:			
Non-inversion	576a	287	102
No-till	179b	194	69
Ploughed	5264c	4391	1553

Figures with a different following letter significantly different at the 5% level

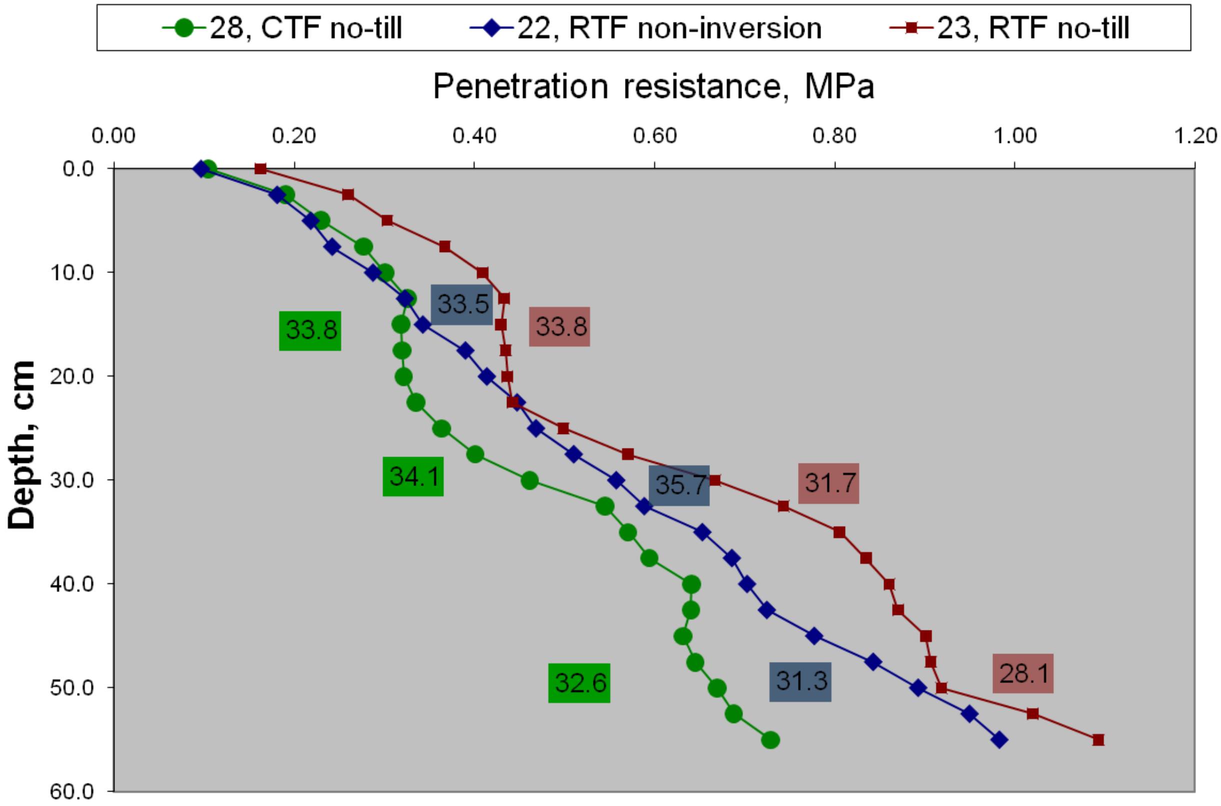


Fig. 4.5. Penetration resistance on 25 April 2008 on three of the fields shown in Fig. 4.1. Numbers are coincident moisture contents, colours as per PR traces.

Results for the measurements taken with the mini disk infiltrometer are presented in Table 4.5. These show that although there was a mean higher conductivity on the non-trafficked soil, the standard errors were such that the data from the two populations could not be separated with confidence. This contrast in results from the earlier occasion and in the presence of an obvious difference in topsoil strength, (as indicated by the PR data and relative difficulty in soil extraction) is probably associated with timing and measurement method. Measuring later in the winter period meant that there had been more time for the top few centimetres of soil to restructure and for some vertical pores to be created, but equally, for raindrop impact to have sealed some pores on this clay soil. Attempts were made to measure infiltration below straw cover, but in most instances the straw had become closely enmeshed in the soil and could not therefore be moved without disrupting the surface. The Disk infiltrometer also releases water under tension and does not therefore flood an area, as was the case for the double ring method. Correlation coefficients for the quadratic equations used to calculate hydraulic conductivity were always in excess of 0.99.

Table 4.5. Hydraulic conductivity measured with a disk Infiltrometer in Jan/Feb 2008 on a trafficked and non trafficked fields at Colworth.

Treatment	Hydraulic conductivity, mm h^{-1}	Standard deviation, mm h^{-1}	Standard error, mm h^{-1}
23, RTF no-till	8.06	8.55	2.286
28, CTF no-till	10.39	13.10	2.93

The degrees of re-structuring described in this and the previous section were in line with work by McHugh et al. (2003 & 2009) who found significant improvements in hydraulic conductivity and available water capacity within four years of traffic being removed from a traditionally managed vertosol (vertisol).

4.3.1.3. Subjective assessments of soil structure

Structure was observed on a number of occasions during the period 2004-2010. In 2005 there were noticeable differences in topsoil structure that closely reflected the four different management strategies (Fig. 4.6). The ploughed soil exhibited a generally good structure but this was interspersed with compact clods similar to those found on the trial site prior to the introduction of CTF in September 2004. In contrast, the minimum tillage treatment revealed a very compact layer immediately below the tillage depth (around 70 mm). Where the soil had been under no-till, the very compact layer extended almost to the surface but this layer was very obviously absent where no-till had been accompanied by controlled traffic.

Following harvest of the OSR in 2006, observations were made on the two no-till treatments (Fig. 4.7). Under CTF, surface clods were relatively easy to extract with a fork and could be broken by hand or fell apart as they were extracted. There was some localised compaction but the clods were characterised by many perforations. At 200 mm depth there was more evidence of compaction, but the clods were still breakable by hand and the soil was moist to the touch but not wet. Between 300 and 350 mm depth there were fewer holes, some yellowing of the soil and the clods looked more compact and were difficult to break. Along natural breakage lines the surfaces tended to be smooth, whereas those broken under force were very rough and well structured.

Extreme compaction was evident in the two-year-old permanent wheelways where aggregates broken out by a subsoiling operation revealed shiny surfaces with few holes (Fig. 4.8). Roots had explored these wheelways, but were only evident in natural fissures.

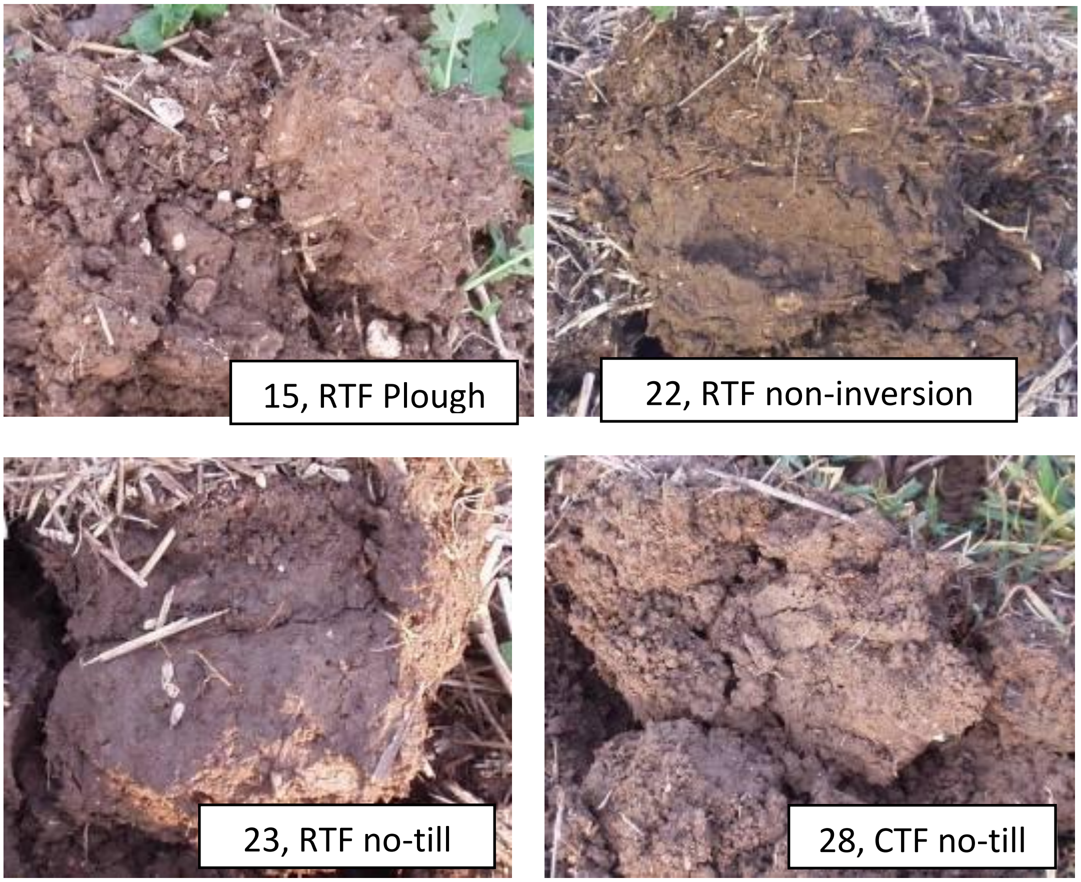


Fig. 4.6. Typical topsoil structure in 2005 following different tillage and traffic.

Fig 4.7. Typical topsoil aggregates taken from the 28, CTF no-till (left) and 23, RTF no-till (right) in August 2006.

Fig.4.8. Large block of soil removed from 2-year old CTF permanent wheelway (left) and a similar block from a wheelway with a natural fracture (right).
In the natural fracture crop roots had spread compared with a forced fracture (on the left side of the same block) where practically none were present.

In 2008, as part of the ongoing demonstration of CTF to a wider audience, a workshop was held at Colworth in April when soil pits were machine dug on the RTF non-inversion and no-till fields as well as the CTF no-till field. A soil structure expert was then employed to assess the soil structure under these three conditions, which reflected 4 years of the different treatments. His observations are summarised below together with a tabulated assessment from each field condition (Tables 4.6 – 4.8, see Table 4.1 for soil particle size analysis which can be taken as typical for all four fields)

The degree of structural degradation below 18 cm depth and in upper subsoil layers was the same in all fields. These layers had moderately strong soil strength (3 cm cube of soil could not be broken between thumb and forefinger) and were structureless and massive consistent with repeated compaction under farm implements/machines. It was considered that even if the episodes of soil compaction are removed the improvement in structural conditions in these soils that readily shrink and swell with changes in moisture content, is likely to take many years. Mechanical intervention (well controlled subsoiling in suitable soil conditions and at suitable depth to ensure shattering) was recommended to restore structure to these layers in a reasonable period of time. The RTF non-inversion field (22) was the only field with a well developed cultivation tilth (from freeze-thaw and/or wetting-drying cycles) in the 0-8 cm depth zone. The CTF field (28), although having moderately firm soil strength resulting from repeated compaction in the past had weakly developed very coarse angular blocky structures in the 0-18 cm layer indicating a degree of restructuring taking place. The field with RTF no-till (23) was considered to be structureless and massive throughout its topsoil and upper subsoil.

In terms of other observations, autumn 2007 was a particularly wet season and the RTF non-inversion treatment was vulnerable to compaction as is plainly visible in Fig. 4.9. This was a typical condition on trafficked fields where non-inversion tillage had been used, both in 2007 and 2008. In June 2009 there continued to be a marked difference in soil

Table 4.6. Details of soil structure in Field 22 (RTF, non-inversion) in April 2008

Depth (cm)	Profile descriptions
0-8	Moist; moderately porous clay loam; strongly developed very fine and fine angular blocky structure; loose soil strength but moderately firm ped strength. Typical wetting-drying and/or freeze-thawing surface tilth of a cultivated Hanslope series
8-24	Very moist; very slightly porous clay loam; semi-deformable; structureless massive but a tendency to part horizontally rather than vertically; very firm soil strength
24-35	Very moist; very slightly porous clay; deformable; structureless massive, locally weakly developed very coarse platy structure; moderately strong soil strength

Table 4.7. Details of soil structure in field 28 (CTF, no-till) in April 2008

Depth (cm)	Profile descriptions
0-18	Moist; slightly porous clay loam; weakly developed very coarse and coarse angular blocky structure; moderately firm soil strength.
18-24	Very moist, very slightly porous clay loam; semi-deformable; structureless massive but a tendency to part horizontally rather than vertically; very firm soil strength
24-35	Very moist, very slightly porous clay; deformable; structureless massive, locally weakly developed very coarse platy structure; moderately strong soil strength

Table 4.8. Details of soil structure in field 23 (RTF, no-till) in April 2008

Depth (cm)	Profile descriptions
0-24	Very moist; very slightly porous clay loam; structureless massive but locally tendency to very coarse platy; moderately strong soil strength.
24-35	Very moist; very slightly porous clay; deformable; structureless massive, locally weakly developed very coarse platy structure; moderately strong soil strength

conditions between the trafficked and non-trafficked treatments (other than on the ploughed ground), as evidenced in Figs 4.10 and 4.11.

Although visual differences were obvious in most cases, the ease of digging provided a much greater indication and contrast. Trafficked no-till soil was generally impossible to dig out from 25 cm depth in one operation, whereas this could always be achieved in controlled traffic fields. Equally, even in high moisture conditions, removing a fork depth of soil from a trafficked non-inversion system was often difficult. The fork could easily be inserted to the cultivation depth of around 50 mm, but below this penetration force increased considerably, as is plainly visible from a number of the figures.

Fig. 4.9. Typical soil condition on a randomly trafficked non-inversion system in autumn 2008 showing a highly compacted zone below the surface tilth

Fig. 4.10. Soil conditions in May 2009 under CTF (left) and RTF (right) no-till

Fig. 4.11. Soil condition in June 2009 under CTF no-till (left) and RTF non-inversion (right)

4.3.1.4. OSR performance

Fig. 4.12 shows one of the OSR roots before and after root trimming.

Fig. 4.12. Before and after trimming the lateral roots away from an OSR root

Figures 4.13 & 4.14 show that on average the plants on the controlled traffic area on 5th April were supporting a larger plant for a given root weight but this must be considered in relation to plant numbers, which were only around 60% of those on the trafficked sites. The lateral and fibrous roots were also a greater proportion of the total root weight. By the 26th April (Figs 4.15 & 4.16) differences in the weight of root supporting the plants had reduced slightly but those on the CTF field were still supporting a slightly larger plant. Equally however, the contrast between the ratio of the weight of root laterals to the tap root had increased in the CTF field, which supports the premise that the larger plants were the result of greater root proliferation in the topsoil. These results were unexpected largely as a result of perception of how roots would respond to different soil conditions. This perception was that a less fangy root would be produced in a soil that had less compaction, but the opposite was the case. In reality, this situation allows the plant to

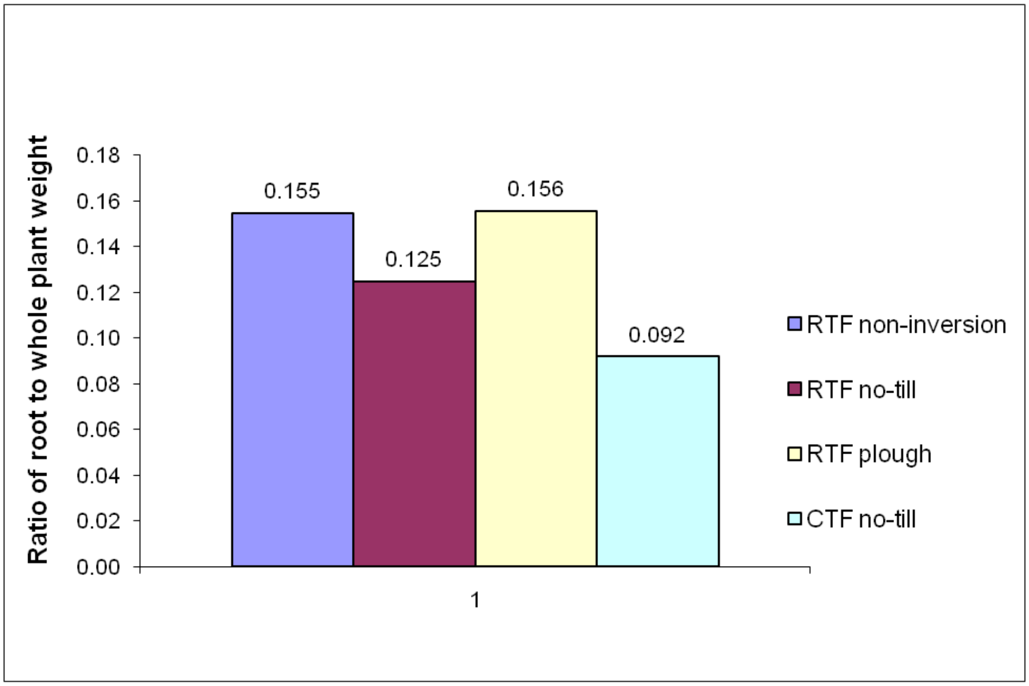


Fig. 4.13. Ratio of root weight to weight of whole OSR plant, 5th April 2006

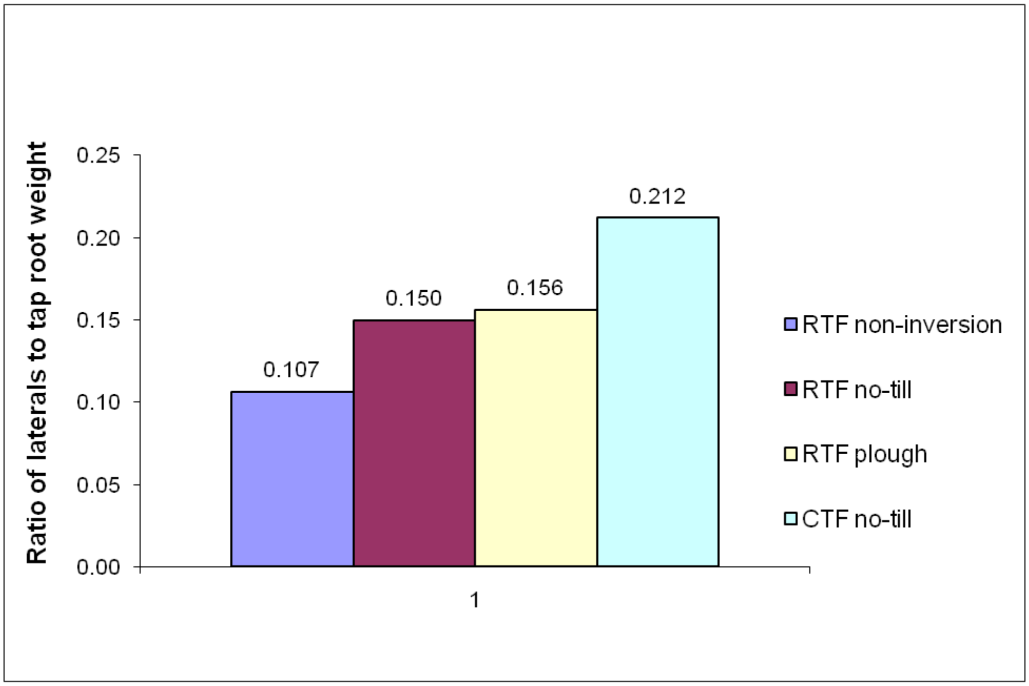


Fig. 4.14. Ratio of root laterals and fibrous roots to total root weight, 5th April 2006

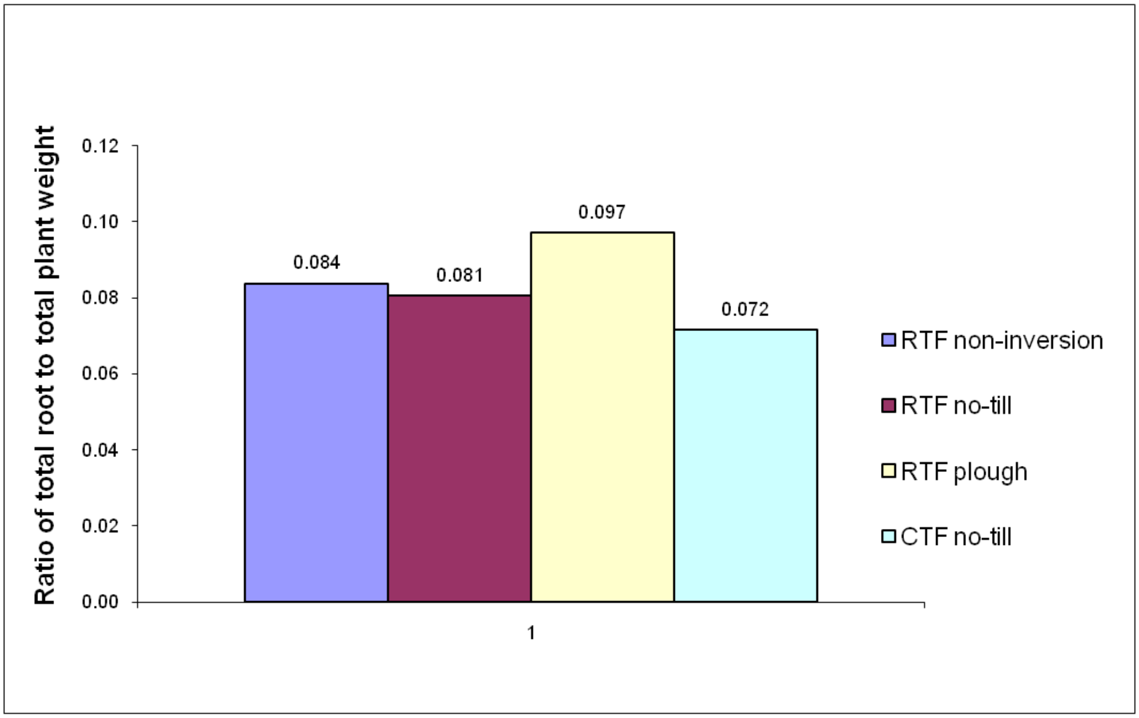


Fig. 4.15. Ratio of root weight to weight of whole OSR plant, 26th April 2006

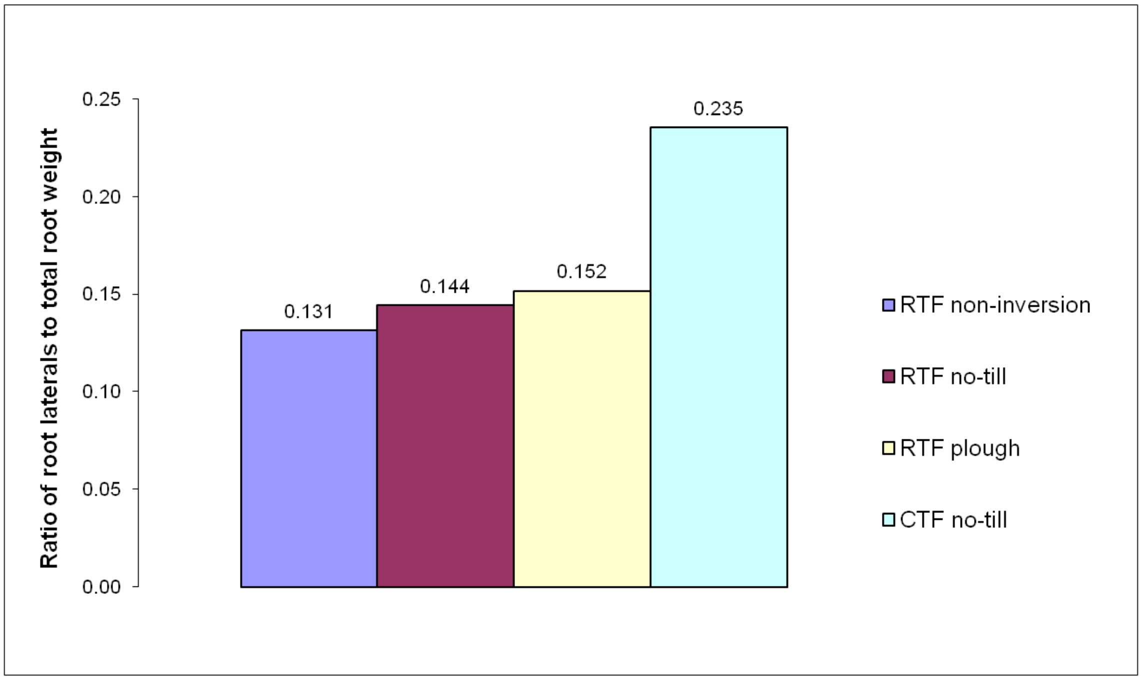


Fig. 4.16. Ratio of root laterals and fibrous roots to total root weight, 26th April 2006

extract more nutrients from the topsoil and in addition to the plant population effect, may have been a reason for the greater crop growth on the controlled traffic field, as illustrated in Fig. 4.17.

It is also in line with the background research, suggesting a more efficient uptake when roots are well branched but rather than an implied species effect, it could be a soil structure related phenomenon. In terms of the effects of plant population on root growth, some indication of the effect is provided by Hutchings and John (2004) in their investigation of the effects on root growth in response to nutrient heterogeneity. This showed that root weight decreased as nutrient supply increased which is a potentially similar condition to one of low plant population. This could be an explanation for the lower root weight recorded on the controlled traffic area (Fig. 4.13).

4.3.1.4.1. OSR yield

Table 4.9 provides data about crop from the different treatments. Although these are comparable they must be treated with caution because they are neither replicated nor without potentially large field factors that will cause differences. There was also the fact that the CTF no-till crop had actually been broadcast rather than drilled because a problem with the drill metering system precluded its use for sowing. The effect that broadcasting had on the yield is difficult to quantify. As will be seen from the table, the crop on the CTF field was robust and had a high yield per plant, but this was not reflected in the field yield, which was about 2% less than the average from the adjacent fields. Considering an average yield reduction within the wheel tracks of 10% and assuming an average predicted 12% yield increase from the bed (literature review), the net field yield increase with CTF would be expected to be around 7%. Whether the field yield would have been greater with the same number of plants is open to conjecture. It is also evident that the nature of the CTF crop led to higher losses through the harvester, compared for example with the trafficked no-till plot. Fig. 4.18 shows field 23 (RTF no-till) and field 28 (CTF no-till) on 21 August. Although both fields had varying amounts of volunteer plants, there appeared to be a far greater number in field 28 (CTF no-till) and this was almost certainly due to a difference in crop characteristic (seed moisture content for example) that affected the harvester separation efficiency or losses at the cutting table. Assessment of seed quality from the CTF treatment compared with conventional practice suggested little difference but did reveal a large contrast in moisture content between the samples.

Fig. 4.17. Growth of OSR on 7 December 2005.
Top left: CTF no-till. Top right: RTF no-till. Bottom left: RTF non-inversion. *Bottom right: RTF plough. Inset: CTF no-till plant compared with crop on the RTF non-inversion field, April 06.*

Table 4.9. Performance of OSR grown on the four fields shown in Fig. 4.1 in the 2005/2006 season at Colworth.

Measurement	CTF no-till	Random traffic treatments		
		No-till	Non-inversion	Plough
Crop yield corrected to 8% moisture, Mg ha^{-1} (all harvested within 2 days of each other in mid August)	4.20	4.20	4.54	4.14
Field area, ha	7.43	10.02	7.18	4.55
Seed rate, kg ha^{-1}	4.61[1]	4.02	5.37	5.36
Plants/m^2 (standard deviation)	41	70	71	90
	(10.9)	(15.8)	(33.8)	(25.8)
Average plant weight on 26 April, g	286	157	168	100
Yield per plant, g	10.3	6.0	6.4	4.6
Moisture content at harvest, % dry basis	11.6	6.8		
Oil content, %	41.4	42.2		

[1] seed broadcast

Fig. 4.18. Volunteer OSR plants 26 days after harvest of the differently managed blocks of land. Left, RTF no-till, right, CTF no-till.

4.3.1.5. Field scale comparisons of CTF and RTF crop yields

The field yields from the Colworth site for the harvest years 2007 to 2010 inclusive are given in Table 4.10.

Table 4.10. Total annual yields from the nine fields in CTF and the seventeen in RTF from 2007 to 2010.

Year	Crop	Yield average, Mg ha^{-1}		Number of fields in sample	
		RTF	CTF	RTF	CTF
2007	W.OSR	3.52	3.59	2	1
	W.Wheat	5.75	5.95	5	3
2008	W.OSR	1.69	2.72	3	1
	S.Barley	6.57	6.23	3	1
	W.Beans	3.55	3.73	4	2
	W.Wheat	9.29	8.13	3	2
2009	S.Barley	4.86	5.61	4	4
	S.Beans	3.17	2.86	3	3
	S.OSR	1.27	1.24	3	1
2010	W.Wheat	5.45	5.58	9	4
	W.Beans	2.93	2.81	4	1
	S.Linseed	1.87	1.48	1	2
	S.Barley	3.66	3.40	3	1
	W.OSR	1.81	1.01	4	1

W = winter: S = spring

These figures would suggest that on a field scale, yield differences between CTF and RTF seem to be small. However, very few yields reflect the yield potential of this soil and climate, suggesting there were other constraints to yield that may not have been soil related. The other point to note is that the CTF yields were achieved with no-till and therefore much lower inputs but with no indication of the yield depression often associated with trafficked no-till (see Literature Review, Chapter 2).

4.3.1.6. Yields from cropped CTF traffic lanes

2008

Table 4.11 shows that the number of ears in the wheel tracks was significantly fewer than on the beds in two out of three cases, while the weight per ear was always significantly less from crop in the tracks. Weights per ear were similar for conventional random traffic and the CTF beds, but the weight per ear in the wheel tracks was always lower than on the beds and compared with RTF, but not significantly so. From these data it is apparent that several things are happening in the wheel tracks. Firstly, there were generally lower tiller numbers, probably brought about by poorer crop establishment (but not measured) and secondly, the ears in the wheel tracks consistently weighed less while ear water content could not be distinguished between treatments. The proportion of grain in one sample from each treatment was calculated by hand threshing, the results of which are given in Table 4.12 and reveal only minor differences but a trend towards a lower proportion in the wheel tracks.

Table 4.11. Crop ear counts and the dry weight of wheat and barley samples taken in August 2008 to determine differences in crop performance and yield.

Fields	Crop	Management	Mean row yield, g	No. of ears	Mean weight, g ear^{-1}	Ear water content, %
37-40	Wheat	CTF bed	378a	140a	2.73a	23.6a
		CTF track	229b**	102a	2.02b*	24.8a
34-38	Wheat	RTF non-inv	292b*	122a	2.42ab	22.2a
42	Wheat	CTF bed	310a	136a	2.28a	20.0
		CTF track	203b**	100b**	2.04b*	22.1
		RTF non-inv	nc	nc	nc	nc
28	Barley	CTF bed	234a	234a	1.08a	19.0
		CTF track	160b**	165b**	0.97b*	19.3
23	Barley	RTF no-till	176b	175b**	1.01ab	16.5[1]

Values with same following letter are not significantly different

* difference significant at $p < 0.05$: ** difference significant at p = < 0.01;

nc = no direct comparison available; [1]sampled 1 hour later on a good drying day

Table 4.12. The proportion of grain in specific whole ear samples determined by hand threshing in 2008

Fields	Management	Proportion of grain	Crop	Ear + grain moisture, %
37-40	CTF bed	0.82	Wheat	23.6
	CTF track	0.81		24.8
34-38	RTF, non-inv	0.82		22.2
42	CTF bed	0.82	Wheat	20.0
	CTF track	0.79		22.1
28	CTF bed	0.89	Barley	19.0
	CTF track	0.87		19.3
23	RTF, no till	0.89		16.5[1]

[1] This field was sampled at least one hour after sampling had been completed in the CTF field and on a good drying day

2009

The results for 2009 are presented in Table 4.13. These tracks receive four vehicle passes each year consisting of harvester, drill plus tractor and roll tractor (the latter two using the same tractor). The modest yield difference between the CTF track and RTF non-inv perhaps reflects the fact that soils recover from compaction relatively slowly, even in the topsoil layers, as indicated from data in Table 4.8 taken from a low traffic intensity no-till system.

The overall effects on crops grown in the different areas for both 2008 and 2009 are shown in Table 4.14. Although ear moisture content was lower from the non-trafficked beds than from the tracks, moisture content in the latter was not significantly different from randomly trafficked soil. This marginal difference is important in demonstrating that slow ripening of grain within the wheel tracks was not an issue. Surprising was the fact that the straw from the RTF treatment was significantly wetter than that from the other areas, but the grain was drier.

Table 4.13. Results of spring barley ear counts from 1 m length of row and the dry weight of straw and ears (corrected to 14% w w^{-1}) taken in August 2009

Field & Management	Mean row yield, g	No. of ears	Weight per ear, g	Ear water content, %	Straw dry weight, g	Straw water content, %
37-40, CTF bed	178a**	167a**	1.07a	13.7a**	60.4a	50.0ab
37-40, CTF track	122b	120b	1.03b*	15.0b	56.8a	49.5a
34-38, RTF non-inv	129b	126b	1.02ab	17.4b	58.7a	41.4b*

Values with same following letter are not significantly different

* difference significant at $p < 0.05$: ** difference significant at $p < 0.01$

Table 4.14. Change in yields (%) on the differently managed areas in 2008 and 2009 for wheat and spring barley.

Change in crop yield	Percentage change		
	Wheat	Spring barley	
	2008	2008	2009
Reduction in cropped tracks compared with CTF beds	39 & 34	35	32
Increase in beds compared with cropped tracks	65	46	46
Increase in CTF beds compared with RTF	30	43	38
Reduction in RTF compared with CTF	23	30	28
Reduction in cropped tracks compared with RTF	21 ns[1]	9 ns[1]	5 ns[1]

[1] ns = not significant at $p = 0.05$

4.3.1.7. Performance of permanent traffic lanes

Observations were conducted over a period of four years on a clay soil and included anecdotal evidence from operators. As anticipated, the permanent traffic lanes needed active management, but this was less than expected. Management consisted of periodic in-filling, with a greater need in the early days of CTF and particularly on the tramlines. The need for early in-filling was dominated by the conditions prior to the introduction of CTF. If ploughing or subsoiling preceded the introduction of CTF or soil conditions were very moist, sinkage of 100 mm on the first pass was not uncommon and needed immediate attention, ideally in harmony with cultural needs. This could be a light tillage operation undertaken from and of course parallel to the traffic lanes. Although most cultivators would have the desired effect as far as the traffic lanes were concerned (provided they did little or no cultivation to the lane itself), the ideal were implements that had lateral soil movement associated with them, discs for example. Firming the lanes by running over them before subsequent heavy rainfall was advisable to avoid water build up beneath loose soil. Experience would suggest avoiding, at all costs, the situation shown in Fig. 4.18. In a moist climate such as the UK, flooding of this wheel track would be inevitable and render it untrafficable. An exception to avoidance of rutting of this nature is in the vegetable industry where keeping on the traffic lanes has been an issue reported from Tasmania (McPhee, personal communication). In this situation, positive action has been taken to deepen the traffic lanes to avoid vehicles slipping off them.

An important aspect of traffic lane management is tyre selection to minimise contact pressures, particularly for those vehicles working in moist conditions. Most operations at Colworth were with tyres at around 1 bar inflation pressure, the exception being the harvester with pressures of around 2 bar. In terms of the intermediates and harvester lanes, these needed little more than the cultivation associated with the no-till drill. Fig. 4.19 shows that even after some years of use, they were often hard to discern on a stubble surface. Of particular interest was the performance of the CTF tramlines compared with conventional practice on the Colworth farm. To this end, a number of fields were walked at the end of November 2010, when CTF had been in place for over four years. The common feature of the CTF tramlines was little or no rutting except in one

Fig. 4.18. Rutted CTF traffic lane in Australia. Such rutting is likely to be a problem in European conditions and should be avoided by careful management

field which had been subsoiled to 300 mm and then cultivated to around 75 mm depth in autumn 2010.All tramlines were firm to walk on and generally dry other than on some headland tracks. In general, there was little contrast between the CTF tracks and those on the conventionally managed fields on the farm, accepting that in November these fields had mostly received only one pass of the spray vehicle. One feature remarked upon by the farm manager was the lesser amount of soil that had picked up on the wheels when traversing the CTF tracks compared with an adjacent field in the same crop sprayed on the same day. However, this latter field had been cultivated compared with the CTF which was in a no-till regime (Fig. 4.20).

Fig. 4.19. Tramline (left) and intermediate traffic lane (right) on a clay soil at Colworth three years after the field had been converted to CTF.

Fig. 4.20. Soil picked up by wheels when running on cultivated soil (left) within a random traffic system compared with spraying on the same day on a CTF no-till field.

Cultivated fields within conventional RTF systems are often problematic in terms of tramlines, especially if they are established after ploughing or subsoiling has been used during crop establishment operations. The problems associated with this were exampled at Colworth one season when beans were being harvested. Rutting of the tramlines was such that the operator was at one moment confronted with the cutting platform digging into the ground and at the next, missing much of the crop by cutting too high. As cutting platforms get wider, undulation of the tramlines becomes a greater issue and this is easily observed during harvesting operations.

Management of the harvester section of the traffic lanes depends upon their extent, the pressure exerted on them and the soil texture. The compaction trial forming part of this thesis provides some research-based evidence of responses, suggesting that loosening these strips could be beneficial on sandy loams, but marginal on clay. Further research on this aspect is being conducted in Switzerland (Anken et al., http://www.agroscope.admin.ch/agrartechnische-systeme/00971/index.html?lang=de accessed 10/1/11) to determine relative yields from areas where they have confined contact pressures to 0.8 bar. Research reported in Chapter 5 suggests that the benefits might be limited.

The conditions for sowing crop in the intermediates and harvester traffic lanes is not unlike direct sowing into extensively trafficked traditional practice. Establishing comparable numbers of plants in these areas may require some adjustment to the drill, a greater coulter depth in these strips for example, or some localised shallow tillage.

4.3.1.7.1. Prediction of wheel track erosion

Table 4.15 provides a summary of the literature in relation to surface infiltration rates referenced earlier. Also included are infiltration data recorded in the fields at Colworth shown in Fig. 4.1. 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 10 mm h^{-1} rainfall intensity (Chambers & Garwood, 2000) would be 600 litres. This equates to 10 litres min^{-1} or 166 ml s^{-1}.

Table 4.15. Infiltration data for the top 50 mm of soil taken from literature and from measurements, the latter with no within-field replication (see Table 4.4)

Soil	Tillage	Infiltration, mm h^{-1}			Paper
		Trafficked	Non-trafficked	Wheel-way	
Silty clay loam[1]	None	0.01	0.36		Ankeny et al., 1990
Silty clay loam[1]	Chisel	0.003	0.63		
Heavy clay[1]	Varied	0.1	6.0		Håkansson, 1985
Silt loam[1]	Plough		870	30	Hamlett et al., 1990
Vertisol/	Varied	3.5	11.5	3.5	Boydell & Boydell, 2003
Red Earth[2]	Varied	1.9[3]	3.5[3]	0.4[3]	
Sandy loam[1]	Varied		15	3	Meek et al., 1992b
Hanslope clay[4]	RTF, plough	5264			Chamen, 2005: raw field
(No within-field	RTF, non-inv	576			data. See section 4.3.1.2
replication of	RTF, no-till	179			
treatments)	CTF , no-till		904		

[1] Soil Survey Staff, 1999; [2] Stephens, 1953; [3] 50–250 mm depth; [4] Hodgson, 1976

This shows that flow rates down permanent wheelways based on directly intercepted rainfall result in relatively modest volumes. Whether this would create sediment or soil loss depends on the velocity of flow and this could be calculated using Manning's formula, namely:

$$V = (1/n)R^{0.67}S^{0.5} \qquad \textit{Equation 4.1}$$

where n is an empirical number related to the surface roughness, R is the area of flow/wetted perimeter and S is the slope.

4.3.2. Regional studies on non-restructuring soils

4.3.2.1. Normanton Lodge Farm

Table 4.16 tabulates results of laboratory measurements, including those from the Keen-Racjowski box. The results show that although this soil is classified as a clay loam, it has a high proportion of silt but the clay present exhibited a limited degree of swelling and shrinking. Table 4.17 shows that the aggregates removed from the farm had a high density but were very unstable as illustrated in Fig. 4.21. Results of the weathering assessment are shown in Fig. 4.22 from which it can be seen that there was little change in the soil, albeit with limited wetting and drying cycles. Fig. 4.23 shows various stages of growth of the wheat sown in the remoulded soil, which at the surface exhibited similar characteristics to field soils.

Table 4.16. Normanton Lodge soil particle size analysis and a number of topsoil physical properties, including volumetric expansion with wetting. (Averages from three samples for each parameter)

Parameter	Topsoil	Subsoil	Topsoil parameter (oven dry sample passing 1 mm sieve)	
% coarse sand	1.77	1.63	Dry bulk density air dry, g/cm^3	1.23
% sand	9.84	9.10	Dry bulk density saturated, g/cm^3	1.17
% fine sand	13.23	12.71	Particle density, g/cm^3	2.41
% total sand	24.84	23.44	Porosity air dry	0.49
% silt	46.76	56.73	Porosity saturated	0.51
% clay	28.40	19.84	Void ratio	0.96
			Gravimetric moisture content air dry, %	1.76
Texture class[1]	Clay loam	Clay loam	Gravimetric moisture content saturated, %	44.26
			Volumetric moisture air dry, %	2.16
			Volumetric moisture saturated, %	51.98
			Volume expansion, %	**7.63**

[1] Soil Survey Staff, 1999

Table 4.17. Properties of the aggregates extracted from Normanton Lodge

Profile position	Moisture content, % w w^{-1}	Wet bulk density, Mg m^{-3}	Dry bulk density, Mg m^{-3}
Topsoil	17.3	1.747	1.444
Subsoil	10.7	1.898	1.694

Fig. 4.21. Condition of large aggregate from Normanton Lodge following 90 minutes immersed in water

Fig. 4.22. Series of photos (left to right) taken on 29th June, 2nd July and 9th July 2006 during which there were four wetting and drying cycles of the soil from Normanton Lodge.

Fig. 4.23. Flower pot filled with air-dried sieved (5 mm) soil from Normanton Lodge and sown with winter wheat on 7/10/06 showing surface conditions before sowing (left) and change in soil conditions with growth stages.

Table 4.18 tabulates results of the consistency tests on the pot soil 10 months after it was remoulded compared with soil in the field. Fig 4.24 shows some examples of the results of "fractionation".

Table 4.18. Summary of VSAs carried out on a field soil at Normanton Lodge and on the remoulded pot soil after 10 months growing winter wheat.

Scores: 2 = Good, 1 = Moderate, 0 = Poor

Aspect	Aspect weighting	Field soil score	Ranking, field	Pot soil score	Ranking, pot
Soil structure & consistency	3	0.1	0.3	0.5	1.5
Soil porosity	3	0.52	1.56	1.5	4.5
Soil mottles	2	1.23	2.46	2	4
Cultivation pan	2	1.05	2.1	n.a.	
Totals, excluding cult. pan		2.90	4.32	4.0	10.0

Fig 4.24. Examples of the results of subjecting aggregates to the soil structure and consistency drop test that forms part of the VSA. Left: field soil, right: pot soil.

These scores clearly show that all aspects of the pot soil were superior in terms of soil quality indicated by the visual soil assessment method, but it was also obvious from both the look and the general characteristics of the pot soil, that a natural structure had not been regained. This is partly illustrated in Fig 4.25 which shows typical aggregates from the field and pot soils. Principally the pot soil lacked the heterogeneity defined by Dexter (1988) as the ideal and confirms the time needed for natural soil structure regeneration.

Fig 4.25. Examples of field aggregates (left) and soil from the test pot (right) taken from Normanton Lodge

4.3.3.2 Extensive field sampling

Results for three of the field soil structures assessments described in section 4.2.2.2 are shown in Table 4.19.

Table 4.19. Summary of VSAs carried out on field soils sampled from trafficked and potentially non-trafficked areas. Rankings are means from 3 replications and have been multiplied by the weighting factors indicated in Table 4.18.

Scores: 2 = Good, 1 = Moderate, 0 = Poor

Aspect	**Ranking** (higher values indicate a better condition)			
	Sandy loam[1]		*Sandy clay loam*[2]	
	Trafficked	Non-trafficked	Trafficked	Non-trafficked
Cultivation pan (x 2)	1.34	2.66	2.00	2.33
Soil porosity (x 3)	0.51	3.51	3.00	3.50
Soil mottles (x 2)	2.34	2.34	2.33	3.67
Total (with weighting applied	8.89	20.53	17.66	22.50

Map references: [1]TL 418123 [2] TL 421124, Ordnance Survey, 1999

All areas considered as non-trafficked resulted in a higher or equal soil quality ranking in each of the three aspects assessed. Conditions in the sand ([3] map reference SP 344943) and sandy loam ([4] map reference SP 352946) fields were such that no aggregates remained intact for the VSA technique to be applied. The sand field (map ref [3]) had just borne a crop of sugar beet and tracking of the field was extensive (Fig 4.25). It was also difficult to find an area that was "non-tracked" and where crop was present, as evidenced from Fig 4.25. The last plough operation with a 6 furrow plough had thrown the soil into the field, leaving around 0.7 m untouched, but the previous ploughing would have placed the in-furrow wheel right at the edge of the crop (see arrow) and this places some constraint on the technique when ploughing is involved.

Figs 4.25. Field conditions following harvest of the sugar beet crop and example of difficulty in finding a non-tracked but cropped area at the edge of the field (right)

In this instance, sampling had to extend into the grass strip at the edge of the field but here, as opposed to the field condition, there was no evidence of a pan at around 32 cm depth. In the field, not only was there extensive evidence of a pan at this depth, but the soil condition was different in two respects. Firstly, the topsoil was in a cloddy rather than a friable state (Fig 4.26). The other difference was that below the pan level the soil was surprisingly dry, and there could be two reasons for this. Firstly, the crop, which had only just been harvested, had obviously been extracting water for quite a long period and secondly and more likely, infiltration into the lower soil layers had almost certainly been impeded by the pan and the topsoil condition.

Fig. 4.26. Soil from the field condition (left) and from the edge of the field

The sandy loam soil[4] had been in spring barley and was now in winter barley. This field had been investigated earlier in the year (July) and had revealed a pan, again at around 32 cm depth, which with water ponded onto it, appeared to be impervious – there was no detectable change in water level in 25 minutes. Below this 15 cm thick pan layer, a similar 25 mm of water added to the surface drained away within 5 minutes. On this later occasion, the pan layer was again found in the body of the field, but wetter conditions meant that it was less obvious. Sampling in "non-trafficked" areas of this field revealed little in the way of a pan and rather better soil structure, although clods were rather easily broken regardless of sampling position (Fig 4.27).

Fig. 4.27. Sandy loam soil showing sampling positions and trafficked (bottom inset) and “non” trafficked soil (top inset)

4.4. CONCLUSIONS

The increased root branching and growth of OSR on controlled compared with randomly trafficked fields was in line with research on root responses (Wolkowski, 1990; Håkansson, 2005; Batey, 2009). Field yield however was little different from the conventionally managed fields alongside suggesting that lower plant population may have been the underlying cause of differences in plant growth.

Hand sampled yields from the trafficked intermediate tracks of the controlled traffic system were not significantly lower than from conventional practice but over two seasons averaged around 10% less. A similar comparison suggested that non-trafficked bed yields averaged 37% more over the same two years. This could be attributed to a greater number of ears as well as a greater ear weight. Differences in the proportion of material other than grain in the ears and straw yield was not differentially affected by traffic management. Grain from the cropped traffic lanes did not exhibit consistent or significantly greater wetness than grain from conventionally managed areas.

Permanent traffic lanes were most effectively managed by the infilling associated with normal cultural operations, such as shallow cultivation or drilling, providing no attempt was made to loosen them. Greater attention to the lanes was needed in the first year of transition and particularly if CTF had been preceded by deep loosening or ploughing. Over a period of four years, the intermediate traffic lanes became largely invisible as a soil feature, but could be discerned within the crop as strips with lesser growth. The permanent tramlines may need a tillage-related infilling every three years or when damage has occurred due to wet conditions. Good quality large diameter radial tyres at low inflation pressures (circa 1.5 bar) are essential for high frequency operations.

On a Hanslope Association clay soil, both soil strength and structure showed distinct signs of improvement within two years of traffic removal to 10 cm depth and within four years to around 18 cm depth. This was reflected in reduced penetrometer resistance, improved infiltration and ease of digging as well as greater friability and visible porosity. Although a trafficked plough treatment had a surface water infiltration around five times greater than no-till CTF, infiltration on the latter was around 400% greater than an equivalent randomly trafficked no-till field alongside.

Objective and subjective assessments of randomly trafficked and potentially non-trafficked cropped areas of a silty clay loam and a number of sandy loam soils suggested that wheel compaction was the dominating influence on the degradation of soil structure. There was no evidence to suggest that these non-restructuring soils developed pans or a tendency to clodiness without the influence of field traffic.

CHAPTER 5

MANAGING COMPACTION IN SHALLOW CULTIVATION SYSTEMS

5.1. INTRODUCTION

Over the past 50 or more years, plant breeding together with improvements in fertilisers and their application, chemical control of weeds, pests and diseases, a better knowledge of the required soil environment and new machines for crop production, have led to significant increases in the yield of many crops (Aizen et al., 2008). The need in the future will be to improve production efficiency to ensure that the required quantity and quality of crop is produced with the minimum of increasingly scarce and expensive resources (Chamen, 1997).

Although mechanisation has provided the means of establishing crops at the optimum time, the sometimes unwanted and harmful effects of wheel compaction are still largely uncontrolled in the UK and limit further increases in yields and reductions in energy requirements. These problems have recently been exacerbated, particularly where cereals are grown, by the widespread use of shallow cultivation or direct drilling. These systems have been found to reduce energy inputs and farm costs (Saunders, 2002; Sijtsma et al., 1998) but they also have negative impacts in the form of soil compaction in the topsoil layers. In the case of direct drilling, compaction may be such that yields are negatively affected in the first few years of adoption (Ball et al., 1994; Carter et al., 1988), but recover in the longer term (Cannell et al., 1994). Deep loosening (subsoiling) may be employed to counter these problems, but this is an expensive process and the subsequent uncontrolled use of vehicles on the land can often lead to the return of severe compaction within one season (Soane et al., 1987). Marks and Soane (1987) also found little evidence of a yield benefit from subsoiling and sometimes the reverse.

Soil compaction is a complex subject. It is defined as; "the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density" (Wilhelm et al., 2004). From a soil management perspective compaction problems can be divided into topsoil and subsoil. While topsoil compaction is more easily ameliorated, subsoil compaction may be permanent and uneconomic to repair (Alakukku et al., 2003). This project looks at how soil compaction in both the topsoil and subsoil might be minimised or avoided when using shallow cultivation systems. To do this, there is a need to identify the main causes of compaction, how it can be remedied or avoided and which methods could be used to reduce or minimise its impact.

5.1.1. Topsoil compaction

The topsoil is generally recognised as the organic-rich layer within which most nutrients are held and where most cultivations take place, but its depth varies greatly from farm to farm and region to region. There are many factors that can lead to topsoil compaction and these vary from one field to another, therefore soil managers, primarily farmers, need to be aware of potential problems that may arise. The most common cause of topsoil compaction is the surface pressure imposed by tyres or tracks, particularly when there is some slip between these elements and the soil (Gonzalez Maziero et al., 1997). A further cause is tillage operations (DeJong-Hughes et al., 2001) either directly under implements such as discs or backward raked tines, or indirectly through aggregate size reduction and sorting.

The individual soil type can be an issue because the inherent soil compactability is affected by texture or the particle size distribution (Jones et al., 2003). A good example of this is when a driveway is gravelled, the contractor will choose a well graded aggregate, which has a range of sizes so that they will fit together to give a firm base. The same can be said for soils, the less uniform the particle size distribution, the more likely that the particles will compact together such as in sandy clay loams which have a natural predilection to form plough pans. Natural compaction also occurs as a result of rainfall impact and in some cases through chemical cementation but more commonly as a result of glaciation, particularly in subsoil layers.

The hidden nature of soil structural degradation leads to specific problems such as poor crop growth or water infiltration that may be blamed on other causes. In addition, soil structural degradation (SSD) is often blamed for poor crop performance when it is not actually present. Farmers rarely link their land management practises to the causes of SSD and remain unaware that many deep ripping exercises may worsen SSD (McGarry and Sharp, 2001).

Topsoil compaction is generally considered to be removed by tillage operations. The main areas of compaction are found in the 10-30 cm range, at shallower depths than most subsoiling operations. The degree of topsoil compaction is largely determined by ground contact pressure (Söhne, 1958). Reducing contact pressure by having a larger contact area can be achieved by using wide section tyres, dual wheels at low inflation pressure, low ground pressure tyres or tracks. Interestingly, a slight degree of topsoil compaction may prove beneficial for some soil types, (Håkansson, 2005; Bouwman and Arts, 2000), indicating that there is an optimum level of compaction for crop growth (Raghavan et al., 1979) including some firming of the seedbed to improve seed to soil contact.

5.1.2. Subsoil compaction

The subsoil is typically the soil between the topsoil and bedrock or a substantially impervious layer. Mostly the transition between topsoil and subsoil is denoted by a change in texture or colour of the soil, the latter often associated with reduced organic matter and leached minerals from above. Akker and Canarache (2000) also identify the plough pan as being at the upper part of the subsoil. It is further defined by Alakukku et al. (2003) as having two distinct layers, the pan layer and the unloosened layer, the latter only being disturbed by drainage operations, including mole ploughing. Subsoil compaction depends on both ground contact pressure and load in the depth range 0.1 – 1 m but thereafter, by load alone (Håkansson, 1994, Olsen, 1994). A good “rule of thumb” for tyres to explain the interaction between pressure and load is that the pressure at the surface reduces to half its value at a depth equivalent to the width of the tyre. This is in line with research by Söhne (1958) and illustrates the false assumption that increasing the width of tyre to accommodate more load at the same pressure will have no detrimental effect. Equally, high pressures exerted near the subsoil, such as in-furrow ploughing, have historically increased the pre-consolidation stress of subsoils and their resistance to further compaction (Jones et al., 2003).

5.1.3. Methods for reducing and alleviating soil compaction

Blackwell et al. (1978) found that dual, wide section tyres at low inflation pressure for agricultural operations on very loose soils resulted in shallower ruts, lower mean contact pressures and therefore a lower mean bulk density (BD) and probably lower soil strength when compared with the effect of conventional sized tyres carrying the same load. The dual, wide section tyres, compacted a much greater volume of soil, but the effects of compaction were lower and were seen to increase yields. Chamen et al. (1992a) had similar results (Fig. 1.1) but there was evidence of a rise in shallow cultivation energy under the low ground pressure system, largely it was thought because of the greater area compacted during each pass (Chamen et al., 1990).

Henshall et al, (1989) found that the wide section tyre, particularly when laden, appeared to cause slightly less compaction in the topsoil than the conventional tyre, and would probably be able to carry greater loads without causing further compaction.

Low pressure tyres undoubtedly reduce rut depth and soil damage, particularly in the topsoil. Unfortunately, this can only occur at the cost of using wider tyres, which are generally more expensive and increase the area wheeled. Tracked vehicles have an advantage in that they lay down area in length rather than width and over a greater area. Their disadvantage is that the load is not distributed evenly with peaks occurring under the drive sprockets and idlers (Ansorge & Godwin, 2007). Additionally, their performance relies on even contact with the ground, which with single tracks, can be compromised when transmitting draught loads.

In terms of subsoil compaction, two key points should be noted. First, stress at the surface under a wheel or track always reduces with depth (Alakukku et al., 2003) and secondly, the pre-consolidation stress at perhaps 0.4 m depth might be higher than that imposed by modest pressures exerted at the surface (Ansorge & Godwin, 2007). Reducing pressures at the surface was one of the recommendations given by Chamen et al. (2003) to reduce or avoid subsoil compaction. Also recommended was keeping the load applied as close to the surface of the soil as possible, adapting cropping to avoid high loading in moist conditions, improving topsoil structure to create a supporting architecture and adopting controlled traffic farming.

Where there is subsoil compaction the normal means of repair is deep soil loosening with tines. This is a labour-intensive high energy operation and should be undertaken within strict guidelines of optimum soil moisture content, tine design and spacing and depth of operation (Spoor & Godwin, 1978; Godwin et al., 1984). Critical to the process is achieving loosening rather than localised compaction around the tines, which occurs if they are working too deep, the soil is too moist or they are too widely spaced. Increased spacing between tines can be achieved by adding upward angled wings to the sides of the main share, so creating a greater degree of disruption. There is a body of thought now however, that only fissuring should be achieved rather than complete disruption to working depth (Spoor et al., 2003) and this requires even greater attention to detail to achieve an effective outcome.

5.1.4. Project aim and objectives

Many growers are trying to reduce their crop establishment costs by reducing tillage inputs, accepting some compromise in delivering the traditional objectives of cultivations, including:

- weed control, either through burial and/or disruption of rooting;
- burial of weeds and residues to counter disease transmission and to facilitate sowing;
- alleviation of soil compaction;
- preparation of a seedbed.

Of particular concern with this compromise is the reduction in alleviation of compaction, which tends to be concentrated in the topsoil layers, due to shallower depths of tillage. One approach to this problem is to reduce contact pressures, either by operating with tracks or by introducing larger or more tyres at low inflation pressure, which can have a dramatic benefit, as indicated in Fig. 5.1.

A further way of addressing the compaction issue is to confine field traffic to the least possible area of permanent traffic lanes, widely known as controlled traffic farming (CTF). Achieving this with a diverse range of machinery is often difficult, particularly when it comes to matching the track and cutting width of grain harvesters. It was therefore of interest to:

1. Consider if equipping harvesters or tractors with tracks rather than wheels reduces the impact of these vehicles on the cropping system.
2. Determine the damaging contribution of different vehicles within a combinable crops regime and the harvester in particular.
3. Assess whether targeted loosening of the soil followed by controlled traffic provides a more effective solution than a complete system of CTF involving the harvester.
4. Use the results to consider if variants of a complete CTF system have the potential to deliver the benefits.

Fig. 5.1. Tracks made by a combine harvester with conventional tyres (left) compared with the same harvester used on the same day with dual wheels front and rear at lowered inflation pressures (right) (after Chamen, 1997).

It is also the case that within any farming system, fields are trafficked differentially, with some areas receiving no traffic, others a single pass with a heavy vehicle, others with a light machine and still others with multiple passes and different combinations of passes. Some of the treatments were therefore designed to assess these situations by separating out a number of different combinations of trafficking so that the results could be used to model a range of different tracking scenarios.

5.2. TREATMENTS AND SITES

5.2.1. Treatments

In all cases and at all sites, treatments were applied track by track or wheel by wheel across the whole plot area and by each of the axles on the machine or machines, as shown in Fig. 5.2. Some overlap between passes was inevitable but the aim was to achieve uniform compaction across the whole of the plot width. All cultural operations (tillage, drilling etc.) were carried out from permanent traffic lanes, thus avoiding any non-treatment compaction. Tillage was with machines incorporating adjustable depth tines (7.5 cm and 22.5 cm nominal in year one and 10 cm in year three) and following discs. Drilling was with a disc drill in year one and tine drills in year three.

Fig. 5.2. Example of the manner of application of the compaction treatments (Chicksands site).

As a result of feedback from the first year of these experiments, it was logical to change a number of the treatments during the course of the project as well as the sites used for the trials. Initially five compaction treatments involving tyres and tracks and two depths of tillage (7.5 cm and 22.5 cm) were applied at one site (Morley) in year one growing winter wheat (Tables 5.1 & 5.2).

Table 5.1. Compaction treatments applied in year one (2007) of the trial at Morley accompanied by tillage at an average of 7.5 cm and 22.5 cm depth.

Treatment description	Treatment name	Tracked area, %			
		Harvester	Tractor & trailer	Cultivation tractor	Drill tractor
1. CTF	CTF	0	0	0	0
2. Wheeled traffic	Wheeled	100	100	100	100
3. Tracked traffic	Tracked	100	100	100	0
4. Tracked harvest then CTF	TComb	100[1]	100[1]	0	0
5. Wheeled harvest then CTF	WComb	100	100[2]	0	0

[1] with Steiger 500. [2] with John Deere 8220

Table 5.2. Machinery used for the tracking operations at Morley listed in Table 2.1.

Treatment	Harvester	Max. wheel or track load, Mg	Grain removal tractor	Cultivation tractor	Drill tractor
2. Wheeled traffic	Claas 460	4.0	JD 8220[2]	JD 8220[2]	JD 6920[1]
3. Tracked traffic	Steiger 500	6.1	JD 8220[2]	JD 8220[2]	JD 6920[1]
4. Tracked harvest + CTF	Steiger 500	6.1			
5. Wheeled harvest + CTF	Claas 460	4.0			

[1] 6920 rear wheel weight, 4.0 Mg [2] 8220 rear wheel weight, 4.5 Mg

Spring barley was then established on this site without further compaction or traffic on the plot area in year two. At Morley the compaction treatments were applied after each operation other than drilling (Table 5.1). With treatments 4 and 5 only the harvester and grain removal tractor were applied (Table 5.1), which in the case of the tracked treatment were both with a Steiger 500 rubber tracked tractor (a rubber tracked harvester could be not be acquired). In year three, a wider range of compaction treatments was applied at two sites (Colworth & Chicksands, Tables 5.3 – 5.7) with the aim of creating sufficient data for modelling the effects of different wheel loads and number of passes.

Table 5.3. Compaction treatments applied at Chicksands in year three (2009) where seedbed cultivation was confined to around 10 cm depth

Treatment and description	Tracked area, %			
	Harvester	Tractor & trailer	Cultivation tractor	Drill tractor
1. CTF, no treatment traffic	0	0	0	0
2. Wheeled cult tractor (WCT)	0	0	100	0
3. Wheeled cult & drill tractor (WCT+WDT)	0	0	100	100
4. Tracked cultivation tractor (TCT)	0	0	100	0
7. Tracked combine + subsoil (TComb+sub)	100	0	0	0
8. Wheeled combine + subsoil (WComb+sub)	100	0	0	0
9. Wheeled tractor & trailer + subsoil (WT&T+sub)	0	100	0	0
10. Tracked cultivation tractor + wheeled drill tractor (TCT+WDT)	0	0	100	100
11. Wheeled drill tractor (WDT)	0	0	0	100

Treatments 2, 3, 4, 10 & 11 were applied before cultivation but after subsoiling
Treatments 7, 8 & 9 were applied on site as found, followed by subsoiling
Drill tractor was applied after subsoiling and cultivation but before drilling
All plots were drilled on 4 October 2009

Table 5.4. Compaction machinery and soil moisture content at time of tracking at Chicksands (2009)

Treatment	Machine				Loading		Soil MC at 25 cm, % w/w
	Harvester	Tractor & trailer	Cultivation tractor	Drill tractor	Max. wheel or track load, Mg	Inflation pressure, bar	
2. WCT			Fendt 936		5	1	15.1
3. WCT+WDT			Fendt 936	JD 6930	5/3.5	1	15.1/13.0
4. TCT			Cat Challenger	JD 6930	7	0.4[1]	15.1/13.0
7. TComb+sub	Claas 600TT				9.5	0.7[1]/2.2	16.1
8. WComb+sub	JD s690i				7.5	1.4	16.1
9. WT&T		JD 6930 + Warwick			3.5/3.75	1	16.1
10.TCT+ WDT			Cat Challenger	JD 6930	7/3.5	0.4[1]/0.9	15.1/13.0
11. WDT				JD 6930	3.5	0.9	13.0

[1] Approximate mean contact pressure under track

Table 5.5. Dates of application of the different compaction treatments at Colworth and Chicksands

Treatment	Machine	Date of treatment	
		Colworth	Chicksands
7. TComb+sub	Tracked combine	2/9/09[1]	5/9/09
8. WComb+ sub	Wheeled combine	1/9/09	28/8/09
4,10. TCT	Tracked cultivation tractor	2/9/09	19/9/09
2,3,10,12. WCT	Wheeled cultivation tractor	2/9/09	16/9/09
3,10,11. WDT	Wheeled drill tractor	7/9/09	22/9/09
9. WT&T	Wheeled tractor and trailer	2/9/09	28/8/09

[1] Simulated with a Claas Challenger tractor

To investigate the effects of deep loosening, a wheeled and tracked harvester and a loaded tractor and trailer were run over the plots at Chicksands in the “as found” field condition, after which the whole site was deep loosened to around 30 cm depth and the plots re-established in exactly the same place (Treatments 7, 8 & 9). After deep loosening, compaction from the tracked and wheeled cultivation tractors was applied and the site was then cultivated with a Väderstad Carrier to around 10 cm depth using the permanent traffic lanes of a controlled traffic system operating at right angles to the length of the plots. Finally, compaction was applied by the drill tractor prior to drilling which was again carried out from the controlled traffic lanes, as illustrated in Fig. 5.3.

At Colworth, a tracked harvester was also unavailable and was replaced by a large tracked tractor (Table 5.7). In addition to the specified treatments, it was possible at Colworth to make other comparisons that included (i) long term CTF no-till, (ii) random traffic no-till (RTF no-till) and (iii) random traffic non-inversion tillage (RTF non-inv). These systems had been studied since 2005 in the same field as the trial (i) and adjacent fields, the latter having always been in the same crop at the same time as the trial field.

Table 5.6. Compaction treatments applied at Colworth in year 3 (2009)

Treatment and description	Tracked area, %			
	Harvester	Tractor & trailer	Cultivation tractor	Drill tractor
1. CTF	0	0	0	0
2. Wheeled combine + cult tractor (WComb+WCT)	100	0	100	0
3. Wheeled combine + cult tractor + drill tractor (WComb+WCT+WDT)	100	0	100	100
4. Tracked tractor + tracked tractor (TCT+TCT)	100	0	100	0
5. Tracked tractor (TCT)	100	0	0	0
6. Wheeled combine (WComb)	100	0	0	0
7. Tracked tractor + subsoil (TCT+sub)	100	0	0	0
8. Wheeled combine + subsoil (WComb+sub)	100	0	0	0
9. Wheeled tractor & trailer (WT&T)	0	100	0	0
10. Wheeled cultivation tractor (WCT)	0	0	100	0
11. Wheeled drill tractor (WDT)	0	0	0	100
12. Wheeled cult + drill tractor (WCT+WDT)	0	0	100	100

Combines, cultivation tractors and tractor and trailer were applied before cultivation
The tracked combine was simulated by a Claas Challenger tractor, track load 7 Mg
Drill tractor was applied after primary cultivation but before power harrowing and drilling
All plots were drilled on 11 September 2009

Table 5.7. Compaction machinery at Colworth. (Treatment 1 (CTF) had no compaction applied)

Treatment^1	Machine				Loading	
	Harvester	Tractor & trailer	Cultivation tractor	Drill tractor	Max. wheel or track load, Mg	Inflation pressure, bar
2. WComb + WCT	JD c670i		JD 7930		7.3/2	2.2/1
3. WComb + WCT+WDT	JD c670i		JD 7930	MF 6290	7.3/2/1.5	2.2/1/1.3
4. TCT+TCT	Claas Challenger		Claas Challenger		7	0.4^2
5. TCT	Claas Challenger				7	0.4^2
6. WComb	JD c670i				7.3	2.2
7.TCT+sub	Claas Challenger				7	0.4^2
8.WComb+sub	JD c670i				7.3	2.2
9. WT&T		Case 956XL + Griffiths			3.9/1.0	2.5
10. WCT			JD 7930		2.5	1
11. WDT				MF 6290	1.5	1.3
12. WCT + WDT			JD 7930	MF 6290	2/1.5	1/1.3

[1] The average soil moisture content at 25 cm depth only ranged from 27.4 to 27.5 % w/w during treatment applications

[2] Contact pressure

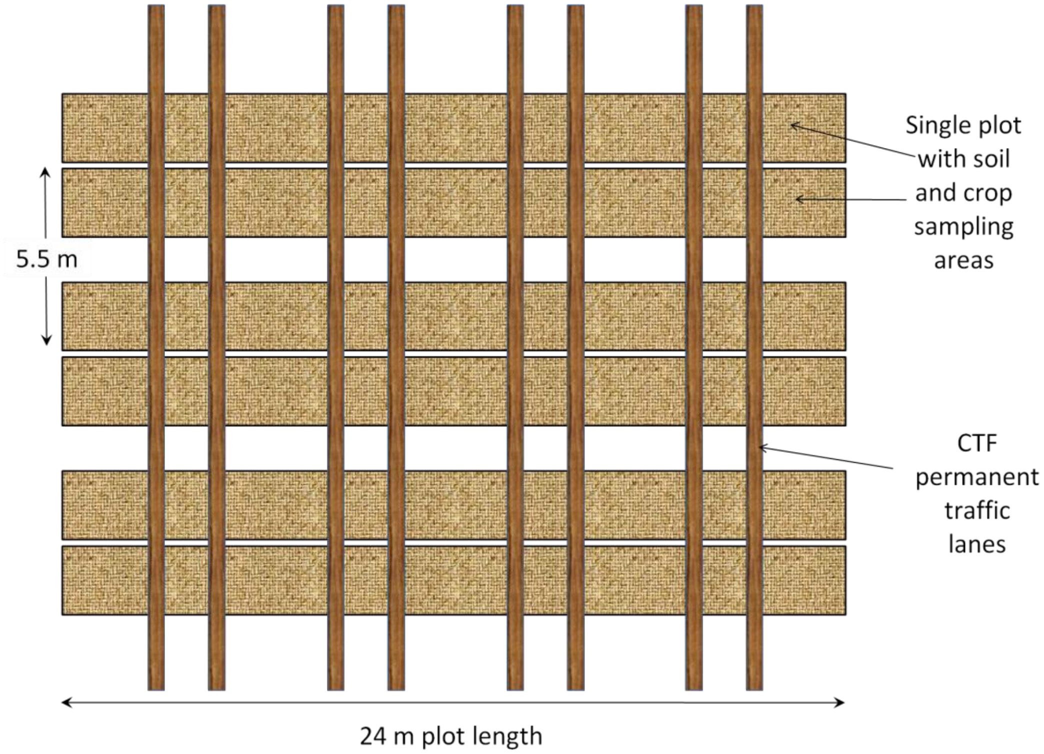


Fig. 5.3. Plot layout at Chicksands illustrating the fact that the treatment areas consisted of a number of rectangles along the plot length.

5.2.2. Sites

The sites were on three different Soil Associations (Hodge et al., 1984), namely:

- Morley was on a typical stagnogley of the Beccles 1 Association;
- Chicksands was on a typical brown earth of the Bearsted 1 Association
- Colworth was on a typical calcareous pelosol of the Hanslope Association.

Components of the soils are listed in Table 5.8. At Morley, the whole site was deep loosened immediately prior to the treatments (August 2007) to a depth of 30 cm. At Colworth, the treatments were imposed on a site which had been in controlled traffic since 2004 (5 years) prior to which “on land” ploughing with a tracked tractor had been practised for 8 years. At Chicksands, as mentioned earlier, the treatments were constrained by the fact that it had not been possible to deep loosen the site a reasonable time in advance. It was also not ideal in that it had been in winter wheat for the past two years but the risk of Take-all was minimised by drilling relatively late and applying a seed treatment in the form of *Latitude*. As the site needed repair deep loosening at 35 cm depth was undertaken across the whole site after treatments 7, 8 and 9 had been applied. Plot widths varied with the sites, but the lengths were all of the order of 24 m and were replicated three times in randomised block designs. At Morley, plots were nominally 6 m wide but the treatment area, as at the other sites, was confined to the gap between the wheel tracks of the permanent traffic lanes. At Morley and Chicksands these were centred at 1.83 m and at Colworth, at 2.2 m, leaving a gap of around 1.1 m and 1.4 m respectively, as exampled in Fig. 5.3. At Chicksands, allowance for commercial practice meant that the length of the plots was divided into rectangular blocks created by cultivator and drill traffic passing at right angles to the plot length. Precise location of these passes was assured to within ± 3 cm as the equipment was being auto-steered with an RTK correction signal. All measurements, including hand sampling for yield, were made within areas unaffected by these operations at right angles.

Table 5.8. Soil particle size analysis, organic carbon and pH of the soils used for the treatments.

Soil property	Units	Depths, mm				
		Topsoil	0 – 100	250-300	0 - 100	250 - 300
		Morley	Chicksands		Colworth	
Size, 0.063 – 2 mm, sand	%	64.8	60.72	59.61	20.05	20.12
Size, 0.002 – 0.063 mm, silt	%	12.2	25.34	26.10	33.34	33.03
Size, <0.002 mm, clay	%	23.0	13.95	14.30	46.62	46.86
pH			6.64	6.91	7.52	8.38
Organic carbon	%		1.80	1.59	2.68	1.00
Soil texture		Sandy clay loam	Sandy loam	Sandy loam	Clay	Clay

Table 5.9 is a record of the rainfall at the sites over the periods of the experiments taken from local weather stations.

Table 5.9. Rainfall at the three sites during the period of the experiments

Month or period	Morley		Chicksands		Colworth	
	2008	2009	2009	2010	2009	2010
Jan-Mar	204	143.6	127.9	139.0	118.3	124.5
April	40.8	19.6	25.4	21.3	24.9	10.9
May	80.0	49.8	21.4	34.3	17.5	40.4
June	52.8	82.8	27.9	34.3	85.9	20.1
July	43.4	109.8	107.4	20.5	81.8	26.2
August	101.8	17.6	66.3	113.7	54.6	117.3
September	51.0	13.2	12.7	46.4	14.2	46.7
Oct-Dec	194.2	229.4	63.5	-	174.1	

5.3. MEASUREMENTS

5.3.1. Soil

Cone penetration resistance (PR) was measured in increments to around 50 cm depth with varying degrees of replication at each depth using a hand-held recording Eijkelkamp Penetrologger with a 30 degree cone of base area 1.3 cm^2. An exception to the manual measurements was in August 2010 at Colworth when a similarly designed cone was hydraulically inserted to around 60 cm depth at ten positions on each plot. On each occasion of PR measurement, simultaneous gravimetric moisture samples were taken over a range of depths in the profile. It was also of interest to assess the compaction effect of the rubber track under the idlers (road wheels) compared with that section of track which lay outside them. Persistence of the effect of deep soil loosening was also tested at Colworth in August 2010 on a field scale using PR, as suggested by Carter (1988). In 2006, two adjacent fields of the same soil texture as the test field were converted to a CTF system. These were and remained at the same point in the cropping cycle and the opportunity was taken in 2006 to deep soil loosen one of these to around 35 cm depth. In August 2010, twenty five separate PR measurements were taken across the contrasting 8 ha fields at random.

Within the replicated trial, volumetric water content ($v\ v^{-1}$) was measured using a DeltaT ThetaProbe (Type ML2x) simultaneously with gravimetric water content (Gw) as part of separate exercises to determine dry BD and water filled pore space (WFPS) by calculation. Measurements were taken on a number of occasions with different replications at a number of depths.

Steady state infiltration tests were conducted at Colworth using a double ring infiltrometer with an outer ring diameter of 35 cm and an inner ring of 17.5 cm. The procedure involved sinking inner and outer rings to around 4 cm depth into random positions on each of the treatment areas. Initially single measurements were taken on each of the plots on every block (36 in total) plus no-till areas of Treatment 1 (CTF) and three replications from an adjacent no-till field managed with random traffic. Water was flooded into the outer ring initially from a hose pipe connected to a water bowser on the headland. As the water level started to rise in the outer ring, water was introduced to the inner ring by pouring it over a sponge to prevent disturbance of the surface soil. Levels in the inner and outer rings were then raised equally until the tops of the rings were reached at which point the inflow was curtailed and the fall in water level was timed between 1 cm marks until the level reached the soil surface or the fall was continuing at a reasonably constant rate. Further replicated measurements were then conducted on selected treatments.

At Chicksands there was no appropriate tanker available for these unconstrained tests so a Decagon Mini Disc Infiltrometer (http://www.ictinternational.com.au/minidisk.htm) was used as an alternative. Measurements were taken at the bottom of 7.5 cm diameter, 12 cm deep holes on a bed of silica sand. The depth of the holes, created by a hand-held auger, coincided with the greatest contrast in PR measured just prior to the infiltration tests.

Statistical analyses

Results were mostly analysed using Genstat (Wedderburn & Wedderburn, 1972; Payne, 2009) to create tables of analysis of variance. Where data included depth as a parameter, all depths were analysed individually but only where these indicated a depth interaction were these results identified.

5.3.2. Crop

Established plant numbers were determined by replicated measurements on each plot covering an area of 0.125 m^2 at Morley, 0.25 m^2 at Colworth and 0.14 m^2 at Chicksands. Crop tillers were measured in a similar manner at Chicksands but were counted as part of the manually sampled yield measurements at Colworth. At Morley, yields were determined with a plot combine, which harvested the entire plot while at Chicksands and Colworth, yields were determined by hand sampling. At Chicksands, this consisted of collecting crop from single areas of 0.75 m x 14 crop rows (spacing 140 mm) representing 1.47 m^2 on each plot. At Colworth, five 0.5 m lengths of two crop rows (at 25 cm spacing) representing a total area of 1.25 m^2 were sampled and bulked for each plot. Following hand separation of the ears from their straws the grain was threshed with a Wintersteiger LD180 laboratory thresher (www.wintersteiger.com). Separated grain was then weighed and its moisture assessed with a Unitron Unimeter or by oven drying.

5.4. RESULTS

5.4.1. Morley

5.4.1.1. Soil penetration resistance (PR)

Results from the single set of PR measurements at Morley taken on 18 November 2008 after all the treatments had been applied, are shown in Fig. 5.4. From these it can be seen that the pressures were divided into two distinct groups but not on a tillage depth basis which had no significant effect. Those with the least pressure were either non-trafficked or trafficked only by the harvest machinery. Intermediate between this least pressure group and those with higher pressures was 7.5 cm deep tillage and single passes of the wheeled harvest machinery followed by CTF. Resistance under the wheeled harvester was greater at the 7.5 cm depth of cultivation than the tracked vehicle, but could not be differentiated at 22.5 cm depth. The greatest contrasts in all the results were in the depth range 12 to 25 cm depth. The mean resistances are tabulated in Table 5.10.

Table 5.10. PR results (MPa) from Morley measured on 18 November 2008. Resistance values with different letters are significantly different at $p < 0.01$. LSD = 0.102

Treatment	1	2	3	4	5	6	7	8	9	10
PR, MPa	1.758 a	2.213 b	2.255 b	1.623 c	1.911 b	1.796 a	2.279 b	2.158 b	1.670 d	1.763 ad
Change	100	126%				100	127%			

Key to treatments: 1/6, CTF/75&225; 2/7, Wheeled/75&225; 3/8, Tracked/75&225;
4/9, TComb/75&225+CTF; 5/10, WComb/75&225+CTF

5.4.1.2. Crop at Morley

Tiller numbers at the end of the first crop year (2008) were significantly greater on treatments 1 (CTF) and 4 (TCT+CTF) at both depths of cultivation for all treatments other than the wheeled combine followed by zero traffic (treatment 5) with 20 cm deep cultivation (Fig. 5.5).

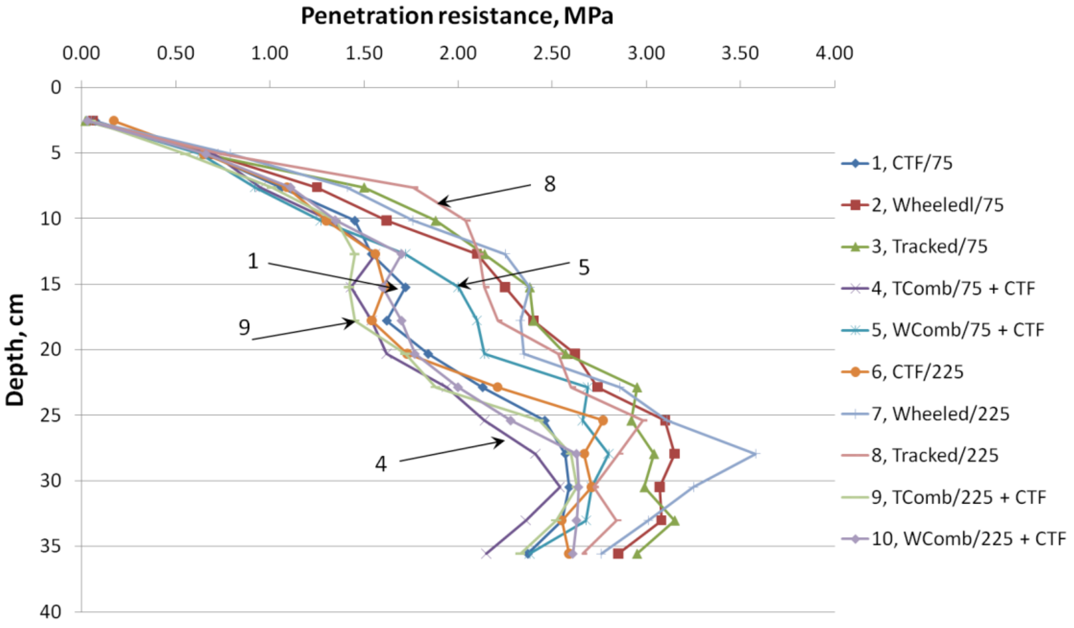


Fig. 5.4. Penetration resistance at Morley on 18 Nov. 2008. Treatment LSD = 0.102 MPa.

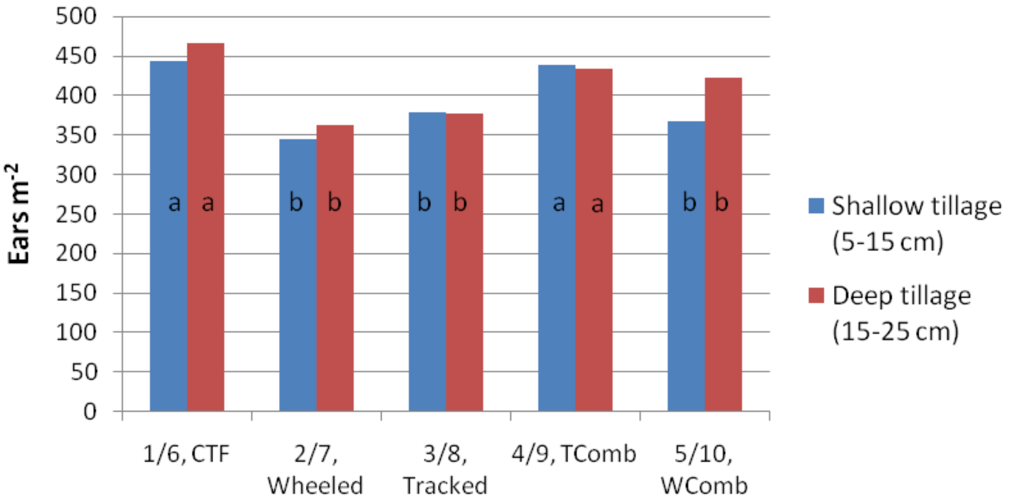


Fig. 5.5. Number of winter wheat ears at Morley prior to harvest in 2008. Columns with dissimilar letters are different at $p < 0.05$.

These differences were reflected in the crop yields shown in Fig. 5.6 with treatment 1 (CTF) returning a significantly greater yield than all treatments other than treatment 4 (Tracked + CTF), which in itself was close to being greater than treatment 3

(Tracked/shallow tillage) (LSD = 1.04 Mg ha^{-1}). Compared with wheeled traffic (Treatment 2), the CTF yields were around 16% higher and the tracked plus CTF around 8% higher. Tillage depth had no significant effect on the yields.

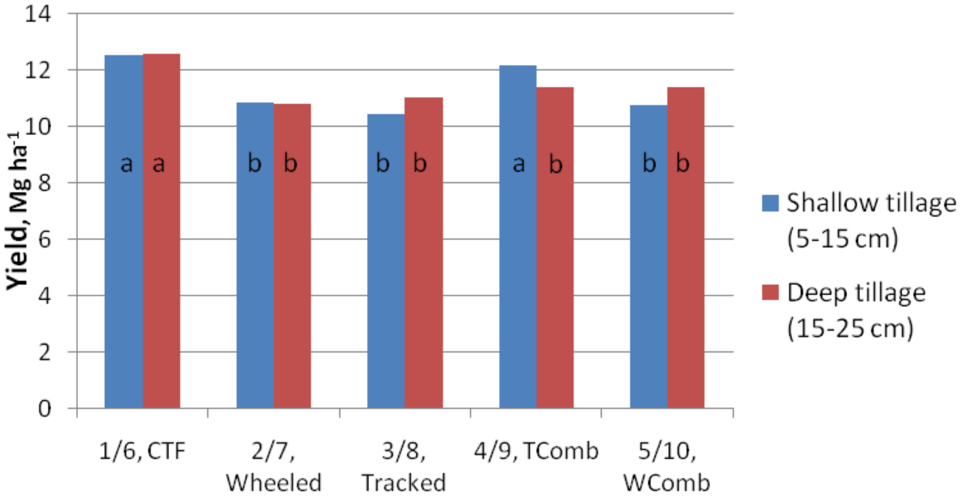


Fig. 5.6. Yield of winter wheat at Morley in 2008. LSD = 1.04 Mg ha^{-1}. Columns with dissimilar letters are different at $p < 0.05$.

Number of spring barley plants established in 2009 averaged 171 m^{-2} with no significant difference between treatments at the 5% level and similarly with fertile tillers, which averaged 634 m^{-2}. Yields are given in Fig. 5.7, but here again, no differences were significant at the 5% level although the trends towards higher yields under CTF and tracked + CTF in wheat from the previous year remained (significant at 10.7% level).

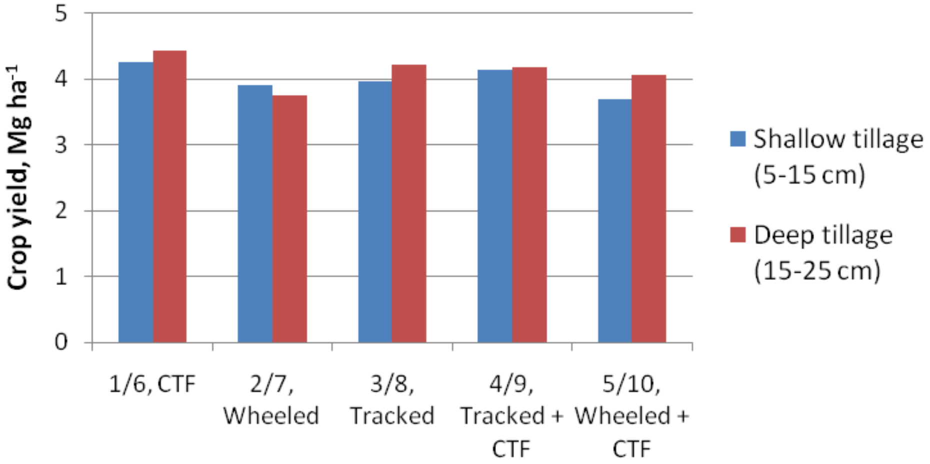


Fig. 5.7. Yield of spring barley at Morley in 2009. Differences only significant at p= 0.107

5.4.2. Chicksands

5.4.2.1. Soil penetration resistance (PR) and coincident moisture content

September 2009

Figure 5.8 shows the effect on PR of the wheeled and tracked cereal harvesters and a tractor and trailer on the "as found" condition. An analysis of variance showed that all the compaction treatments resulted in a significant increase in PR (at pr < 0.001) compared with the "as found" condition. In addition, PR under the tracked combine was significantly greater than the wheeled combine at the 1% level and the tractor and trailer at the 5% level. These differences were particularly pronounced between 0 and 8 cm depth where resistances for the wheeled vehicles rose by an average of 31% and by 91% under the tracked combine. Below this there were no significant differences.

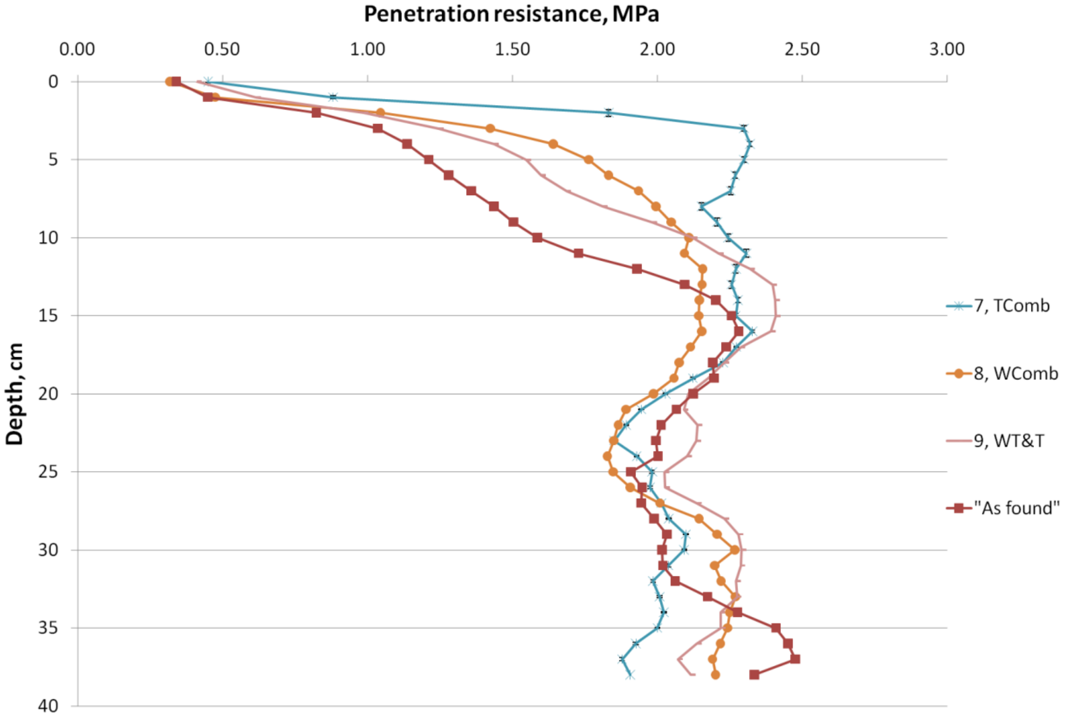


Fig. 5.8. Cone penetration resistance at Chicksands on 5/9/09 showing the results of tracking with the tracked and wheeled harvesters and the tractor and trailer combination compared with the "as found" condition.
(Treatment x depth least significant difference at pr = 0.05 (LSD_5) = 0.314 MPa)

Fig. 5.9 illustrates the conditions both pre- and post-subsoiling of the site together with the impact of the other compaction treatments applied after subsoiling. Subsoiling had a profound effect on resistance in the profile, reducing pressure from around 2.3 MPa at 15 cm depth to around 0.6 MPa (Fig. 5.9 "As found compared with 1 (CTF)). Loads imposed

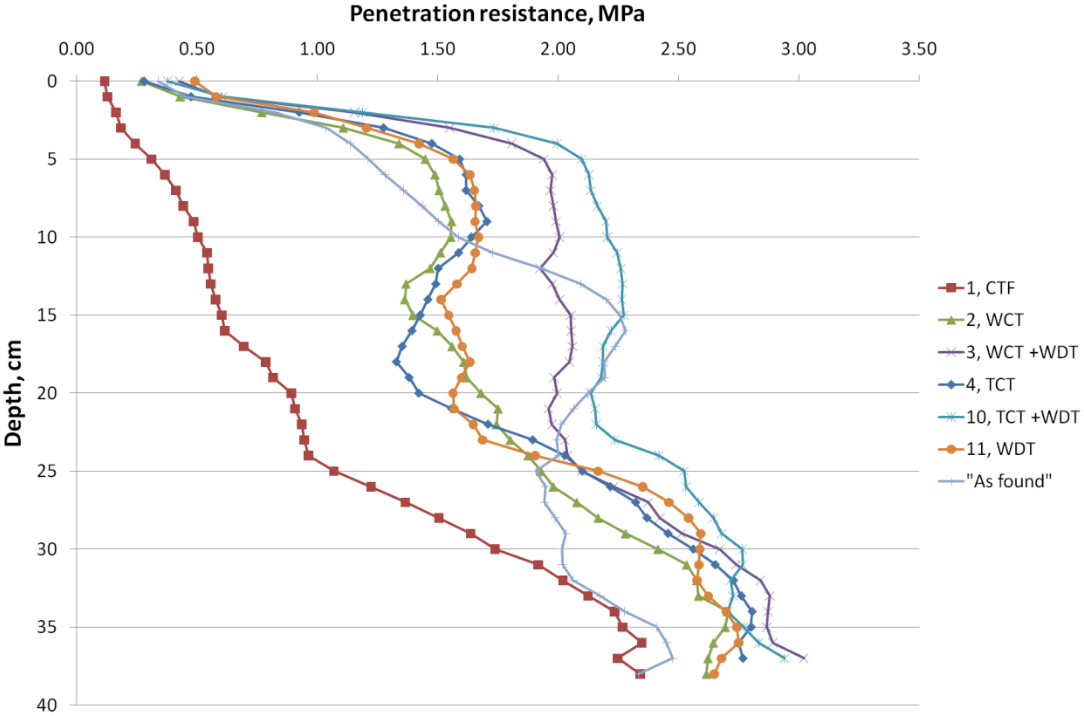


Fig. 5.9. Cone penetration resistance at Chicksands on 22/9/09 showing the effect of subsoiling to around 35 cm depth and the effect of loads imposed subsequently.
The CTF treatment represents conditions after soil deep loosening with no subsequent traffic.

after soil deep loosening increased resistance significantly. An analysis of variance of these data suggested that over the whole profile:

1 (CTF) < than all the other treatments
2 (WCT) < 3 (WCT+WDT) and 10 (TCT+WDT)
4 (TCT) < 10 (TCT+WDT)
11 (WDT) < 3 (WCT+WDT) and 10 (TCT+WDT)

all at $p < 0.01$ with a LSD of 0.151 MPa. There was also evidence to suggest that PR under the wheeled compared with the tracked cultivation tractor was slightly less overall reflecting perhaps the lighter wheel load (5 cf 7 t), but the contrast in PR was not consistent throughout the profile, as will be evidenced from Fig. 5.9.

Application of the drill tractor as the second vehicle increased resistance significantly, both in combination with the wheeled and with the tracked tractor (Tr 2 cf Tr 3 and Tr 4 cf Tr 10) but could not be distinguished from treatments 2 (WCT) & 4 (TCT) on its own. The combinations increased resistance compared with the non-trafficked soil (1, CTF) to 34 cm and 37 cm depth respectively (LSD = 0.379 MPa). On all occasions, the non-trafficked soil retained a significantly lower strength than where any compaction had been applied.

The effect of track pressure under or outside the idlers was significant, with the PR under the idlers averaging 1.847 MPa compared with 1.572 MPa (LSD = 0.068 MPa, Fig. 5.10). There was also a change in effect with depth, with the difference reaching a maximum of nearly 1 MPa (LSD = 0.404 MPa) at around 20 cm depth and then diminishing rapidly to zero at around 27 cm, just shallower than the depth of subsoiling.

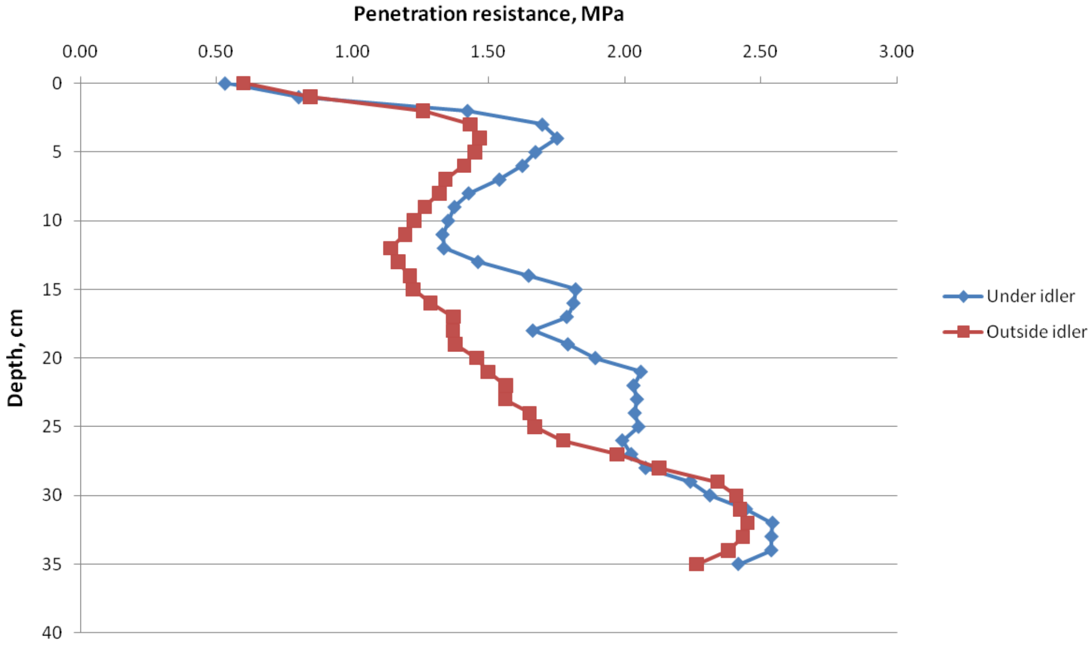


Fig. 5.10. Cone penetration resistance under the rubber belts of the tracked tractor at Chicksands measured under the track idlers and beneath the unsupported belt.

January 2010

A further set of PR measurements were taken at the end of January 2010 when moisture levels were considerably higher than in September. An analysis of variance of the coincident gravimetric moisture (mc) data plotted in Fig. 5.11 showed that there was no treatment x depth effect but treatment 10 (TCT+WDT) had a lower moisture content than all but treatments 2 (WCT) and 3 (WCT+WDT), while treatment 2 (WCT) was lower than treatment 8 (WComb+sub). There was a notable linear reduction in moisture content with depth on the CTF plot compared with most others, perhaps indicating a lack of stratification in the profile and more consistent hydraulic properties.

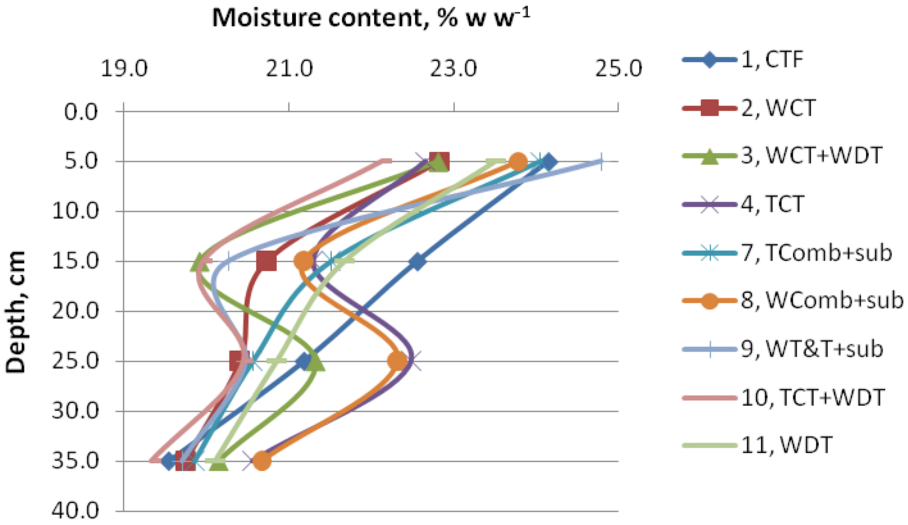


Fig. 5.11. Change in gravimetric soil moisture content with depth at Chicksands on 26/01/10 coincident with penetrometer measurements.

The PR again showed a clear distinction between those treatments which had received traffic after subsoiling and those that had not. There was also a further distinction between treatments that had been trafficked post harvest and then deep loosened (i.e. treatments 7, 8 & 9) and a treatment that had received no post harvest traffic (1 CTF) (Fig. 5.12 and Table 5.11 with the full data set). These data also showed subtle differences between resistances on the trafficked plots. For example Treatment 1 (CTF) had a lower PR than all other treatments, including 7 (TComb+sub), 8 (WComb+sub) and 9 (WTT+sub) while these had a lower PR than all the other treatments. Similarly, treatments 3 (WCT+WDT) & 10 (TCT+WDT) although not significantly different, are discretely separated from all the others with higher resistance over practically the whole depth of the profile. In addition to the depth x treatment analysis, averages of the PR readings were assessed against depth and soil moisture content, the latter sampled at four depths in the profile. In this analysis, treatment x depth was not significant, so depth and moisture content were used as covariates, thus allowing for their influence. The results in Table 5.11 show that whereas treatments 2 (WCT) and 4 (TCT) were significantly different in the full data set, they were no longer so when moisture content was allowed for. The post harvest trafficked and subsoiled treatments were also no longer significantly higher in PR than treatment 1 (CTF). These results also revealed that soil moisture content had a significant effect on PR. A multiple linear regression was therefore used to determine the relationship between mc, depth and PR. The analysis revealed one reading having undue leverage on the results and some with high residuals, removal of which provided a regression significant at pr = < 0.001 with 90.6% of the variance accounted for.

Table 5.11. Mean values of penetration resistance on 26 January 2010 at Chicksands. Values with different letters are significantly different at the 5% level.

	Treatment								
Data set	1, CTF	2, WCT	3, WCT + WDT	4, TCT	7, TComb +sub	8, WComb +sub	9, WTT +sub	10, TCT + WDT	11, WDT
Full[1]	0.7474	0.8836	0.9848	0.9524	0.8566	0.8288	0.8495	0.9716	0.9104
	a	b	c	d	e	e	e	c	b
PR+MC[2]	0.686	0.780	0.893	0.796	0.696	0.713	0.699	0.872	0.779
	a	b	c	b	a	a	a	d	b

[1] Individual PR readings at specific depths

[2] Average PR readings around the mean depth of moisture measurement

The resulting relationship between parameters was:

$$PR = 0.03206 \times \text{depth (cm)} - 0.01242 \times \text{mc (\% w/w)} + 0.390 \qquad \textit{Equation 5.1}$$

Overall, these January results, despite the higher moisture content and thus reduced contrast between treatments, showed that the compaction imposed by the initial treatments, was mostly removed by the subsoiling operation, but quickly re-established if traffic was imposed subsequently. Similarly, the intensity of subsequent traffic in terms of number of passes could still be detected.

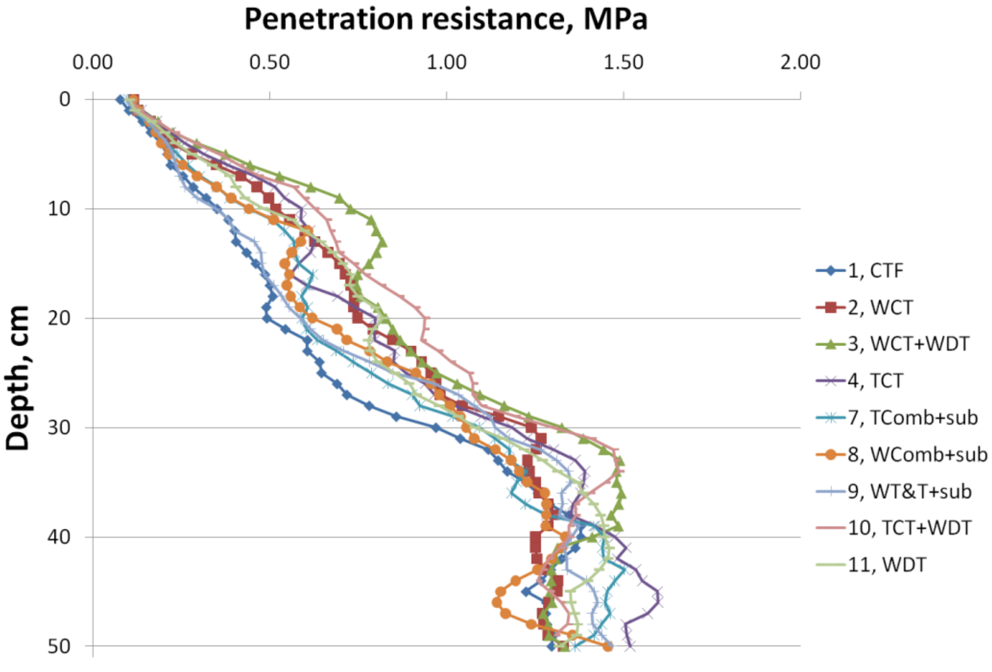


Fig. 5.12. Cone penetration resistance on 26/01/10 at Chicksands showing results from all treatments. Treatment LSD = 0.031 MPa.

April 2010

A further set of penetration resistance and soil moisture measurements were made after a dry period at the end of April 2010. Figure 5.13 shows that the contrasts between those treatments which had been subsoiled and those which had not were still very evident. An analysis of variance determined that there was no treatment x depth interaction but that the average resistance under:

1 (CTF) < all other treatments

7 (TComb+sub), 8 (WComb+sub) & 9 (WTT+sub) < all except treatment 1

There was also evidence to suggest that treatment 3 (WCT+WDT) had a greater resistance than all other treatments although this contrast disappeared when readings with high residuals were removed. Underlying this however was the fact that the PR under treatment 10 (TCT+WDT) was greater than 2 (WCT), 4 (TCT) & 11 (WDT) at around 8 cm deep and close to being significant, suggesting similar conditions to those found during earlier measurements. On the basis of magnitude of effect in the topsoil, the earlier evidence of greater resistance under the tracked combine was not universally evident with the tracked tractor, but there remains good evidence of the effect of repeated passes and multiple axles.

A further analysis using average resistance values coincident with soil moisture data suggested that there was no treatment x depth interaction and this allowed an analysis of covariance using soil moisture content and depth as covariates. This revealed that:

Treatments 1, 7, 8 & 9 < all others.

i.e., all treatments which had been loosened after compaction or no compaction (1, 7, 8 & 9) could now no longer be distinguished, as suggested in the January data. Also, the differentiation between treatment 10 (TCT+WDT) and the other treatments was no longer apparent. In this data set, although moisture content was found to have an effect on PR, it was not at a statistically significant level. This was also the case for the treatments which had no effect on soil moisture, so a multiple linear regression was not performed.

Fig. 5.14 shows, as in January (Fig. 5.11), that there was a markedly linear change in gravimetric moisture content with depth on the CTF plots (albeit in the opposite direction to January), which was absent elsewhere, again suggesting perhaps more uniform hydraulic properties. An analysis of variance revealed that there was no treatment x depth interaction but that moisture content on:

Treatment 9 (WT&T+sub) > all others except treatment 11 (WDT)

Treatment 11 (WDT) > treatments 4 (TCT+TCT) and 7 (TCT+sub)

These variations probably reflect temporal differences in crop growth rather than a direct physical effect because the latter defies logical explanation.

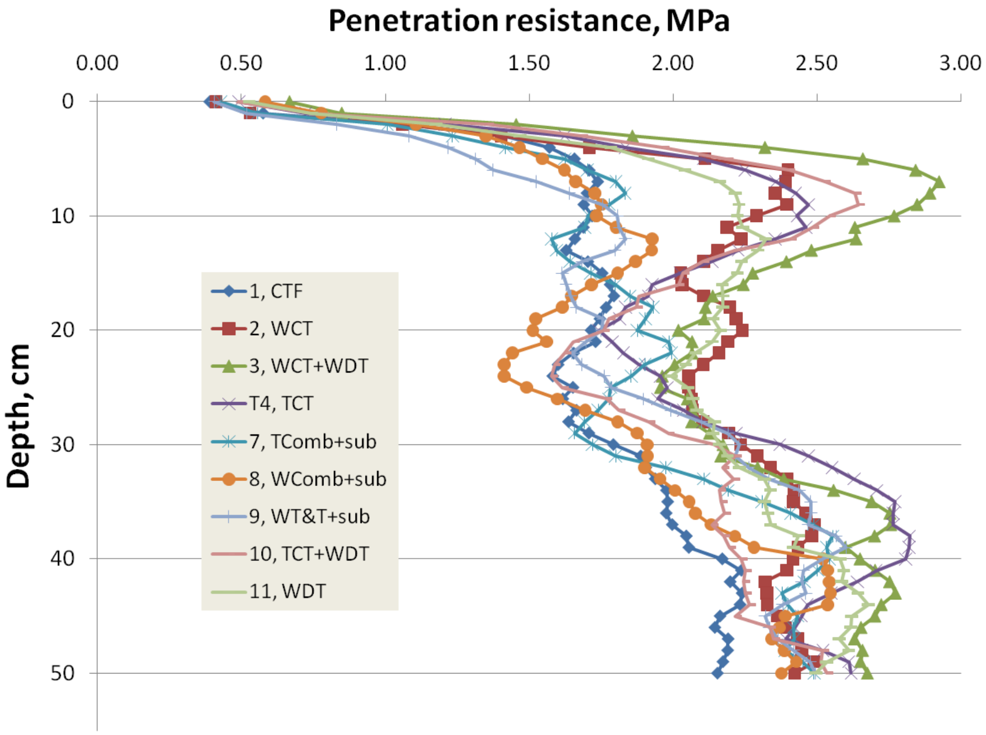


Fig. 5.13. Penetration resistance on 23 April 2010 at Chicksands. LSD: Treatment = 0.066 MPa, Tr x D = 0.474 MPa

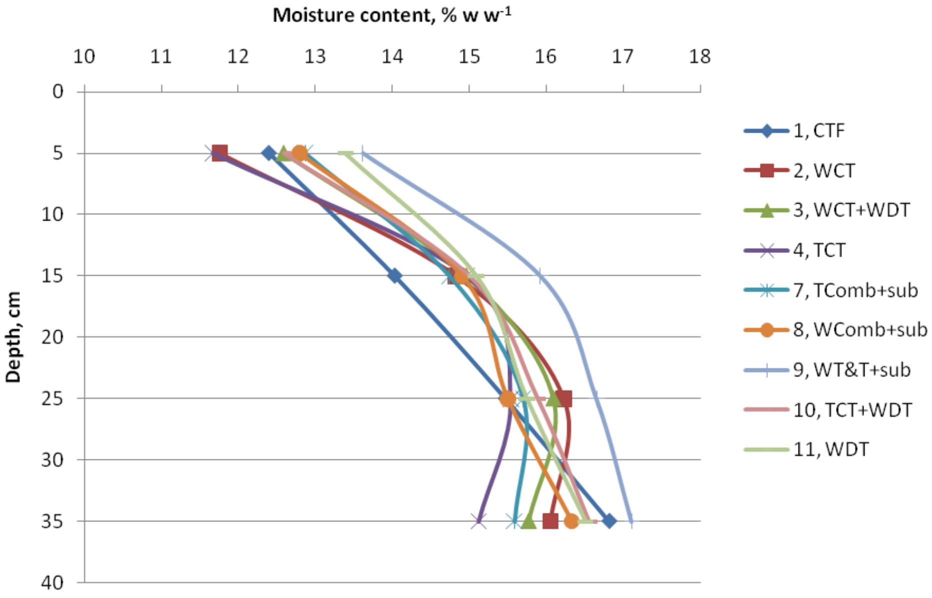


Fig. 5.14. Change in soil moisture content with depth coincident with the penetrometer measurements at Chicksands on 24 April 2010. Treatment LSD = 0.70% w w^{-1}.

5.4.2.2. Soil moisture content (MC), bulk density (BD), water filled pore space (WFPS) and porosity

September 2009

Table 5.12 shows that changes in MC, BD, WFPS and porosity due to the treatments were mostly in the top 5 cm, with all traffic resulting in a significant increase in these parameters compared with the initial condition, mirroring the PR results. Also noticeable and again mirroring the PR results, is the greater impact of the tracked combine in this layer and a lower WFPS at 25 cm than either of the wheeled treatments.

Table 5.12. Moisture content, bulk density and WFPS following initial treatments at Chicksands (prior to deep loosening) in September 2009.

Treatment	5 cm depth				25 cm depth			
	MC, %				MC, %			
	w w^{-1}	v v^{-1}	BD, g cm^{-3}	WFPS, %	w w^{-1}	v v^{-1}	BD, g cm^{-3}	WFPS, %
1. Field, as found	14.5a	16.9a	1.17a	26.6a	16.1a	24.3a	1.57a	40.1a
7. TComb+sub	15.6a	25.4b	1.64b	41.0b	16.1a	24.9a	1.51a	37.8a
8. WComb+sub	14.5a	21.4bc	1.48c	49.6b	16.1a	24.3a	1.55a	61.6b
9. WT&T+sub	14.5a	20.3ac	1.40c	43.4b	16.1a	25.3a	1.51a	58.6b

Values with different letters are significantly different at $p < 0.05$

March 2010

The results of volumetric and gravimetric moisture measurements, made at the beginning of March at a depth of 12 cm show, other than for treatment 8 (WComb+sub), a lot of similarities with each other as may be expected (Fig. 5.15a & b). However, analyses of variance revealed that there were no significant differences within the gravimetric or volumetric data but differences in the latter were significant at the 10% level ($p = 0.076$) with an associated LSD of 2.771%. The only effect on bulk density (Fig. 5.16) was again for Treatment 8, which was significantly lower than on all the other treatments. Effects on water filled pore space were not significant.

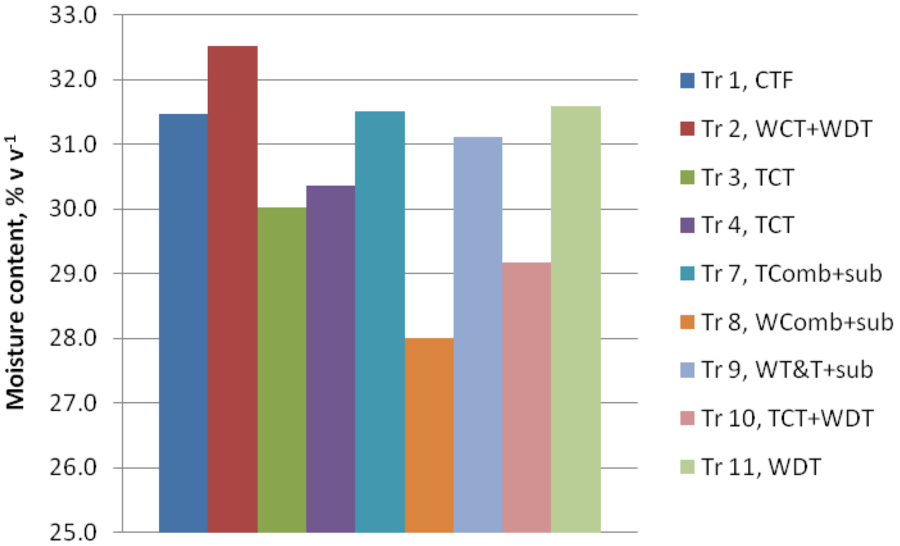


Fig. 5.15a. Volumetric moisture content on 2 March 2010 at Chicksands measured at 12 cm deep in the profile. Treatment 8 < all others at p = 0.076

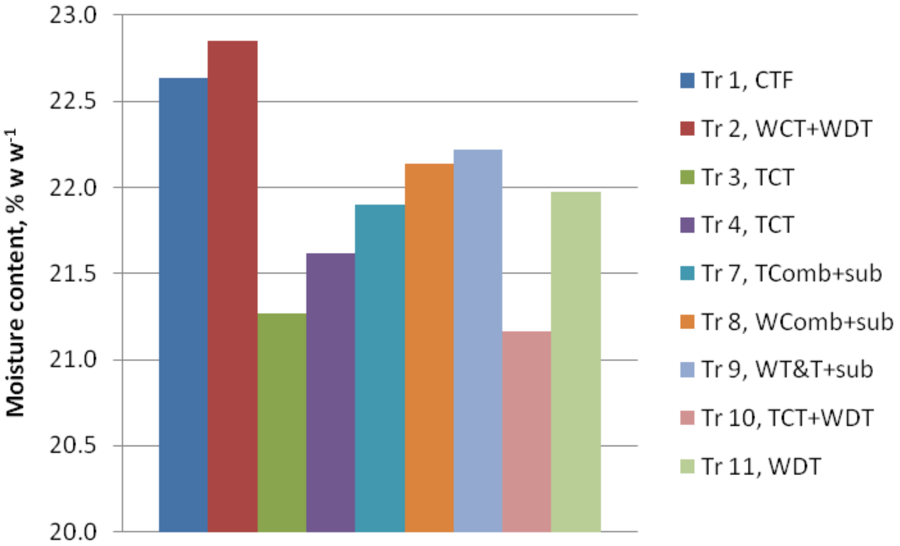


Fig. 5.15b Gravimetric moisture content (MC) on 2 March 2010 at Chicksands measured at 12 cm deep in the profile. (No significant difference between treatments)

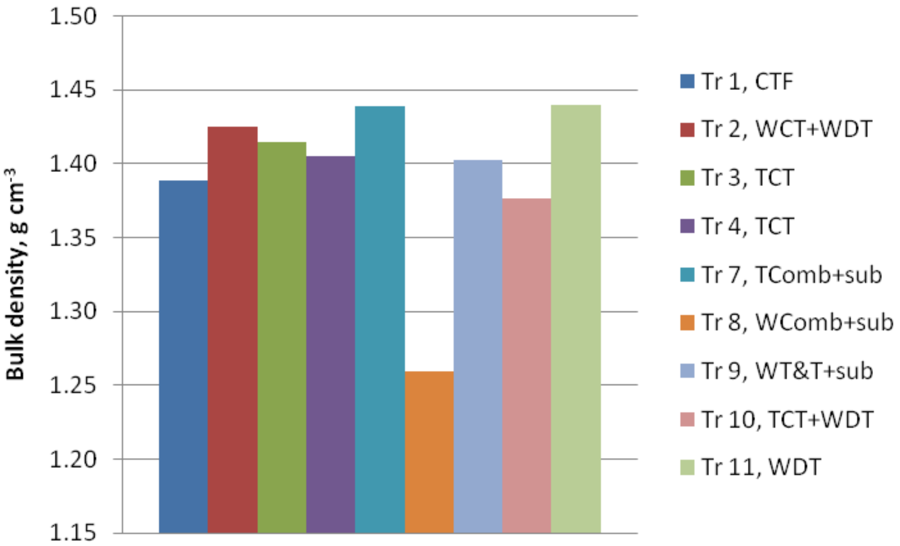


Fig. 5.16. Bulk density at Chicksands on 2 March 2010 measured at 12 cm deep in the profile. Treatment 8 < all others at $p < 0.05$

5.4.2.3. Infiltration and hydraulic conductivity

April 2010

Infiltration tests were conducted on 12 April at 12 cm deep at three locations on each of the plots with a suction of 1 cm. Results (Fig. 5.17) and an analysis of variance showed that the hydraulic conductivity on treatments 8 (WComb+sub) and 9 (WT&T+sub) could not be distinguished, but the conductivity on treatment 8 was significantly greater than on all the other treatments.

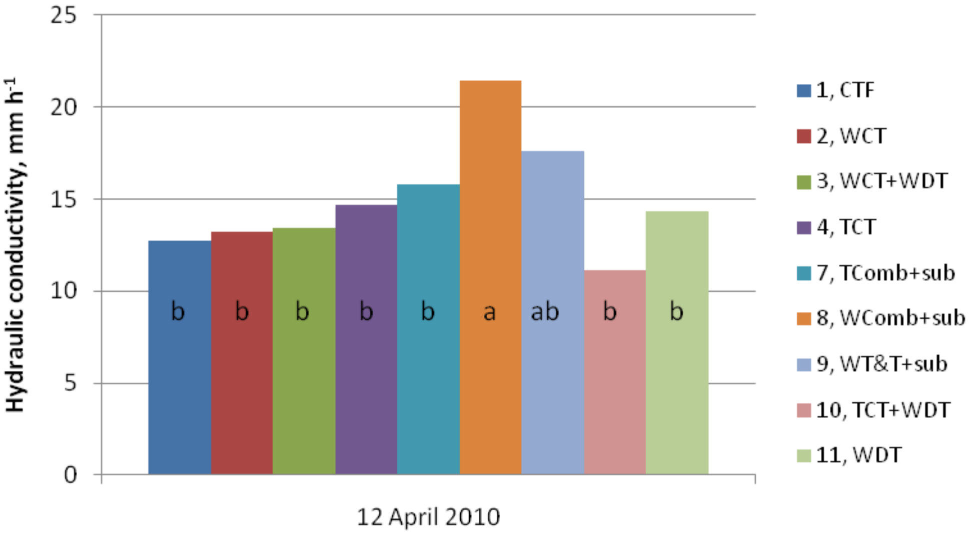


Fig. 5.17. Hydraulic conductivity at Chicksands measured at 12 cm depth on 12 April with the mini disc infiltrometer set at a suction of 1 cm. LSD 5.28 mm h^{-1}.
Columns with dissimilar letters are different at $p < 0.05$

5.4.2.4. Crop at Chicksands

The number of established winter wheat plants was measured on 26 January 2010, averaging 195 m^{-2} with an analysis of variance suggesting no significant difference between any of the treatments. Similarly, there was no significant difference in tiller numbers between treatments measured on 5 July 2010 (Table 5.13).

Table 5.13. Plant and tiller numbers at Chicksands

Treatment	Plants m^{-2}	Tillers m^{-2}
1, CTF	200	432
2, WCT	211	445
3, WCT+WDT	193	472
4, TCT	199	446
7, TComb+sub	200	417
8, WComb+sub	186	432
9, WT&T+sub	180	446
10, TCT+WDT	196	427
11, WDT	190	500

Samples for yield determination were taken on 25 July 2010. An analysis of variance of grain yield revealed that there were no significant differences between treatments, even at the 10% level (Fig. 5.18). Standard errors were high probably reflecting contrasts in water availability across the site in what was a very dry spring and summer (Table 2.9).

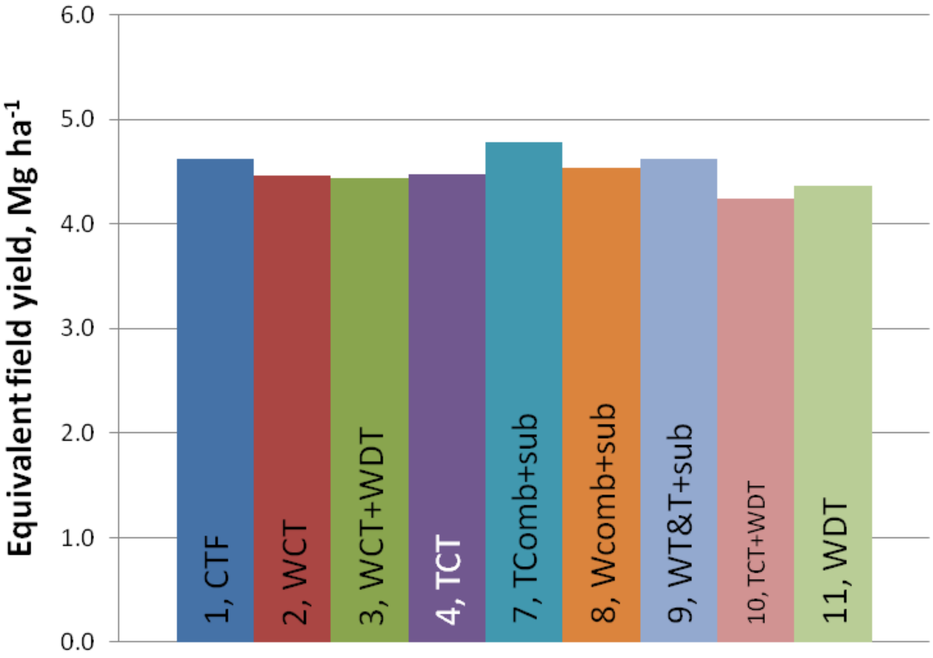


Fig. 5.18. Yields of winter wheat at Chicksands converted from sampled areas to Mg ha^{-1}. Differences in yield were not significant.

5.4.3. Colworth

5.4.3.1. Soil penetration resistance (PR) and coincident moisture content

September 2009

Figure 5.19 shows the change in cone resistance when the compaction treatments were applied to the initial non-trafficked condition. Unlike at Chicksands, there was very little sinkage, so measurement depths were likely to have been similar for all treatments. All compaction treatments led to a notable increase in resistance compared with the non-trafficked condition and from just below the surface to around 25 cm depth. There was no depth x treatment effect but treatment 1 (CTF) had a significantly lower resistance than all the other treatments, while treatments 2 (WComb+WCT), 6 (WComb), and 9 (WT&T) all had a significantly greater resistance than treatments 4 (TCT+TCT) and 5 (TCT), suggesting that tracks had limited the increase in resistance compared with wheels on similarly loaded vehicles. If the limited gravimetric moisture data at 5 cm (24.9%) and 20 cm (27.7%) depth were included in an analysis of covariance using mc and depth as covariates (Tr x depth was not significant), the only change was to treatment 5 (TCT) which no longer had a significantly lower PR than treatments 2 (WComb+WCT), 6 (WComb), and 9 (WT&T).

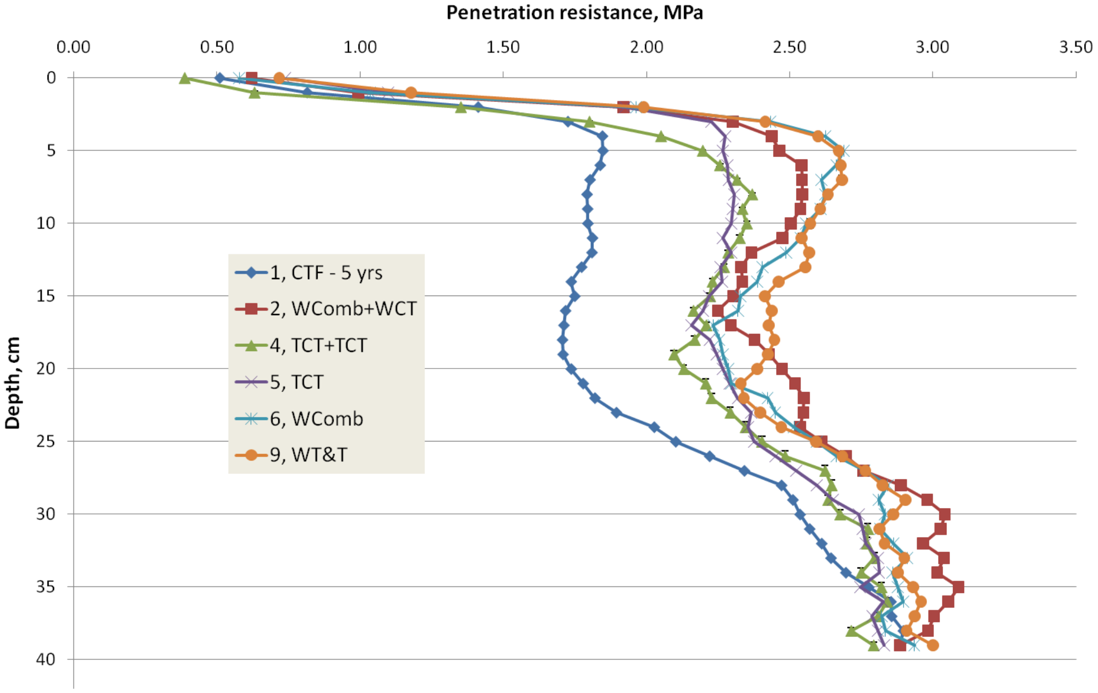


Fig. 5.19. Cone penetration resistance at Colworth on 6/9/09 showing the initial condition on the site (CTF, non-trafficked for 5 years) and the conditions following the compaction treatments.

LSD = 0.118 MPa. (LSD = 0.292 MPa when mc and depth used as covariates)

December 2009

A further set of PR and mc measurements were recorded on 28/12/2009 when moisture levels were much higher than in September. Figure 5.20 shows that many of the contrasts in soil strength indicated in September were still evident, despite the higher soil moisture content. An analysis of variance revealed that treatment, depth and treatment x depth were all significant at pr < 0.001 and further that treatment differences at the 5% level were:

7 (TCT+sub) and 8 (WComb+sub) < all the others but 7 < 8

12 (WCT+WDT) > all others

3 (WComb+WCT+WDT) > 1 (CTF), 2 WComb+WCT, 4 (TCT+TCT), 9 (WT&T), 11 (WDT) plus other subtle differences (Treatment LSD = 0.041 MPa). The effects of subsoiling were obviously very evident and there remains support for a multiple pass effect but mixed messages in terms of tracks. A further analysis using average resistance values coincident with soil moisture data suggested that there was no treatment x depth interaction and this allowed an analysis of covariance using soil moisture content and depth as covariates. These results suggested the following differences in PR between treatments at the 5% level:

7 (TCT+sub) & 8 (WComb+sub) < all other treatments

1 (CTF) & 9 (WT&T) < 10 (WCT) & 12 (WCT+WDT)

Further scrutiny of these data showed that these differences did not deviate with depth and there was no evidence that tracked or wheeled machines led to higher or lower PR at particular depths in the profile. The anomaly here is the lower resistance under the wheeled tractor and trailer combination (9, approx. max. 3.9 Mg wheel load) compared with the lighter load due to the cultivation tractor (10, WCT, 2.5 Mg).

A multiple linear regression of all the data suggested a relationship of the following nature:

$$PR\ (MPa) = 0.03798 \times Depth\ (cm) - 0.03142 \times MC\ (\%\ w/w) + 1.426 \qquad \textit{Equation 5.2}$$

with depth and moisture content explaining 86.3% of the variance.

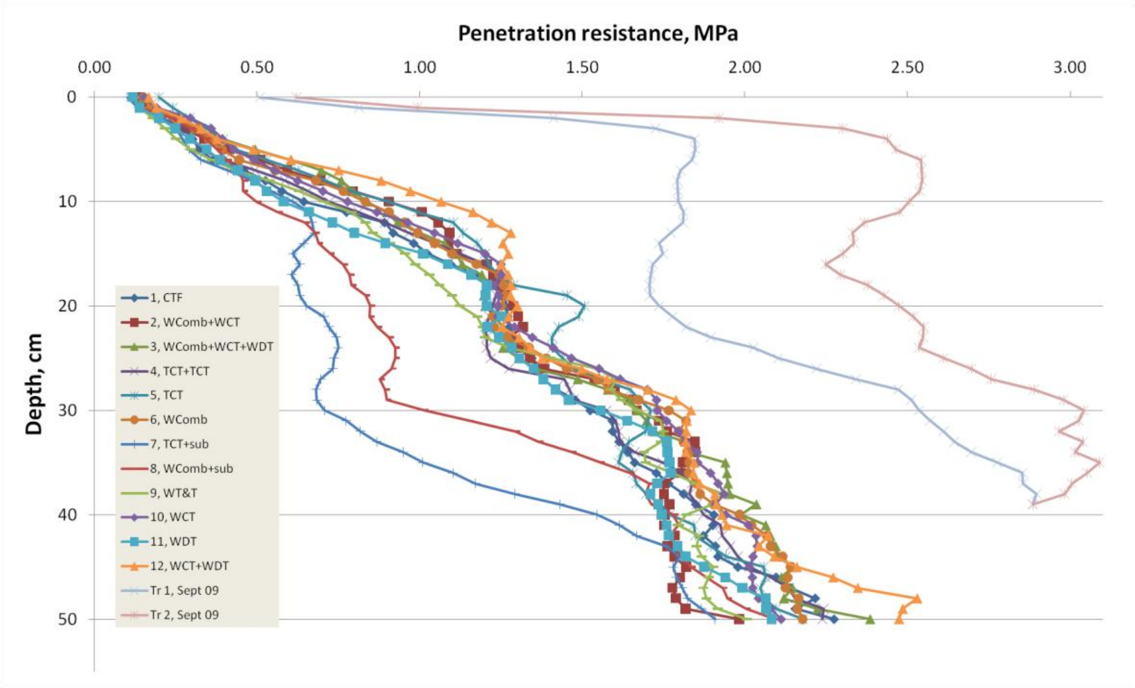


Fig 5.20. Cone penetration resistance at Colworth on 28/12/09. Treatment LSD = 0.041; Tr x Depth LSD = 0.290 MPa

Figure 5.21 shows that there was a consistent and significant variation in moisture content with depth for all treatments but this did not vary significantly between treatments. Unlike at Chicksands, there was little evidence of a linear change in this parameter with depth on the non-trafficked soil (1, CTF).

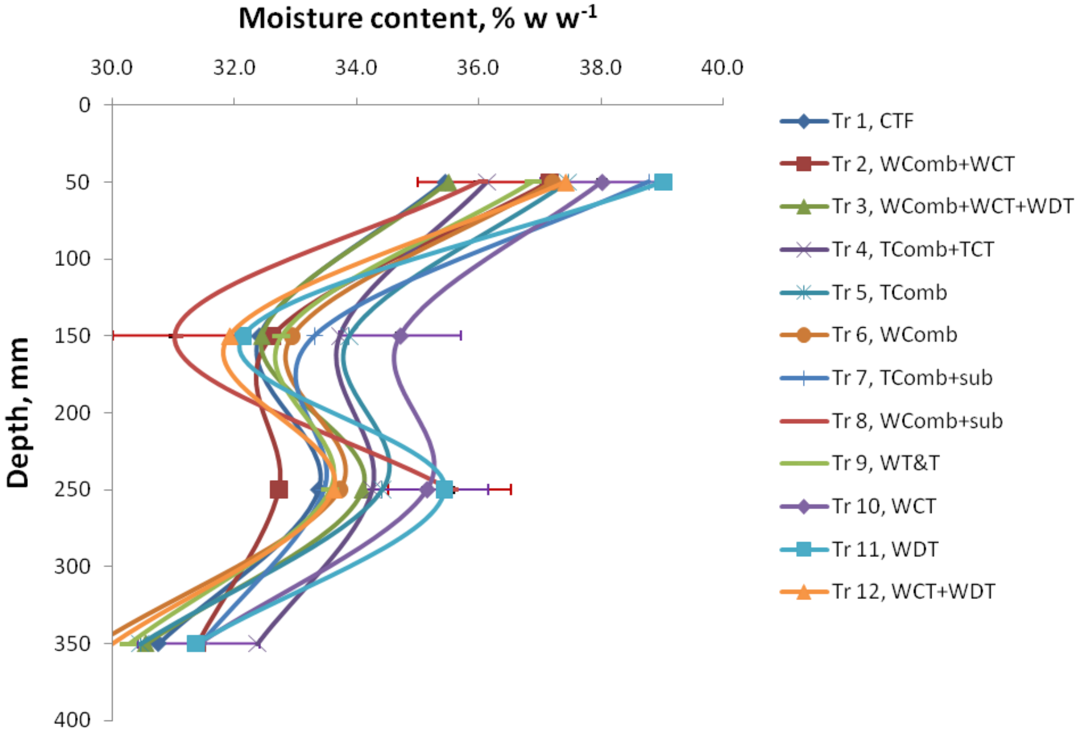


Fig. 5.21. Variation in soil moisture content with depth at the time of penetrometer measurements on 28/12/09 at Colworth. There was no significant difference in moisture content between treatments (p = 0.172, LSD = 1.37%).

April 2010

As at Chicksands, a further set of penetrometer measurements were recorded when the soil had dried to a similar level as that found on the site initially (Sept 2009). Analysis of the data without allowance for differences in soil moisture content resulted in a complex range of differences (Table 5.14). Overall however, the same story emerges, that multiple passes tended to increase resistance as well as the wheeled combine (i.e. 2 (WComb+WCT) > 9 (WT&T), 10 (WCT) & 11 (WDT)). Also remaining obvious was the effect of subsoiling which maintained a lower soil strength on these plots compared with all the others (Fig. 5.22).

Table 5.14. Mean penetration resistance adjusted for covariates (depth and soil moisture content) on 24 April 2010 at Colworth. LSD = 0.054 MPa

Treatment	1 CTF	2 WComb +WCT	3 WComb +WCT+WDT	4 TCT+TCT	5 TCT	6 WComb	7 TCT+sub	8 WComb +sub	9 WT&T	10 WCT	11 WDT	12 WCT +WDT
PR, MPa	1.897 c	2.069 c	2.223 b	1.813 cde	2.188 b	1.967 c	1.399 fg	1.338 fg	1.859 d	1.789 e	1.743 f	2.291 ad

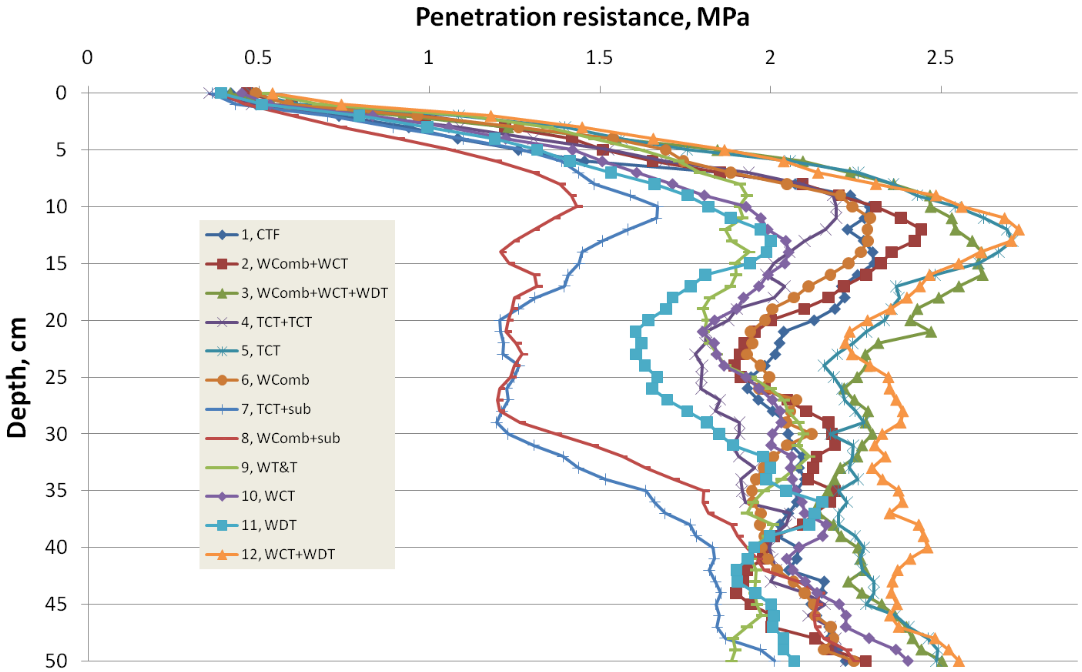


Fig. 5.22. Cone penetration resistance at Colworth on 24 April 2010.

An analysis of variance using PR averaged over depth ranges to coincide with moisture measurements revealed that there was no interaction between depth and treatment which allowed, as for the December data, an analysis of covariance with depth being treated as a variate. This showed that in this instance, moisture content had no effect but the following differences were revealed at the 5% level for PR:

7 (TCT+sub) and 8 (WComb+sub) < all other treatments
2 (WComb+WCT)> 4 (TCT+TCT), 10 (WCT), 11 (WDT)
3 (WComb+WCT+WDT) > 1 (CTF), 4 (TCT+TCT), 6 (WComb), 9 (WT&T), 10 (WCT), 11(WDT)
5 (TCT) > 1, 4, 9, 10, 11
12 (WCT+WDT) > 1, 4, 6, 9, 10, 11

Overall, these results provide clear evidence of a reduction in PR where subsoiling is followed by controlled traffic. In contrast, there was an increase in PR with multiple vehicles or axles compared with a single pass. There was also some evidence to suggest that tracks tended not to increase the level of PR to the same extent as the wheels on equivalent or lighter vehicles. An exception to this trend was on treatment 5 (TCT) although these data appear to be an anomaly because PR under this one pass was greater than when two passes were used as with Tr 4 (TCT+TCT). There was also no difference between treatments that had been tracked once (other than 4) and CTF, which had received no tracking.

Although there was no effect of moisture content on penetration resistance, there were differences in moisture between treatments (Fig. 5.23). There was however no interaction between treatment and depth, so an analysis of covariance was again used with depth as a variate to assess differences in moisture. This showed that in terms of gravimetric water content:

3 > 5, 6, 9, 11
8 < 9
9 > 3, 8, 12
12 < all but 2 and 8

These differences don't appear to have any particular significance in terms of other parameters but might be correlated with crop performance at this stage of crop growth.

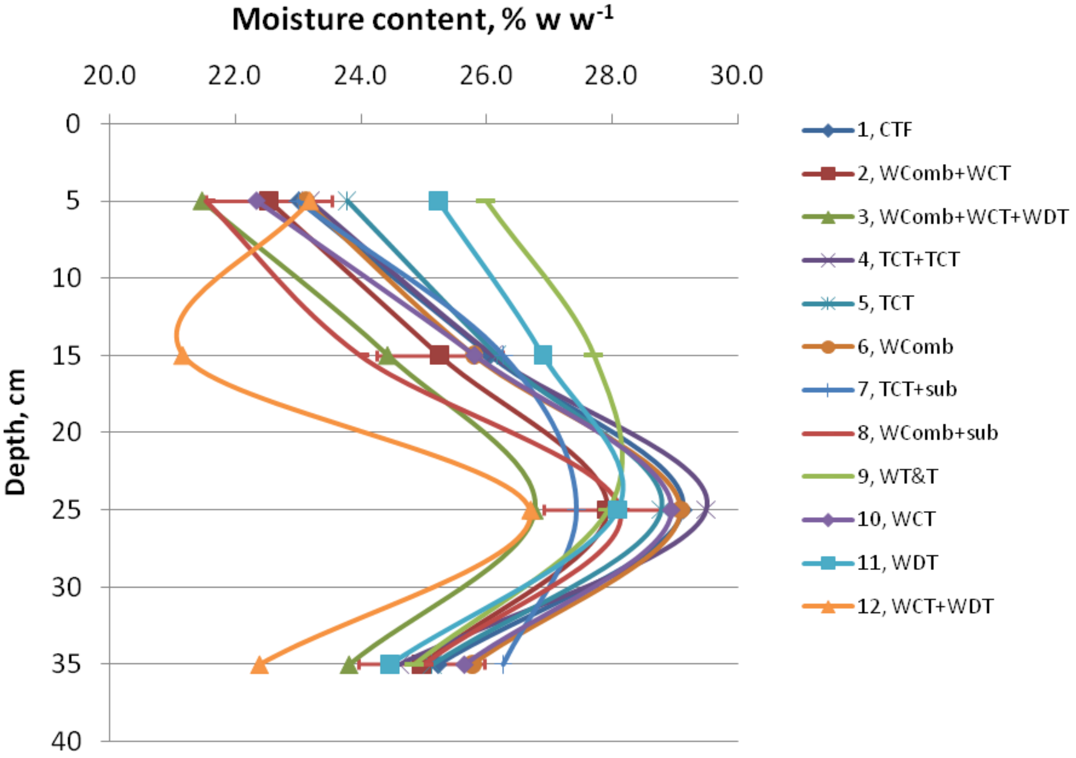


Fig. 5.23. Moisture profiles on 24 April 2010 coincident with the penetration resistance measurements depicted in Fig 4.3.1.4 at Colworth. LSD = 1.83%.

August 2010

Penetration resistance profiles for the hydraulically inserted cone penetrometer were acquired together with gravimetric moisture content post harvest and an overview of all the PR results is illustrated in Fig. 5.24.

Using only the PR and depth data an analysis of variance identified the following differences, significant at the 5% level:

7 (TCT+sub) & 8 (WComb+sub) < all other treatments, and chiefly in the depth range 25 – 40 cm

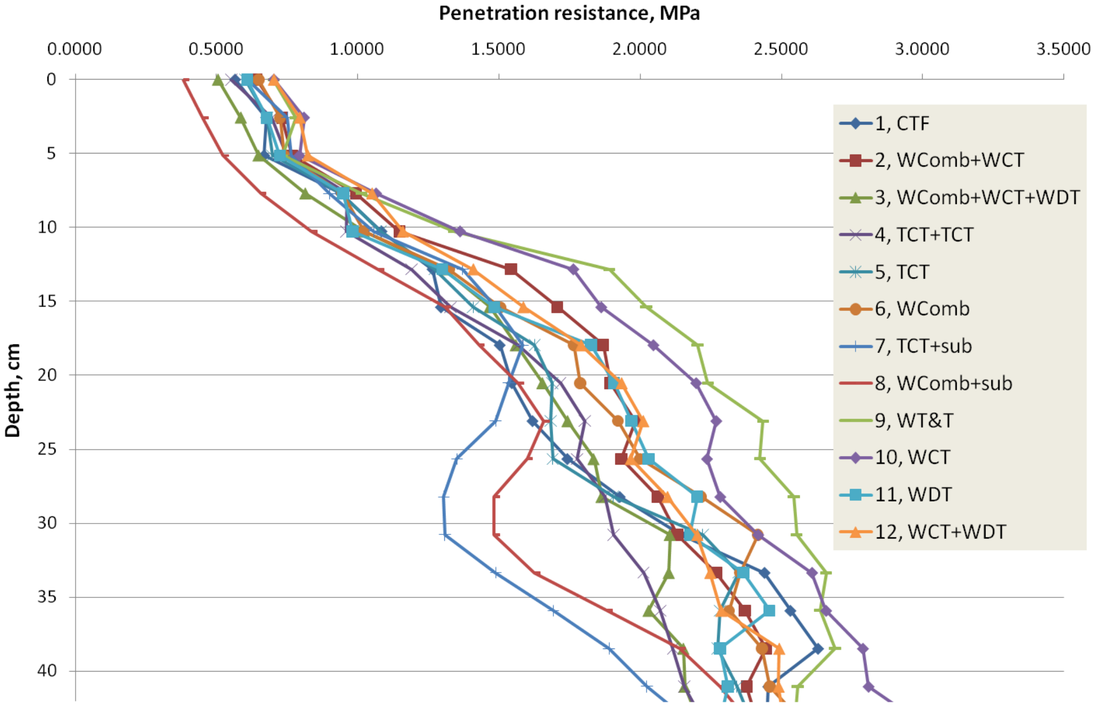


Fig. 5.24. Cone penetration resistance on the different plots at Colworth on 25 August 2010, measured using a hydraulically inserted probe. Treatment LSD = 0.120 MPa

9 (WT&T) & 10 (WCT) > all other treatments, mostly in the depth range 10 – 40 cm
3 (WComb+WCT+WDT) & 4 (TCT+TCT) < 6 (WComb), 10 (WCT) & 12 (WCT+WDT)

Other than the results for treatments 7 and 8, these data seem to make little sense and may have been influenced to a greater or lesser extent by soil moisture content. The aggregated PR together with soil moisture data, were therefore used in a further analysis of variance. This suggested that there was no treatment x depth interaction and it was therefore possible to carry out an analysis of covariance using depth and soil moisture content as variates. Results showed that covariates, depth and moisture content were all significant at pr <0.001 and in terms of penetrometer resistance, differences at the 5% level were:

7 < 1 (CTF), 2 (WComb+WCT), 5 (TCT), 6, 9, 10, 12
8 < 6 (WComb), 9 (WT&T), 10 (WCT), 12 (WCT+WDT)
9 and 10 > 1, 2, 3, 4 (TCT+TCT), 5, 11

The main effects of allowing for moisture content are to lessen the contrasts for treatments 8, 9 and 10 and to remove altogether the lower strength status of treatments 3 and 4. Overall the data show the lasting effect of subsoiling but there is also a suggestion that it was more effective following the tracked combine, or at least the effect has been more prolonged. It is also apparent that the PR remained lower under both one and two passes of the tracked tractor compared with a single pass of the wheeled equivalent.

There remain anomalies however, not least of which is the relatively high strength under treatments 9 and 10, not something that has been apparent before and for which there is no logical explanation, particularly as the PR for these treatments in April was well below that for multiple vehicles and indeed the single pass of the tracked tractor (Tr 5, Fig. 5.24) A multiple linear regression analysis of the data showed that there was a relationship between PR, mc and depth that was significant at less than the 1% level with 74.1% of the variance being accounted for. The equation relating PR to moisture content and depth was:

$$PR = 0.03841 \times \text{depth (cm)} - 0.054 \times \text{mc} (\%\ w\ w^{-1}) + 2.335 \qquad \textit{Equation 5.3}$$

Results of the measurements to assess the persistence of subsoiling effects in the absence of further traffic are presented in Fig. 5.25. The standard errors show that differences were significant over much of the profile and are reinforced rather than diminished by the difference in soil moisture status.

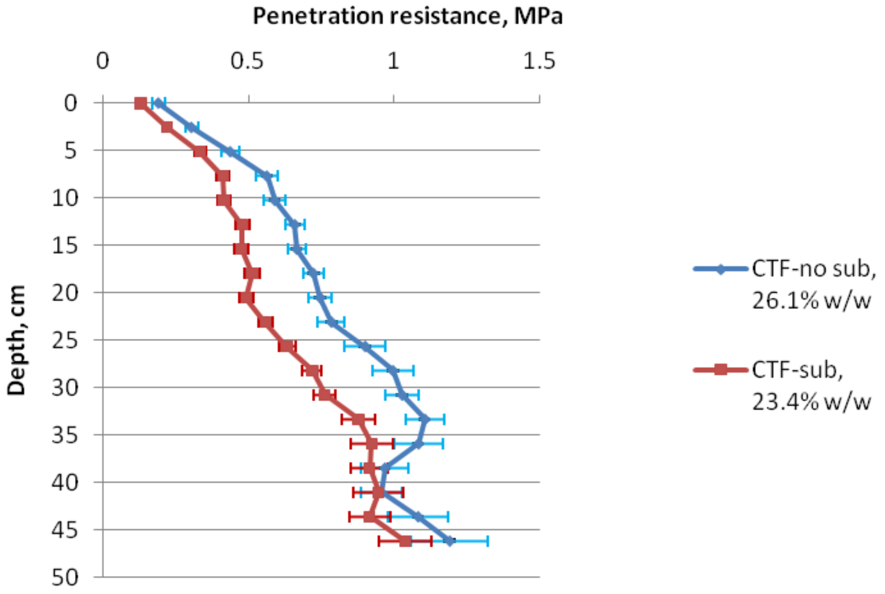


Fig. 5.25. Cone penetration resistance in two adjacent fields at Colworth which were converted to CTF in 2006, one of which was subsoiled (CTF-sub) to 35 cm depth, the other not (CTF-no sub).

Moisture contents are the profile averages. Bars are standard errors.

5.4.3.2. Soil moisture content (MC), bulk density (BD) and water filled pore space (WFPS)

September 2009

Table 5.15 lists the moisture conditions for the six compaction treatments applied before cultivation and their impact on soil bulk density and water filled porosity.

Table 5.15. Soil moisture content, (MC) bulk density (BD) and water filled pore space (WFPS) following initial treatments at Colworth, 2-5 September 2009.

Treatment	5 cm depth				25 cm depth			
	MC, % $w\ w^{-1}$	$v\ v^{-1}$	BD, $g\ cm^{-3}$	WFPS, %	MC, % $w\ w^{-1}$	$v\ v^{-1}$	BD, $g\ cm^{-3}$	WFPS, %
1. CTF	23.3	27.9a**	1.20a	43.0a	27.6	36.2a	1.32ab	55.0a
2. WCcomb+WCT	24.8	33.7b	1.36b*	50.8b**	27.8	36.5a	1.32ab	55.2ab
4. TCT+TCT	26.0	33.5b	1.26a	51.0b**	28.3	36.2a	1.28a	55.0a
5. TCT	25.9	33.6b	1.31a	51.0b**	27.7	37.2a	1.34ab	56.3ab
6. WComb	24.6	33.2b	1.35b*	50.4b**	27.6	37.7a	1.37b*	57.2b**
9. WT&T	24.6	34.0b	1.39b*	51.8b**	27.4	37.6a	1.37b*	56.8b**

Values with different letters are significantly different:
* $p = < 0.05$; ** $p < 0.01$

Changes in bulk density compared with the non-trafficked soil were mostly confined to the surface levels and were modest. This may have reflected the relatively dry condition of the surface soil meaning that bulk density in this layer was naturally elevated due to shrinkage. The lower density of treatment 4 (TCT+TCT) at 20 cm depth compared with treatments 6 (WComb) and 9 (WT&T) must be viewed with some caution, largely because of the higher density of treatment 5 (TCT) compared with 4. Calculated water filled pore space in the top 5 cm on the other hand was affected by all the treatments compared with CTF and some of these differences were still evident at 25 cm depth.

March 2010

Volumetric and gravimetric soil moisture measurements were taken again on 1 and 24 March 2010. On the 1 March, surface to 6 cm depth measurements were taken on six of the treatment plots and also on differently trafficked and cultivated fields alongside with very similar soil properties as indicated by an EMI scan. Overall, no treatment differences in bulk density (Fig. 5.26) were significant but for those areas outside the main experiment (see section 2), the following differences were found:

Bulk density:	CTF no-till > 1 (CTF), 2 (WComb+WCT), 4 (TCT+TCT), 6 (WComb), 8 (Wcomb+sub) RTF no-till > all other treatments and conditions
MC, % w/w	4 (TCT+TCT) < 1 (CTF), 8 (WComb+sub), CTF no-till, RTF non-inv, RTF no-till
MC, % v/v	no significant differences
WFPS	no significant differences

Non-inversion tillage and no tillage had a marked influence on density but as some of these data were from adjacent fields rather than the replicated plots, these differences need to be treated with some caution.

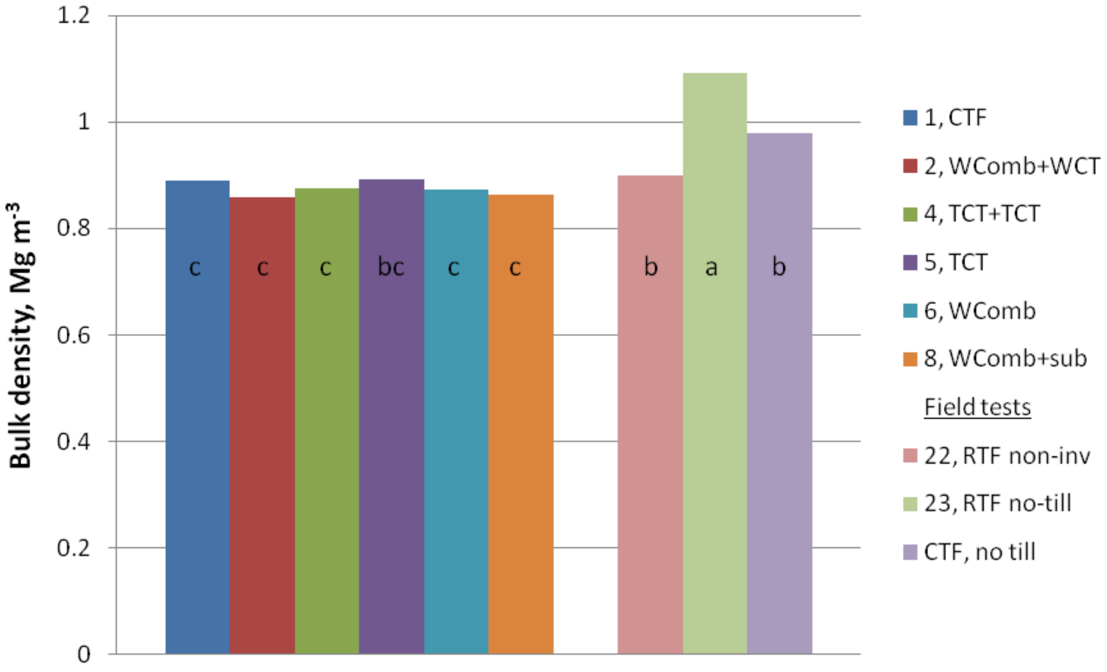


Fig. 5.26. Soil bulk density in the top 6 cm of the profile measured on 1/3/10 at Colworth on a selection of treatments including CTF no-till in the same field (LSD = 0.102 Mg m^{-3}). Columns with dissimilar letters are different at $p < 0.05$
Also results for RTF non-inv and RTF no-till systems in immediately adjacent fields.

There were large contrasts in water filled pore space but none of the differences were significant reflecting large variability between sampling sites. Compaction and deep tillage had rather greater contrasts than shallow or no tillage (Fig. 5.27) with compaction tending to increase WFPS but more particularly with two passes and with tracks.
On 24 March, gravimetric and volumetric moisture measurements were taken at 15 cm depth on all plots and results suggested that the greatest contrast in directly measured and derived variables (bulk density and WFPS) was between those treatments which had been subsoiled following compaction and those that had not. Treatment 7 (TCT+sub) for example had a lower volumetric water content than all but treatment 1 (CTF), while treatment 8 (WComb+sub) was mostly lower than all but the more lightly compacted treatments (2, 4, 6, 9) and the adjacent CTF no-till. Similarly and as illustrated in Fig 5.28, density of the subsoiled treatments was also less under treatment 7 (TCT+sub) than all the others while that on treatment 8 (WComb+sub) tended to mirror the volumetric water content data with no differentiation between this treatment and treatments 5 (TCT), 11 (WDT), 12 (WCT+WDT) and CTF no-till. Density under CTF no-till was also significantly greater than under treatment 11 (WDT). The difference between CTF no-till and treatment 1 (CTF with 10 cm tillage), although not significant, is surprising considering this measurement was from below tillage depth.

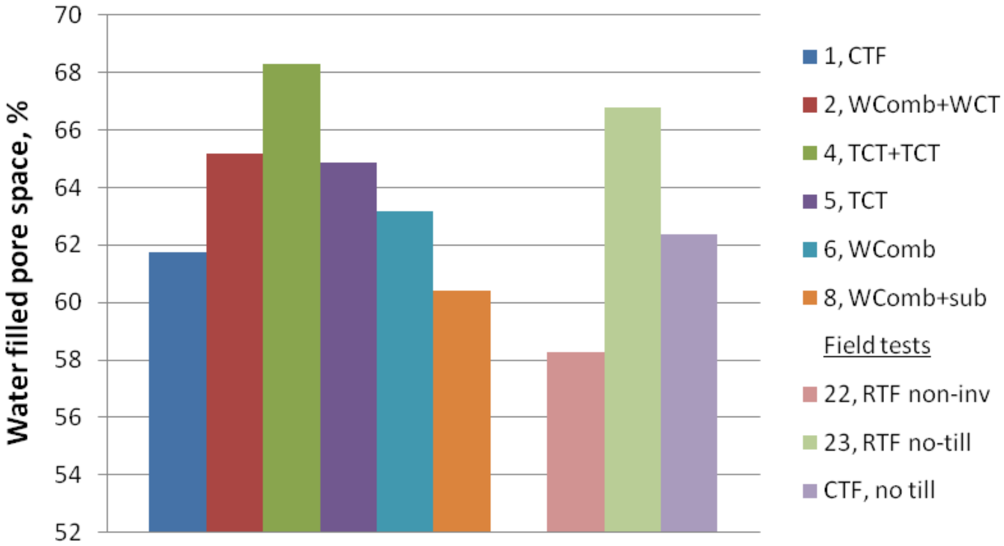


Fig. 5.27. Soil water filled pore space in the top 6 cm of the profile measured on 1/3/10 at Colworth on a selection of treatments including CTF no-till in the same field (LSD = 7.3%). No significant differences.

Also results for RTF non-inv and RTF no-till systems in immediately adjacent fields.

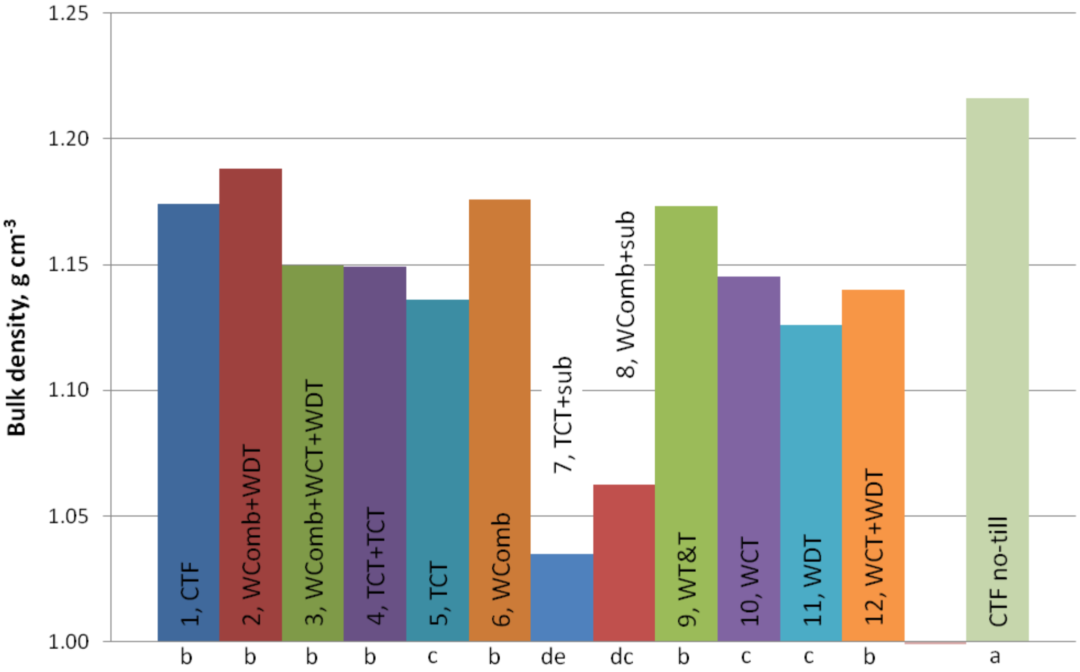


Fig. 5.28. Bulk density at 15 cm depth calculated from volumetric and gravimetric moisture measurements taken on 24 March 2010 at Colworth.

Columns with dissimilar letters are different at $p < 0.05$. LSD = 0.087 g cm^{-3}

Differences in WFPS were less discernable and not significant (Fig. 5.29), but two trends are apparent. First, multiple passes or axles tended to increase the percentage WFPS (but not in the case of Treatment 9) and subsoiled treatments tended to lower the percentage. The latter might suggest that drainage has been enhanced by deep loosening, allowing water to travel more freely to a greater depth in the profile.

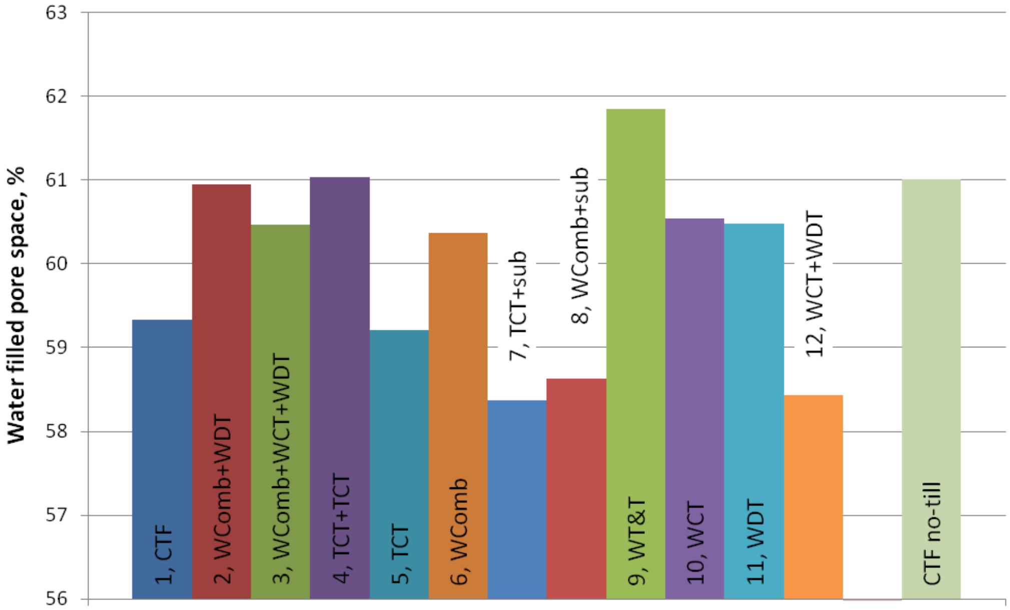


Fig. 5.29. Water filled pore space at 15 cm depth calculated from volumetric and gravimetric moisture measurements taken on 24 March 2010 at Colworth. No significant differences.

5.4.3.3. Infiltration and hydraulic conductivity

March 2010

On 11 March, a single measurement of steady state infiltration with the double ring infiltrometer was made on each of the 36 plots, the results of which are presented in Fig. 5.30. Differences between treatments were significant only at the 10% probability level. Principal among the effects was higher infiltration on treatment 6 and lower values on the no-till plots. The higher infiltration on treatment 6 appears to be an anomaly but the effect of tillage was consistent.

A further set of measurements with three replications on four of the treatments was conducted on 23 March and results shown in Fig. 5.31. With the additional replications the anomaly of treatment 6 was no longer apparent, with the following results significant at pr = 0.05:

7 (TCT+sub) > all other than 1 (CTF)
1 (CTF) > 6 (WComb), CTF no till, RTF no till

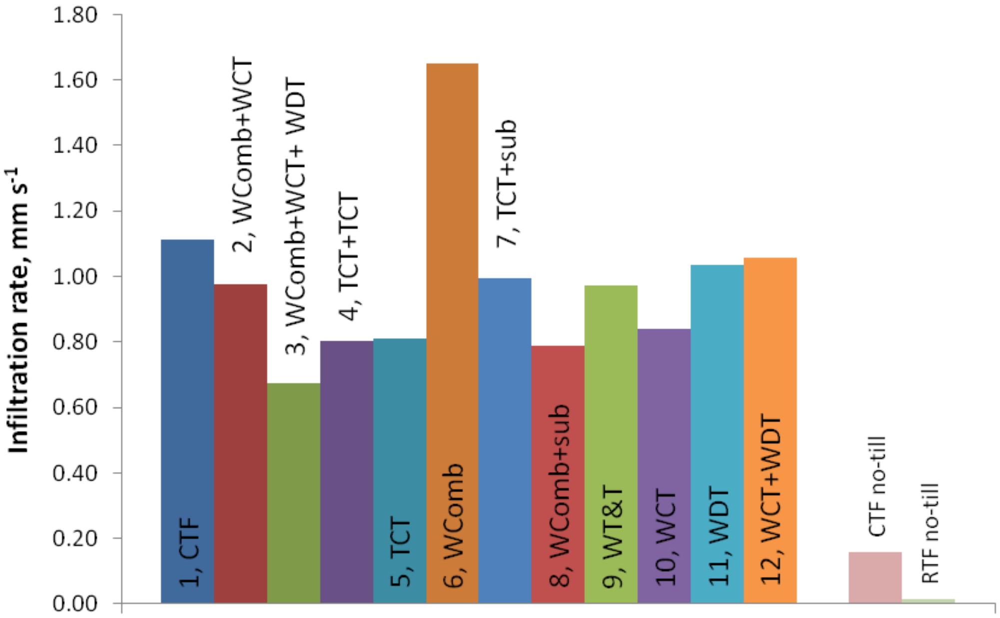


Fig. 5.30. Steady state infiltration measured with a double ring infiltrometer at Colworth on 11 March 2010 including results from adjacent trafficked (RTF) and non-trafficked (CTF) no-till areas. Treatment 6 > all others at $p = 0.10$

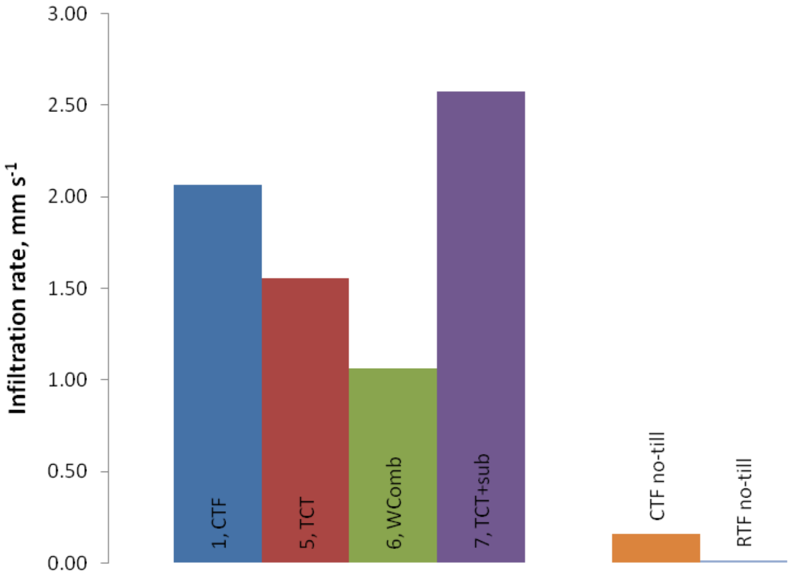


Fig. 5.31. Steady state infiltration on selected treatments at Colworth on 23 March 2010 using three replications per plot plus results from adjacent trafficked (RTF) and non-trafficked (CTF) no-till areas.

Columns with dissimilar letters are different at $p < 0.05$. LSD = 1.253 mm s^{-1}

Although results from outside the main experiment must be viewed with caution, it was very apparent that tillage again increased infiltration rate (1, CTF compared with CTF no-till) as did the absence of traffic (CTF no-till compared with RTF no-till, with both fields having been in no-till for 5 years).

5.4.3.2 Crop at Colworth

Established plant numbers were determined from measurements taken on 28/12/2009 and number of wheat ears on 29/7/10. Analyses of variance suggested that there were no significant differences in plant numbers but fertile tillers did vary as indicated in Table 5.16.

Samples for yield assessment were recorded on 29 July (Fig. 5.32) with an analysis of variance revealing that Treatments 1 (CTF), 10 (WCT) and 12 (WCT+WDT) returned significantly greater yields (at the 5% probability level) than Treatments 3 (WComb+WCT+WDT), 5 (TCT), 7 (TCT+sub) and 11 (WDT), mirroring the closely related tiller numbers. The least significant difference between treatments was 0.6188 t ha^{-1}.

Table 5.16. Plant and tiller numbers at Colworth, 2009-2010.

Treatment	Plants m^{-2}	Tillers m^{-2} LSD = 23.2
1, CTF	139a	352a
2, WComb+WCT	117a	333a
3, WComb+WCT+WDT	119a	315b
4, TCT+TCT	100a	338a
5, TCT	115a	323b
6, WComb	116a	340a
7, WComb+sub	126a	322b
8, TCT+sub	120a	345a
9, WT&T	111a	329a
10, WCT	120a	349a
11, WDT	112a	321b
12, WCT+WDT	120a	349a

To determine if there were any underlying soil-related causes for the yield differences, data from relevant soil measurements were extracted and are shown in Table 5.17.

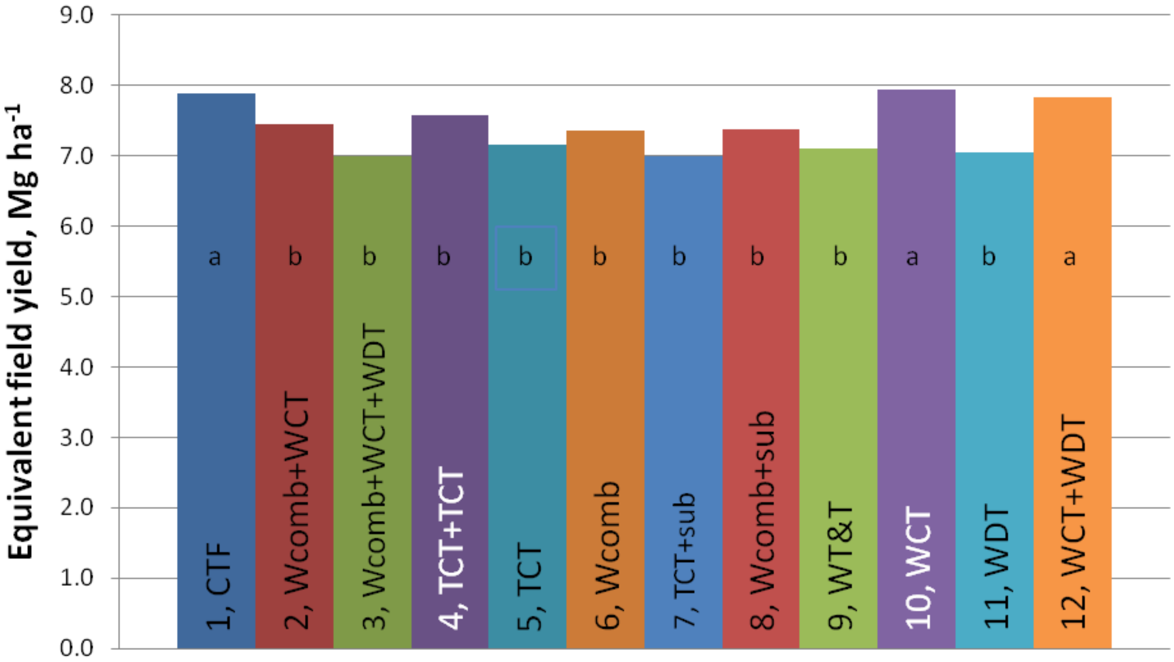


Fig. 5.32. Crop yield from the different treatments at Colworth sampled on 29 July 2010. Columns with dissimilar letters are different at $p < 0.05$. LSD = 0.619 Mg ha^{-1}

Table 5.17. Soil conditions on the plots exhibiting the greatest yield differences

		Treatment and soil value					
Parameter	**Date**	**1**	**3**	**7**	**10**	**11**	**12**
Crop yield, t ha^{-1}	Aug 10	7.9	7.0	7.0	7.9	7.0	7.8
Average penetration resistance, 10-40 cm, bar	Dec 09	1.4	1.4	0.8	1.3	1.3	1.5
Average soil moisture, 0-40 cm, %	Dec 09	33.0	33.1	34.3	34.8	34.5	33.2
Bulk density at 15 cm, g cm^{-3}	Mar 10	1.17	1.15	1.03	1.15	1.13	1.14
WFPS at 15 cm, %	Mar 10	59	60	58	60	60	58
Infiltration, cm s^{-1}	Mar 10	0.053		0.051			
Average penetration resistance, 10-40 cm, bar	Apr 10	2.11	2.35	1.42	1.99	1.85	2.41
Average moisture content, 0-35 cm, %	Apr 10	25.9	24.1	25.7	25.7	26.2	23.4
Average penetration resistance, 0-40 cm, bar	Aug 10	0.71	0.68	0.60	0.86	0.75	0.77
Average moisture content, 0-60 cm, %	Aug 10	25.5	26.8	25.7	25.7	24.6	26.0

Key to treatments: **1** CTF; **3** WComb+WCT+WDT; **7** TCT+sub; **10** WCT; **11** WDT; **12** WCT+WDT

In the case of Treatment 7 (CTF+sub), there were marginal differences in bulk density in March compared with the other treatments and a substantially lower penetration resistance on all occasions of measurement. It is perhaps this lower strength and density that had an influence on yield but the consistently similar soil conditions under Treatment 8 (WComb+sub) did not appear to have the same effect. A possible factor was a variable blackgrass population, which although catered for by careful selection, may have had some influence. However, a check on those plots which were most affected did not explain the outcomes recorded here.

5.5. DISCUSSION

It is important to note that although vehicle compaction was applied to the plots track by track, there was little evidence of a noticeable rut being formed, even when up to three passes were applied. This mimicked what often occurs in fields in small areas but is rarely noticed because some form of surface soil disturbance immediately covers it up. Although relatively evenly compacted, there was almost certainly variation in stress applied to the surface, purely by virtue of the tyre and track designs, and this was demonstrated under a tracked tractor at Chicksands (Fig. 5.10).

5.5.1. Penetration resistance

The unexpected and inexplicable results at Morley were the lower PR values under treatments 4 and 9 (TComb + CTF at both depths of cultivation), which with two passes of the rubber tracked tractor would have been expected to have higher PR values than treatments 1 and 6 (CTF at both depths of cultivation). The elevated PR under the tracked compared with the wheeled combine at Chicksands in September, particularly in the top 15 cm is in line with results on a sandy loam reported by Ansorge & Godwin (2007), particularly for a stratified soil condition. The cause of this elevated resistance is perhaps the peak loads which occur under the track idlers mimicking the effect of several axles. (Ansorge & Godwin, 2007). Following subsoiling, the increase in PR with two vehicle passes (Fig. 5.9) was such that the soil appeared to be in a stronger condition than it was before it was loosened. Chan et al. (2006) also found this to be the case with a consequent reduction in root growth of wheat and a reduced yield of oilseed rape. Bennie and Botha (1986) similarly drew these conclusions but additionally found that deep loosening soon after wheeling did not restore the soil to the same yield potential compared with where no wheeling had occurred. Soane et al. (1987) concluded that management strategies following loosening had an important influence on the longevity of the loosening effect.

Below about 25 cm depth, some caution must be exercised in comparing the pre and post subsoiling results in these experiments because the soil surface from which the measurements were taken was at a different level. Sinkage of the tracked vehicle was around 3 cm in between the lugs and about 7.5 cm under them. The equivalent for the wheeled vehicles was around 2 and 5.5 cm. From these data it can be seen that other than for the CTF treatment, the pre-subsoiling curves are probably coincident with the post subsoiling data, or at least, not significantly different at around 25 cm depth. The relative position at around 30 cm depth between the “as found” compared with the post treatment traces is around 5 cm suggesting that subsoiling has actually led to compaction deeper in the profile The critical question is did the vehicles sink 5 cm more than the original soil level? This seems unlikely, particularly as the offset is more than 10 cm in places. In January 2010, when soil moisture levels at Chicksands had risen by around 5% throughout the profile, there was still evidence of the multiple axle effect. In April, when the soil was around 6% drier than in January (15% compared with 21%), greater contrasts in strength had reappeared (Fig 5.13). In this instance, all compacted plots showed a peak strength at around 8 cm depth, which was notably absent on the non-trafficked plots. There was also still evidence in this layer of a greater effect of multiple passes but no consistent effect of tracks compared with wheels, with strength levels alternating with depth. The effect of repeated passes is in line with the work of Horn et al. (2003) who explained the process as a combination of soil shearing and rearrangement of soil aggregates, and this occurs even in dry conditions.

Overall, results from Chicksands showed a greater level of PR under tracked vehicles compared with their wheeled equivalents but this was not the case at Morley and was probably due to the difference in track design (discussed later). Where a lighter wheeled tractor was employed (WDT), this had a significantly lower PR than the combined effect of a heavy (WCT) + light tractor (WDT) but could not be differentiated from a single pass with a heavy tractor. This suggests that multiple tracking is important, even if subsequent passes are with a lighter vehicle, as found by Botta et al. (2006). Certainly any tracking after soil deep loosening was very detrimental as found by Håkansson (1976) and Soane et al. (1986). Munkholm et al. (2005) suggested that on-land ploughing was needed to maintain a recently loosened profile to a condition no-better than that of a non-loosened profile. In the work reported here, there was some evidence that loosening did not fully restore soil that had been recently trafficked, as also found by Voorhees et al. (1978) in previously trafficked ploughed soils. However, this difference in restoration at Chicksands, as indicated by PR, could not be detected 8 months later. Similarly at this later time, the contrasts between the different compaction treatments could only be detected lower in the profile but differences between those treatments that had been deep loosened and then either run over or not, were still very evident at all depths.

The unexpected result from Colworth was the significant increase in soil strength from the first tracking (Fig. 5.19) by both heavy and light vehicles in a relatively dry soil condition (profile average 26.3%), where tyre or track imprints were hard to discern. Although these differences diminished over the winter period, they became evident again as the soil dried. To some extent this increase in strength in dry soil could be associated with a smaller contact area, as found by Lamandé & Schjønning (2010b). They determined that tyre contact area increased by 149% due to sinkage when soil water content approximately doubled.

Where tracking had been modest at Colworth, there was some evidence to suggest recovery of the soil, as if it had been compressed within an elastic rather than a plastic range, which is in accord with Söhne's (1958) elasticity theory. On this clay at Colworth results from the tracked vehicle were inconsistent, showing both reduced and increased impacts compared with its wheeled counterparts. For example, in September 2009 (Fig.

5.19), PR profiles from the tracked tractor were consistently lower than from the wheeled vehicles, whereas in April, exactly the opposite was the case (Fig. 5.22). Again this same figure in April gives contradictory evidence, showing a single pass with the tracked vehicle having greater PR than two passes. There was also no evidence at this time of a difference between treatments that had been tracked once (other than 4) and CTF, which had received no tracking. A possible explanation is an element of elasticity, as suggested above, particularly at this site which had been largely undisturbed by tillage or compaction for 5 years. Ajayi et al. (2010) determined that susceptibility to compaction often depended more on soil structure than texture, particularly for soils of this nature with a high clay content.

Fig. 5.32 shows results from those treatments at Colworth which were sampled on all four measurement dates. These data are intriguing in that the resistance profiles in September 2009 and April 2010 are very similar but surprisingly different contrasts exist. Treatments 1 (CTF) and 9 (WT&T) for example show very different trends between the measurement dates and one pass with the tracked vehicle has, as indicated above, resulted in greater PR than two passes. There is no explanation for these differences, which by August seem to have largely disappeared, only to be replaced by PR values very similar to those measured in September of the previous year.

In terms of average profile soil moisture contents between measuring occasions, those taken in Sept, April and August were similar at between 25% and 26% while those in December averaged 33.7%. At these high moisture contents in December, there were few contrasts between any of the particular PR data. For those treatments which assessed the effects of subsoiling at Colworth, a very different picture emerges (Fig. 5.33). Here the effects of soil loosening were obvious on every measurement occasion, although in August 2010, they were confined to the 30-40 cm depth level. In terms of subsoiling effect, the PR data from Colworth show clear evidence of its persistence in the absence of traffic (Fig. 5.25) but the effects of traffic following subsoiling were not well tested on this site.
A perplexing and inexplicable aspect is the relative PR profiles of treatments 1 (CTF) and 9 (WT&T) on the four measuring occasions. In Sept 09 and August 10, the PR under treatment 9 was noticeably and significantly greater than under treatment 1, whereas in December and April, the opposite was the case, although differences in these latter instances were not significant when soil moisture contrasts were accounted for. A critical aspect in terms of soil response is its actual state at the time of compaction and whether applied stresses exceed those already present.

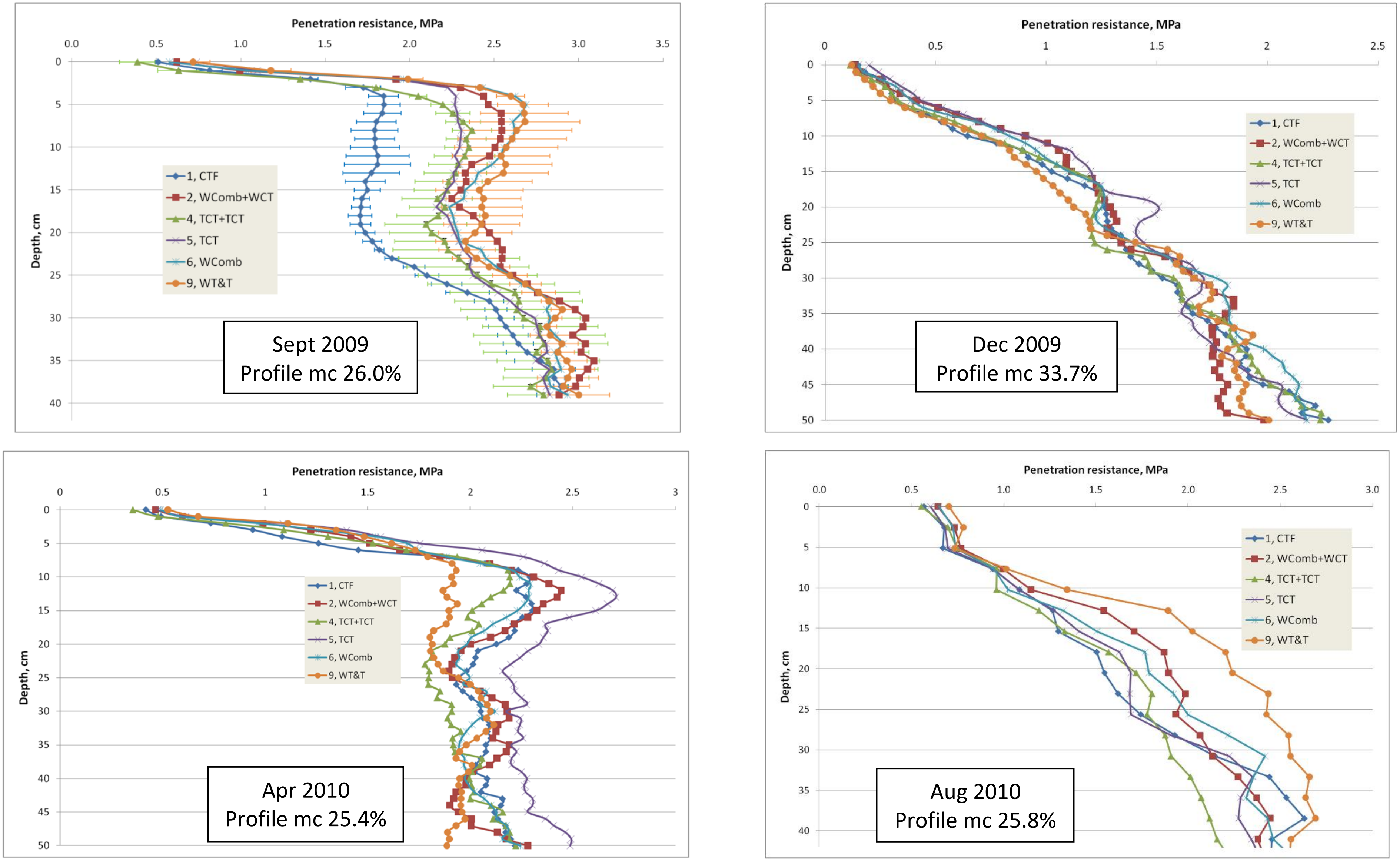
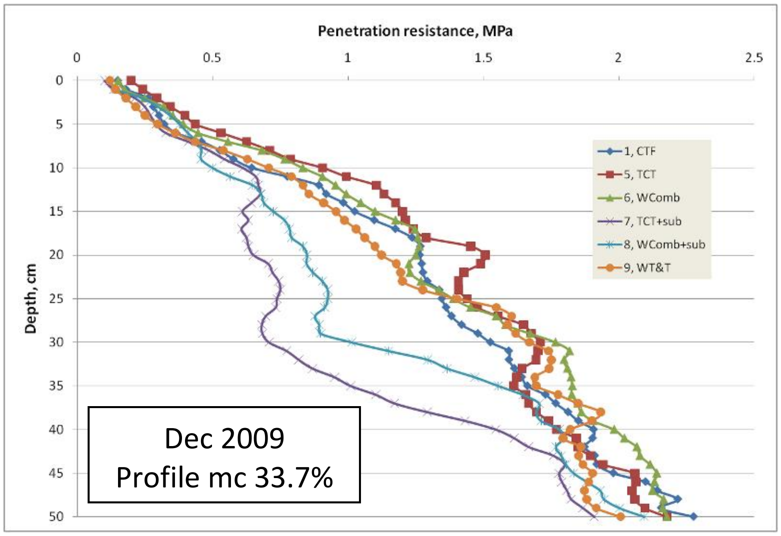
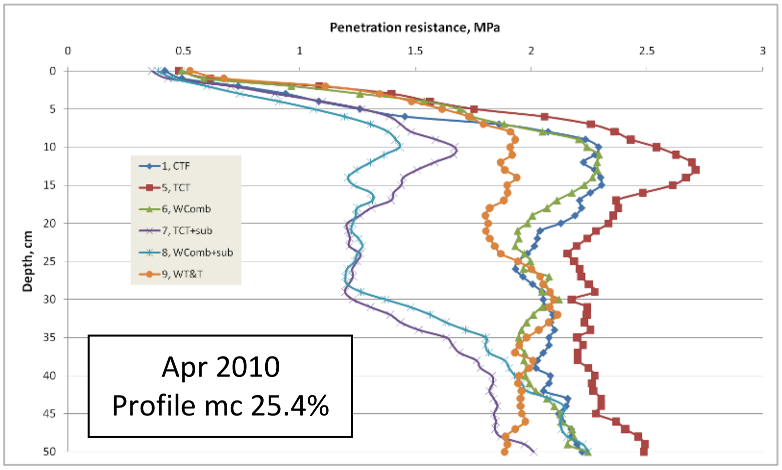


Fig. 5.32. Comparison of penetration resistance on the six treatments which were measured on all four measurement dates at Colworth





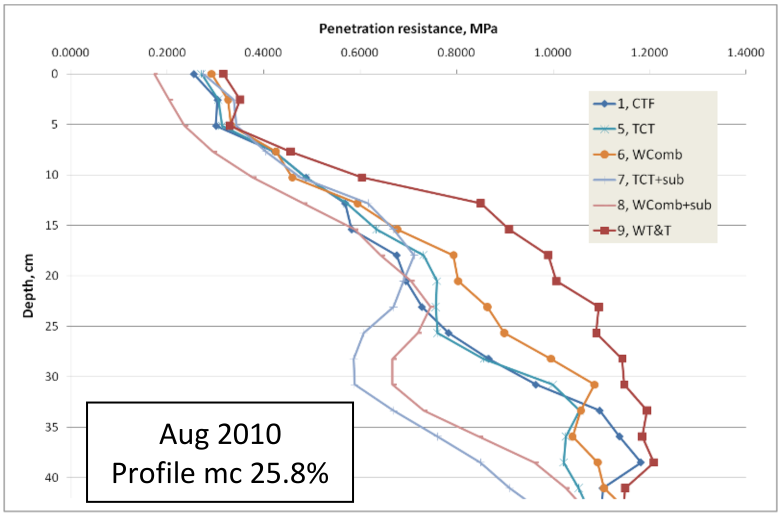


Fig. 5.33. Penetration resistance for treatments which contrasted the effects of subsoiling at Colworth

5.5.2. Moisture content, bulk density and WFPS

Results of bulk density from March 2010 at Chicksands, when measurements were taken at 12 cm depth (Fig. 5.16) serve mainly to confuse due to their irrational nature in relation to subsoiling. The only consistency is with the wheeled combine (Tr 8) where its lower density is reflected by its higher hydraulic conductivity in a separate set of measurements around one month later (Fig. 5.17). This lack of similarity between treatments 1, 7, 8 and 9 is further confounded by the resonance of PR data (Figs 5.12 & 5.13). A possible explanation is the coincidence of measuring points with areas where subsoiling had been less effective, such as midway between tines across the width of the machine.

At both the Chicksands and Colworth sites, the large contrasts in cone penetration resistance, particularly between trafficked and non-trafficked areas in September were notably absent in terms of bulk density. This differentiation between bulk density and cone resistance is not uncommon (Bennie & Botha, 1986; Taboada et al., 1999; McHugh et al., 2003, Unger, 1996), but is seldom explained or discussed. For example, which of the two measures has greater meaning or correlation with plant growth, seedbed production and soil function? Russell (1988) suggests that plant roots only grow vigorously in well-aerated moist soils and may only be affected by compaction if this restricts channels large enough for roots to penetrate. In terms of seedbed production, does a small change in bulk density lead to several fold increases in penetration resistance and can this be explained? The likelihood is that there are ranges of bulk density over which penetration resistance is only marginally affected. Elbanna & Witney (1987) suggest that resistance is a function of soil specific weight (bulk density) as well as clay and moisture content, but these data suggest that other factors may be involved, for example, soil structure and organic matter, which are likely to influence the bonding between soil particles as well as shearing resistance and cohesion. Soil function in terms of infiltration and drainage may be perfectly adequate in high strength and high density soils, providing there are a sufficient number and continuity of pores large enough to carry water. It may therefore be concluded that low bulk density and penetration resistance are only indicative of good crop performance and soil function rather than a guarantee that this will be the case.

5.5.3. Infiltration

The significantly greater hydraulic conductivity on treatment 8 (WComb+sub) at Chicksands compared with all but treatment 9 may reflect a real treatment effect in which the deep loosening led to a different outcome under the wheeled combine. It is easily observed that the more compact the soil, the greater the cloddiness produced by cultivations (Voorhees, 1983, Voorhees et al., 1978), and this could effect water movement. Certainly in the case of Treatment 1 (CTF), which was also subsoiled at the outset, the lack of initial compaction may have led to a contrast in soil conditions which to some extent was suggested by penetrometer data that lacked the contrasts of the treatments compacted before subsoiling.

At Colworth, the single measurements of steady state infiltration on each plot in March were insufficient to address the enormous variability from one position to another. Results using three replications showed a more consistent and logical trend (Fig. 5.31) with the loosened profile (Tr 7) exhibiting only a slightly greater infiltration compared with treatment 1 which had been converted to controlled traffic five years earlier without any deep soil loosening then or during this experiment. Other evidence suggesting that infiltration on treatment 1 (CTF) would be amongst the highest, is conflicting. Density for example tended to be among the higher values, but these data do not provide any indication of pore continuity or tortuosity, which are likely to have an overriding influence on infiltration.

Infiltration on the controlled traffic no-till area at Colworth was substantially lower than on the cultivated CTF plots (treatment 1) but still around 12 times greater than on the adjacent randomly trafficked no-till field (see Section 4.3.1 for more details).

5.5.4. Crop yield

The main trend in yields was for them to respond positively to zero traffic (CTF) but differences were not always significant. There were also instances when yields responded positively to tracked vehicles and where repair (deep soil loosening) of compaction had been followed by controlled traffic (Chicksands). The positive and significant yield responses to CTF from Morley in the first year were not repeated subsequently. It was not altogether surprising that there was little difference in the average yields from the tracked and wheeled traffic systems at Morley because the tracked system employed a number of wheeled vehicles that were common to the wheeled system (see Table 2.2). Differences in yields at the other sites were generally modest or bore little relation to treatment. At Chicksands, overall yields were constrained by a very dry period during the main growing phase with the expectation that water availability due to differences in soil structure might have been crucial. The absence of differences may have been due to the fact that most moisture seeking roots, and particularly in dry seasons, reach to 1 m or more (Miller, 1938; Russell, 1988), well below the depth influenced by the compaction treatments. On the heavy soil at Colworth, loosening after applied compaction suggested a consistent yield reduction, possibly prompted by the dry conditions, although there are no obvious soil data to support this. Equally however, soil that had been without traffic for some years returned one of the highest average yields suggesting a structure that was fundamentally different from those that had recently been loosened. Interesting here is the fact that although the subsoiling operation had maintained reduced soil strength throughout the growing season, crop yields did not respond positively to this, as was noted by Marks & Soane (1987) on a range of UK soils. The benefits and their longevity were also questioned by Soane et al. (1987) in terms of soil conditions. Equally, soil strength, which under the prolonged CTF treatment was generally intermediate, led to a yield significantly greater than many of the other treatments. This could suggest that it is not a certain upper level of strength that determines soil/crop performance, rather an element of strength combined with optimal structural components such as pore size and continuity and thus aeration and drainage. Similarly, structure of this nature may also be preferable for extensive root exploration, providing pores which are neither too large nor too small.

The relatively higher yields for treatments 10 (WCT) and 12 (WCT+WDT) at Colworth are difficult to explain and are not supported by any specific soil condition. The differences in moisture content for example highlighted in April do not seem to have resulted in a consistent effect on yield. The low moisture content on treatment 12 coinciding with a high yield, was not mirrored by the higher yields for treatments 1 (CTF) and 10 (WCT) where April moisture levels were close to the average. Plotting crop yield against factors such as maximum imposed loads and number of loads showed little or no correlation, but the number of loadings multiplied by each load did provide a suggestion of a correlation, as illustrated in Fig. 5.34. This is in line with Tijink (1994) quoting from Rowland (1972) suggesting that the mean maximum pressure under a wheel or track is more meaningful than the average pressure.

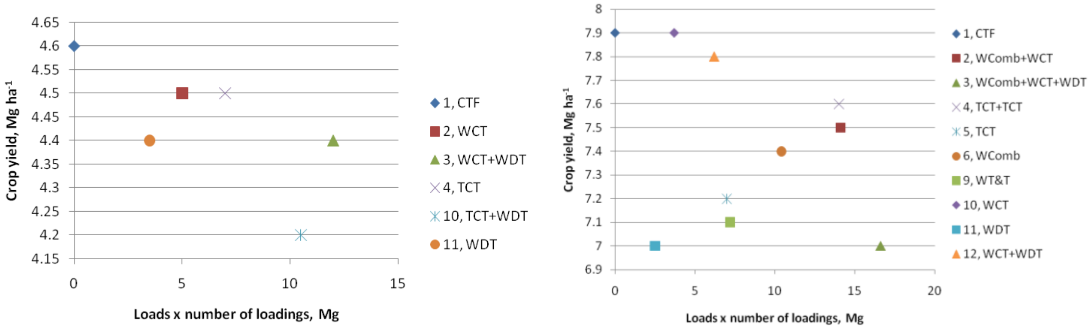


Fig. 5.34. Relationship between crop yield and the maximum individual wheel or track loads multiplied by the number of occasions they were applied (left Chicksands, right Colworth).

Most importantly, at Colworth it provides some explanation for the high yields from treatments 10 (WCT) and 12 (WCT+WDT), which were compacted with relatively light vehicles. An explanation for the low yield from treatment 11 (WDT) was not forthcoming however, nor for treatments 5 (TCT) and 9 (WT&T).

5.5.5. Tracks versus wheels

The contrast in results from tracks on the harvester compared with tracks on the tractors was almost certainly associated with track design (Fig. 5.35), the track load and the presence or absence of a following wheel. Fig. 5.35 shows that there were more idlers or road wheels on the tracked tractors compared with the tracked combine and that these covered more or less of the width of the tracks. In terms of track design, results showed that even a relatively small unsupported width of the rubber belt was found to create significantly less stress in the soil than the area under the road wheels (Fig. 5.10). Garber & Wong (1981) working with what can only be assumed are metal tracks (inferred from the date of publication because track material is not specified) found that increasing the number of road wheels reduced the maximum ground pressure and improved the uniformity of pressure distribution. Ansorge & Godwin

(2008) determined that the effect of a following tyre on the rear axle of a tracked harvester was dependent upon the stress imposed by the track. If the following tyre did not exceed the bearing capacity of the soil created by the track, no further compaction occurred and in general, this was the case. However, there was some evidence to suggest an increase where a smaller higher pressure tyre was used, as was the case with the tracked harvester employed in these experiments. An optimum design of track could be that illustrated in Fig. 5.36, where a large number of road wheels are employed but even here, there is a significant proportion of the rubber belt outside the idlers and thus contributing relatively little in terms of support. A further advantage of this track is the fact that it can rotate around its axle and therefore maintain a more even contact with the ground.

Fig. 5.35. The different track designs involved in the compaction treatments.
Top left, tracked harvester at Chicksands: top right, tracked tractor at Colworth: bottom left, tracked tractor at Morley: bottom right, tracked tractor at Chicksands

Fig. 5.36. Example of a more favourable design of rubber belt track with many idlers but still with a significant element of the belt unsupported at the extremity of its width.

5.6. ASSESSMENT OF OBJECTIVE OUTCOMES

The aim of this section is to determine whether the research answered the questions raised within the objectives.

Objective 1. What is the damaging contribution of different vehicles within a combinable crops regime and the harvester in particular?

Higher loads and repeated passes had a more profound negative effect on soil properties than they did on crop yields, but yields tended to be depressed by traffic of any nature with no discernable differential between vehicle types or running gear. Tracks had both greater and lesser effects on soil properties compared with tyres largely due to their differing loads and designs. The greatest effect was in the topsoil and was associated with a tracked harvester as also found by Ansorge & Godwin (2008).

Objective 2. Does targeted loosening of the soil followed by controlled traffic provide a more effective solution than a complete system of CTF involving the harvester?

At Chicksands, although there were no significant differences in crop yield from the different treatments, yields from the CTF plots and those loosened after compaction were all marginally greater than from the other treatments. At Colworth, almost the opposite was the case for the loosened profiles, with one of the subsoiled treatments returning the lowest yield. Based on the fact that the CTF treatment at Colworth returned one of the highest yields, it would appear that a "naturalized" soil structure without compaction or regular loosening may be the optimum. Whether this state is achieved more quickly and without risk to yield by judicious loosening of a damaged profile, only further research may reveal. One obvious outcome of the measurements at Chicksands and as found by Soane et al. (1987) was that loosening followed by traffic is particularly deleterious, with strength levels rising rapidly to their previous values with just two passes and possibly to a greater depth.

If the cost of targeted deep loosening on more fragile soils (£15-£20[3] ha^{-1} (Nix, 2008)) is less than the investment and running costs of a complete CTF system, it would be a viable option, providing controlled traffic can be maintained until the next harvest. On heavy soils, the evidence suggests that it would be questionable. In terms of soil function, loosening followed by controlled traffic had positive effects, particularly those associated with aeration and water movement.

Objective 3. Does equipping harvesters or tractors with tracks rather than wheels reduce the impact of these vehicles on the cropping system?

On the sandy loam soil at Chicksands there was evidence to suggest that the tracked harvester increased topsoil strength to a greater degree than an equivalent wheeled machine but the reverse was the case both lower in the profile at this site and generally on the other sandy loam soil at Morley. Similarly at this site, yields were improved by a tracked harvester operating within an otherwise controlled traffic regime. Other comparisons of lighter wheeled and tracked vehicles provided no consistent evidence of one being superior to the other either in terms of soil conditions or crop yield despite the tracked vehicles always being heavier than their wheeled counterparts.

An inherent advantage of tracks is that they lay down area in length rather than width and therefore with a given size of implement, they impact less of the field area. As

---

[3] Assuming subsoiling at 6-8 m centres at 5 km h^{-1} with two tines positioned in the harvester tracks

tracking of any nature tended to have negative consequences in terms of soil function and crop yield, the lower the tracked area the better the outcome on a field scale.

5.7. CONCLUSIONS

Morley and Chicksands (sandy clay loam and sandy loam respectively)

In general, deep loosened and subsequently non-trafficked compared with trafficked soil:

- always exhibited lower strength in terms of penetration resistance;
- returned higher crop yields (significant at Morley);
- had more favourable hydraulic properties.

Heavy tracked vehicles (combine harvester, 9.5 Mg per track) can increase topsoil strength beyond that of a wheeled equivalent (7.5 Mg per wheel) but may have less impact deeper in the profile. This contrast and PR profile was less pronounced with lighter tracked vehicles (7 Mg per track) and even reversed on some occasions. These differences in soil responses were almost certainly due to contrasts in track design and axle configurations between harvesters and tractors.

On these lighter soils, increasing loads and frequency of passes generally increased soil strength proportionally regardless of running gear (wheels or rubber tracks) but their effects on bulk density were less consistent. Subsoiling loosened the profile significantly but if carried out immediately, rather than several weeks after a compaction event, the effects seemed to be more persistent (Fig. 5.12). Where tracking was applied immediately after subsoiling, only two machine passes were needed to return the soil to its previous or a rather worse condition in terms of strength. In all cases, non treatment-trafficked soil retained lower soil strength both before and after subsoiling and for the duration of the experiment. Similarly, hydraulic conductivity was improved by these conditions as was crop performance.

Although yield differences between non-trafficked and trafficked conditions were not always statistically significant, yields from non-trafficked soil were never less and ranged from 5% to 16% greater than their compacted counterparts irrespective of 10 cm or 22.5 cm depth of cultivation. There was no discernable benefit from using lighter tractors and fewer passes after the soil had been deep loosened, but subsoiling without further traffic had a beneficial effect on yield. Where a well designed tracked vehicle was used conventionally within a controlled traffic system, there was evidence of a yield improvement compared with a similar system involving compaction from a wheeled vehicle (Morley, Fig. 5.6).

Colworth (clay)

On this soil, there was some evidence to suggest that the rubber tracked tractor with a weight of 7 Mg per track (also used to simulate a combine harvester) had not increased strength and density to the same degree as the wheeled harvester (7.3 Mg per wheel) or other lighter wheeled vehicles, but effects on water filled pore space were inconsistent over time. Although the effects of subsoiling to 35 cm depth were very evident in terms of soil conditions at 15 cm depth, such as lowering strength (by c.27%)

and density (by c. 24%) while improving infiltration (by c. 30%) at the surface, these benefits were not generally reflected in crop yields in a season with a dry spring and early summer.

In contrast, the maintenance of non-trafficked soil for six years on a calcareous clay soil delivered conditions more favourable for yield (c. 10% increase) and water infiltration (c. 60% increase) and in general, soil strength compared with trafficked conditions.

Soil which had not been trafficked for six years (without prior loosening) exhibited a higher PR and density compared with the same soil subjected to a harvester pass followed by deep loosening and controlled traffic. The effects of deep soil loosening followed by controlled traffic were discernable after four years as revealed by a 29% reduction in penetration resistance (compared with no loosening) in the 10-30 cm depth profile. Bulk density in the top 15 cm was generally increased by traffic and decreased by subsoiling while the reverse was the case in terms of water filled pore space.

Modelling

The fact of a tenuous negative relationship at Chicksands and Colworth between crop yield and the product of the maximum individual wheel or track loads and the number of passes, suggests that predicting traffic effects on yield may be possible. However, far more data from different climates and soils would be needed to confirm this relationship.

CHAPTER 6

6. A study of CTF systems and their economics

6.1. INTRODUCTION

Controlled traffic farming is any system which confines field traffic to the least possible area of permanent traffic lanes. This definition prescribes neither the tillage to be employed nor the area of the traffic lanes, which are decided by the practitioner and the constraints under which they are operating. However, these aspects impinge heavily on the economics which will be determined by:

- the cost and timescale of conversion to CTF;
- the running costs of the CTF system;
- the return in terms of sustained crop yields.

Taking the last of these factors first, crop income will depend upon:

- yield from the non-trafficked beds;
- yield from the cropped traffic lanes.

Work by Chamen & Audsley (1993) considered all these aspects other than the cost and timescale for conversion to CTF (see economics section in literature review (Chapter 2)). In their definitive study of a rotation of wheat, barley, beans and oilseed rape (OSR) using the Silsoe Arable Farm model (Audsley, 1981), detailed account was taken of the rates of work, timeliness of operations, energy inputs and the transmission efficiencies of the different machinery involved, including both conventional and gantry tractors. The 6 m tractor-based CTF system was found to be £18 ha^{-1} less profitable than conventional plough-based practice on medium soil, but £25 ha^{-1} more profitable than the same comparison on heavy soil. Gaffney & Wilson (2003) in their comprehensive desk-top study used a steady state analysis technique to calculate long-term average costs and returns for four different systems based on a five-year rotation in Australia. They included some of the implementation costs and considered reductions in field efficiency for the CTF systems as well as testing yield effects and input savings. Their cautious estimate of the benefit of changing to CTF based on a 3 m track gauge for all equipment was AU$32 ha^{-1} (£19 ha^{-1} at March 2011 prices).

Assumed in the work by Chamen & Audsley (1993) was a yield increase on non-trafficked soil of 7% compared with traditional practice based on research up to the early 1990s. Evidence presented in the literature review forming part of this thesis, suggests that the greater damage caused by machines that have grown heavier over the intervening years has driven this up to an average reduction in yield across eight crops of around 12% compared with no traffic. Responses across crops varied however as indicated in Fig. 6.1 with the average for wheat rising by just 1% to 8%. The relatively larger responses from barley and oats compared with wheat reflect the fact that most of these crops were sown in the spring rather than pre-winter. This almost certainly also reflects that the potential for soil damage is greater in the spring when the profile is usually drying rather than wetting. Unfortunately only one set of data is available for OSR (Chan et al., 2006) suggesting a 34% reduction in yield caused by traffic. However, Chan et al. (2006) also quote from four papers reporting positive responses to deep soil ripping before planting OSR with an average increase in yield of 18% compared with sites without deep ripping.

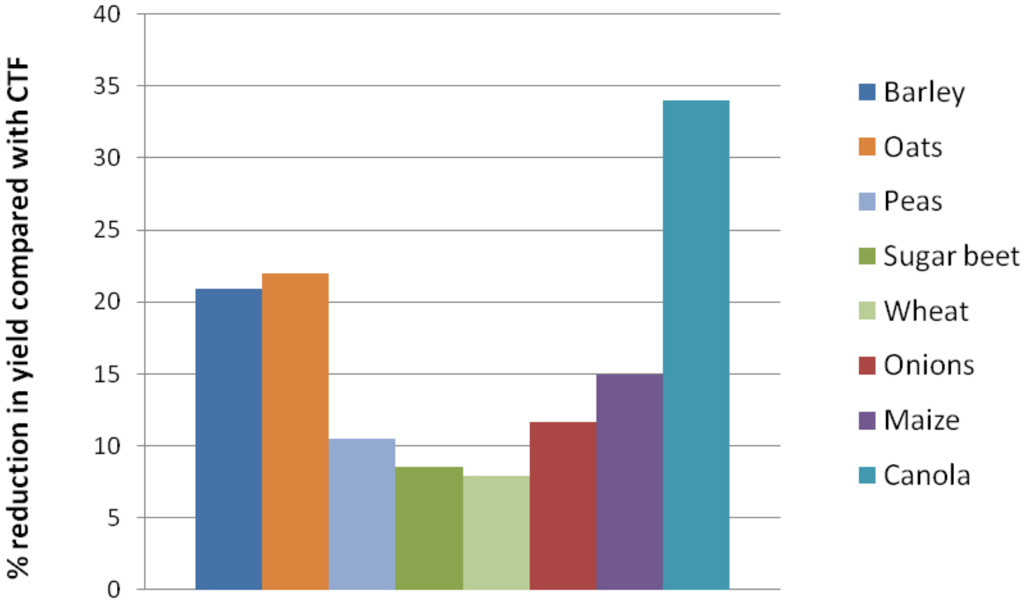


Fig. 6.1. Percent loss in crop yield of different crops grown on soil with traditional traffic management compared with non-trafficked soil. (see Literature Review)

A further impact on yield which is less likely to be apparent from research is the fact that most CTF systems do not employ the plough on a regular basis and maybe not at all. In this situation, Chamen & Audsley (1993) assumed that an extra £57 ha^{-1} (at 1993 prices) would be needed to sustain yields in terms of additional chemical weed control measures. Nearly 20 years later and changes in machinery, chemicals and management skills mean that this disparity is less obvious (Richards, personal communication, March 2011). This is also confirmed by data from Colworth (see section 4.2.1) which show no consistent difference in herbicide costs between tillage or traffic but an increase in molluscicide use (Table 6.1).

It is also very dependent upon the skills of the individual in terms of operations and their timing. Part of this is learning how to manage non-trafficked soil optimally in terms of tillage, weed control and crop residue management as well as the cropped traffic lanes. Yields from cropped traffic lanes are an integral part of the economics of any CTF system but research data are either lacking or are considered to be the traditional practice against which non-trafficked soils are compared (e.g. Jorajuria & Draghi, 1997). Measurements at Colworth (Chapter 4) taken after 2-4 years of controlled traffic, with seasonal passes of a harvester and two tractor operations suggested that yields of wheat and barley in the intermediate traffic lanes were reduced by an average of 10% compared with traditional practice.

Table 6.1. The average cost across fields (£ ha^{-1}) of different inputs associated with cropping, traffic and establishment method over two seasons from 2007 at Colworth.

Traffic system	Establishment method	Crop & variety	Seed	Herbicide	Molluscicide	Field work
2007/2008						
Random	Non-inversion	WWheat, Cordiale	71	64		157
CTF	No-till	WWheat, Cordiale	69	67	18	103
Random	Non-inversion	WOSR, Castille	38	44	10	170
CTF	No-till	WOSR, Castille	44	35	33	105
Random	Plough	W. beans, Wizard	57	84		139
CTF	No-till	W. beans, Wizard	57	67		50
Random	Plough	S. barley, Tipple	62	23		147
Random	Non-inversion	S. barley, Tipple	62	31		162
Random	No-till	S. barley, Tipple	62	43		71
CTF	No-till	S. barley, Tipple	62	42		64
2008/2009						
Random	Non-inversion	SOSR, Palladium	47	52	10	153
CTF	No-till	Exclbr/Palladium	100[1]	58	29	76
Random	Plough	S. beans, Fuego	66	51		170
Random	No-till	S. beans, Fuego	66	62		51
CTF	No-till	S. beans, Fuego	66	57		51
Random	Non-inversion	S. barley, Tipple	52	74		105
CTF	No-till	S. barley, Tipple	51	65		51
CTF	No-till	Wheat/barley	138[2]	98	24	105

[1] Winter OSR Excalibur was replaced by Spring OSR (Palladium) due to slug damage

[2] The initial crop of wheat failed due to slug activity and was sown to barley in the spring

The cost of conversion to CTF is influenced by the timescale; the longer this is the greater is the likelihood that the transition will follow a normal machinery replacement policy. The only difference in the policy will be to select machine and track widths that are compatible with the CTF system chosen. It is probable that some machinery modifications or more costly alternatives will be required however, either in the form of wheel centres to achieve a particular track width, or with the length of combine harvester unloading augers, as indicated by Chamen (2005). The principal and major cost of conversion will be for the satellite guidance system and the correction signal needed to steer vehicles to the sub decimetre level. Two principal options exist, either a satellite or a ground based correction, the latter referred to as Real Time Kinematic (RTK). Although it is possible to use the satellite based correction signal for CTF, it is of lower accuracy (±100 mm) than RTK (±20 mm) and needs a manual correction on practically every pass across the field. Presently RTK is more expensive but its cost is reducing year on year while availability is also increasing rapidly. In some countries it is already being offered free and will almost certainly become the generic correction signal in the future. Typical costs for an RTK base station that provides the correction over a radius of around 10 km is £12,000 plus the cost of installation. The base station can auto-steer any number of machines, each of which have their own receivers, which if "auto-steer" ready cost around £15,000 each. Equipping vehicles with the hydraulics for auto-steering can cost an additional £5,000, or a motorised system can be attached to or replace the existing steering wheel with similar associated costs.

The return on investment in guidance systems with the less accurate and time dependent (15 minutes) repeatable positioning using a satellite based correction signal can mostly be justified on the basis of reduced overlaps alone. Costs for this are around £10,000 for each vehicle receiver assuming the vehicle is auto-steer ready. In addition to this is a monthly licence fee for signal reception at around £100 month^{-1}. Typically this provides a 3% reduction in overlap area during the application of chemicals compared with traffic lanes created by physical markers during crop drilling. This reduction can be supported by extensive satellite imagery, such as is available from Google Earth (http://www.google.co.uk/intl/en_uk/earth/index.html) or as indicated in the research by Batte & Ehsani (2006). With the RTK correction, overlap savings of around 4% can be anticipated as a result of guidance delivering pass to pass accuracy of ± 20 mm with no time dependency.

The running costs of a CTF compared with a traditional system are likely to be influenced by:

- the depth and intensity of tillage needed to maintain or repair soil structure and to create an appropriate seedbed;
- the relative efficiencies of the machine systems, governed largely by the rolling resistance of the vehicles and their operational efficiency in the field;
- weed and pest control;
- fertiliser use efficiency;
- interest on capital investment.

As well as the soil conditions which influence crop yields, timeliness of sowing and other operations have a critical influence. These are governed by the number of days available for particular operations on different soil types, local weather and the work rate of the operation concerned. Spraying for example can only be carried out on a fraction of the days when ploughing is possible because it is not only influenced by the soil conditions and local rainfall, but also the wind speed. It is immediately obvious that assessing the economics of any field production system is complex with many influencing factors. Most economics assessments cannot deal with this complexity and therefore only provide partial solutions. In contrast, the Silsoe Arable Farm Model (SAFM) (Audsley, 1981) is a linear programming system that can assess the economic and technical bounds within which a machine or system must operate if it is to be commercially viable. It can provide a complete representation of any farming system, taking account of energy inputs and work rates as well as the days available for different operations on different soils under different rainfall conditions. With these data built or fed in to its input screens, it calculates farm gross margins (FGM). These are the sum of the crop gross margins less rotational losses, timeliness losses for drilling and harvesting, labour, and machinery costs including fuel and repairs. This is equivalent to profit before deduction of fixed costs such as rent, office etc.

6.2. CONTROLLED TRAFFIC SYSTEMS

To realize any controlled traffic system requires matching of all the track gauges of the field vehicles and machines involved as well as the implement operating widths. Particular attention is drawn to the term “operating” in the context of implements because with a guidance system it can be practical and cost-effective to use implements at less than their actual width. In the Australian grains industry, it is common practice to match all track gauges to that of the harvester and a standard of 3 m has been adopted, this being achievable on most harvesters without modification (Tullberg et al., 2003; Vermeulen et al., 2010). In Europe, this is less practical because it often makes the overall width of all vehicles wider than the farm tracks or roads upon which they need to drive (Vermeulen et al., 2010). Compromises have therefore been made and have led to a number of different tracking systems (Chamen, 2005), which include the system depicted in Fig. 6.2. One difficulty with this and other systems is the length of the unloading auger of the harvester, which must reach a trailer or chaser in the adjacent tractor track. This often requires either a longer standard auger or extension of the longest auger available. Although this system has some constraints, it is also flexible in that implement widths can be matched by small changes to the tracks widths of the vehicles. A further system is one that has an implement width which is different from the harvester cut width as well as two track gauges. For this system to work it has to satisfy the following relationship:

Implement width = 2 x harvester track gauge, which must be one third of the harvester cut width.

Other systems are possible because there are no “hard and fast rules” with CTF, it is simply a matter of minimising the tracked area conducive to practicality and cost effectiveness, the latter being dominated by the trafficked area where yields are compromised. The following study addresses some of these issues.

6.3. AIMS AND OBJECTIVES

The aim of the research described here was to assess the relative profitability of a traditional farming system with an element of machinery guidance using a satellite-based correction signal and no traffic control and a CTF system using an RTK correction signal delivered to the key machines. The objective was to achieve this basic comparison by using data from a farm recently converted to a controlled traffic system and then test the relative importance to farm profit of different aspects of the CTF systems, such as yield responses, timeliness and machinery investment.

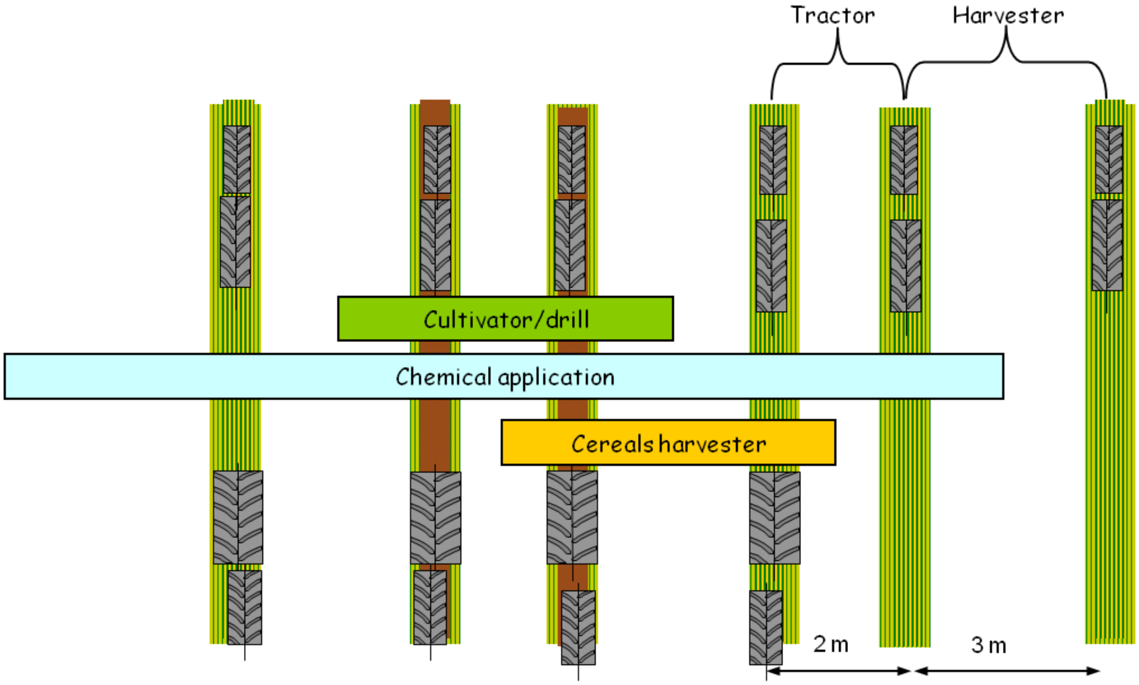


Fig. 6.2. A CTF system where tractors straddle adjacent passes of the harvester. *Implement width is the addition of the two track gauges – in this case 5 m (after Shaw, personal communication, 2005)*

6.4. METHODOLOGY

The basis of the assessments was a 1400 ha farm in Nottinghamshire (Farmeco) which had converted in 2009 from a traditional farming system of non-inversion tillage to one using an 8 m CTF system with little or no tillage and direct seeding, as described by Roberts (2010). In general, new prices for the machines were taken from the farm records but where these were absent they were taken from Nix (2008) with a 9% allowance for inflation. Where specific required sizes were not quoted, equations were developed from the range of sizes given. Table 6.2 outlines the prices researched for the various machines and guidance systems used by Farmeco.

With the traditional system, auto-steer was provided on the combine harvester with a laser which detects the edge of the cut crop and steers the vehicle accordingly. For the other three vehicles, satellite-based correction receivers were installed but licenses to receive the signals were only purchased for three months on two of them and for 12 months on the third. These were added as variable costs. When CTF was introduced, the correction signal changed to a Real Time Kinematic (RTK), this affording higher accuracy and repeatable positioning. As the farm also purchased its own base station, there was no ongoing license cost.

Table 6.3 provides an outline of the operations used to establish, tend and harvest the crops in the two year rotation of wheat and OSR. Table 1B of Appendix B provides details of the amount and price of chemicals applied. In the traditional system, around

Table 6.2. Operating widths and purchase prices of the principal machinery used in the study.

Machine or equipment	Width, m	Purchase price, £ Traditional	 CTF
Horsch Terrano cultivator	7.5	34,998	
Knight Triple press	8	50,000	
Subsoiler + broadcaster + press	4	14,000	14,000
Simba Freeflo cultivator drill	6	54,000	
Väderstad Seedhawk tine drill	8		58,814
Horsch Optipak tyre press	8		24,000
Simba X-press disc cultivator	4		18,000
Wil-Rich spring tine cultivator	8		1000
Rolls	9	18,500	
Self propelled sprayer	36	123,500	
Trailed sprayer (x 2)	24		79,672
Combine harvester, 74 Mg h^{-1} gross	9	275,225	
Combine harvester, 64 Mg h^{-1} gross	9		230,827
All Terrain Vehicle (ATV)		8,000	8,000
118 kW 4 wd tractor		57,706	61,633
118 kW 4 wd tractor (2nd of two in CTF system)			61,633
170 kW high speed tractor		79,470	
224 kW 4 wd tractor			113,679
246 kW 4 wd tractor			124,481
300 kW rubber tracked tractor		187,400	
372 kW articulated 4 wd tractor		186,348	
Navigation and autosteer:			
Satellite-based correction	3 machines	30,000	
Signal licenses (machines/months) @ £105 $month^{-1}$	2x3 & 1x12	£1.35 $ha^{-1}a^{-1}$	
RTK correction	4 machines		61,000
Base station and repeater			13,000
Total investment		1,119,147	869,739
	Capital saving with CTF		249,408

10% of the area was deep loosened each season with this being targeted on known problem areas, such as headlands. This was generally achieved during establishment of the OSR crop with an ageing deep cultivator in combination with a press in front of which seed was broadcast. Phosphate and potash were all applied in liquid form with the traditional system and as solids during drilling with the CTF system. With the CTF system, headland compaction is confined to the outer 8 m of the headlands. This is dealt with on about 5% of the total area annually, either while establishing OSR using a 4 m

Table 6.3. Sequence of machinery operations used to establish, tend and harvest wheat and OSR at Farmeco

Traditional system before conversion to CTF		**After conversion to CTF**	
Machinery	Width, m	Machinery	Width , m
Wheat			
Tine + disc cultivator + triple press	7.5	Desiccate weeds	24
Cultivator drill	6	Disc cultivator (on some headlands)	4
Rolls	9		8
SP sprayer	36	Tine drill + press	24
Combine harvester (74 Mg h^{-1} gross)	9	Trailed sprayer	8
		Combine harvester (64 Mg h^{-1} gross)	
OSR			
Tine + disc cultivator + broadcast + press	7.5	Tine drill + tyre press	8
Rolls	9	Subsoiler + broadcast + press	4
Subsoiler + broadcast + press	4	Trailed sprayer	24
SP sprayer	36	Combine harvester (64 Mg h^{-1} gross in wheat)	8
Combine harvester (74 Mg h^{-1} gross in wheat)	9		

subsoiler fitted with a seed broadcaster followed by a press. With shallower compaction, a separate pass with a disc cultivator is used in front of the wheat drill. The inputs required for the different soil engaging operations were based on the same concepts as those described by Chamen & Audsley (1993) with some revision to account for change in equipment and practices. For example, the spraying operation in this study used a self-propelled machine and faster road travel speeds and refill times. Water quantities have also diminished since the early 1990s from around 200 litres per hectare to 150. Unlike the analysis in 1993 where machine numbers were estimated, the number of machines in this study was known from the farm data and it was necessary therefore to align work rates and time available to match the numbers actually on the farm. It was also necessary to calculate forward speeds and power requirements to allow for differences in soil conditions. The literature review suggested that for tillage operations to around 100 mm depth, the draught on non-trafficked soil would be around 37% less (average from Table 2.8), as compared to trafficked soil. In terms of the CTF operations involved in this study, the figure related principally to the tine drill but because around 25% of the area is trafficked (Fig. 6.2), the actual reduction in draught experienced would be around 28% (0.75 x 0.37), not allowing for any additional draught associated with the compacted wheel tracks. A conservative estimate of 25% was therefore assumed. As the formula used by the model to calculate the work rate for drilling incorporates factors associated with hopper size, time to refill, maintenance, field size and distance from the farmstead, the only way a reduction in draught can be allowed for is to increase the engine power of the pulling tractor. To translate the

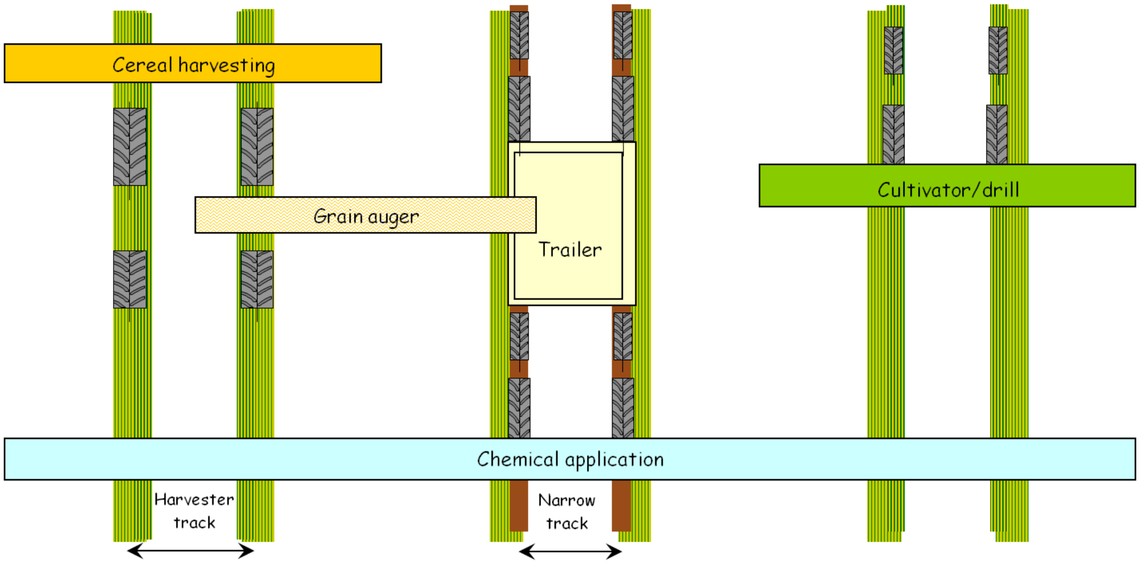


Fig. 6.2. Scaled illustration of the type of controlled traffic system adopted by Farmeco. The tracked area of the system is around 25%, of which the wider track of the harvester contributes 10%.

reduction in draught to engine power, an allowance has to be made for transmission efficiency, rolling resistance and wheel slip. Data from Chamen & Audsley (1993) suggest a transmission efficiency of 0.88 for mechanical transmissions and a tractive efficiency of 0.715 for four-wheel drive tractors, although the latter maybe somewhat better on permanent traffic lanes, so a figure of 0.8 was assumed. An overall figure for power amplification at the tractor may therefore be calculated as 0.25 x 0.88 x 0.8 = 0.176. This was tested as a separate scenario for the tine drill in the CTF system. It was also the case that the drill used in the traditional system had a high element of cultivation built into it and an associated high draught requirement. To account for this, it was assumed that the lower engine power of the tractor used in the CTF system could achieve a similar work rate to the traditional system, as indicated in Tables 2A & 3A of the Appendix.
The work rates for harvesting overall were calculated on the basis of 70% of the gross output of the combine in wheat (Chamen & Audsley, 1993), with the work rate in OSR being slower and calculated as 4.05 $y\ T^{-1}$ where y is the yield in Mg ha^{-1} and T the combine gross output in Mg h^{-1}.
The following provides an overview of the initial assumptions for running the model. 1400 ha farm on a clay soil with a two year rotation of OSR and winter wheat with prices estimated for 2011;

1. Traditional system. 74 Mg h^{-1} gross output combine steered with a LASER system, three auto-steer satellite based correction receivers. Crop establishment with a tine cultivator and press and a cultivator drill followed by rolls. 10% of the area subsoiled each season.

2. CTF system. 64 Mg h^{-1} gross output harvester, four auto-steer RTK correction receivers together with an RTK base station and one repeater. Crop establishment by direct drilling with 5% of the area being subsoiled each season.

6.5. RESULTS AND DISCUSSION

Table 6.4 shows results for the initial or baseline assumptions which were summarised above. Table 6.5 provides a comparison between data from Nix for a traditional crop production system and the results for the traditional system in this study.

Table 6.4. Costs and profitability for the two farm scenarios with initial assumptions for the CTF system

Farm system	Regular employees, no.	Fixed costs, £ ha^{-1} (machinery only)	Crop gross margins, £ ha^{-1}	FGM, £ ha^{-1}
Traditional	2.3	178.06	1289.60 (wheat) 1230.30 (OSR)	968.30
CTF	2.2	137.72	1283.90 (wheat) 1228.00 (OSR)	1042.70

Table 6.5. Comparison of crop yields, prices and crop gross margins for traditional systems quoted by Nix (2008) and those assumed and calculated in this study.

Source	Crop yields, t ha^{-1}		Crop prices, £ t^{-1}		Crop gross margins, £ ha^{-1}	
	Wheat[1]	OSR	Wheat[1]	OSR	Wheat[1]	OSR
Nix, 2008	9.75	4.25	135	300	805	810
This study	10.2	4.1	140	300	1290	1230

[1] Feed wheat

From this it can be seen that the variable costs associated with the crop gross margins calculated in this study were appreciably lower. They were therefore checked against current good commercial practice (Richards, personal communication, March 2011) and found to be in line, as indicated in Table 1B of Appendix B. The only difference between inputs for the traditional and the CTF system is an assumed greater cost for molluscide based on experience from some farms operating with CTF and no-till (Table 1B, Appendix B).

The improved profitability shown in Table 6.4 with the CTF system was accompanied by a £249,408 lower capital investment in machinery, representing a 22% saving compared with the farm's previous traditional practice. This compares with a 69% saving predicted by McPhee et al. (1995b) although this was with irrigated double cropping in semi-arid conditions with a more complex traditional system. The number of machines selected by the model and their associated costs are shown in Table 6.6.

Table 6.6. Numbers of machines and their associated annual costs predicted by the model for the traditional and controlled traffic systems

	Traditional farming system			Controlled traffic system		
Description	Number	Annual cost, £ unit^{-1}	Total cost, £	Number	Annual cost, £ unit^{-1}	Total cost, £
Regular labour	2.3	14,700	33,810	2.2	14,700	32,340
Tractors, 110 kW	1.5	14,819	22,229			
Tractors, 118 kW				1.2	15,828	18,994
Tractors, 224 kW				0.3	29,193	8,758
Tractors, 246 kW				1	31,967	31,967
Rubber track tractor, 300 kW	1.1	48,150	52,965			
Artic. tractor, 372 kW	0.6	47,854	28,712			
Hi speed tractor, 171 kW	0.8	20,408	16,326			
Auto-steer - satellite correction	2.1	7,704	16,178			
Auto-steer - RTK correction				1.6	19,003	30,405
Horsch Terrano cultivator	0.6	4,585	2,751			
Triple press	0.6	12,840	7,704			
Simba Freeflo drill	1.1	13,867	15,254			
Subsoiler + press	0.2	3,595	719			
Rolls	0.8	4,751	3,801			
Väderstad Seedhawk drill				1	15,102	15,102
Horsch Optipak tyre press				1	6,163	6,163
Simba X-press disc cultivator				0.1	4,622	462
Slug pelleter	0.9	524	472	0.4	727	291
All terrain vehicle (ATV)	0.9	2,054	1,849	0.4	2,054	822
Self propelled sprayer	0.7	20,892	14,624			
Trailed sprayer				0.7	6,739	4,717
Claas 580 tracked combine				0.7	59,276	41,493
Claas 600 tracked combine	0.8	43,807	35,046			
	Total farm costs		252,439			191,513

One of the differences between the traditional system and the new controlled traffic operation is that the latter has a smaller throughput harvester. If the larger harvester is substituted, farm profit is increased by £9.60 ha^{-1} (Table 6.7), reflecting the interactive effect that the harvest workrate has on the time available and timeliness of subsequent operations. However, it will be noticed from Table 6.2 that the operating width of the combine harvester is 8 m, rather than the 9 m offered by its cutting platform. This is the constraint of the controlled traffic system on the harvester, but is compensated by increasing forward speed. Having a larger capacity harvester may therefore not actually be more profitable in this context because the additional forward speed needed to maintain throughput may not be practical or achievable. A further sensitivity test applied was the potential for a reduction in draught on the tine drill due to CTF. As mentioned in the methodology, this was investigated by assuming an extra 17.6% of engine power available at the same tractor cost. Results suggested an increase in profit of £7.50 ha^{-1} for the CTF system over and above the baseline figure of £74 ha^{-1} (Table 6.7)

Because the results suggest a 7.7% increase in profit for the controlled traffic system, investigating the effects of a crop yield increase due to CTF would just add an

Table 6.7. Summary of baseline results together with sensitivity and other assessments which either add or subtract to the baseline results

Farming system	**Sensitivity test**	**Farm profit, £ ha^{-1}** Traditional	 CTF
Traditional	**Baseline**	**968.30**	
Controlled	**Baseline**		**1042.70**
traffic	74 t h^{-1} harvester compared with 64 t h^{-1}		+9.60
	Lower drill draught (extra engine power)		-7.50
	4% & 9.5% yield increases for wheat & OSR		+87.00
	respectively		+3.13
	Greater accuracy with RTK		-6.90
Traditional	6% timeliness penalty for wheat, Oct 8th – Oct 21st	-8.10	
	6% timeliness penalty for wheat, Oct 8th – Oct 21st		

equivalent percentage in profit. The predicted net increase in field yield based on an 8% increase for wheat in the non-trafficked beds and a 10% reduction in the cropped wheel tracks, is shown in Table 6.8. This 4% increase in yield for wheat would add £57 ha^{-1} to the return from the wheat area. Yield data for OSR are less certain but results from Spink et al. (2009) and Hamilton et al. (2003) suggest that an increase of 15% would not be unreasonable.

Table 6.8. Example of calculation matrix to determine net field yields of wheat from the tracked area of any particular controlled traffic system.

Non trafficked yield increase cf. conventional random traffic, %					8
Yield reduction in wheel tracks cf conventional traffic, %					10
Tramline spacing, m	**Tracked width of tramlines, m**	**Tracked area of tramlines, %**	**Tracked area of CTF system, %**	**Extra area tracked by CTF system, %**	**Net yield increase, %**
24	0.8	3.3	25.5	22.2	4.0

Using the same calculator, the net field yield response for this controlled traffic system growing OSR would be 9.5%, adding around £117 ha^{-1} return for this crop and an overall 17% increase in profit to the farming business. Without any yield benefits the extra £75.40 ha^{-1} profit from the CTF system still provides a reasonable buffer for any additional chemical costs that may be associated with non-inversion techniques. This increase in profit is less than that predicted by Bowman (2008) but his study, also based on actual farm enterprises, considered the additional cropping that CTF could bring in the predominantly dry climate of Australia. His calculations suggested a 17% return on capital investment but that is less easily calculated in this study because second hand prices of the traditional equipment are unknown. A shortcoming of this study is that two parallel farms have been assumed with all new equipment on each.

Based on the gross costs for controlled traffic equipment, the return on investment is around 14% with a payback period of 7 years. The benefit is also less than that predicted by Mason et al. (1995) in their desk top study based on a farm property in Australia growing wheat, maize, soybeans and sorghum. They questioned whether an increase in profit of £102 ha^{-1} at 1995 prices was sufficient to compensate landholders for the increased complexity of CTF and direct drilling. This is in complete contrast to the view of the Farmeco landholders who clearly identify the simplicity that CTF brings to their farming operations (Roberts, 2010). A further test of interest is to consider the effect of a reduction in crop prices, which in 2011 are high compared with historical prices. Reducing both crop prices by 30% nearly halved the profit but maintained the monetary difference between the systems at an almost identical level of £73 ha^{-1}. However, in terms of profitability, the CTF system was now nearly 13% more profitable than conventional practice rather than the baseline value of 7.7%.

Looking in more detail at the results there appears to be some spare capacity in the CTF machinery, but this does not include the drill or the tractor pulling it, which are both fully utilised, as indicated in Table 6.6. The time period for drilling could be extended but with an end date already well into October, timeliness penalties are likely to become a significant factor. Spink et al. (2000) assessed the effect on winter wheat yield of time of sowing over two seasons with six different varieties. They found that wheat yield was reduced by an average of 0.65 t ha^{-1} (6%) if time of sowing was delayed from the end of October until the middle of November. In the baseline results no timeliness penalties for the sowing of wheat were included for either system, but if a 6% yield penalty is applied to wheat sown between October 8 and October 21 (the latest period presently allowed by the model), profit was reduced by £8.10 ha^{-1} for the traditional system and by £6.90 for the CTF system, with no change in machinery complement for either system. If this penalty is increased to 5%, profit drops by £6.80 ha^{-1} with no change in machinery. This suggests that the traditional system is slightly more sensitive to time constraints, as may be expected from the additional operations involved. In terms of the spare capacity for the trailed sprayer, the additional machine purchase was planned by Farmeco largely for contracting operations.

Mention was also made in the introduction of the potential for the more accurate guidance offered by the RTK correction to deliver a 1% reduction in chemical costs compared with the satellite based correction used within the traditional operations. Referring to Table 1B (Appendix B), this saving would add £3.13 ha^{-1} to the profit for the CTF system. These and all the other sensitivity tests are summarised in Table 6.7.

A crucial argument missing from the discussion so far is that these lower inputs and running costs could just as well be achieved within a random traffic scenario, in essence a conventional no-till system. Some additional costs would be incurred in terms of the greater draught requirement of the drill but these are unlikely to offset the extra profit indicated. The main question therefore is about any yield penalty associated with a randomly trafficked no-till system. The farm manager at Farmeco stressed that on his land he would not contemplate changing to no-till without traffic control. Certainly the limited literature would tend to support this view with an average reduction for OSR and wheat in the range 4-10% when converting to no-till within a conventional traffic system. To calculate the effect of this with the mathematical model would need some further interaction with the farmer to determine the machinery needed. At best it would be a reduction equivalent to an average yield loss of 7%, equating to approximately £95 ha^{-1} across the whole farm. Often, those practising direct drilling techniques will employ rotational deep loosening of the soil to counteract the build up of compaction, but this is by no means a universal practice. According to Nix (2008), deep loosening costs around £53 ha^{-1} and if employed on one third of the Farmeco farm each year, would cost an additional £17.80 ha^{-1} and increase the profit differential between the systems by 9.9% bringing it to 17.6% in favour of the CTF system.

6.6. CONCLUSIONS

Data from a 1400 ha commercial farm that converted to a CTF system in 2009, suggests that the capital investment in the machinery needed for growing OSR and wheat on a clay soil is reduced by 22%. Similarly, the controlled traffic system increased net operating profit (excluding buildings and land costs) by around 8% (£74.40 ha^{-1}), without taking into consideration any increase in yield. With an increase in yield of 4% for wheat and 9.5% for OSR estimated from research data, net operating profit would increase by around 17% overall. Included in the conversion to controlled traffic was a change to direct drilling of both crops over most of the area. Although there are relatively few data regarding lower yields under trafficked no-till compared with conventional tillage, a predicted average 7% reduction would have compromised Farmeco income by around £95 ha^{-1} if they had not also changed to CTF. Soil deep loosening might counter this problem but would, if carried out on a rotational basis on one third of the area, cost £53 ha^{-1}. Without any yield improvement, this would increase the profit in favour of the CTF to nearly 18%.

Throughput of the combine harvesters used in the systems had a measurable impact on profitability. If the larger harvester used by the traditional system were also used with the CTF system rather than the smaller capacity machine, an additional £9.60 ha^{-1} would raise overall profit by 1%. The model suggested that the CTF system was over stocked in terms of some of the machinery, particularly the trailed sprayer and intermediate sized tractor, the latter combination being used for contracting, the income from which was not considered.

CHAPTER 7

7. Discussion

A number of things have become obvious over the six years of this study, most of which have become apparent in the last twelve months! Maybe there's something about the blindingly obvious that hides it from the human psyche until such time as we are in the right frame of mind to accept it! This frame of mind was initiated when someone asked, "does controlled traffic work?" The question should actually have been, "is it possible to achieve controlled traffic in a practical and cost effective manner" because there is absolutely no reason why the soil management part of it should not work. If we can't improve crop output and soil function by removing traffic, it's not that removing traffic is wrong, it's because we haven't learnt how to manage soil that is now <u>not</u> uncontrollably changed by field vehicles. And that is where this debate cross references with my main hypothesis about avoiding vehicle compaction and improvement of soil structure. In fact, should that part of the main hypothesis have been posed as a question rather than a statement, for example, "if we avoid impacting soils with field vehicles, do we have enough knowledge to allow us to manage soils in a way that will improve and maintain their structure (and function) while enhancing crop yields?" The answer is probably that we don't because we haven't had the freedom to investigate this while wheels or tracks have been running randomly over the soil.

The literature review revealed the immense resilience of soils to keep working and growing crops in the most adverse conditions, probably as a result of their biological evolutionary component to survive along with the crops that are grown in them. To some extent the unconscious reaction by growers adopting controlled traffic has been to act on the old adage "if it's not bust, don't fix it". Most have turned to no-till, largely because it's cheaper, but also because they can also be more confident that they haven't "broken" the soil. Most have said that they would never dream of changing to no-till without also controlling where their traffic runs. In this way they "liberate" perhaps more than 80% of their soils from annual damage, but they also know exactly where the compaction is, should they need to manage it in some way. And this raises another of the main topics – the installation and maintenance of the permanent traffic lanes. These are the main infrastructure of any controlled traffic system and my assumption was that we should minimize their area and leave them well alone, other than ensuring they don't get too deeply rutted. My view on this has also changed, prompted not only by the research conducted as part of the thesis but also by the practical approach of growers and their innovative ideas.

The discussion is divided into four main topics, namely:

1. The effect of field traffic on soil structure and workability
2. The management of permanent traffic lanes
3. The economics of conversion to and maintenance of controlled traffic systems

4. Practical challenges associated with CTF

7.1. THE EFFECT OF FIELD TRAFFIC ON SOIL STRUCTURE AND WORKABILITY

Any debate on this subject must first ask the question, “what is soil structure?” Dexter (1988) describes a good soil structure as one that “exhibits a high degree of heterogeneity between the different components or properties of soil”, but this says nothing about its function or the effect it has on the growth of crops, both of which are the main reason for conducting research into soils. But, does this good soil structure always deliver positively to both these aspects simultaneously? In crop growth terms Boone & Veen (1994) state that “crop growth is less than potential when the uptake of water, oxygen or nutrients is less than the demand of the crop”. Further, two of the reasons for constrained potential are a limited supply from the soil to the roots and limited activity of the root system, both of which are governed at least in part by soil structure. In terms of the soil’s hydraulic properties, there are two specific demands on this, which may or may not be mutually compatible. First is an adequate supply of water to the crop and second is dealing efficiently with an excess of rainfall, and soil structure impacts not only infiltration and drainage but also on temporal effects such as nitrous oxide emissions and methane fluxes.

The critical question therefore is does uncontrolled vehicle compaction always compromise these requirements? The body of evidence from both the literature review and from field observations and measurements would suggest that it does and the reverse would therefore seem to deliver positively to sub hypothesis (c) namely “Most soils maintain a healthy structure in the absence of traffic and the intense tillage associated with it”. The underlying thread contained in the literature is that soil is like any other material and behaves largely according to well established physical laws – there is no “muck and magic”, only our inability to understand the complex relationships that exist in natural systems that are impacted by the unpredictable activities of soil fauna and weather patterns. In simple terms, the weaker the soil and the heavier the load, the greater is the likelihood that the strength and bulk density will increase as a result of applied loads whose impact will depend upon the pressure exerted and its dynamics. A particular soil’s resistance to these loads will depend upon its moisture status (wetter = weaker), organic matter content, initial bulk density and history. Its history may for example mean that its pre-consolidation stress (geological compaction) is already high at some depth in the profile and/or its resistance to deformation has been increased by high levels of organic matter that through structure generation have created a stronger architecture (Russell, 1988). The literature also confirmed tyre effects on the soil that can be approximated by the statement that the pressure at the soil surface (which is proportional to the tyre inflation pressure) reduces to half its value at a depth equivalent to the width of the tyre (Tijink, 1994). This explains the fact that higher loads reach deeper into the profile even if they impose the same pressure at the surface. This approximation is less valid in terms of tracked vehicles which impose loads in a very different manner from tyres and these are discussed below in relation to sub hypothesis (g) (“The damage done by grain harvesters running outside controlled traffic lanes can be minimised by fitting them with rubber tracks or with targeted soil loosening”).

The work on soil compaction reported in Chapter 3 was conducted on an Evesham Series calcareous clay. This seems to have been particularly responsive to wheel compaction, with significant increases in strength even from relatively light loads at the surface. Also characteristic of this soil was surface weathering that left a fine crumb structure on the surface, particularly following wetting and drying periods. This condition was less evident when controlled traffic was established on the Hanslope clay soil at Colworth (Chapter 4) without initial loosening. Although a better structure developed with time, both at the surface and lower in the profile, a fine crumb at the surface was often less evident, as recorded in Tables 4.6-4.8 in Chapter 4, four years after controlled traffic had been established. The question however was, “do soils maintain a healthy structure in the absence of traffic?” The fact that these vertisols have improved with time would suggest that they do, and the literature evidence from sands and silts would suggest this also to be the case providing their structure has been improved by deep loosening prior to CTF adoption. There is indicative if not scientifically proven evidence from the work reported in Chapter 4 that even on these soils, long periods without traffic does lead to improved conditions.

7.1.1. Soil bulk density and cone penetration resistance

In general the effect of imposing wheel loads on different soils was predictable, providing account was taken of initial soil conditions such as moisture and organic matter content and bulk density and the loads and pressures applied. As figures 2.3-2.5 attest, knowing only the wheel loads is far from adequate in being able to predict the outcome in terms of changes in bulk density and penetration resistance. However, practically all the research identified increases in soil bulk density and penetration resistance with traffic at a given site and on a given soil. The extent of these increases varied widely because loads, soils, number of passes and soil conditions also varied. Wheeling in dry conditions tended to have less effect but not universally so (Yavuscan , 2000; Trautner and Arvidsson, 2003). Evidence in Chapter 5 also suggested this, with soil strength on a relatively dry clay soil (c. 26% w w^{-1}) increasing with all wheel loads, albeit on a soil that had been non-trafficked for five years. It’s also not so much a case of did wheel loads cause compaction but did the loads applied move the soil condition from one that was optimum to one that was not? Increased levels of organic matter in the topsoil help to reduce a soil’s susceptibility to compaction (Diaz-Zorita & Grosso, 2000) and confirm the logic of adopting practices that minimise its loss.

The literature and research conducted here suggest that most soils can maintain a healthy structure in the absence of traffic, (for example the work of Carter et al. (1991) and Meek et al. (1988, 1989)). Campbell et al. (1986) working in the opposite extreme of climate also found that no-till could be practised in the absence of traffic but not where it was present. Bulk density, penetration resistance and shear strength were all lower under zero traffic. Raper et al. (1994) on the other hand, suggested that “in row” subsoiling could be just as effective as traffic avoidance in maintaining ideal soil conditions, but this obviously has an energy and cost penalty and could only be maintained from season to season with some form of traffic management in between.

Lighter machines and lower pressures did not seem to avoid soil degradation in terms of raised bulk density and penetration resistance which built up with repeated passes (Jorajuria et al., 1997; Zhang et al., 2006; Canarache et al., 1984; Campbell et al., 1986; Voorhees et al., 1986). One could argue that this progressive build up of compaction could be countered by deep loosening on a regular basis, but as has been highlighted, this is costly and can make the soil more vulnerable to compaction and often to greater depths in the profile (Schäfer-Landefeld et al., 2004; Marks & Soane, 1987; Soane et al., 1987 and results in Chapter 5).

The repeated pass response raises the question, what are the mechanisms involved that are different from the load related effect? It can perhaps be likened to knocking a post into the ground; the energy imparted by each blow is not different, but the post continues deeper into the profile at increasingly smaller increments. It is for this reason that it may take six passes for effects to be noticeable (e.g. Hassan et al., 2007). This effect also has implications as far as rubber belted tracks are concerned. Tijink (1994) considers the first conception of a track as “a portable railway that is laid down in … front of the vehicle” and that is “travelled over and picked up again”. Loads are transmitted to the ground through a number of “roadwheels” which in effect run over the portable track and impart peaks of load that vary with track tension and roadwheel width and number, as indicated in Fig. 7.1.

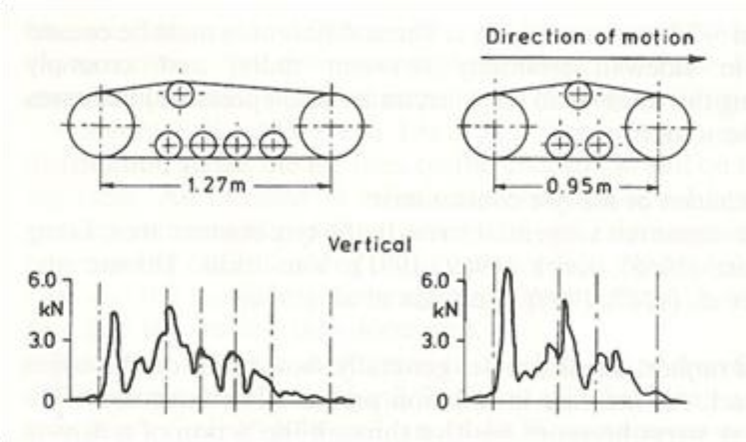


Fig. 7.1. Vertical force distribution under two types of rigid tracks with the same load and drawbar pull on loose sand (after Tijink, 1994)

There may therefore be a trade-off between average ground contact pressure and number of loadings but even ground pressure is uncertain. Tijink (1994) quoting from Rowland (1972) suggests that rather than the average pressure as normally calculated from load and track contact area, use should be made of the mean maximum pressure, defined as the mean value of the maxima occurring under all the roadwheels. Undoubtedly, the issue is complex but this overview confirms the importance of track design and its implications in delivering positively or negatively to hypothesis (g). Persistence of soil compaction, particularly deeper in the profile was also evident, (Voorhees et al., 1986; Radford et al., 2003) but some argued that bulk density and penetration resistance were not the ideal means of measuring it. They preferred an extensive description of soil structure and this limitation was borne out in results from the research conducted in Chapter 5.

7.1.2. Greenhouse gases

Although the number of papers dealing very specifically with the effect of soil compaction on nitrous oxide (N_2O) emissions are limited (Sitaula et al., 2000; Ball et al., 1999a, 1999b, 2008; Vermeulen & Mosquera, 2009) all identified poor aeration as the underlying cause of increased emissions from compacted soils. There is also a wealth of circumstantial evidence to link increased emissions of this damaging greenhouse gas with soil compaction (Rochette, 2008; Ball et al., 2008) and this tends to be exacerbated in no-till systems (Rochette, 2008). Six et al. (2004) in their review also recognised the need to improve nitrogen management in no-till systems. In the short term, no-till compared with conventional tillage increased the global warming potential (GWP) and this was only mitigated after ten or more years in humid climates and uncertainly in dry climates after twenty years. It is logical therefore to consider that CTF might, through increased soil porosity, bring some mitigation particularly as nitrous oxide emissions are increasingly recognised as a global problem associated with poor soil structure (The Royal Society, 2011).

7.1.3. Soil workability

The term “workability” has been used in this context because it embraces a number of characteristics of soils. In part it is related to strength and the relative ease of cultivation (the breaking out of aggregates from the main body of the soil) but it also encompasses “tilth”, the result of cultivation. Much of the work described in the published papers on the Evesham Series clay in Chapter 3 demonstrated an improvement in tilth, as well as a reduction in tillage implement draught on non-trafficked soil. Similar data were measured elsewhere (Lamers et al., 1986; Dickson & Ritchie, 1996; Dickson & Campbell, 1990; Tullberg et al., 2003). This reduction in energy requirement has been reflected on commercial farms adopting controlled traffic systems. Unfortunately it is not easy to demonstrate a reduction in energy for directly comparable operations because farmers have taken the next logical step by either reducing the depth or intensity of tillage or avoiding tillage altogether. They have however claimed a 50% reduction in fuel use on their farms as a combined effect of converting to CTF and no-till (Barnes, Challen, Manfield, personal communications, 2010). With these reductions in energy being imparted to the soil there are also savings in wearing parts, primarily in terms of those components in direct soil contact. None of the research quantified savings of this nature

but it can be seen clearly as greater wear on soil engaging components that work directly behind the wheels or tracks of the vehicles pulling implements.
Although there was great consistency in demonstrating a reduction in draught and energy savings when vehicle compaction was avoided, there were instances in the literature where this did not occur, despite being in directly comparable conditions. This can happen when traffic treatments occur in dry conditions one season and these more favourable conditions are carried forward to the next season, thus reducing the contrasts between trafficked and non-trafficked soil. This was not universally the case however and in some instances no plausible explanation can be offered.

7.1.4. Pore space, water holding capacity and drainage

As discussed in the previous section the outcomes of running wheels or tracks over different soil types in different conditions is almost entirely predictable and this is also the case in terms of hydraulics. However with hydraulics there is a conflict between the laws of gravity and capillary attraction, the former always tending to pull water down in the profile, the latter pulling water in many different directions including upwards. These conflicting forces raise the question posed in the main hypothesis “what is improved soil structure”? The reality is that we probably only have a perception of what this is and no clearly defined and quantifiable ideal for any particular soil type, crop and weather conditions. However, avoiding <u>uncontrolled</u> soil compaction provides the opportunity to create an ideal once we know what that is. If achieving non-trafficked soil is indeed practical and cost effective (part of the overarching hypothesis) with existing machinery, the challenge is to improve on this machinery and more importantly, to research what optimum soil structure should be targeted in the field. This optimum will be one that delivers water and nutrients efficiently to the crop (and this includes allowing the roots to proliferate unhindered) while dealing effectively with excess rainfall.

7.2. THE MANAGEMENT OF PERMANENT TRAFFIC LANES

Two interacting and key issues arise as far as the traffic lanes are concerned. First they must be strong enough to support the traffic imposed on them (and the intensity of this varies according to whether it is an “intermediate” or a “tramline”) and develop the traction required and secondly, they should support as great a crop yield as possible. These two things are mutually incompatible and are the main reasons that separate traffic and crop zones are proposed. However, with the present design of vehicles used in the field, most farmers find it difficult to achieve tracked areas of less than 20%. If crop were not grown in the intermediate wheel tracks not only would there be a greater loss in yield, there may also be more extensive weed problems (less crop competition) and also greater potential for erosion. Evidence from the literature and from the research and observation reported in Chapter 4 suggests that undisturbed traffic lanes do provide a reliable means of field access. However, the question must be asked, should the intermediates be loosened during crop drilling to improve crop performance (Fig. 7.2) and if so, to what depth? The field studies at Colworth revealed lower tiller numbers in the traffic lanes reflecting observed poorer crop establishment. Anecdotal evidence suggests that crop establishment can be improved if they are lightly cultivated (Manfield, personal communication, 2010), but to what extent will this loosening compromise traffickability nine months later for example, during harvesting operations? The practicality and costs of this alternative approach need to be investigated and the conclusion of Lamers et al. (1986) that compaction under permanent traffic lanes can extend up to 25 cm laterally should be borne in mind, even if the main effects are directly below the traffic lane.

Fig. 7.2. Retarded crop growth in an intermediate traffic lane when cropped with spring barley on a Hanslope clay soil

7.3. YIELD RESPONSES TO SOIL COMPACTION

There was a consistent trend both from the field trials and from the literature towards lower yields where vehicle compaction of any nature had been applied to soils, particularly when these were wet. Responses when wet can often be extreme with reductions ranging from 20-80%. This is logical and not surprising because soils are particularly vulnerable when moist and undergo more extreme change, mostly in terms of loss of porosity and aeration. Lack of aeration seems to be the main reason for poor root growth which is reported as a primary cause of poor crop performance; to some extent this was illustrated from the work at Colworth on oilseed rape rooting (Chapter 4). Although negative yield responses to vehicle compaction do not occur every year compared with conventional practice, research has firmly established that the risk is always present. Farming is a high risk occupation so the reliability and economics of avoiding this risk are the reasons for a number of the other hypotheses being addressed in this thesis.

The variation in yield response to vehicle compaction is almost certainly associated with local and seasonal conditions but also with the experimental design and methodologies. In the literature it was often difficult to know what the comparison between trafficked and non-trafficked soils actually was. In many instances it was between systems that do or don't traffic the soil after mouldboard ploughing and this operation is rarely described – for example whether the tractor was in the furrow, what tyres and inflation pressures were used and what the working width of the plough was. These aspects are crucial, especially when dealing with crops such as potatoes and sugar beet. To try and smooth out these variable affects, data from the many references consulted were entered into a spreadsheet and provided an overview as shown in Figs 7.3a & 7.3b. Surprisingly, these suggest that those crops often considered more sensitive to compaction such as potatoes and peas, do not lose as much yield as forage crops and oats for example. To some extent this can be understood with potatoes because soil is ridged up around them and is not run over subsequently. With sugar beet, caution must be exercised because because some of the trials took no account of subsoil compaction, which even if present, was not remedied. Results were also logical for forage crops because traffic is cumulative and there are often long periods between loosening cultivations.

There seems to be a good case for developing "designer" soil profiles for different crops, soils and climatic regions. Creating a favourable pore size distribution, inter-connectivity and size range for example. Could non-trafficked soil be managed more precisely to ensure adequate drainage and aeration when required while allowing enough capillary attraction to supply water from deep in the profile to roots that have not been prevented from reaching sufficiently deep? This might be achieved in the absence of random field trafficking and was indeed suggested by Beylich et al. (2010).

In terms of no-till, yield responses were very variable but there was a consensus suggesting yield depression in the first few years after conversion, with yields gradually rising in the following years to traditional levels. The key question is can this yield depression with no-till be avoided if CTF is adopted simultaneously? Such evidence as there is would suggest that it can.

7.5. ECONOMICS OF CONVERSION TO AND MAINTENANCE OF A CTF SYSTEM

The economics of conversion to CTF are dominated by the timescale and the investment needed in guidance and auto-steer technology. Leaving the guidance technology aside, the cost of conversion to CTF tends to zero with time. This is because the changes required can often be accommodated within normal machinery replacement. Those things that may not be covered are extension of the unloading auger on a combine harvester for example and any standardisation of the track widths of the machinery involved. Modelling this aspect of conversion is fraught with difficulty because every farm is different and timescales for conversion differ dramatically, and for this reason was not attempted in Chapter 6. This difference in timescale is evidenced by farmers in the UK, some of whom have converted to CTF in 18 months while others have taken five or more years.

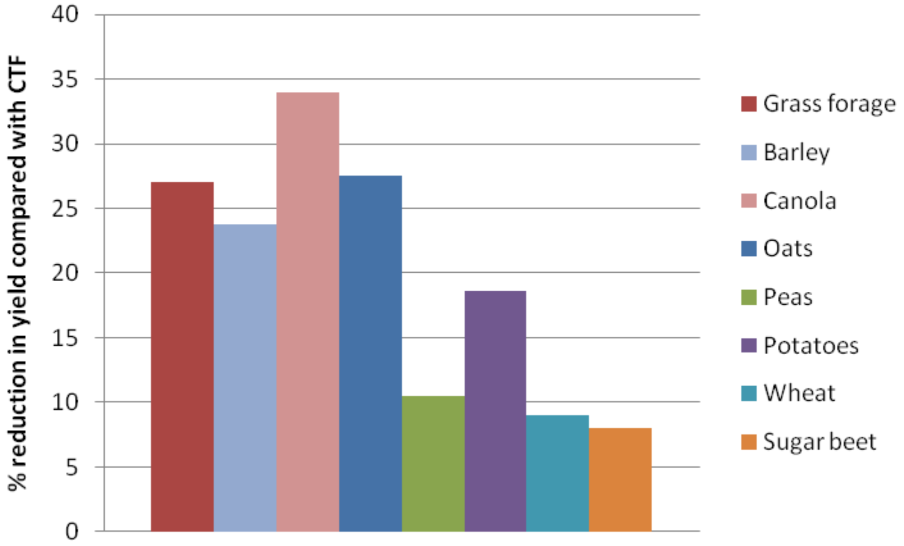


Fig. 7.3a. Reduction in yields (%) of combinable crops grown with varying degrees of controlled traffic compared with crops grown with varying amounts of soil compaction.

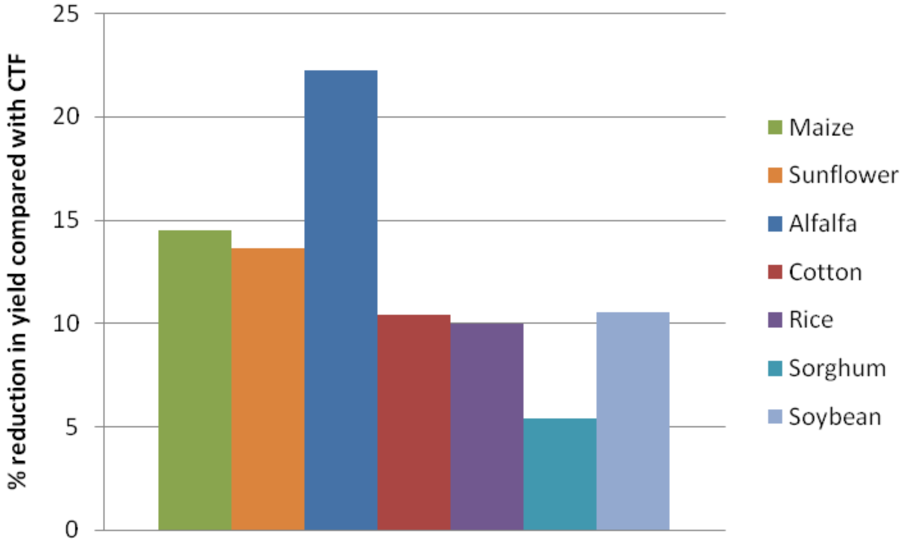


Fig. 7.3b. Reduction in yields (%) of a further range of crops grown with varying degrees of controlled traffic compared with crops grown with varying amounts of soil compaction.

Investment in the guidance technology (approximately £30,000 for 3 machines with a satellite based correction or £75,000 for 4 machines with an RTK correction) will bring benefits other than those directly associated with CTF. These are mostly in the form of reduced overlaps and their associated savings and both investment levels can bring these benefits. However, CTF is considerably easier with the RTK correction and will always be recommended because the alternative (satellite-based correction) requires a permanent mark on the ground for practically every pass across the field. Calculations must therefore take these differences into account but most of the research reviewed on this aspect came from Australia, where the RTK correction is almost exclusively used in a CTF context. Increases in profit from conversion to CTF ranged from around 70% to well over 100% with associated returns on investment of anything between close to zero and 17%. In Europe, other than the economics study in Chapter 6, only one paper was found and this reported a 5% loss on medium soil to a 12% gain in profit on heavy land, suggesting that conversion was more difficult to justify.

Only the paper by Vermeulen & Mosquera (2009) mentioned the economics of conversion to controlled traffic for vegetable growers and this was for a seasonal system, i.e. the CTF system did not include harvesting or the ploughing required for soil remediation. The lack of data for vegetables reflects complex systems where conversion could be over very many years and involve a wide range of machinery. Only one vegetable grower in the UK is known to be converting to CTF and after around 5 years still needs further investment to integrate their harvesting operations.

In terms of the study undertaken as part of this thesis, results again showed the importance of crop yield in determination of profit levels, particularly when prices are high as they are in 2011. If crop prices dropped by 30% results suggested that the CTF system increased its profitability by just over 5% from 7% to 13% compared with the traditional system. Although differences in profit were modest, return on investment in machinery and guidance systems with CTF was around 12%.

7.6. PRACTICAL CHALLENGES ASSOCIATED WITH CTF

One of the greatest challenges to achieving practical CTF systems is overcoming a well established mindset which never perceived that vehicles could be auto-steered to precisely the same traffic lane year in year out. It is only when the need to do this is accepted more widely that appropriate systems will be engineered. And they can be engineered, as the present mechanisation of agriculture attests with innovative, sophisticated and high output machines covering every aspect of crop production. Equally, these massively heavy vehicles traverse the soil with little regard for the relatively fragile medium upon which they run. The research has shown that this may not be an acceptable practice in the future but as running them in the same place permanently is now possible and proving to be a practical and cost effective option, doing so would seem to be prudent.

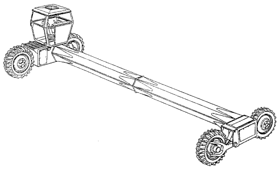
CTF systems are presently constrained only by the machinery designs and investment needed to make them a reality. In a global context however there are a number of remaining constraints to such systems that include:

- matching of machinery wheel track widths that minimise the area of land lost to traffic lanes, particularly for narrower gauge systems;
- no operations can be conducted at a width narrower than the basic implement gauge;
- headland turns tend to track additional areas;

- poor machinery standardisation.

Although only mentioned briefly in the introduction to the thesis, wide track systems could be considered as the ultimate and most appropriate solution for CTF. They offer unique benefits as the field replacement for tractor-based systems and have the following additional advantages compared with existing tractor-based systems:

1. They can set out wheel tracks within any shape or size of field without the need for satellite navigation
2. A highly stable platform for chemical applications and precise crop management
3. Ability to deal with part width, offset loads and deep soil operations
4. Standard headland turns regardless of field shape and angle of approach
5. Greater stability on slopes
6. Potential for reducing machinery investment through lighter implements and fewer self-propelled machines.



Recent history has shown that these machines have only been embraced in the high value crop industry and mostly as harvesting aids (Tillett & Holt, 1987). A change of this magnitude may need more than the right commercial environment and therefore the present demand for higher crop yields produced more efficiently and with less impact on the environment may provide just such an incentive.

CHAPTER 8

8. Conclusions

- While low ground pressure systems have advantages in terms of soil care, they are not a sustainable alternative to systems of controlled traffic farming (CTF) that permanently confine all machinery compaction to the least possible area of permanent traffic lanes. Low ground pressure systems using wheels reduce the severity of compaction but their greater area extent has a detrimental effect, particularly in the topsoil. Rubber belted tracks on harvesters for example, mitigate the area problem but still cause greater compaction in the topsoil, (particularly on lighter soils) than equivalent wheel systems. However, because the compaction is shallower it requires less energy to remedy. On lighter soils this topsoil compaction is more effectively removed than on clays where more judicious deep loosening may be needed to avoid a yield loss in dry conditions. The benefits of soil loosening can be quickly negated by the effects of random field traffic but equally, prolonged in its absence.

- The non-trafficked soil created by CTF has fundamental advantages in terms of soil structure and hence aeration, infiltration, hydraulic conductivity, erosion, soil loss and water and nutrient uptake. In almost all cases, CTF improves yields with significantly lower inputs of energy, machinery and time while being both practical and more profitable in the case studies undertaken in England.

In particular it can be concluded from the field and desk-top studies that:

- The yield of wheat (*Triticum aestivum*) from non-trafficked soil in the replicated plot experiments produced a maximum and significant differential of +16% compared with random traffic. Hand sampling from extensive trials with wheat and barley also supported these conclusions. This significant increase in yield is in agreement with data from the literature which are in the range -9 to +90% with an average response of +21%.
- There was some evidence from the replicated field trials to suggest that crop yield might be predictable from the product of the maximum individual wheel or track loads and the number of passes.
- Although the field scale studies revealed that crop yields from the direct sown traffic lanes were between 5 and 22% lower than those from crops sown with non-inversion tillage and conventional traffic, these differences were not statistically significant. This reduction was around 9% when compared with

conventional traffic and no-till. The differences were largely due to reduced tiller numbers in the traffic lanes reflecting poorer crop establishment.

- All indicative measures of soil structure were improved in the absence of traffic or made poorer by traffic-induced compaction. In particular:
    - The results of the replicated plot experiments demonstrated increases in penetration resistance of 47% and 45% on a sandy loam (Bearsted 1 Association) and on a Hanslope Association clay soil respectively in the presence of traffic. These were approximately mid way in the range reported in previous studies of 7-82%, where their differential was little affected by load or contact pressure, often due to the masking effect of repetitive loading. The bulk density of the topsoil was reduced only by deep loosening on the sandy loam soil and only by the absence of traffic on the clay soil, with differential due to the latter reaching -13%. This again is mid range to the results of earlier studies which suggested that field traffic increases bulk density by between 6 and 20%. Traffic also impaired seedbed quality by increasing the size of aggregates by a factor of two and decreasing its heterogeneity. In soils without traffic the energy for seedbed preparation decreased by between 29% and 87%.
    - Replicated field studies on a sandy loam soil (Bearsted 1 Association) showed an increase in porosity of approximately 5% and hydraulic conductivity of around 40%, both as a result of deep loosening but there was little consistent effect of traffic. Soil porosity on a Hanslope Association clay soil was reduced by around 3% by traffic. These results were in line with the literature where soil porosity was typically reduced by 10% as a result of field traffic while saturated hydraulic conductivity decreased by up to 98%.
    - The results of replicated studies on a Hanslope Association clay soil showed increases in infiltration in the range 200-400% with further enhancement due to 100 mm deep tillage. This is in agreement with earlier field studies which indicated that soil surface water infiltration increased by 84-400% in the absence of traffic.
    - Avoiding compaction on a Hanslope Association clay soil improved soil conditions as indicated above and these measures were supported and confirmed by visual assessments of soil structure by a professional soil surveyor with 40 years of field experience.

- Permanent non-cropped traffic lanes used for chemical applications as well as autumn and spring cultural operations in a CTF system can be sustained with low frequency (3-4 years) infilling provided they are not abused by poor quality high pressure tyres and used in over-wet conditions. Intermediate cropped traffic lanes with lower traffic intensity require little or no targeted management and returned yields similar to but slightly lower than those achieved with conventional traffic management.

- The economics of conversion to a controlled traffic system are dominated by the timescale for change and the cost of the guidance system needed to keep vehicles running in the same tracks. The cost of guidance systems for CTF can be offset by the savings in fuel, time and chemicals which more accurate driving delivers. If the timescale and cost are considered carefully significant improvements in operating profit can be achieved as well as the investment in machinery. Economics analyses suggest that machinery investment can be reduced by more than 20% and farm gross margins improved by 8-17%.

Avoiding soil compaction is not controversial; it avoids the energy needed for both its creation and repair while delivering positively to improved soil structure, crop yields and crop production efficiency. Controlling traffic does not preclude soil firming, loosening or maintaining the status quo; it merely offers the conditions under which these choices can be made without being compromised by wheels or tracks.

Future research should be directed towards enhancing the management of permanent traffic lanes as well as non-trafficked soil. Research should be targeted at delivering optimised conditions for crop production and soil function as well as methods for maximising non-trafficked areas. The development of future mechanisation should embrace the concept of wider track gauges as a means of delivering more cost effective CTF systems.

References

A

Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., Klein, A.M. (2008). Long-term global trends in crop yield and production reveal no current pollination shortage but Increasing pollinator dependency. *Current Biology*, 18 (20): 1572-1575.

Ajayi, A.E., Dias Junior, M.S., Curi, N., Okunola, A., Teixeira Souza, T.T., Silva Pires, B. (2010). Assessment of vulnerability of Oxisols to compaction in the Cerrado Region of Brazil. *Pedosphere*, 20 (2): 252-260.

Akbarnia, A., Alimardani, R., Baharloeyan, S. (2010). Performance comparison of three tillage systems in wheat farms. *Australian Journal of Crop Science*, 4 (8): 586-589.

Akker, J.J.H. & Canarache, A. (2000). Concerted Actions on subsoil compaction in Western European countries and on subsoil compaction in Central and Eastern European countries. Proceedings of the 3rd workshop of the Concerted Action "Experiences with the impact of subsoil compaction on soil, crop growth and environment and ways to prevent subsoil compaction. 14-16 June, Uppsala, Sweden: 7-19.

Alakukku, L. (1996). Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. *Soil and Tillage Research*, 37 (4): 223-238.

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

Alakukku, L. & Elonen, P. (1995). Long-term effects of a single compaction by heavy field traffic on yield and nitrogen uptake of annual crops. *Soil & Tillage Research*, 36: 141-152.

Angers, D.A. (1997). Impact of tillage practices on organic carbon and nitrogen in cool, humid soils of eastern Canada. *Soil and Tillage Research*, 41: 191–201.

Ankeny, M.D., Kaspar, T.C., Horton, R. (1990). Characterization of tillage and traffic effects on unconfined infiltration measurements. *Soil Science Society of America Journal*, 54: 837–840.

Ansorge, D, Godwin, R.J. (2008). The effect of tyres and a rubber track at high axle loads on soil compaction, Part 2: Multi-axle machine studies. *Biosystems Engineering*, 99: 338-347.

Ansorge, D, Godwin, R.J. (2007). The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies. *Biosystems Engineering*, 98: 115-126.

Arndt, W. & Rose, C.W., (1966). Traffic compaction of soil and tillage requirements. *Journal of Agricultural Engineering Research, 11 (3): 170–187.*

Arvidsson, J. (2001) Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden. I. Soil physical properties and crop yield in six field experiments. *Soil & Tillage Research*, 60: 67–78.

Arvidsson, J. & Håkansson, I. (1996). Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. *Soil and Tillage Research*, 39 (3-4): 175-197.

Audsley, E. (1981). An arable farm model to evaluate the commercial viability of new machines or techniques. *Journal of Agricultural Engineering Research*, 11: 182-187.

B

Bai, Y., He, J., Li, H., Wang, Q., Chen, H., Kuhn, N.J., Hikel, H., Gong, Y. (2009). Soil structure and crop performance after 10 years of controlled traffic and traditional tillage cropping in the dryland Loess plateau in China. *Soil Science* 174 (2): 113-119

Baker, C.J., Saxton K.E., eds, (2007). No-tillage seeding in conservation agriculture. CAB International, Wallingford, UK. 326 pp.

Bakker, D., Hamilton, G., Bathgate, A. (1998). Economic assessment and requirements of permanent raised beds in WA. Proceedings of the Second National Controlled Traffic Conference, Gatton, Queensland, 27–27 August, pp. 13–17.

Bakker, D.M., Harris, H., Wong, K.Y. (1995). An analysis of different permanent bed and wheel track configurations in cotton growing. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 39–45.

Balesdent, J., Henu, C., Balbane, M. (2000). Relationship of soil organic matter dynamics to physical protection and tillage. *Soil & Tillage Research*, 53: 215–230.

Ball, B.C, Crichton, I, Horgan, G.W. (2008). Dynamics of upward and downward N2O and CO2 fluxes in ploughed or no-tilled soils in relation to water-filled pore space, compaction and crop presence. *Soil & Tillage Research*, 101: 20-30.

Ball, B.C., Parker, J.P., Scott, A. (1999a). Soil and residue management effects on cropping conditions and nitrous oxide fluxes under controlled traffic in Scotland. 2. Nitrous oxide, soil N status and weather. *Soil and Tillage Research*, 52 (3-4): 191-201.

Ball, B.C., Scott, A., Parker, J.P. (1999b). Field N2O, CO2 and CH4 fluxes in relation to tillage, compaction and soil quality in Scotland. *Soil and Tillage Research*, 53, (1): 29-39.

Ball, B.C., Lang, R.W., Robertson, E.A.G., Franklin, M.F. (1994). Crop performance and soil conditions on imperfectly drained loams after 20–25 years of conventional tillage or direct drilling. *Soil & Tillage Research*, 31 (2-3): 97-118.

Batey, T. (2009). Soil compaction and soil management – a review. *Soil Use and Management*, 25 (4): 335-345.

Batte, M.T., Ehsani, M.R. (2006). The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. *Computers and Electronics in Agriculture*, 53: 28-44.

Bayliss, G.T.S. (1972). *Plant and Soil*, 36: 233–234.

Bell, M.J., Stirling, G.R., Pankhurst, C.E. (2003). The impact of management on the health of soils supporting the Australian grain and sugarcane industries. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 95–117.

Benites, J.R., Derpsch, R, McGarry, D. (2003). The current status and future growth potential of conservation agriculture in the world context. Proceedings of the

International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 120–129.

Bennie, A.T.P. & Botha, F.J.P. (1986). Effect of deep tillage and controlled traffic on root growth, water use efficiency and yield of irrigated maize and wheat. *Soil & Tillage Research*, 7 (1/2): 85–95.

Bessam, F. & Mrabet, R. (2003). Long-term changes in particulate organic matter under no-tillage systems in a semiarid soil of Morocco. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 144–149.

Beylich, A., Oberholzer, H-R., Schrader, S., Höper, H., Wilke, B-M. (2010). Evaluation of soil compaction effects on soil biota and soil biological processes in soils. *Soil & Tillage Research*, 109: 133-143.

Blackwell, P.S., Ward, M.A., Lefevre, R.N., Cowan, D.J. (1985). Compaction of a swelling clay soil by agricultural traffic, effects upon conditions for growth of winter cereals and evidence for some recovery of structure. *Journal of Soil Science*, 36 (4): 633–650.

Blackwell, P.S. & Dickson, J.W. (1978). Soil compaction under conventional and dual wide section tyres carrying the same load over loose soil. Departmental Note. Scottish Institute of Agricultural Engineering, Penicuik, Scotland.

Blunden, B. G.; McBride, R. A.; Daniel, H.; Blackwell, P. S. (1994). Compaction of an earthy sand by rubber tracked and tyred vehicles. *Australian Journal of Soil Research*, 32, (5): 1095-1108.

Boardman, J., Evans, R., Ford, J. (2003). Muddy floods on the South Downs, southern England: problem and responses. *Environmental Science & Policy*, 6: 69–83.

Bochtis, D.D., Sørensen, C.G., Green, O., Moshu, D., Olesen, J. (2010). Effect of controlled traffic on field efficiency. *Biosystems Engineering*, 106: 14-25.

Bole, J.B. (1973). Influence of root hairs in supplying soil phosphorus to wheat. *Canadian Journal of Soil Science,* 53: 169–175.

Boone, F.R. & Veen, B.W. (1994). Mechanisms of crop responses to soil compaction. In: B.D. Soane, C. van Ouwerkerk, eds, Soil Compaction in Crop Production. Elsevier Science Publishers, B.V., Amsterdam: 237-364.

Botta, G.F., Tolon-Becerra, Tourn, M., Lastra-Bravo, X., Stadler, S. (in press). Agricultural traffic: motion resistance and soil compaction in relation to tractor design and different soil conditions. *Soil & Tillage Research*, in press

Botta, G.F., Rivero, D., Tourn, M., Bellora Melcon, F., Pozzolo, O., Nardon, G, Balbuena, R., Tolon Becerra, A, Rosatto, H., Stadler, S. (2008). Soil compaction produced by tractor with radial and cross-ply tyres in two tillage regimes. *Soil & Tillage Research*, 101: 44-51.

Botta, G.F., Jorajuria, D., Rosatto, H., Ferrero, C. (2006). Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina. *Soil & Tillage Research*, 86: 9-14.

Botta. G.F., Jorajuria, D., Balbuena, R., Rosatto, H. (2004). Mechanical and cropping behavior of direct drilled soil under different traffic intensities: effect on soybean (*Glycine max* L.) yields. *Soil & Tillage Research*, 78: 53–58.

Bouwman, L.A.; Arts, W.B.M. (2000). Effects of soil compaction on the relationships between nematodes, grass production and soil physical properties. *Applied Soil Ecology*, 14: 213-222

Bowman, K. (2008). Economic and environmental analysis of converting to controlled traffic farming. Proceedings of the 6th Australian Controlled Traffic Farming Conference, Dubbo, NSW, Australia. 12-14 August: 61-68.

Boydell, B. & Boydell, C. (2003). A decade of directions: trials and tribulations of precision agriculture and controlled traffic at 'Marinya'. Keynote address. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 196–207.

Brady, N.C. & Weil, R.R. (1999). The Nature and Properties of Soils. Twelfth Edition. ISBN 0-13-852444-0. Prentice-Hall Inc., Upper Saddle River, New Jersey 07458.

Braunack, M.V. & McGarry, D. (2006). Traffic control and tillage strategies for harvesting and planting of sugarcane (Saccharum officinarum) in Australia. *Soil & Tillage Research*, 89, 86-102.

Braunack, M.V., McPhee, J.E., Reid, D.J. (1995). Controlled traffic to increase productivity of irrigated row crops in the semi-arid tropics. *Australian Journal of Experimental Agriculture*, 35: 503–513.

Breland, T.A. & Hansen, S. (1996). Nitrogen mineralization and microbial biomass as affected by soil compaction. *Soil Biology and Biochemistry*, 28 (4-5): 655-663.

BSI (British Standards Institute). (1990). Sedimentation by the pipette method BS 1377: Part 2.

C

Campbell, D.J., Dickson, J.W., Ball, B.C., Hunter, R. (1986). Controlled seedbed traffic after ploughing or direct drilling under winter barley in Scotland, 1980–1984. *Soil & Tillage Research*, 8: 3–28.

Canarache, A. & Van den Akker, J.J.H. (2003). SOCOLIT and SOCODB, two European databases on soil compaction. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 265–270.

Canarache, A., Colibas, J., Colibas, M., Horobeanu, I., Patru, V., Simota, H., Trandafirescu, T. (1984). Effect of induced soil compaction by wheel traffic on soil physical properties and yield of maize in Romania. *Soil & Tillage Research*, 4: 199–213.

Cannell, R.Q., Hawes, J.D. (1994). Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. *Soil & Tillage Research*, 30 (2-4): 245-282.

Carter, L.M., Meek, B.D., Rechel, E.A. (1991). Zone production system for cotton: soil response. *Transactions of the ASAE*, 34 (2): 354–360.

Carter, L.M., Meek, B., Rechel, E. (1988). Zone production research with wide tractive research vehicle. Proceedings of the 11th conference of the International Soil Tillage Research Organisation, Edinburgh, UK., 1: 221-225.

Carter, M.R. (1990). Development of direct-drilling systems for sandy loam soils in the cool humid climate of Atlantic Canada. *Soil & Tillage Research*, 16: 371-387.

Carter, M.R. (1988). Penetration resistance to characterize the depth and persistence of soil loosening in tillage studies. *Canadian Journal of Soil Science*, 68 (4): 657-668.

Carter, M.R., Johnstone, H.W., Kimpinski, J. (1988). Direct drilling and soil loosening for spring cereals on a fine sandy loam in Atlantic Canada. *Soil & Tillage Research*, 12 (4): 365-384.

Chambers, B.J. & Garwood, T.W.D. (2000). Monitoring of water erosion on arable farms in England and Wales. 1990–94. *Soil Use & Management*, 16: 9–99. http://ec.europa.eu/environment/soil/pdf/results_organistaitons.pdf

Chamen, W.C.T., (2005). Controlled traffic farming – its benefits and realisation. In: Daniel Jorajuría, Daniel Giménez, Víctor Sánchez Girón, eds. Agricultural soil reology under traffic. *Revista de la Facultad de Agronomia* 106 (1) Suplemento pp. 107-129. Facultad De Ciencias Agrarias Y Forestales Universidad Nacional De La Plata, Argentina.

Chamen, W.C.T. (2002). *Biotrac – a wider horizon for agriculture*. Biovelop AB, Helsingborg, Sweden, 12 pp.

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

Chamen, W.C.T. (1997). Soil cultivation: new methods and technologies. Proceedings of the 9th meeting of the full members of the Club of Bologna, Bologna. 9: 73-85.

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

Chamen, W.C.T., Dowler, D., Leede, P.R., Longstaff, D.J. (1994). Design, operation and performance of a gantry system: experience in arable cropping. *Journal of Agricultural Engineering Research*, 59: 45–60.

Chamen, W.C.T. & Audsley, E. (1993). A study of the comparative economics of conventional and zero traffic systems for arable crops. *Soil & Tillage Research*, 25: 369–390.

Chamen, W.C.T., Watts, C.W., Leede, P.R., Longstaff, D.J. (1992a). Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime. *Soil & Tillage Research*, 24: 359–380.

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

Chamen, W.C.T. & Cavalli, R. (1994). The effect of soil compaction on mole plough draught. *Soil & Tillage Research*, 32: 303–311.

Chamen, W.C.T., Chittey, E.T., Leede, P.R., Goss, M.J., Howse, K.R. (1990). The effect of tyre soil contact pressure and zero traffic on soil and crop responses when growing winter wheat. *Journal of Agricultural Engineering Research*, 47: 1–21.

Chamen, W. C. T., Cope, R. E., Patterson, D.E. (1979). Development and performance of a high output rotary digger. *Journal of Agricultural Engineering Research*, 24 (3), 301 318.

Chan, K.Y., Oates, A., Swan, A.D., Hayes, R.C., Dear, B.S., Peoples, M.B. (2006). Agronomic consequences of tractor wheel compaction on a clay soil. *Soil & Tillage Research*, 89, 13-21.

Clarkson, D.T. (1981). Nutrient interception and transport by root systems. In: C.B Johnson (Ed) Physiological processes limit plant productivity. London, Butterworths, 395 pp.

Cockcroft, B. & Olsson, K.A. (2000). Degradation of soil structure due to coalescence of aggregates in no-till, no-traffic beds in irrigated crops. *Australian Journal of Soil Research*, 38: 61–70.) Conrad, J.O. & Veihmeyer, F.J. 1929. Root development and soil moisture. Hilgardia, 4: 113–124.

Conway, G. (2011). Food security and agricultural development: the challenges ahead. Paper presented at a two-day discussion meeting, 28 Feb.–1 March 2011. The Royal Society, 6-9 Carlton House Terrace, London SW1Y 5AG.

Cooper, A. W., Trouse, A. C., Dumas, W. T., Williford, J. R. (1983). Controlled traffic farming, a beneficial cultural practice for southern U.S. agriculture. American Society of Agricultural Engineers, Paper 83-1547, 14 pp.

Cooper, A.W., Trouse, A.C., Jr., Dumas, W.T. (1969). Controlled traffic in row crop production. Proceedings of the 7th International Congress on Agricultural Engineering (CIGR), Baden-Baden, Germany, Section III, Theme 1: 1-6.

Culik , M.P., de Souza, J.L., Ventura, J.A. (2002). Biodiversity of Collembola in tropical agricultural environments of Espírito Santo, Brazil. *Applied Soil Ecology*, 21 (1): 49-58.

Czyz, E. A., Dexter, A.R. (2009). Effect of traditional, reduced and zero-tillage for winter wheat on soil physical properties. Proceedings of the 18th ISTRO Triennial Conference, Izmir, Turkey, June 15-19.

D-E

Dao, T.H. (1996). Tillage systems and crop residue effects on surface compaction of a Paleustoll. *Agronomy Journal*, 88: 141–148.

Deen, W. & Kataki, P.K. (2003). Carbon sequestration in a long-term conventional versus conservation tillage experiment. *Soil & Tillage Research*, 74: 143–150.

DeJong-Hughes, J., Moncrief, J.F., Voorhees, W.B., Swan, J.B. (2001). Soil compaction – causes, effects and control. Regents of the University of Minnesota. Available at: http://www.extension.umn.edu/distribution/cropsystems/dc3115.html

Dexter, A.R. (1988). Advances in characterisation of soil structure. *Soil & Tillage Research*, 11: 199–238.

Diaz-Zorita, M. & Grosso, G.A. (2000). Effect of soil texture, organic carbon and water retention on the compactibility of soils from the Argentinian pampas. *Soil and Tillage Research*, 54: 121–126.

Dickson, J.W. & Ritchie, R.M. (1996). Zero and reduced ground pressure traffic systems in an arable rotation 2. Soil and crop responses. *Soil and Tillage Research*, 38 (1-2): 89-113.

Dickson, J.W. & Campbell, D.J. (1990). Soil and crop responses to zero- and conventional-traffic systems for winter barley in Scotland, 1982–1986. *Soil and Tillage Research*, 18: 1–26.

Dowler, D. (1980). Improvements in or relating to agricultural implements. Patent number 1 578 857. The Patent Office, London.

Dowler, D. (1977). Improvements in or relating to agricultural implements (The Monotrail). British Patent Specification GB 1578857.

Dresser, M.L., Blackburn, D.W.K., Stranks, S.N., Dain-Owens, A., Godwin, R.J. (2006). Effect of tillage implements and vehicle loads on buried archaeology. Proceedings of the International Soil Tillage Research Organisation triennial conference "Sustainability – its impact on soil management and environment, 28 August – 3 September, Kiel, Germany, pp. 42-47.

Elbanna, E.B. & Witney, B.D. (1987). Cone penetration resistance equation as a function of the clay ratio, soil moisture content and specific weight. *Journal of Terramechanics*, 24 (1): 41-56.

Eriksson, J., Håkansson, I., Danfors, B. (1974). The effect of soil compaction on soil structure and crop yields. Swedish Institute of Agricultural Engineering, Uppsala, Report 354, 82 pp. (In Swedish, version translated into English 1975 by J.K. Aase, USDA-ARS, Washington, DC.

Evans, R. (2002). An alternative way to assess water erosion of cultivated land – field-based measurements: and analysis of some results. *Applied Geography*, 22: 187–208.

Evans, R. (1990). Soils at risk of accelerated erosion in England and Wales. *Soil Use & Management*, 6 (3): 125–131.

Evans, R. & Brazier, R. (2005). Evaluation of modelled spatially distributed predictions of soil erosion by water versus field-based assessments. *Environmental Science & Policy*, 8 (5): 493–501.

F-G

Ferguson, H. (1933). Tractor-drawn agricultural implement. United States patent number 1916945 (A).

Ferguson, S.A., Fielke, J.M., Riley, T.W. (1998). Wear of cultivator shares in abrasive South Australian soils. *Journal of Agricultural Engineering Research*, 69 (2): 99-105.

Fielke, J.M., Riley, T.W., Slattery, M.G., Fitzpatrick, R.W. (1993). Comparison of tillage forces and wear rates of pressed and cast cultivator shares. *Soil & Tillage Research*, 25: 317-328.

Fischer, G., van Velthuizen, H., Shah, M., Nachtergaele, F.O. (2002). Global agro-ecological assessment for agriculture in the 21st century: methodology and results. International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria. ISBN 3-7045-0141-7.

FAO (Food and Agriculture Organization), (2001). Digital soil map of the world and derived soil properties. FAO, Viale delle Terme di Caracalla, 00100 Rome.

FAO (Food and Agriculture Organization) (1988). FAO/UNESCO Soil Map of the World 1:5,000,000: Revised Legend, with corrections. World Resources Report 60, FAO, Rome.

Forbes, J.C. & Watson, R.D. (1992). Plants in agriculture. Cambridge, UK, University Press. 355 pp.

Fream, W. (1962). Fream's Elements of Agriculture. Ed. D.H. Robinson, 14th edition. John Murray, Albermarle St, London. 796 pp.

Friedrich, T. (2003). Engineering for conservation agriculture – trends, concepts and challenges in a global perspective. Keynote address. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 452–457.

Fulajtar, E. (2002). Impact of compaction on soil nutrient state – Slovakian experience. In Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action "Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 157–158.

Gaffney, J. & Wilson, A. (2003). The economics of zero tillage and controlled traffic farming for Western Downs farms. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 458–464.

Garber, M. & Wong, J.Y. (1981). Prediction of ground pressure distribution under tracked vehicles – II. Effects of design parameters of the track-suspension system on ground pressure distribution. *Journal of Terramechanics*, 18: 71-79.

Ghildyal, B.P., Tripathi, R.P. (1987). Soil physics. Wiley Eastern Limited, 4835/24 Ansari Road, Daryaganj, New Dehli 11002. 656 pp.

Głąb, T., Kopeć, S. (2009). Effect of soil compaction on root system morphology and yields of meadow fescue (*Festuca pratensis*). *Polish Journal of Environmental Studies*, 18 (2): 219-225.

Godwin, R.J., Spoor, G., Soomro, M.S. (1984). The effect of tine arrangement on soil forces and disturbance. *Journal of Agricultural Engineering Research*, 30: 47-56.

Godwin, R.J., Spoor, G., Leeds-Harrison, P. (1981). An experimental investigation into the force mechanics and resulting soil disturbance of mole ploughs. *Journal of Agricultural Engineering Research*, 26: 477-497.

Gonzalez Maziero, J.V., Mialhe, L.G., Corrêa. I.M., Yanai, K., De Menezes, J.F. (1997). Effects of tractor driving wheel slip on soil compaction. *Bragantia* 56 (1): 191-197.

Goss, M.J. (1987). The specific effects of roots on the regeneration of soil structure. In: Soil Compaction and Regeneration, edited by G.M. Monnier and M.J. Goss. A.A. Balkema, Rotterdam, p. 145-155.

Goss, M.J. & Reid, J.B. (1981). Interaction between crop roots and soil structure. Aspects of crop growth agronomy conference. Bournemouth. Ministry of Agriculture, Fisheries and Food, London, pp 34–48.

Grabski, A.S., So, H.B., Shafer, B.M., Desborough, P.J. (1995). A comparison of the impact of 14 years of conventional and no-till cultivation on physical properties and crop yields of a loam soil at Grafton NSW. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 97–102.

Graham, J.P., Blackwell, P.S., Armstrong, J.V., Christian, D.G., Howse, K.R., Dawson, C.J., Butler, A.R. (1986). Compaction of a silt loam by wheeled agricultural vehicles. II. Effects on growth and yield of direct drilled winter wheat. *Soil & Tillage Research*, 7: 189-203.

Grains Research & Development Corporation. (2000). Does row orientation effect soil loss? http://www.grdc.com.au/growers/oft/oft_search/docs/qld/q12.

H-I

Haining, J., Tyler, C. (1970). Ploughing by steam. ISBN 0909798493/0-906798-49-3

Håkansson, I. (1990). A method for characterising the state of compactness of the plough layer. *Soil & Tillage Research,* 16: 105-120.

Håkansson I. (2005). Machinery-induced compaction of arable soils – incidence, consequences and countermeasures. Swedish University of Agricultural Sciences, Division of Soil Management. Report no. 109, 153 pp.

Håkansson, I. (Ed). (1994). Subsoil compaction by high axle load traffic. *Special edition of Soil & Tillage Research*, 29: 105-306.

Håkansson I. & Reeder, R.C. (1994). Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. *Soil & Tillage Research*, 29: 277-304.

Håkansson I., Ward, V.B., Elonen, P. Raghavan, G.S.V., Lowery, B. van Wijk, A.L.M, Rasmussen, K, Riley, H. (1987). Effect of high axle-load traffic on subsoil compaction and crop yield in humid regions with annual freezing. *Soil & Tillage Research*, 10: 259–268.

Håkansson I., Henriksson, L., Gustafsson, L. (1985). Experiments on reduced compaction of heavy clay soils and sandy soils in Sweden. Proceedings of the International Conference on Soil Dynamics, 17-19 June, Auburn University, Auburn, AL, USA, 995-1009.

Håkansson I. (1976). Eleven Swedish field experiments with subsoiling and deep ploughing 1964-1975. Agricultural College of Sweden, Uppsala, Division of Soil Management, Rep. 42, 35 pp (in Swedish with English summary)

Halkett, P.A. (1858). On guideway agriculture: being a system enabling all the operations of the farm to be performed by steam power. *Journal of the Society of Arts*, 7, 41–53.

Hamilton, G., Bakker, D., Houlbrooke, D, Hetherington, R., Spann, C. (2003). Permanent raised beds prevent waterlogging and increase the productivity of dryland farming areas in Western Australia. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 524–530.

Hamilton, G., Bakker, D., Tipping, P. (1998). Lessons learned in the art of laying out permanent raised beds. Proceedings of the Second National Controlled Traffic Conference, Gatton, Queensland, 27–27 August, pp.83-86.

Hamlett, J.M., Melvin, S.W., Horton, R. (1990). Traffic and soil amendment effects on infiltration and compaction. *Transactions of the ASAE*, 33 (3): 821–826.

Hamza, M.A. & Anderson, W.K. (2005). Soil compaction in cropping systems. A review of the nature, causes and possible solutions. *Soil & Tillage Research*, 82: 121-145.

Hassan, F.U., Ahmad, M., Ahmad, N., Kaleem Abbasi, M., (2007). Effects of subsoil compaction on yield and yield attributes of wheat in the sub-humid region of Pakistan. *Soil & Tillage Research*, 96, 361-366.

Henshall, J.K. & Smith, D.L.O. (1989). An improved method of presenting comparisons of soil compaction effects below wheel ruts. *Journal of Agricultural Engineering Research*, 42 (1): 1-13.

Hodge, C.A.H., Burton, R.G.O., Corbett, W.M., Evans, R., Seale, R.S. (1984). *Soils and their use in Eastern England*. Soil Survey of England and Wales, Bulletin No. 13.

Hodgson, J.M. (Ed) (1976). Soil Survey field handbook. Soil Survey Technical Monograph No. 5. Cranfield University, Bedfordshire, UK.

Holland, J.M. (2004). The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agriculture, Ecosystems and Environment*, 103: 1-25.

Hood, C.E., Williamson, R.E., Young, R.E. (1985). Multi-purpose lateral-travel frames for fruit and vegetable production. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1010–1022. Office of Continuing Education, Auburn University, Alabama.

Horn, R., Way, T, Rostek, J. (2003). Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. *Soil & Tillage Research*, 73: 101-106.

Houšková, B, Montanarella, L. (2008). The natural susceptibility of European soils to compaction. In: *Threats to Soil Quality in Europe*. Edited by Gergely Tóth, Luca Montanarella and Ezio Rusco: Publications Office, Office for Official Publications of the European Communities, Luxmbourg.

Hutchings, M.J. & John, E.A. (2004). The effects of environmental heterogeneity on root growth and root/shoot portioning. *Annals of Botany*, 94: 1-8.

Imeson, A.C. & Kwaad, F.J.P.M. (1990). The response of tilled soils to wetting by rainfall and the dynamic character of soil erodibility. In: J. Boardman, I.D.L. Foster & J.A. Dearing (Eds), *Soil erosion on agricultural land*. J. Wiley & Sons Ltd, Chichester, UK., 687 pp.

Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., Lal, R. (2001). Subsoil compaction effects on crops in the Punjab, Pakistan I. Soil physical properties and crop yield. *Soil & Tillage Research*, 59: 57-65.

J- K

Jansson, K.J. & Johansson, J. (1998). Soil changes after traffic with a tracked and a wheeled forest machine: a case study on a silt loam in Sweden. *Forestry* (Oxford) 71, 57–66.

Javurek, M. 2002. Economic aspects of soil overcompaction in the Czech Republic. In: Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action "*Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction*. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 253–256.

Jensen, L.S., McQueen, D.J., Shepherd, T.G. (1996). Effects of soil compaction on N-mineralization and microbial-C and -N. I. Field measurements. *Soil and Tillage Research*, 38 (3-4): 175-188.

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

Jorajuria, D., Draghi, L., Aragon, A. (1997). The effect of vehicle weight on the distribution of compaction with depth and the yield of Lolium/Trifolium grassland. *Soil and Tillage Research*, 41 (1-2): 1-12.

Karunatilake, U., van Es, H.M., Schindelbeck, R.R. (2000). Soil and maize response to plow and no-tillage after alfalfa-to-maize conversion on a clay loam soil in New York. *Soil and Tillage Research*, 55 (111-2): 31-42.

Kettlewell, P.S., Stephenson, D.B., Atkinson, M.D., Hollins, P.D. (2003). Summer rainfall and wheat grain quality: relationships with the Norther Atlantic Oscillation. *Weather*, 58: 1-9.

Koch, H-J. (2009). Relations between soil structural properties and sugar beet yield on a Luvisol. *Pflanzenbauwissenschaften*, 13 (2): 49-59.

Koch, H-J., Heuer, H., Tomanová, O., Märländer, B. (2008). Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. *Soil & Tillage Research*, 101: 69-77.

Komatsuzaki, M., Ohta, H., 2007. Soil management practices for sustainable agro-ecosystems. *Sustainability Science*. 2, 103-120.

Kooistra, M.J. & Tovey, N.K. (1994). Effects of compaction on soil microstructure. In: B.D. Soane, C. van Ouwerkerk, eds, *Soil Compaction in Crop Production*. Elsevier Science Publishers, B.V., Amsterdam: 91-111.

Koolen, A.J., Lerink, P., Kurstjens, D.A.G., van den Akker, J.J.H., Arts, W.B.M. (1992). Prediction of aspects of soil-wheel systems. *Soil & Tillage Research*, 24, 381–396.

Košutic´, S., Filipovic´, D., Gospodaric´, Z., Kovačev, I., Čopec, K., Salokhe, V. M., Jayasuriya, H. P. W., Soni, P. (2007). Effect of soil tillage systems in winter wheat production on gleyic podzoluvisol in Croatia. Proceedings of the International Agricultural Engineering Conference, Bangkok, Thailand, 3-6 December. Cutting edge technologies and innovations on sustainable resources for world food sufficiency, unpaginated.

Kroulík, M.; Kumhála, F.; Hůla, J.; Honzík, I. (2009). The evaluation of agricultural machines field trafficking intensity for different soil tillage technologies. *Soil & Tillage Research*, 105: 171-175.

L

Lamandé, M. & Schjønning, P. (2010a). Transmission of vertical stress in a real soil profile. Part II: Effect of tyre size, inflation pressure and wheel load. *Soil & Tillage Research*, available on-line 1 November 2010.

Lamandé, M. & Schjønning, P. (2010b). Transmission of vertical stress in a real soil profile. Part III: Effect of soil water content. *Soil & Tillage Research*, available on-line 1 November 2010.

Lamers, J.G., Perdok, U.D., Lumkes, L.M., Klooster, J.J. (1986). Controlled traffic farming systems in the Netherlands. *Soil & Tillage Research*, 8: 65–76.

Larsen, W.E., Nielsen, G.A., Tyler, D.A. (1994). Precision navigation with GPS. *Computers and Electronics in Agriculture*, 11: 85-95.

Li, Y.X., Tullberg, J.N., Freebairn, D.M. (2007). Wheel traffic and tillage effects on runoff and crop yield. *Soil & Tillage Research*, 97, 282-292.

Li, Y.X., Tullberg, J.N., Freebairn, D.M. (2001). Traffic and residue cover effects on infiltration. *Australian Journal of Soil Research*, 39: 239–247.

Lipiec, J. (2002). Impact of compaction on soil nutrient state – Polish experience. In Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action "*Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction*. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 159–161.

Lorimer, R. (unknown). The adoption of GPS in cropping agriculture. Web-based document accessed on 27/2/11 at: http://www.gisdevelopment.net/technology/gps/techgps_002.htm

M

Malthus, T.R. (1798), 1st edition. An essay on the principle of population with *A Summary View* (1830), and Introduction by Professor Antony Flew. Penguin Classics. ISBN 0-14-043206-X.

Marks, M.J. & Soane, G.C. (1987). Crop and soil response to subsoil loosening, deep incorporation of phosphorous and potassium fertiliser and subsequent soil management on a range of soil types. Part 1: Response of arable crops. *Soil Use and Management*, 3: 115-123.

Mason, R.M., Page, J.R., Tullberg, J.N., Buttsworth, R.K. (1995). The economics of controlled traffic: South Burnett case study. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 109–114.

Maynard, M.J. (1995). Permanent beds: the Riverina version of controlled traffic. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 18–24

McGarry, D. & Sharp, G. (2001). A rapid, immediate, farmer-usable method of assessing soil structure condition to support conservation. In: Garcia-Torres, L., Benites, J., Martinez-Vilela, A. (Eds), First World Congress on Conservation Agriculture, 1-5 October 2001, Madrid. Natural Resources Science: 209-214.

McHugh, A.D., Tullberg, J.N., Freebairn, D.M. (2009). Controlled traffic farming restores soil structure. *Soil & Tillage Research*, 104: 164-172.

McHugh, A., Tullberg, J., Freebairn, D. (2003). Effects of field traffic removal on hydraulic conductivity, plant available water and water capacity. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 717–723.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J., Hilton, D.J. (1995a). Controlled traffic for irrigated double cropping in a semi-arid tropical environment. Part 2. Tillage operations and energy use. *Journal of Agricultural Engineering Research*, 60: 183–189.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J., Hilton, D.J. (1995b). Controlled traffic for irrigated double cropping in a semi-arid tropical environment. Part 1. Machinery requirements and modifications. *Journal of Agricultural Engineering Research*, 60: 175–182.

Medvedev, V.V., Laktionova, T.N., Lyndina, T.E. (2002a). Estimation of agricultural crop losses in the Ukraine through soil overcompaction. In *Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action "Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction*. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 213–223 .

Medvedev, V.V., Lyndina, T.E., Laktionova, T.N. (2002b). Impact of compaction on soil nutrient state – Ukrainian experience. *In Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action "Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction*. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 163–169.

Meek, B.D., Rechel, E.R., Carter, L.M., DeTar, W.R. (1992). Bulk density of a sandy loam: traffic, tillage and irrigation-method effects. *Soil Science Society of America Journal*, 56: 562–565.

Meek, B.D., Rechel, E.A., Carter, L.M., DeTar, W.R. (1989). Changes in infiltration under alfalfa as influenced by time and wheel traffic. *Soil Science Society of America Journal*, 53 (1): 238–241.

Meek, B.D., Rechel, E.A., Carter, L.M., DeTar, W.R. (1988). Soil compaction and its effect on alfalfa in zone production systems. *Soil Science Society of America Journal*, 52 (1): 233–236.

Mengel, D.B., & Hawkins, S.E. (1994). Soil sampling for P, K, and lime recommendations. Purdue University Extension. http://www.ces.purdue.edu/extmedia/AY/AY-281.pdf.Met Office, (2005). Extreme weather in the UK. http://www.metoffice.gov.uk/climate/uk/extremes/index.html

Metianu, A.A., Johnson, I.M., Sewell, A.J. (1990). A whole crop harvester for the developing world. *Journal of Agricultural Engineering Research*, 47: 187-195.

Michelin Tyre plc (2007). Agricultural tyre range & technical data. Stoke-on-Trent, England: 91 pp.

Miller, E.C. (1938). *Plant physiology*. McGraw-Hill Book Company, New York and London.

Miyazawa, F., Yoshida, T., Sawamura, A., Taniwaki, K. (1987). Gantry system. Proceedings of the International Symposium on Agricultural Mechanization and International Cooperation in High Technology Era, University of Tokyo, 3rd April: 109-114.

Moody, J. (2005). Relative performance of agricultural enterprises. Western Australian No-Till Farming Association Annual Conference, Perth, Australia, 2005.

Mooney, S. J., Korošak, D. (2009). Using complex networks to model two- and three-dimensional soil porous architecture. *Soil Science Society of America Journal,* 73 (4): 1094-1100.

Mouazen, A.M. (2002). Mechanical behaviour of the upper layers of a sandy loam soil under shear loading. *Journal of Terramechanics*, 39: 115-126.

Mrabet, R. (2003). Mediterranean conservation agriculture: paradigm for cropping systems. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 774–779.

Mullins, C.E., Young, I.M. Benbough, A.G., Ley, G.J. (1983). Hard-setting soils. *Soil Use & Management*, 3 (2): 79–83.

Munkholm, L.J., Schjønning, P. and Rüegg, K. (2005) Mitigation of subsoil compaction by light traffic and on-land ploughing. I. Soil response. *Soil & Tillage Research*, 80: 149-158.

Munkholm, L.J., Schjønning, P., Rasmussen, K.J., Tanderup, K. (2003). Spatial and temporal effects of direct drilling on soil structure in the seedling environment. *Soil & Tillage Research*, 71: 162–173.

N-O-P-Q

Nix, (2008). Farm Management Pocketbook, 39th Edition (2009). The Pocketbook, 2 Nottingham Street, Melton Mowbray, Leicestershire LE13 1NW. ISBN 978-0-9541201-7-7.

Olsen, H.J. (1994). Calculation of subsoil stresses. *Soil & Tillage Research*, 29: 111-123.

Ordnance Survey (1999). Explorer map 193. Luton & Stevenage, Hitchin & Ampthill, 1:25,000 scale. Ordnance Survey, Southampton, UK.

Owsiak, Z. (1999). Wear of spring tine cultivator points in sandy loam and light clay soils in southern Poland. *Soil & Tillage Research*, 50 (3-4), 333–340.

Pagliai, M., Marsili, A., Servadio, P., Vingozzi, N., Pellegrini, S. (2003). Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. *Soil & Tillage Research*, 73: 119–129.

Patterson, D. E., Chamen, W. C. T., Richardson, C. D. (1980). Long term experiments with tillage systems to improve the economy of cultivations for cereals. *Journal of Agricultural Engineering Research* 25 (1): 1-35.

Payne, R.W. (2009). Genstat. *Computational Statistics* 1: 255-258.

Perdok, U.D., Lamers, J.G. (1985). Studies of controlled agricultural traffic in The Netherlands. Proceedings of the International Conference on Soil Dynamics, National Tillage Machinery Laboratory, June, Auburn, U.S.A., Vol. 5: 1070-1086.

Pollard, F. & Elliott, J.B. (1978). The effect of soil compaction and method of fertilizer placement on the growth of barley using a concrete track technique. *Journal of Agricultural Engineering Research*, 23: 203–216.

Pollard, F. & Webster, R. (1978). Research Note. The persistence of the effects of simulated tractor wheeling on sandy loam subsoil. *Journal of Agricultural Engineering Research*, 23: 217–220.

Qingjie, W., Hao, C., Hongwen, L., Wenying, L., Xiaoyan, W., McHugh, A.D., Jin, H., Huanwen, G. (2009). Controlled traffic farming with no tillage for improved fallow water storage and crop yield on the Chinese Loess Plateau. *Soil & Tillage Research* 104 (1): 192-197.

R

Radford, R. & Yule, D. (2003). Compaction persists for five years after cessation of wheel traffic on a Vertisol in Central Queensland. Proceedings of the International Soil

Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 949–954.

Radford, B.J., Yule, D.F., McGarry, D., Playford, C. (2001). Crop responses to applied soil compaction and to compaction repair treatments. *Soil and Tillage Research*, 61 (3-4): 157-166.

Radford, B.J., Davis, R.J., McGarry, D., Pillai, U.P., Rickman, J.F., Walsh, P.A., Yule, D.F. (2000). Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. *Soil & Tillage Research*, 54: 155–170.

Radford, B. J., Yule, D. F. (1996). Controlled traffic: on-farm technology for the future. Australian Institute of Agricultural Science and Technology (AIAS) Occasional Publication, 93: 403-407.

Raghavan, G.S.V., McKyes, E., Baxter, R., Gendron, G. (1979). Traffic-soil-plant (maize) relations. *Journal of Terramechanics*, 16, (4): 181-189.

Raper, R.L., Reeves, D.W., Burt, E.C., Torbert, H.A. (1994). Conservation tillage and traffic effects on soil condition. *Transactions of the American Society of Agricultural Engineers*, 37: 763–768.

Rasmussen, R.J. (1994). Experiments with non-inversion tillage systems in Scandinavia – impacts on crop yields, soil structure and fertilisation. In: *Experience with the applicability of no-tillage crop production in the West-European countries*. Proceedings of the EC-workshop – I, Giessen, 27-28 June. pp 39-48.

Reicosky, D.C., Reeves, D.W., Prior, S.A., Runion, G.B., Rogers, H.H., Raper, R.L. (1999). Effects of residue management and controlled traffic on carbon dioxide and water loss. *Soil and Tillage Research*, 52 (3-4): 153-165.

Reintam, E., Trükmann, K., Kuht, J., Nugis, E., Edesi, L., Astover, A., Noormets, M., Kauer, K., Krebstein, K., Rannik, K. (2009). Soil compaction effects on soil bulk density and penetration resistance and growth of spring barley (Hordeum vulgare L.). Acta Agriculturæ Scandinavica. Section B, *Plant Soil Science,* 59 (3): 265-272.

Richardson, R.C.D. (1967). The wear of metals by hard abrasives. *Wear*, 10 (4): 291–309.

Roberts, M. (2010). Farmeco plans a controlled traffic future. *Profi International*, November 2010: 50-53.

Rochette, P., (2008). No-till only increases N_2O emissions in poorly-aerated soils. *Soil & Tillage Research*, 101: 97-100. Short communication.

Rohde, K. & Yule, D. (2003). Soil compaction and controlled traffic farming research in Central Queensland. Proceedings of the International Soil Tillage Research Organisation 16^{th} Triennial conference, Brisbane, 13–18 July, pp. 1020–1027.

Rousseva, S. (2002). Impact of soil compaction on crop production – Bulgarian experience. In: Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action “Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 225–227.

Rowland, D. (1972). Tracked vehicle ground pressure and its effect on soft ground performance. Proceedings of the 4^{th} International Conference of the ISTVS, Stockholm, Sweden. Volume 1, pp. 353-384.

Rusanov, V.A. (1991). Effects of wheel and track traffic on the soil and on crop growth and yield. *Soil & Tillage Research*, 19: 131-143.

Russell, E.W. (1988). *Russell's soil conditions and plant growth*. 11th ed. Longman Scientific & Technical, Harlow, England.

S

Sadras, V.O., O'Leary, G.J., Roget, D.K. (2005). Crop responses to compacted soil: capture and efficiency in the use of water and radiation. *Field Crops Research*, 91: 131-148.

Saunders, C. (2002). Optimising the performance of shallow high speed mouldboard ploughs. Unpublished PhD Thesis, Cranfield University at Silsoe, Bedford, MK45 4DT, UK.

Schäfer-Landefeld, L., Brandhuber, R., Fenner, S., Koch, H-J., Stockfisch, N. (2004). Effects of machinery with high axle load on soil properties of normally managed fields. *Soil & Tillage Research*, 75: 75–86.

Sheesley, W. (1978). Can traffic control boost alfalfa yields? *Agricultural Engineering*, 59 (8) 20–22.

Shepherd, T.G. (2009). Visual Soil Assessment. Volume 1. *Field guide for pastoral grazing and cropping on flat to rolling country*. 2nd Edition. Horizons Regional Council, Palmerston North, New Zealand. 106 p. ISBN 978−1−877468−75−9

Sijtsma, C.H., Campbell, A.J., McLaughlin, N.B., Carter, M.R. (1998). Comparative tillage costs for crop rotations utilizing minimum tillage on a farm scale. *Soil & Tillage Research*, 49 (3): 223-231.

Silburn, D.M., Simpson, B.W., Hargreaves, P.A. (2002). Management practices for control of runoff losses from cotton furrows under storm rainfall. II. Transport of pesticides in runoff. *Australian Journal of Soil Research*, 40: 21–44.

Sisti, C.P.J., dos Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S., Boddey, R.M. (2004). Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. *Soil & Tillage Research*, 76: 39–58.

Sitaula, B.K., Hansen, S., Sitaula, J.I.B., Bakken, L.R. (2000). Effects of soil compaction on N_2O emission in agricultural soil. *Chemosphere - Global Change Science*, 2 (3-4): 367-371.

Six, J., Ogle, S.M., Breidt, F. J., Conant, R.T., Mosier, A.R., Paustian, K. (2004). The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Global Change Biology*, 10: 155-160.

Smith, K.A. & Conen, F. (2004). Impacts of land management on fluxes of trace greenhouse gases. *Soil Use & Management*, 20: 255–263.

Smith, P. (2004). Soils as carbon sinks: the global context. *Soil Use & Management*, 20: 212–218.

Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith, Jo U., Falloon, P, Coleman, K. (2001). Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. *Nutrient Cycling in Agroecosystems* 60: 237-252.

Soane, B.D., Dickson, J.W., Campbell, D.J. (1982). Compaction by agricultural vehicles: a review. III. Incidence and control of compaction in crop production. *Soil & Tillage Research*, 2: 3–36.

Soane, G.C., Godwin, R.J., Marks, M.J., Spoor. G. (1987). Crop and soil response to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management on a range of soil types. Part 2: Soil structural conditions. *Soil Use & Management*, 3:123-130.

Soane, G.C., Godwin, R.J., Spoor. G. (1986). Influence of deep loosening techniques and subsequent wheel traffic on soil structure. *Soil & Tillage Research*, 8: 231-237.

Söchtig, W. & Larink, O. (1992). Effect of soil compaction on activity and biomass of endogenic lumbricids in arable soils. *Soil Biology and Biochemistry*, 24:,(12): 1595–1599.

Söhne, W., (1958). Fundamentals of pressure distribution and soil compaction under tractor tires. *Agricultural Engineering*, 276-281 + 290.

SSLRC (Soil Survey and Land Resource Centre) (1997). *Soil survey field handbook*, Soil Survey Technical Monograph No. 5. Cranfield University, Bedfordshire, UK.

Soil Survey Staff, (1999). *Soil taxonomy – a basic system of soil classification for making and interpreting soil surveys*. USDA-National Resources Conservation Service, Government Printing Office, Washington, DC 20402

Spence, C.C. (1960). *God speed the plow*. University of Illinois Press, Urbana, IL, USA. 183 pp.

Spink, J., Foulkes, M.J., Gay, A., Bryson, R., Berry, P., Sylvester-Bradley, R., Semere, T., Clare, R.W., Scott, R.K., Kettlewell, P.S., Russell, G. (2000). Reducing winter wheat production costs through crop intelligence information on variety and sowing date, rotational position and canopy management in relation to drought and disease control. Report No. 235, Home Grown Cereals Authority, London.

Spink, J., Street, P., Sylvester-Bradley, R., Berry, P. (2009). The potential to increase productivity of wheat and oilseed rape in the UK. Report to the Government Chief Scientific Advisor, January. 136 pp.

Spoor, G. (1997). Benefits from traffic control. *Landwards*, 52 (1): 2–5.

Spoor, G., Tijink, F.G.J., Weisskopf, P. (2003). Subsoil compaction: risk, avoidance, identification and alleviation. *Soil & Tillage Research*, 73: 175-182.

Spoor, G. & Godwin, R.J. (1978). An experimental investigation in the deep loosening of soil by rigid tines. *Journal of Agricultural Engineering Research*, 23: 243-258.

Stalham, M.A., Allen, E.J., Rosenfeld, A.B., Herry, F.X. (2007). Effects of soil compaction in potato (*Solanum tuberosum*) crops. *Journal of Agricultural Science*, 145 (4): 295-312.

Stewart, G.A. & Vyn, T.J. (1994). Influence of high axle loads and tillage systems on soil properties and grain corn yield. *Soil and Tillage Research*, 29: 229–235.

Strahan, R., Hoffman, A. (2009). Estimating the economic implications for broad acre cropping farms in the Fitzroy Basin catchments of adoption of best management practices. http://www.fba.org.au/publication/downloads/Report-FINAL-Fitzroy-Basin-BMP-24-August-2009_RC.pdf

Strutt, N. (1970). *Modern Farming and the Soil*. Ministry of Agriculture, Fisheries and Food (Department for Environment, Food and Rural Affairs), Smith Square, London SW1P 3JR

T-U

Taboada, M.A., Micucci, F.G., Cosentino, D.J., Lavado, R.S. (1999). Comparison of compaction induced by conventional and zero tillage in two soils of the Rolling Pampa of Argentina. *Soil and Tillage Research*, 49: 57–63.

Taylor, J.H. (1994). Development and benefits of vehicle gantries and controlled traffic systems. In: B.D. Soane, C. van Ouwerkerk, eds, *Soil Compaction in Crop Production*. Elsevier Science Publishers, B.V., Amsterdam: 521-537.

Taylor, J.H., (1991). Gantry vehicles for agriculture: International development and potential. Proceedings of the 5th European Conference of the International Society for Terrain Vehicle Systems, 460-467. National Soil Dynamics Laboratory, Auburn, AL, USA.

Taylor, J.H. (1989). Controlled traffic research: An international report. Proceedings of the 11th Congress of Agricultural Engineering (CIGR), Dublin, Ireland. 3: 1787-1794.

Taylor, J.H. (1983). Benefits of permanent traffic lanes in a controlled traffic crop production system. *Soil & Tillage Research*, 3: 385-395.

Tebrügge, F. & Düring, R.A. (1999). Reducing tillage intensity — a review of results from a long-term study in Germany. *Soil and Tillage Research*, 53 (1): 15-28.

The Royal Society. (2011). Reducing greenhouse gas emissions from agriculture. In: *Royal Society programme and abstracts*, 6-9 Carlton House Terrace, London, 28 Feb – 1 Mar. 2011.

The Stationery Office Ltd, (1986). *The Road Vehicles (Construction and Use) Regulations 1986 (as amended)*, PO Box 29, St Crispins House, Duke Street, NORWICH NR3 1GN, UK

Thompson, J.A., (1995). Irrigated cropping on permanent raised beds in Southern New South Wales. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 21-24.

Tijink, F.G.J. (1994). Quantification of vehicle running gear. In: B.D. Soane, C. van Ouwerkerk, eds, *Soil Compaction in Crop Production*. Elsevier Science Publishers, B.V., Amsterdam: 391-415.

Tillett, J.N. & Holt, J.B. (1987). The use of wide span gantries in agriculture. *Outlook Agriculture*, 16: 63-67.

Titmarsh, G., Waters, D., Wilson, A., Wockner, G., Burgis, M. Connolly, R. (2003). Experiences in runoff and erosion of controlled traffic farming systems, Southern Queensland. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 1235–1240.

Torbert, H.A. & Reeves, D.W. (1995). Traffic and residue management systems: effects on fate of fertilizer N in corn. *Soil and Tillage Research*, 33 (3-4): 197-213.

Trautner, A. & Arvidsson, J. (2003). Subsoil compaction caused by machinery traffic on a Swedish Eutric Cambisol at different soil water contents. *Soil & Tillage Research*, 73: 107-118.

Tullberg, J.N. (2000). Wheel traffic effects on tillage draught. *Journal of Agricultural Engineering Research*, 75 (4): 375–382.

Tullberg, J. (1997). Tractor-based systems for traffic control in Australia. *Landwards*, 52 (4): 12-15.

Tullberg, J., Yule, D.F., Neale, T., Chapman, W. (2006). Controlled traffic: a matter for science or practice? Proceedings of the 17th Triennial Conference of the International Soil Tillage Research Organisation, Kiel, Germany, 28 August – 23 September. 364-366.

Tullberg, J., Yule, D.F., McGarry, D. (2003). 'On track' to sustainable cropping systems in Australia. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 1271–1285.

Tullberg, J.N., Ziebarth, P.J., Li, Y. (2001). Tillage and traffic effects on runoff. *Australian Journal of Soil Research*, 39: 249–257.

Unger, P.W. (1996). Soil bulk density, penetration resistance, and hydraulic conductivity under controlled traffic conditions. *Soil and Tillage Research*, 37 (1): 67-75.

V

Van den Akker, J.J.H. (2006). Evaluation of soil physical quality of Dutch subsoils in two databases with some threshold values. Proceedings of the International Soil Tillage Research Organisation triennial conference "Sustainability – its impact on soil management and environment, 28 August – 3 September, Kiel, Germany, pp. 1615-1620

Van den Akker, J.J.H., Arvidsson, J., Horn, R. (Eds) (2003). Experiences with the impact and prevention of subsoil compaction in the European Union. *Soil & Tillage Research*, 73: 1-186.

Vermeulen, G.D, Tullberg, J.N., Chamen, W.C.T. (2010). Controlled Traffic Farming. In: D. Athanasios & T. Bartzanas, eds, *Soil Engineering*, Springer Verlag, Soil Biology series, ISSN 1613-3382, ed Prof. Dr. Ajit Varma, pp 101-120.

Vermeulen, G.D. & Mosquera, J. (2009). Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. *Soil & Tillage Research*, 102, 126-134.

Vermeulen, G.D., Mosquera, J., van der Wel, C., van der Klooster, A., Steenhuizen, J.W., (2007). Potential of controlled traffic farming with automatic guidance on an organic farm in the Netherlands. In: Stafford, J.V. (Ed.), Proceedings of the Precision Agriculture'07. Papers presented at the 6th European Conference on Precision Agriculture, June 3–6, 2007, Skiathos, Greece, pp. 473–481.

Vermeulen, G.D. & Perdok, U.D. (1994). Benefits of low ground pressure tyre equipment. In: B.D. Soane, C. van Ouwerkerk, eds, *Soil Compaction in Crop Production*. Elsevier Science Publishers, B.V., Amsterdam: 447-478.

Voorhees, W.B. (1987). Assessment of soil susceptibility to compaction using soil and climatic databases. *Soil & Tillage Research*, 10: 29–38.

Voorhees, W.B. (1983). Relative effectiveness of tillage and natural forces in alleviating wheel-inuced soil compaction. *Soil Science Society of America Journal*, 47: 129-133.

Voorhees, W.B., Nelson, W.W., Randall, G.W. (1986). Extent and persistence of subsoil compaction caused by heavy axle loads. *Soil Science Society of America Journal*, 50: 428–433.

Voorhees, W.B. & Lindstrom, M.J. (1984). Long-term effects of tillage method and soil tilth independent of wheel traffic compaction. *Soil Science Society of America Journal*, 48: 152–156.

Voorhees, W.B., Senst, C.G., Nelson, W.W. (1978). Compaction and soil structure modification by wheel traffic in the northern Corn Belt. *Soil Science Society of Americal Journal*, 42: 344-349.

W-Z

Wagger, M.G. & Denton, H.P. (1989). Influence of cover crop and wheel traffic on soil physical properties in continuous no-till corn. *Soil Science Society of America Journal*, 53 (4): 120–1210.

Watts, C.W., Dexter, A.R., Longstaff, D.J. (1996a). An assessment of the vulnerability of soil structure to destabilisation during tillage. Part II. Field trials. *Soil and Tillage Research*, 37: 175-190.

Watts, C.W., Dexter, A.R., Dumitru, E., Canarache, A. (1996b). Structural stability of two Romanian soils as affected by management practices. *Land Degradation and Development*, 7: 217-238.

Weaver, J.E. (1926). *Root development of field crops*. New York, McGraw-Hill.

Webb, B., Blackwell, P., Riethmuller, G., Lemon, J. (2004). Tramline farming systems: technical manual. Department of Agriculture Western Australia, GRDC Project DAW 718. Bulletin 4607. ISSN 1448-0352.

Wedderburn, J.N. & Wedderburn, R.W.M. (1972). Generalised linear models. Journal of the Royals Statistical Society. Series A (General) 135 (3): 370-384.

Wells, A. A. (1951). Soil mechanics and tillage. Ph.D. Thesis, University of Cambridge, (unpubl.)

Whalley, W.R., Watts, C.W., Gregory, A.S., Mooney, S.J., Clark, L.J, Whitmore, A.P. (2008). The effect of soil strength on the yield of wheat. *Plant Soil*, 306, 237-247.

Whitmore, A.P., Whalley, R.W., Bird, N.R.A., Watts, C.W., Gregory, A.S. (2010). Estimating soil strength in the rooting zone of wheat. *Plant and Soil*, 339: 363-375.

Wilhelm, W.W, Johnson, J.M.F, Hatfield, Voorhees, W.B., Linden, D.R. (2004). Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review. *Agronomy Journal*, 96 (1): 1-17.

Williford, J.R. (1985). A controlled traffic cropping system for the Mississippi Delta. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1132–1138. Office of Continuing Education, Auburn University, Alabama.

Wolkowski, R.P. (1990). Relationship between wheel-traffic-induced soil compaction, nutrient availability and crop growth: a review. *Journal of Production Agriculture*, 3 (4):460–469.

Yalcin, H. & Cakir, E. (2006). Tillage effects and energy efficiencies of subsoiling and direct seeding in light soil on yield of second crop corn for silage in Western Turkey. *Soil & Tillage Research*, 90: 250-255.

Yavuzcan, H.G. (2000). Wheel traffic impact on soil conditions as influenced by tillage system in Central Anatolia. *Soil and Tillage Research*, 54 (3-4): 129-138.

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal*, 61: 10240-1030.

Zhang, S., Simelton, E., Lövdahl, L., Grip, H., Chen, D. (2006). Simulated long-term effects of different soil management regimes on water balance in the Loess Plateau, China. *Field Crops Research*, 100: 311-319.

FURTHER READING

References consulted but not referred to directly in the text

A-fr

Abu-Hamdeh, N.H. (2003). Soil compaction and root distribution for okra as affected by tillage and vehicle parameters. *Soil & Tillage Research*, 74: 25–35.

Adem, H.H. (1995). Specific design limits for Tatura Permanent Beds. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 25–28.

Adem, H.H., Tisdall, J.M., Willoughby, P. (1984). Tillage management changes size distribution of aggregates and macro-structure of soils used for irrigated row-crops. *Soil & Tillage Research*, 4: 561–576.

Alakukku, L. (1997). *Long-term soil compaction due to high axle load traffic*. University of Helsinki. (PhD thesis)

Alblas, .I., Wanink, F., van den Akker, J. and van der Werf, H.M.G., (1994). Impact of traffic-induced compaction of sandy soils on the yield of silage maize in The Netherlands. *Soil & Tillage Research*, 29: 157- 165.

Angers, D.A., Samson, N., Légère, A. (1993). Early changes in water-stable aggregation induced by rotation and tillage in a soil under barley production. *Canadian Journal of Soil Science*, 73: 51–59.

B-fr

Bakken, L.R., Børresen, T., Njøs, A. (1987). Effect of soil compaction by tractor traffic on soil structure, denitrification and yield of wheat (*Triticum aestivum* L.). *Journal of Soil Science*, 38 (3): 541–552.

Bakker, D.M. & Barker, T.M. (1998). Soil structure assessment and 3-dimensional visualisation of a Vertosol under controlled traffic. *Australian Journal of Soil Research*, 36: 603–620. .

Bakker, D. & Hamilton, G. (1998). Production performance of permanent raised beds in widely differing soil and climatic regimes in WA. Proceedings of the Second National Controlled Traffic Conference, Gatton, Queensland, 27–27 August, pp. 18–22.

Ball, B.C. & Ritchie, R.M. (1999). Soil and residue management effects on arable cropping conditions and nitrous oxide fluxes under controlled traffic in Scotland. 1. Soil and crop responses. *Soil and Tillage Research*, 52 (3-4): 177-189.

Ball, B.C. & O’Sullivan, M.F. (1982). Soil strength and crop emergence in direct drilled and ploughed cereal seedbeds in seven field experiments. *Journal of Soil Science*, 33: 609–622.

Bauder, J.W., Randall, G.W., Schuler, R.T. (1985). Effects of tillage with controlled wheel traffic on soil properties and root growth of corn. *Journal of Soil & Water Conservation*, 40: 382–385.

Bauer, A. & Black, A.L. (1994). Quantification of the effect of soil organic matter content on soil productivity. *Soil Science Society of America Journal*, 58: 185–193.

Bayhan, Y., Kayisoglu, B., Gonulol, E. (2002). Effect of soil compaction on sunflower growth. *Soil and Tillage Research*, 68: 31–38.

Beard, F.R., McClendon, R.W., Manor, G. (1995). Comparing widespan equipment with conventional machinery systems for soybean production. *Applied Engineering in Agriculture*, 11 (6): 795–800.

Blackwell, P. (1998). Customised controlled traffic farming systems instead of standard recommendations. Proceedings of the Second National Controlled Traffic Conference, Gatton, Queensland, 27–27 August, pp. 23–26.

Blackwell, P., McKenzie, D, Webb, B., Lemon, J., Barber, P., Fretwell, G., Bignell, G., Moffat, N. (2004). Compaction of ‘heavy’ soils by cropping traffic and estimated benefits of Tramline Farming. Crop Updates to Agribusiness of Western Australia, Department of Agriculture, Geraldton, WA.

Blackwell, P.S., Webb, B., Lemon, J., Rietmuller, G. (2003). Tramline farming: pushing controlled traffic further for Mediterranean farming systems in Australia. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 171–174.

Bondarev, A.G. (2002). Impact of machinery traffic on soil and subsoil compaction, on changes in physical properties and on fertility of soils in Russia. In *Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action “Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction*. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 189–195.

Boone, F.R. & Veen, B.W. (1994). Mechanisms of crop responses to soil compaction. In B.D. Soane & C. van Ouwerkerk, eds. *Soil compaction in crop production* pp. 237–264. Amsterdam, Elsevier Science B.V. 662 pp.

Braunack, M.V., Arvidsson, J, Håkansson, I. (2006). Effect of harvest traffic on soil conditions and sugar cane (Saccharum officinarum) response to environmental conditions in Queensland, Australia. *Soil & Tillage Research*, 89, 103-121.

Braunack, M.V., McGarry, D., Halpin, N.V. (2003). The economic advantage of reduced tillage planting of sugarcane in Australia. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 208–212.

Breay, T. (1983). Forward planning helps minimise seedbed wheelings. *British Sugar Beet Review*, 51 (2): 25–27.

Burt, E.C., Reeves, D.W., Raper, R.L. (1994). Energy utilization as affected by traffic in a conventional and conservation tillage system. *Transactions of the American Society of Agricultural Engineers*, 37: 759–762.

Butterworth, B. (2002). Nitrate nonsense. *Landwards*, 57 (3): 6–7.

C-fr

Canillas, E.C., Vilas, M., Salokhe, V.M. (2002). A decision support system for compaction assessment in agricultural soils. *Soil & Tillage Research*, 65: 221–230.

CEC - Commission of The European Communities. (2006). Communication "Thematic Strategy for Soil Protection" COM 231 final, Annex 2 -Results of the Internet Consultation. (WWW document).

Chamen, W.C.T. (2009). CTF – the story so far. *Landwards*, 64 (3): 12-14.

Chapman, W., Spackman, G.B., Yule, D.F., Cannon, R.S. (1995). Controlled traffic development on dryland broadacre farms in Central Queensland. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 115–122.

Coelho, M.B., Mateos, L., Villalobos, F.J. (2000). Influence of a compacted loam subsoil layer on growth and yield of irrigated cotton in Southern Spain. *Soil and Tillage Research*, 57 (3): 129-142.

Conservation Farmers Inc., (2003). *Controlled traffic farming guide*. PO Box 1666, Toowoomba, Qld 4350, Australia, 43 pp. (also available at: http://www.cfi.org.au/100106b.php

D-E-fr

Deckers, J., Driessen, P., Nachtergaele, F.O., Spaargaren, O., Berding, F. (2003). Anticipated developments of the World Reference Base for soil resources. In: Soil Classification: a global desk reference, 2003. H. Eswaran, T. Rice, R. Ahrens & B.A. Stewart (eds), pp. 245–256. CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

Department of Agriculture Western Australia. (2004). *Tramline Farming Systems – Technical Manual*. Compiled by B. Webb, P. Blackwell, G. Riethmuller & J Lemon. Bulletin 4607, ISSN 1448-0352. GRDC Project DAW 718, 88 pp.

Dexter, A.R. (1978). Tunnelling in soil by earthworms. *Soil Biology and Biochemistry*, 10: 447–449.

Diaz-Zorita, M. (2000). Effect of deep-tillage and nitrogen fertilization interactions on dryland corn (*Zea mays* L.) productivity. *Soil and Tillage Research*, 54 (1-2): 11-19.

F-G-fr

FAO, (2001). Lecture notes on the major soils of the world. P. Driessen, J. Deckers, O Spaargaren and F. Nachtergaele (eds). Food and Agriculture Organization of the United Nations, Rome, 334 pp.

Farmers Weekly, (2004). Good vibes for disease tool. Reed Business Information, Sutton, Surrey SM2 5AS. July 9-15. p. 50.

Flowers, M.D. & Lal, R. (1998). Axle load and tillage effects on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio. *Soil & Tillage Research*, 48: 21–35.

Frost, J.P. (1988). Effects on crop yield of machinery traffic and soil loosening. 1. Effects on grass yield of traffic frequency and date of loosening. *Journal of Agricultural Engineering Research*, 39 (4): 301–312.

Frost, J.P. (1988). Effects on crop yield of machinery traffic and soil loosening. 2. Effects on grass yield of soil compaction, low ground pressure tyres and date of loosening. *Journal of Agricultural Engineering Research*, 40 (1): 57–69.

Gerik, T.J., Morrison, J.E. Jr., Chichester, F.W. (1987). Effects of controlled-traffic on soil physical properties and crop rooting. *Agronomy Journal*, 79: 434–438.

Gliemeroth, G. 1952. Water content of the soil in relation to the root development of some cultivated plants. *Zutschruft fur Acher und Pflangenban*, 95: 21–46.

H-I-fr

Hansen, S. (1996). Effects of manure treatment and soil compaction on plant production of a dairy farm system converting to organic farming practice. *Agriculture, Ecosystems & Environment* 56 (3): 173-186.

Hartemink, A.E. (1998). Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. *Geoderma*, 85 (4): 283-306.

Heineke, H.J., Eckelmann, W., Thomasson, A.J., Jones, R.J.A., Montanarella, L., Buckley, B. (Eds) (1998). *Land information systems – development for planning the sustainable use of land resources*. European Soil Bureau Research Report No. 4. EUR 17729 EN. Office of the Official Publications of the European Communities, Luxembourg. 546 pp.

Holloway, R.E. & Dexter, A.R. (1990). Compaction of virgin soil by mechanized agriculture in a semiarid environment. *Land Degradation and Rehabilitation*, 2: 107–115.

Hulme, P.J., McKenzie, D.C., MacLeod, D.A., Anthony, D.T.W. (1996). An evaluation of controlled traffic with reduced tillage for irrigated cotton on a Vertisol. *Soil and Tillage Research*, 38 (3-4): 217-237.

Hulugalle, N.R. & Entwistle, P. (1997). Soil properties, nutrient uptake and crop growth in an irrigated Vertisol after nine years of minimum tillage. *Soil and Tillage Research*, 42 (1-2): 15-32.

J –K-fr

Janzen, D.C., Hefner, R.E., Erbach, D.C. (1985). Soil and corn response to track and wheel compaction. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1023–1038. Office of Continuing Education, Auburn University, Alabama.

Johnson, B.S. & Erickson, A.E. (1991). Sugar beet response to subsoiling and wheel traffic. *Agronomy Journal*, 83 (2): 386–390.

Johnson, J.F., Voorhees, W.B., Nelson, W.W., Randall, G.W. (1990). Soybean growth and yield as affected by surface and subsoil compaction. *Agronomy Journal*, 82 (5): 973–979.

Jorajuria, D. & Draghi, L. (1997). The distribution of soil compaction with depth and the response of a perennial forage crop. *Journal of Agricultural Engineering Research*, 66 (4): 261-265.

Khalilian, A., Hood, C.E., Palmer, J.H., Garner, T.H., Bathke, G.R. (1991). Soil compaction and crop response to wheat/soybean interseeding. *Transactions of the ASAE*, 34 (6): 2299–2303.

Kirstjens, D.A.G., Kropff, M.J., Perdok, U.D. (2004). Method for predicting selective uprooting by mechanical weeders from plant anchorage forces. *Weed Science*, 52: 123–132.

Kisu, M. (1985). Automatic field work apparatus. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1039–1045. Office of Continuing Education, Auburn University, Alabama.

Koch, J., Heuer, H., Tomanová, O. (2007). Soil properties and sugar beet growth as affected by repeated passes of heavy machinery and soil tillage. *VDI Berichte*, 2007, 447-453.

L-fr

Lal, R. (1996). Axle load and tillage effects on crop yields on a Mollic Ochraqualf in Northwest Ohio. *Soil and Tillage Research*, 37 (2-3): 143-160.

Lal, R. & Ahmadi, M. (2000). Axle load and tillage effects on crop yield for two soils in central Ohio. *Soil and Tillage Research*, 54 (1-2): 111-119.

Leiva, F.R. & Morris, J. (2001). Mechanization and sustainability in arable farming in England. *Journal of Agricultural Engineering Research*, 79: 81–90.

Leiva, F.R. & Morris, J. (2004). Alternative mechanisation practices for sustainability in arable farming in England. In press.

Lipiec, J. (2002). Impact of soil compaction on crop productivity – Polish experience. In Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action “Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp.229–233.

Lipiec, J., Nosalewicz, A., Smarz, M. (2002). Root growth and water uptake of wheat as affected by soil compaction. In Proceedings of the 3rd workshop, INCO COPERNICUS Concerted Action “Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction. A. Canarache, E. Dimitru & R. Enache, eds. Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 171–177.

M-fr

Malhi, S.S., Lemke, R., Farrell, R., Leach, D. (2003). Influence of tillage and crop residue management on seed yield, soil quality and greenhouse emissions. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 690–695.

Mammana, E. & Ohua, J.O. (1997). Millet yield as affected by tractor traffic in a sandy loam soil in Borno State, Nigeria. *Soil and Tillage Research*, 42 (1-2): 133-140.

Manor, G. (1995). Automatic field machine technology. *Journal of Terramechanics*, 32: 79–90.

Mason, R., Page, J., Cloete, M. (1998). Using minimum tillage and controlled traffic to reduce the risk of cropping in the Burnett. Proceedings of the Second National Controlled Traffic Conference, Gatton, Queensland, 27–27 August, pp. 27–30. .

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

McGarry, D. & Sharp, G. (2003). A comparison of soil physical properties and soil morphology under adjoining fields of conventional and reduced till with controlled traffic. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 708–715.

McKeyes, E., Negi, S., Douglas, E., Taylor, F., Raghavan, V. (1979). The effect of machinery traffic and tillage operations on the physical properties of a clay and on yield of silage corn. *Journal of Agricultural Engineering Research*, 24: 143–148.

McPhee, J.E., Braunack, M.V., Garside, A.L., Reid, D.J., Hilton, D.J. (1995). Controlled traffic for irrigated double cropping in a semi-arid tropical environment. Part 3. Timeliness and trafficability. *Journal of Agricultural Engineering Research*, 60: 191–199.

McQueen, D.J. & Shepherd, T.G. (2002). Physical changes and compaction sensitivity of a fine-textured, poorly drained soil (Typic Endoaquept) under varying durations of cropping, Manawatu Region, New Zealand. *Soil and Tillage Research* 63 (3-4): 93-107.

Meek, B.D., Rechel, E.R., Carter, L.M., DeTar, W.R., Urie, A.L. (1992). Infiltration rate of a sandy loam soil: effects of traffic, tillage and plant roots. *Soil Science Society of America Journal*, 56 (3) 908–913.

Meek, B.D., DeTar, W.R., Rolph, D., Rechel, E.R, Carter, L.M. (1990). Infiltration rate as affected by an alfalfa and no-till cropping system. *Soil Science Society of America Journal*, 54 (2): 505–508.

Melander, B., Jørgensen, M.H., Elsgaard, L. (2004). Recent results in the development of band steaming for intra-row weed control. Proceedings of the 6th European Weed Research Society Physical and Cultural Weed Control workshop, Lillehammer, Norway, 8–10 March. Norwegian Crop Research Institute, Høgskoleveien 7, 1432 Ås, Norway, p. 21.

Metreveli, V.I., Didebulidze, A.K., Gabeliya, D.I., Ramazashvili, R. E. (1990). Automated electric drive of a bridge unit. *Tekhnika V Sel'Skom Khozyaistve*, 1: 33–36. (in Russian)

Moreno, F., Murer, E.J., Stenitzer, E., Fernández, J.E., Girón, I.F. (2003). Simulation of the impact of subsoil compaction on soil water balance and crop yield of irrigated maize on a loamy sand soil in SW Spain. *Soil & Tillage Research*, 73: 31–41.

Morrison, J.E., Jnr. (1985). Machinery requirements for permanent wide beds with controlled traffic. *Applied Engineering in Agriculture*, 1: 64–67.

N-O-P-Q-fr

Nachtergaele, F.O., Berding, F.R., Deckers, J. (2001). Pondering hierarchical soil classification systems. In: Soil Classification 2001. E. Micheli, F.O. Nachtergaele, R.J.A. Jones and L. Montanarella (eds), pp 71–79. European Soil Bureau Research Report No. 7, EUR 20398 EN, (2002), 248 pp. Office for Official Publications of the European Communities, Luxembourg.

Negi, S.C., McKeyes, E., Raghavan, G.S.V., Taylor, F. (1981). Relationships of field traffic and tillage to corn yields and soil properties. *Journal of Terramechanics*, 18 (2): 81–90.

Nugis, E., Kuht, J., Viil, P., Loogus, H. (2003). Controlled traffic crop production in Estonia. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 857–862.

Ockerby, S.E. & Punter, L.D. (1995). Controlled traffic: an integral part of a new rice cropping system for the dry tropics. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 172–175.

Oni, K.C. & Adeoti, J.S. (1986). Tillage effects on differently compacted soil and on cotton yield in Nigeria. *Soil & Tillage Research*, 8: 89–100.

Ostapov, V.I., Ostapchenko, V.I., Goncharov, I.F., Ganich, L.A. (1985). Gantry agriculture - raising the efficiency of improved lands. *Mekhanizatsiya i Elektrifikatsiya Sel'Skogo Khozyaistva*, 4: 10–11. (in Russian)

Palmqvist, (2008). Evaluation of the environmental benefits of controlled traffic farming. MSc Thesis, Cranfield University, Cranfield, UK. 73 pp.

Pangnakorn, U., George, D.L., Tullberg, J.N., Gupta, M.L. (2003). Effect of tillage and traffic on earthworm populations in a vertosol in South-East Queensland. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp 881–885.

Peries, R., Bluett, C., Wightman, B., Rab, A., Islam, N. (2003). Is controlled traffic farming changing soil structure under raised beds in Southern Victoria? Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July.

Pearce, T.G. (1984). Earthworm populations in soils disturbed by trampling. *Biological Conservation*, 29: 241–252.

Pillai, U., Harris, R., Chinn, C., McGarry, Radford, B., Yule, D. (2003). Comparison of soil management systems in ameliorating compaction of two Vertosols. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 929–937.

Price, G.H., Smethurst, P.J., Sparrow, L.A., Sojka, R.E. (2003). Soil quality – to regulate or to manage? Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 938–942.

Pringle, M.J. & Lark, R.M., (2007). Scale- and location-dependent correlations of soil strength and the yield of wheat. *Soil & Tillage Research*, 95, 47-60.

Quiroga, A.R., Buschiazzo, D.E., Peinemann, N. (1999). Soil compaction is related to management practices in the semi-arid Argentine pampas. *Soil and Tillage Research*, 52 (1-2): 21-28.

R-fr

Radcliffe, D.E., Manor, G., Clark, R.L., West, L.T., Langdale, G.W., Bruce, R.R. (1989). Effect of traffic and in-row chiselling on mechanical impedance. *Soil Science Society of America Journal*, 53: 1197–1201.

Radford, B.J., Yule, D.F., McGarry, D., Playford, C. (2007). Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. *Soil & Tillage Research*, 97, 249-255.

Radford, B.J., Wilson-Rummenie, A.C., Simpson, G.B., Bell, K.L., Ferguson, M.A. (2001). Compacted soil affects soil macrofauna populations in a semi-arid environment in central Queensland. *Soil Biology and Biochemistry*, 33 (12-13): 1869-1872.

Radics, L., Glemnitz, M., Hoffmann, J., Czimber, G.Y. (2004). Compostion of weed floras in different agricultural management systems within the European climatic gradient. Proceedings of the 6th European Weed Research Society Physical and Cultural Weed Control workshop, Lillehammer, Norway, 8–10 March. Norwegian Crop Research Institute, Høgskoleveien 7, 1432 Ås, Norway, p. 62 & separate report, 9 pp.

Raper, R.L. (2005). Agricultural traffic impacts on soil. *Journal of Terramechanics*, 42: 259-280.Rasmussen, I. 2004. The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Research*, 44 (1): 12–20.

Rasmussen, I.A. & Holst, N. (2003). Computer model for simulating the long-term dynamics of annual weeds: from seedlings to seeds. *Aspects of Applied Biology*, 69: 277–284. See also: http://web.agrsci.dk/plb/nho/fieldweeds.htm

Rastorguev, V.M., Smolyakov, V.F., Simonov, L.M. (1990). Bridge unit. *Tekhnika V Sel'Skom Khozyaistve*, 1: 36–38. (in Russian)

Rechel, E.A., Carter, L.M., DeTar, W.R. (1987). Alfalfa growth response to a zone-production system. I. Forage production characteristics. *Crop Science*, 27 (5): 1029–1034.

Reeves, D.W., Rogers, H.H., Droppers, J.A., Prior, S.A., Powell, J.B. (1992). Wheel-traffic effects on corn as influenced by tillage system. *Soil & Tillage Research*, 23: 177–192.

S-fr

Science Communication Services, (1989). Potential for gantry systems in Australian agriculture. Energy Technology Update, Department of Primary Industries and Energy, Australian Government, Canberra. ISSN 1030-2778.

Sedaghatpour, S., Ellis, T., Hignett, C., Bellotti, B. (1995). Six years of controlled traffic cropping research on a red brown earth at Roseworthy in South Australia. Proceedings of the National Controlled Traffic Conference, Rockhampton, Queensland, 13–14 September, pp. 69–75.

Silburn, D.M., Freebairn, D.M., Rattray, D.J. (2003). Tillage and the environment – tradeoffs and challenges. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 1134–1141.

Stenitzer, E. & Murer, E. (2003). Impact of soil compaction upon soil water balance and maize yield estimated by the SIMWASER model. *Soil & Tillage Research*, 73: 43–56.

Stewart, L. E. D., Copland, T. A., Dickson, J. W., Douglas, J. T. (1998). Economic evaluation of traffic systems for arable and grass crops on an imperfectly drained soil in Scotland. *Journal of Sustainable Agriculture*, 12 (1): 41-56.

Sturz, A.V. Carter, M.R., Johnston, H.W. (1997). A review of plant disease, pathogen interactions and microbial antagonism under conservation tillage in temperate humid agriculture. *Soil and Tillage Research*, 41 (3-4): 169-189.

T-U-fr

Tisdall, J.M. & Adem, H.H. (1988). An example of custom prescribed tillage in South-eastern Australia. *Journal of Agricultural Engineering Research*, 40: 23–32.

Torbert, H.A. & Reeves, D.W. (1995). Interactions of traffic and tillage applied to cotton on N movement below the root zone of a subsequent wheat crop. *Soil and Tillage Research*, 33 (1): 3-16.

Trautner, A. & Arvidsson, J. (2003). Subsoil compaction caused by machinery traffic on a Swedish Eutric Cambisol at different water contents. *Soil & Tillage Research*, 73: 107–118.

Trouse, A.C. (1985). Development of the controlled traffic concept. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1112–1119. Office of Continuing Education, Auburn University, Alabama.

V-fr

Varsa, E.C., Chong, S.K., Abolaji, J.O., Farquhar, D.A., Olsen, F.J. (1997). Effect of deep tillage on soil physical characteristics and corn (*Zea mays* L.) root growth and production. *Soil and Tillage Research*, 43 (3-4): 219-228.

Voorhees, W.B. (1991). Compaction effects on yields – are they significant? *Transactions of the ASAE*, 34 (4): 1667–1672.

Voorhees, W.B., Johnson, J.F., Randall, G.W., Nelson, W.W. (1989). Corn growth and yield as affected by surface and subsoil compaction. *Agronomy Journal*, 81 (2): 294–303.

Voorhees, W.B., Evans, S.D., Warnes, D.D. (1985). Effect of preplant wheel traffic on soil compaction, water use and growth of spring wheat. *Journal of the Soil Science Society of America*, 49 (1): 215–220.

Voorhees, W.B., Nelson, W.W., Randall, G.W. (1985). Soil and crop response to wheel traffic on highly productive soils of the Northern Corn Belt. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1120–1131. Office of Continuing Education, Auburn University, Alabama.

Vossen, P. & Meyer-Roux, J. (1995). Crop monitoring and yield forecasting activities of the MARS Project. In: European Land Information Systems for Agro-environmental

Monitoring. D. King, R.J.A. Jones & A.J. Thomasson (eds). EUR 16232 EN, p. 11–29. Office of Official Publications of the European Communities, Luxembourg.

W-Z-fr

Wang, X, Gao, H.W., Li, H.W. (2003). Runoff and soil erosion from farmland under conservation tillage. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July, pp. 1347–1353.

Watts, C.W. & Dexter, A.R. (1997). The influence of organic matter in reducing the destabilisation of soil by simulated tillage. *Soil and Tillage Research*, 42: 253-275.

Wesley, R.A. & Smith, L.A. (1991). Response of soybean to deep tillage with controlled traffic. Transactions of the ASAE, 34 (1): 113–119.

Whalley, W.R., Dumitru, E., Dexter, A.R. (1995). Biological effects of soil compaction. *Soil and Tillage Research*, 35: 53–68.

Whalley, W.R., Leeds-Harrison. P.B., Clark, L.J., Gowing, D.J.G. (2005). Use of effective stress to predict the penetrometer resistance of unsaturated agricultural soils. *Soil & Tillage Research*, 84 (1): 18-27.

Williford, J.R. (1980). A controlled traffic system for cotton production. *Transactions of the ASAE*, 23: 65-70.

Wolkowski, R.P. (1991). Corn growth response to K fertilization on three compacted soils. *Soil & Tillage Research*, 21: 287–298.

Young, S.C., Grisso, R.D., Dumas, W.T., Johnson, C.E. (1985). Long term tillage requirements with controlled traffic. Proceedings of the International Conference on Soil Dynamics, Volume 5, pp. 1139–1151. Office of Continuing Education, Auburn University, Alabama.

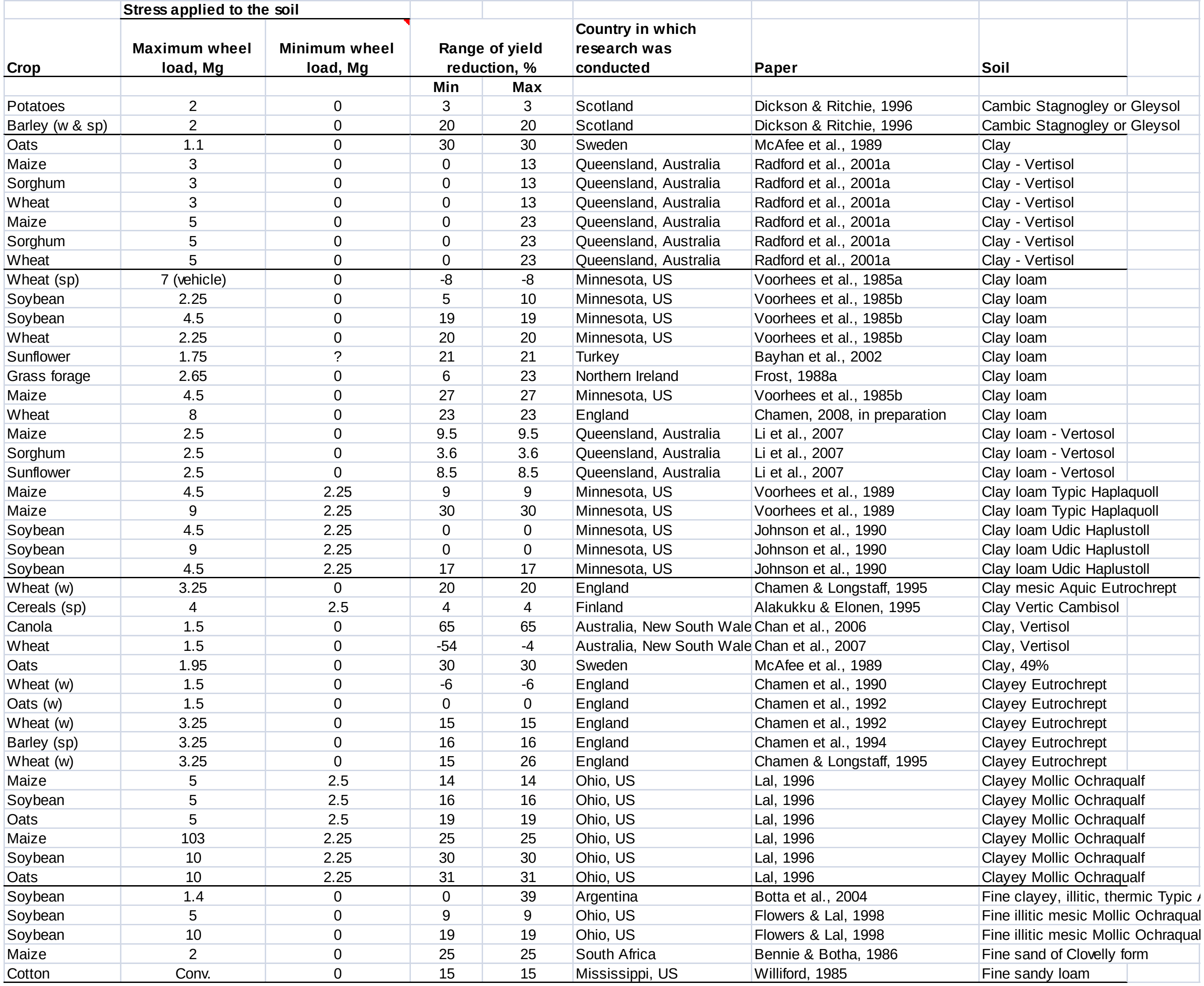
APPENDIX A

SUMMARY OF RESEARCH DATA LISTING DIFFERENT SOIL AND CROP RESPONSES TO WHEEL LOADS

Tables 1A – 3A

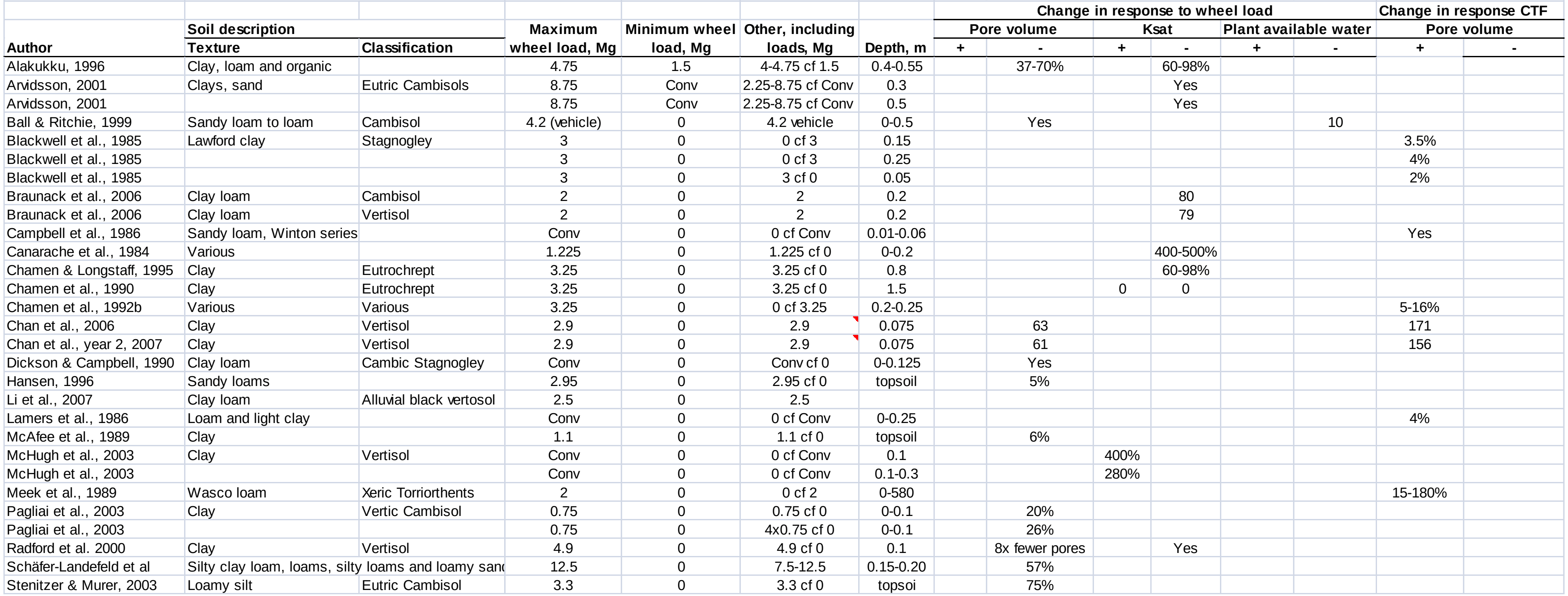
			Stress applied to the soil			Results			
	Soil description		Maximum wheel load, Mg	Minimum wheel load, Mg	Experiment duration, y	Bulk density, %	Depth of mesrmnt, m	Pen. Res., %	Depth of mesrmnt, m
Author	Texture	Classification							
Abu-Hamdeh, 2003	Loam	fine mixed mesic Typic Haplustox	8	0	1	22	0-0.48	39	0-0.48
Blackwell et al., 1985	Lawford clay	Stagnogley	3	0	4			13	0.3
Bondarev, 2002		Chernozem	1.2	0		15	0.07-0.14		
Bondarev, 2002		Chernozem	1.2	0		21	0-0.2		
Botta et al., 2004		Typic Argiudol	1.38	0	1, continuing	13.5	0-0.15		
Braunack et al., 2006	Clay loam	Cambisol	2	0	5	15	0.2	48	0.4
Braunack et al., 2006	Clay loam	Vertisol	2	0	5	17	0.2	46	0.3
Canarache et al., 1984			1.225	0		25	0-0.2	28	
Chamen & Audsley, 1993	Sand & clay		2.5	0		5		75	
Chamen & Cavalli, 1994	Clay	Eutrochrept	3.25	0	5	17	0-0.175	23	0-0.45
Chamen & Longstaff, 1995	Clay	Eutrochrept	3.25	0		17	0-0.175	24	0-0.45
Chamen et al., 1990	Clay	Eutrochrept	3.25	0	2			100	0.05
Chamen et al., 1990	Clay	Eutrochrept	3.25	0		8	0.2	35	0-0.45
Chamen et al., 1992a	Clay	Eutrochrept	3.25	0		12	0.3	44	0.2-0.35
Chamen et al., 1992b	Various	Various	3.25	0		8	0-0.2		
Chamen, 2008, in preparation	Clay	Calcareous pelosol	8	0	3			19	0-0.55
Chamen, 2008, in preparation	Clay	Calcareous pelosol	8	0	3			39	0-0.55
Chan et al., 2006	Clay	Vertisol	2.9	0	2	22	0.075		
Chan et al., 2007	Clay	Vertisol	2.9	0	2	20	0.075		
Hansen, 1996	Sandy loams		2.95	0		27	0-0.2	100	0.225
Jorajuria et al., 1997	Clay	Typic Argiudol	0.8	0		48	0-0.3	56	0.3
Jorajuria et al., 1997			1.4	0		44	0-0.3	96	0.3
Jorajuria et al., 1997			0.8	0		23	0.3-0.6	58	0.6
Jorajuria et al., 1997			1.4	0	1	28	0.3-0.6	81	0.6
McAfee et al., 1989	Clay		1.09	0	1	10.0	0.1-0.2		
Meek et al., 1988			2.5	0		13	0.15		
Meek et al., 1989	Wasco loam	Xeric Torriorthents	1.25	0		5.8	0.2-0.29		
Pagliai et al., 2003	Clay	Vertic Cambisol	0.75	0	1	7.9	0-0.1	12.5	0-0.4
Pagliai et al., 2003	Clay	Vertic Cambisol	0.75	0		11.7	0-0.1	49.9	0-0.4
Pangnakorn et al., 2003		Vertisol	0.75	0		11.7	0-0.1	50	0-0.4
Radford & Yule, 2003	Clay	Vertisol	5	0	5			13	0.18-0.36
Schäfer-Landefeld et al., 2004	Various		10	0		7.5	0.15-0.2		
Stenitzer & Murer, 2003	Loamy silt	Eutric Cambisol	3.3	0	1	27	0-0.3	88	0-0.3
Stewart & Vyn, 1994	London loam	Typic Hapludoll	6	2	3	6.9	0-300	87	0-0.3
Yavuzcan, 2000			1.1	0		15	0-0.05	52	0-0.1
Zhang et al., 2006	Fine silt	Typic Agriboroll	0.54	0	6	23	0-0.2	95	0.15-0.2

Fig. 1A. The effect of different wheel loads applied to different soils in different parts of the world as part of research assessing their impact on bulk density and penetration resistance. The blocks in blue and yellow reflect graphed data appearing in Figs 2.3-2.5



	Stress applied to the soil						
Crop	Maximum wheel load, Mg	Minimum wheel load, Mg	Range of yield reduction, %		Country in which research was conducted	Paper	Soil
			Min	Max			
Potatoes	2	0	3	3	Scotland	Dickson & Ritchie, 1996	Cambic Stagnogley or Gleysol
Barley (w & sp)	2	0	20	20	Scotland	Dickson & Ritchie, 1996	Cambic Stagnogley or Gleysol
Oats	1.1	0	30	30	Sweden	McAfee et al., 1989	Clay
Maize	3	0	0	13	Queensland, Australia	Radford et al., 2001a	Clay - Vertisol
Sorghum	3	0	0	13	Queensland, Australia	Radford et al., 2001a	Clay - Vertisol
Wheat	3	0	0	13	Queensland, Australia	Radford et al., 2001a	Clay - Vertisol
Maize	5	0	0	23	Queensland, Australia	Radford et al., 2001a	Clay - Vertisol
Sorghum	5	0	0	23	Queensland, Australia	Radford et al., 2001a	Clay - Vertisol
Wheat	5	0	0	23	Queensland, Australia	Radford et al., 2001a	Clay - Vertisol
Wheat (sp)	7 (vehicle)	0	-8	-8	Minnesota, US	Voorhees et al., 1985a	Clay loam
Soybean	2.25	0	5	10	Minnesota, US	Voorhees et al., 1985b	Clay loam
Soybean	4.5	0	19	19	Minnesota, US	Voorhees et al., 1985b	Clay loam
Wheat	2.25	0	20	20	Minnesota, US	Voorhees et al., 1985b	Clay loam
Sunflower	1.75	?	21	21	Turkey	Bayhan et al., 2002	Clay loam
Grass forage	2.65	0	6	23	Northern Ireland	Frost, 1988a	Clay loam
Maize	4.5	0	27	27	Minnesota, US	Voorhees et al., 1985b	Clay loam
Wheat	8	0	23	23	England	Chamen, 2008, in preparation	Clay loam
Maize	2.5	0	9.5	9.5	Queensland, Australia	Li et al., 2007	Clay loam - Vertosol
Sorghum	2.5	0	3.6	3.6	Queensland, Australia	Li et al., 2007	Clay loam - Vertosol
Sunflower	2.5	0	8.5	8.5	Queensland, Australia	Li et al., 2007	Clay loam - Vertosol
Maize	4.5	2.25	9	9	Minnesota, US	Voorhees et al., 1989	Clay loam Typic Haplaquoll
Maize	9	2.25	30	30	Minnesota, US	Voorhees et al., 1989	Clay loam Typic Haplaquoll
Soybean	4.5	2.25	0	0	Minnesota, US	Johnson et al., 1990	Clay loam Udic Haplustoll
Soybean	9	2.25	0	0	Minnesota, US	Johnson et al., 1990	Clay loam Udic Haplustoll
Soybean	4.5	2.25	17	17	Minnesota, US	Johnson et al., 1990	Clay loam Udic Haplustoll
Wheat (w)	3.25	0	20	20	England	Chamen & Longstaff, 1995	Clay mesic Aquic Eutrochrept
Cereals (sp)	4	2.5	4	4	Finland	Alakukku & Elonen, 1995	Clay Vertic Cambisol
Canola	1.5	0	65	65	Australia, New South Wale	Chan et al., 2006	Clay, Vertisol
Wheat	1.5	0	-54	-4	Australia, New South Wale	Chan et al., 2007	Clay, Vertisol
Oats	1.95	0	30	30	Sweden	McAfee et al., 1989	Clay, 49%
Wheat (w)	1.5	0	-6	-6	England	Chamen et al., 1990	Clayey Eutrochrept
Oats (w)	1.5	0	0	0	England	Chamen et al., 1992	Clayey Eutrochrept
Wheat (w)	3.25	0	15	15	England	Chamen et al., 1992	Clayey Eutrochrept
Barley (sp)	3.25	0	16	16	England	Chamen et al., 1994	Clayey Eutrochrept
Wheat (w)	3.25	0	15	26	England	Chamen & Longstaff, 1995	Clayey Eutrochrept
Maize	5	2.5	14	14	Ohio, US	Lal, 1996	Clayey Mollic Ochraqualf
Soybean	5	2.5	16	16	Ohio, US	Lal, 1996	Clayey Mollic Ochraqualf
Oats	5	2.5	19	19	Ohio, US	Lal, 1996	Clayey Mollic Ochraqualf
Maize	103	2.25	25	25	Ohio, US	Lal, 1996	Clayey Mollic Ochraqualf
Soybean	10	2.25	30	30	Ohio, US	Lal, 1996	Clayey Mollic Ochraqualf
Oats	10	2.25	31	31	Ohio, US	Lal, 1996	Clayey Mollic Ochraqualf
Soybean	1.4	0	0	39	Argentina	Botta et al., 2004	Fine clayey, illitic, thermic Typic /
Soybean	5	0	9	9	Ohio, US	Flowers & Lal, 1998	Fine illitic mesic Mollic Ochraqual
Soybean	10	0	19	19	Ohio, US	Flowers & Lal, 1998	Fine illitic mesic Mollic Ochraqual
Maize	2	0	25	25	South Africa	Bennie & Botha, 1986	Fine sand of Clovelly form
Cotton	Conv.	0	15	15	Mississippi, US	Williford, 1985	Fine sandy loam

Fig. 2A. The effect of different wheel loads applied to different soils in different parts of the world as part of research assessing their impact on crop yields displayed by soil type.



							Change in response to wheel load						Change in response CTF	
	Soil description						Pore volume		Ksat		Plant available water		Pore volume	
Author	Texture	Classification	Maximum wheel load, Mg	Minimum wheel load, Mg	Other, including loads, Mg	Depth, m	+	-	+	-	+	-	+	-
Alakukku, 1996	Clay, loam and organic		4.75	1.5	4-4.75 cf 1.5	0.4-0.55		37-70%		60-98%				
Arvidsson, 2001	Clays, sand	Eutric Cambisols	8.75	Conv	2.25-8.75 cf Conv	0.3				Yes				
Arvidsson, 2001			8.75	Conv	2.25-8.75 cf Conv	0.5				Yes				
Ball & Ritchie, 1999	Sandy loam to loam	Cambisol	4.2 (vehicle)	0	4.2 vehicle	0-0.5		Yes				10		
Blackwell et al., 1985	Lawford clay	Stagnogley	3	0	0 cf 3	0.15							3.5%	
Blackwell et al., 1985			3	0	0 cf 3	0.25							4%	
Blackwell et al., 1985			3	0	3 cf 0	0.05							2%	
Braunack et al., 2006	Clay loam	Cambisol	2	0	2	0.2				80				
Braunack et al., 2006	Clay loam	Vertisol	2	0	2	0.2				79				
Campbell et al., 1986	Sandy loam, Winton series		Conv	0	0 cf Conv	0.01-0.06							Yes	
Canarache et al., 1984	Various		1.225	0	1.225 cf 0	0-0.2				400-500%				
Chamen & Longstaff, 1995	Clay	Eutrochrept	3.25	0	3.25 cf 0	0.8				60-98%				
Chamen et al., 1990	Clay	Eutrochrept	3.25	0	3.25 cf 0	1.5			0	0				
Chamen et al., 1992b	Various	Various	3.25	0	0 cf 3.25	0.2-0.25							5-16%	
Chan et al., 2006	Clay	Vertisol	2.9	0	2.9	0.075		63					171	
Chan et al., year 2, 2007	Clay	Vertisol	2.9	0	2.9	0.075		61					156	
Dickson & Campbell, 1990	Clay loam	Cambic Stagnogley	Conv	0	Conv cf 0	0-0.125		Yes						
Hansen, 1996	Sandy loams		2.95	0	2.95 cf 0	topsoil		5%						
Li et al., 2007	Clay loam	Alluvial black vertosol	2.5	0	2.5									
Lamers et al., 1986	Loam and light clay		Conv	0	0 cf Conv	0-0.25							4%	
McAfee et al., 1989	Clay		1.1	0	1.1 cf 0	topsoil		6%						
McHugh et al., 2003	Clay	Vertisol	Conv	0	0 cf Conv	0.1			400%					
McHugh et al., 2003			Conv	0	0 cf Conv	0.1-0.3			280%					
Meek et al., 1989	Wasco loam	Xeric Torriorthents	2	0	0 cf 2	0-580							15-180%	
Pagliai et al., 2003	Clay	Vertic Cambisol	0.75	0	0.75 cf 0	0-0.1		20%						
Pagliai et al., 2003			0.75	0	4x0.75 cf 0	0-0.1		26%						
Radford et al. 2000	Clay	Vertisol	4.9	0	4.9 cf 0	0.1		8x fewer pores		Yes				
Schäfer-Landefeld et al	Silty clay loam, loams, silty loams and loamy sand		12.5	0	7.5-12.5	0.15-0.20		57%						
Stenitzer & Murer, 2003	Loamy silt	Eutric Cambisol	3.3	0	3.3 cf 0	topsoi		75%						

Fig. 3A. The effect of different wheel loads applied to different soils in different parts of the world as part of research assessing their impact on pore volume and saturated hydraulic conductivity (Ksat).

APPENDIX B

Tables 1B – 3B

Table 1B. Amounts and prices for chemicals applied to the crops within the two farming systems at Farmeco in Chapter 6.

Traditional system			**Rate, unit ha^{-1}**		**Cost ha^{-1}, £**		**Overall farm costs, £**		
Product	**Unit**	**Price $unit^{-1}$, £**	**Wheat**	**OSR**	**Wheat**	**OSR**	**Wheat**	**OSR**	**Total**
N fertiliser	kgN	0.71	160	120	113.60	85.20	79520	59640	139160
P fertiliser	kgP_2O_5	0.32	60	50	19.20	16.00	13440	11200	24640
K fertiliser	kgK_2O	1.00	32	30	32.00	30.00	22400	21000	43400
		Total fertiliser costs			**164.80**	**131.20**	**115360**	**91840**	**207200**
Broad spectrum[1]	Tenth of dose	6.5	10	10	65.00	65.00	45500	45500	91000
Fungicide	Tenth of dose	7.2	10	7	72.00	50.40	50400	35280	85680
Molluscicide	Tenth of dose	0.7	5	10	3.50	7.00	2450	4900	7350
Desiccant	Tenth of dose	0.75	10	10	7.50	7.50	5250	5250	10500
Growth regulator[2]	Tenth of dose	0.75	10	0	7.50	0.00	5250	0	5250
Insecticide	Tenth of dose	0.7	5	10	3.50	7.00	2450	4900	7350
Trace elements					12.50	11.00	8750	7700	16450
		Total chemical costs			**171.50**	**147.90**	**120050**	**103530**	**223580**
		Total fertilisers and chemicals			336.30	279.10	235410	195370	430780

CTF system			**Rate, unit ha^{-1}**		**Cost ha^{-1}, £**		**Overall farm costs, £**		
Product	**Unit**	**Price $unit^{-1}$, £**	**Wheat**	**OSR**	**Wheat**	**OSR**	**Wheat**	**OSR**	**Total**
N fertiliser	kgN	0.71	160	120	113.60	85.20	79520	59640	139160
P fertiliser	kgP_2O_5	0.32	60	50	19.20	16.00	13440	11200	24640
K fertiliser	kgK_2O	1.00	32	30	32.00	30.00	22400	21000	43400
		Total fertiliser costs			**164.80**	**131.20**	**115360**	**91840**	**207200**
Broad spectrum[1]	Tenth of dose	6.5	10	10	65.00	65.00	45500	45500	91000
Fungicide	Tenth of dose	7.2	10	7	72.00	50.40	50400	35280	85680
Molluscicide	Tenth of dose	0.7	15	15	10.50	10.50	7350	7350	14700
Desiccant	Tenth of dose	0.75	10	10	7.50	7.50	5250	5250	10500
Growth regulator	Tenth of dose	0.75	10	0	7.50	0.00	5250	0	5250
Insecticide	Tenth of dose	0.7	5	10	3.50	7.00	2450	4900	7350
Trace elements					12.50	11.00	8750	7700	16450
		Total chemical costs			**178.50**	**151.40**	**124950**	**105980**	**230930**
		Total fertilisers and chemicals			343.30	282.60	240310	197820	438130

[1] These are average application rates and costs for a number of chemicals applied as a mix

[2] Due to input limitations in the model, the cost for the growth regulator was added to the fungicide

Table 2B. Details of operations used to establish and harvest equal areas of wheat and OSR under the <u>traditional production system</u> at Farmeco in Chapter 6.

		Operation period						Purchase
Operation	System definition	Start	End	h/ha	% area	Machinery	Size	price, £
Winter wheat								
Autumn cults	Cultivations-autumn	Jul-16	Sep-23	0.28	100	Artic tractor	372 kW	186,348
						Terrano	7.5 m	34,998
						Triple press	8m	50,000
Desiccate (Sept)	Spray - boom	Aug-13	Oct-07	0.06	100	SP sprayer	4000 litres	123,500
Plant WWheat	Drill cereals	Aug-27	Oct-21	0.38	100	RubTrac Tractor	300 kW	187,500
						Simba Freeflo	6 m	54,000
Roll-autumn	Roll	Aug-27	Oct-21	0.2	100	4 wd tractor	110 kW	57,706
Slug pelleting	Spreading pellets	Sep-10	Nov-18	0.08	100	ATV	20 kW	8,000
						Slug pelleter	18 m	3,100
Spray Oct/Nov	Spray - boom	Oct-08	Nov-18	0.05	100	SP sprayer	4000 litres	123,500
Fertilise(Mar)	Spread N fertiliser	Feb-26	Mar-25	0.06	100	SP sprayer	4000 litres	123,500
Spray Mar/Apr	Spray - boom	Feb-26	Apr-22	0.05	100	SP sprayer	4000 litres	123,500
Spray April	Spray - boom	Mar-12	May-06	0.05	100	SP sprayer	4000 litres	123,500
Fertilise(Apr)	Spread N fertiliser	Apr-09	May-06	0.06	100	SP sprayer	4000 litres	123,500
Spray May	Spray - boom	May-07	Jun-03	0.05	100	SP sprayer	4000 litres	123,500
Fertilise(May)	Spread N fertiliser	May-21	Jun-03	0.06	100	SP sprayer	4000 litres	123,500
Spray early June	Spray - boom	Jun-04	Jun-17	0.05	100	SP sprayer	4000 litres	123,500
Combine WWheat	Combine-wheat	Jul-30	Sep-09	0.12	100	Claas 600	74 t/h	275,225
						4 wd tractor	110 kW	57,705
						Hi Speed Tractor	170 kW	79,470
Winter oilseed rape								
Plant W.OSRape/Grass	Drill OSR/Grass	Jul-30	Sep-23	0.33	90	Artic tractor	372 kW	186,348
						Terrano	8 m	21,736
						Triple press	8 m	50,000
Sub + Broadcast WOSR	Broadcast OSR	Aug-13	Sep-23	0.44	10	RubTrac Tractor	300 kW	187,500
						Subsoiler + press	4 m	14,000
Roll-OSR	Roll	Aug-13	Sep-23	0.33	100	4 wd tractor	110 kW	57,705
						Rolls	9 m	18,500
Slug pelleting	Spreading pellets	Sep-10	Nov-18	0.08	100	ATV	20 kW	8,000
						Slug pelleter	18 m	3,100
Spray Oct/Nov	Spray - boom	Oct-08	Nov-18	0.05	100	SP sprayer	4000 litres	123,500
Fertilise(Mar)	Spread N fertiliser	Feb-26	Mar-25	0.06	100	SP sprayer	4000 litres	123,500
Spray MidApril	Spray - boom	Apr-09	May-06	0.05	100	SP sprayer	4000 litres	123,500
Fertilise(Apr)	Spread N fertiliser	Apr-09	May-06	0.06	100	SP sprayer	4000 litres	123,500
Spray MidMay	Spray - boom	May-07	Jun-03	0.05	100	SP sprayer	4000 litres	123,500
Spray June-2	Spray - boom	Jun-04	Jun-17	0.05	100	SP sprayer	4000 litres	123,500
Combine W.OSRape	Combine-rape/peas	Jul-16	Aug-12	0.22	100	Claas 600	74 t/h	275,225
						4 wd tractor	110 kW	57,705
						Hi Speed Tractor	171 kW	79,470

Table 3B. Details of operations used to establish and harvest equal areas of wheat and OSR under the <u>CTF production system</u> at Farmeco in Chapter 6.

		Operation period						Purchase
Operation	System definition	Start	End	h/ha	% area	Machinery	Size	price, £
Winter wheat								
Autumn cults	Cultivations-autumn	Jul-30	Oct-07	0.41	5	Disc cultivator	4 m	18,000
						Nav RTK	£	61,000
Desiccate (Sept)	Spray-boom	Aug-13	Oct-21	0.05	100	Trld sprayer	4000 l	39,836
						Nav RTK	£	61,000
Plant WWheat	Drill cereals	Aug-27	Oct-21	0.34	100	4 wd tractor	246	124,481
						Tine drill	8 m	58,808
						Tyre press	8 m	24,000
						Nav RTK	£	61,000
Slug pelleting	Spreading pellets	Sep-10	Nov-18	0.08	100	ATV + pelleter	24	4,300
Spray Oct/Nov	Spray - boom	Oct-08	Nov-18	0.05	100	Trld sprayer	4000 litres	39,836
Fertilise(Mar)	Spread N fertiliser	Feb-26	Apr-08	0.06	100	Trld sprayer	4000 litres	39,836
Spray Mar/Apr	Spray - boom	Feb-26	Apr-22	0.05	100	Trld sprayer	4000 litres	39,836
Spray April	Spray - boom	Mar-12	May-20	0.05	100	Trld sprayer	4000 litres	39,836
Fertilise(Apr)	Spread N fertiliser	Apr-09	May-06	0.06	100	Trld sprayer	4000 litres	39,836
Spray May	Spray - boom	May-07	Jun-03	0.05	100	Trld sprayer	4000 litres	39,836
Fertilise(May)	Spread N fertiliser	May-21	Jun-03	0.06	100	Trld sprayer	4000 litres	39,836
Spray early June	Spray - boom	Jun-04	Jun-17	0.05	100	Trld sprayer	4000 litres	39,836
Combine WWheat	Combine-wheat	Jul-30	Sep-09	0.13	100	Claas 580 TT	64 t h^{-1}	230,827
						Nav RTK	£	61,000
						4 wd tractor	118 kW	61,633
						Nav RTK	£	61,000
						4 wd tractor	224 kW	113,679
						Nav RTK	£	61,000
Winter oilseed rape								
Plant W.OSRape/Grass	Drill OSR/Grass	Jul-30	Sep-23	0.27	95	4 wd tractor	246 kW	124,481
						Tine drill	8 m	58,808
						Nav RTK	£	61,000
Sub + Broadcast WOSR	Broadcast OSR	Aug-13	Sep-23	0.44	5	4 wd tractor	246 kW	124,481
						Nav RTK	£	61,000
						Subsoil+press	4 m	14,000
Slug pelleting	Spreading pellets	Sep-10	Nov-18	0.08	100	ATV + pelleter	24	4,300
Spray Oct/Nov	Spray - boom	Oct-08	Nov-18	0.06		Trld sprayer	4000 litres	39,836
Fertilise(Mar)	Spread N fertiliser	Feb-26	Apr-08	0.13		SP sprayer	4000 litres	39,836
Spray MidApril	Spray - boom	Apr-09	May-06	0.06		SP sprayer	4000 litres	39,836
Fertilise(Apr)	Spread N fertiliser	Apr-09	May-20	0.13		SP sprayer	4000 litres	39,836
Spray MidMay	Spray - boom	May-07	Jun-03	0.06		SP sprayer	4000 litres	39,836
Spray June-2	Spray - boom	Jun-04	Jun-17	0.06		SP sprayer	4000 litres	39,836
Combine W.OSRape	Combine-rape/peas	Jul-16	Aug-12	0.25		Claas 580 TT	64 t h^{-1}	230,827
						4 wd tractor	118 kW	61,633
						Nav RTK	£	61,000
						4 wd tractor	224 kW	113,679
						Nav RTK	£	61,000