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CONTROLLED TRAFFIC FARMING – FROM WORLDWIDE RESEARCH TO ADOPTION IN EUROPE AND ITS FUTURE PROSPECTS

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Controlled traffic farming is a machinery management system that confines all field vehicles to the least possible area of permanent traffic lanes. It has developed in response to research evidence of widespread soil damage from compaction due to field traffic. The history of research on soil compaction is explored and found to be a relatively new phenomenon. Controlled traffic farming as a topic for research did not appear until the 1980s although its principles and benefits were well established before then. Research expanded over the next decades but changed subtly to more reviews on the topic as well as emphasis on environmental deliverables and some economics studies. Few if any researchers attempted to develop on-farm systems using existing machinery until the mid 1990s when a small and dedicated team in Australia encouraged farmers to experiment. This quickly led to rapid expansion across the continent to its present day c. 13% of the cropped area. Despite changes to extension services in northern Europe at around the turn of the century and a move to subsidiarity, this did not alter the model of controlled traffic adoption. This followed a similar pattern to that in Australia involving individuals rather than organizations.

Keywords: soil compaction management; controlled traffic farming; increased crop yield; reduced erosion; reduced tillage; reduced carbon farming; wide span vehicles; gantry tractors; extension; adoption

Controlled traffic farming (CTF) is a field machinery management system which is used to protect soils from the indiscriminate change in their structure caused by unsystematic and extensive trafficking by farm vehicles (Hamza and Anderson, 2005). It creates two zones, non-trafficked crop beds and cropped or non-cropped traffic lanes, both of which are optimized for their different functions. Disorganized or random traffic causes an increase in the bulk density of any given soil, which increases its strength and reduces its porosity (Chen et al., 2010; Rasaily et al., 2012; Tullberg, 2000). These two changes can have a dramatic effect on a wide range of soil characteristics, such as amenability for crop sowing, establishment and nurture, the infiltration and drainage of water and as a medium for gaseous exchange and for soil-living animals (Gasso et al., 2013; Gasso et al., 2014). These effects are intensified with repeated passes (Botta et al., 2006) and particularly when they are accompanied by increasingly high loads, as has been the case over the past eighty or more years. Figure 1 depicts the rise in pressure stress in soils due to changes in machinery from the 1930s to the present. The stresses are derived from tyre data and a stress factor using mathematical formulae developed by Koolen et al. (1992).

As will be seen, there has been an inexorable rise in pressures at depth in the soil, interrupted only by the introduction of radial ply tyres that reduced surface pressures for a given load. Although further development of radial tyres has improved their performance, lowered pressures have not been able to offset the effects of increases in load.

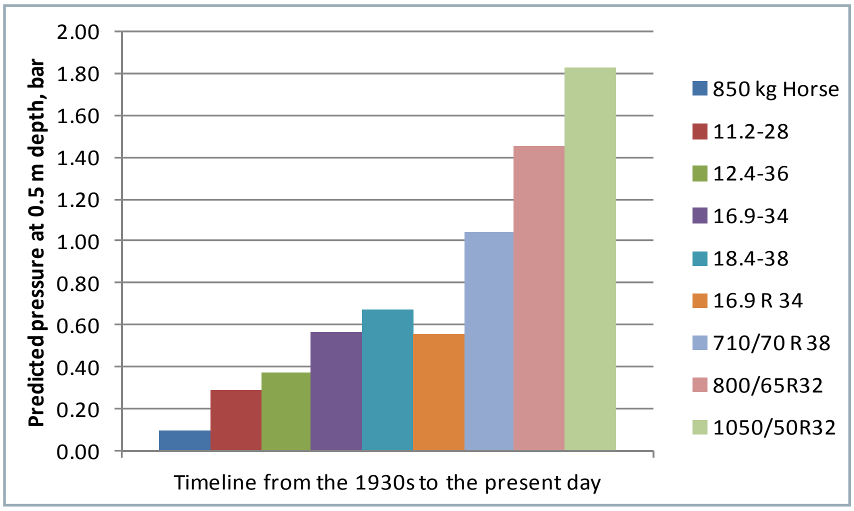

Figure 1 Change in soil stress at 0.5 m depth predicted for different loads and pressures at the surface under a horse and under tyres of increasing size
Source: Koolen et al., 1992

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The aim of this paper is to trace the research response to the increasing levels of soil degradation caused by rising stress levels from field traffic. It also aims to determine the role fundamental research and engineering in particular have played in the adoption of controlled traffic farming as a response to these rising stress levels. Does research have a role in its further development and future direction?

History of Soil Compaction Research

It seems that the term "soil compaction" is relatively modern. It was absent in Loudon's "An Encyclopaedia of Agriculture" (Loudon, 1825) while the term "wheeling" in the 1820s referred to moving loads with a wheelbarrow! The differing performance of wheels on soils was however astutely recognised in this example of the time. "Where the soil is firm, there wheeling will be best performed, but when soft and deep, the centre of gravity should be nearer the operator", with the added comment on wheelbarrows, "men do half as much work as with hods", meaning they were less efficient with a wheelbarrow!

On considering a scrutiny of physical databases for research relating to soil compaction, this did not seem likely to reveal anything significant because a search of the Scopus database on "soil compaction" even in the decade up to 1970 was dominated by how to create the greatest amount of soil compaction most efficiently! These of course were associated with civil engineering projects for buildings and roads but about 5% did relate to agriculture. Interestingly, Kouwenhoven published two papers relating to potatoes (Kouwenhoven, 1967; Kouwenhoven, 1970) in both of which he suggests using narrow tyres to limit the area over which compaction is applied, leaving more loose soil for potato ridging – the principle of controlled traffic but not mentioned as such!

Between 1970 and 1980, the number of papers on soil compaction had risen to over 500, but those relating to agricultural and biological sciences were still amongst the minority at 84, 80% of which were in the last 5 years of the decade. By the end of the next decade, those relating to agriculture and biology had risen to 432 representing nearly 30% of research on soil compaction. By 2010, this proportion had risen to nearly 50%.

If the search terms "zero" and "traffic" are introduced in addition to "soil compaction", there are no results between 1960 and 1970, but four in the next decade, all of which relate to maize and all from one author (Raghavan et al., 1978; Raghavan et al., 1979a; Raghavan et al., 1979b; Raghavan et al., 1979c). Over the next decades these results increase and level off to around 20 per decade but the topics have expanded to a wider range of crops and include economics, gaseous exchange, crop rooting and all aspects of soil structure.

History of Controlled Traffic Research

As far as a history of controlled traffic farming is concerned, the paper by Chamen (2003) provides a reasonably succinct overview. In research terms, "controlled traffic farming" does not appear in the Scopus database until 1982, but as a recognised term it seems already to be well established as reflected in the paper entitled "Pros and Cons of Controlled Traffic Farming" by Roy Morling (Morling, 1982). It seems that the advantages of controlled traffic were also well established by then with keywords from the paper including "improved tractive effect, increased crop yield, reduced compaction, reduced erosion, reduced tillage, reduced water and nutrient losses". It should be stressed here though that there is a difference between controlled traffic and controlled traffic farming (CTF). CTF is a whole system that optimises all aspects of the crop production system, not just the traffic management.

Surprisingly, from the early 1980s until around 2000, the number of research papers which mentioned CTF remained at about ten per decade, but those in the 1980s and early 1990s (Chamen et al., 1992; Chamen and Audsley, 1993; Lamers et al., 1986; Soane et al., 1980a; Soane et al., 1980b; Soane et al., 1982; Soane and Van Ouwerkerk, 1994; Taylor, 1992) were probably key in confirming the main benefits which were outlined by Morling (1982). Research on controlled traffic increased greatly from 2000 onwards with a total of over 70 published papers between then and the present day. Interestingly, the emphasis of the research changes subtly during this period. In the early years, the main thrust as in the previous two decades, was comparing traditional practice with CTF, measuring for example crop yield differences, infiltration rates and soil conditions in general. Later in the period, results of longer term assessments of CTF compared with traditional practice occur as well as reviews (Gasso et al., 2013; Hamza and Anderson, 2005). There is also more research on environmental effects of CTF (Gasso et al., 2013), economics studies (Kingwell and Fuchsbichler, 2011; Poggio et al., 2007; Qingjie et al., 2009; Vermeulen and Mosquera, 2009) and layout considerations (Galambošová and Rataj, 2011; McPhee et al., 2013) alongside comparisons in efficiency (Bochtis et al., 2010) and machinery requirements (McPhee and Aird, 2013).

A feature of practically all controlled traffic experiments however were machinery systems that could not immediately or easily be transferred to farm practice. Never before had there been a need to match implement widths or the track gauges of the vehicles that powered them, meaning that very little commercial equipment was available. Researchers often had to build special equipment or make do with achieving non-trafficked soil on a very limited scale. These constraints were perhaps least limiting in Australia, where the track gauge of a combine harvester for example (around 3 m), could be matched by other vehicles without precluding their use on farm tracks or rural roads, the latter having "dirt" strips along their edges that allow vehicles to pull off the main highway. The landmark research carried out by Lamers et al. (1986) proved to be unique in Europe in that it too matched all track gauges at 3 m. I use the term "landmark" purposefully because this research in particular answered most of the questions that even now we still seem to be asking! However, the fact remained, very few if any of the research projects considered how CTF systems could be transferred to commercial practice. This meant that farmers when presented with the results, however positive, could not imagine how they could introduce such a system with their existing machinery, nor necessarily with anything that they could readily purchase. This highlights the shortcomings of the research which was conducted on CTF. Very few if any of the projects used systems that could be directly transferred to farms.

In some cases agricultural research engineers built novel equipment that aimed to demonstrate not only the different characteristics of trafficked and non-trafficked soils, but the suitability of a fully customised controlled traffic machinery system. Carter et al. (1991) built a wide tractive research vehicle that spanned 10 m and had customised machinery that latched to its framework. In a cotton production system they reported lower soil impedance, higher water infiltration and reduced operations for field preparation without any reduction in crop yield. Readers of Carter's paper might be surprised that no mention is made of the performance of the novel vehicle used for the experiments, but as with so many research projects, politics was a factor and the authors were obliged only to consider it as a tool that provided them with the research data. Similar work was carried out at Auburn by Taylor (1992) who built a substantial 8 m span machine that was capable of lifting a small combine harvester with which to harvest crops. It was however designed primarily for research, not as a prototype tractor and most of the work seems to have concentrated on designing and optimising prepared traffic lanes (Monroe et al., 1989; Monroe and Taylor, 1989).

Similar work was carried out in the UK in the 1980s (Chamen and Longstaff, 1995; Chamen et al., 1992; Chamen et al., 1994) but had the aim of assessing the vehicle's performance as well as crop and soil responses in a controlled traffic regime. To make full use of the features of the system and to research the engineering aspects, many of the implements had to be designed from scratch. For example, firming of the soil with rolls was considered to be just as important as it is with conventional practice, but trailed rolls were impractical. Mounted rolls were therefore designed and downward pressure on them regulated by hydraulic transfer of weight from the vehicle. This worked well as illustrated in Figure 2.

The greatest challenge in the project was designing a cereals harvester that fully maintained the 12 m wide non-trafficked bed. A number of "false starts" meant that this took some years to achieve, but a novel three drum and concave system (Metianu et al., 1990; Chamen et al., 1994) together with a cleaning shoe eventually provided a harvester that worked on an experimental scale. By 1994, most of the equipment needed to sustain the large scale field trials was in place but politics again intervened. The development was now considered to be too "near market" for a research institute to be carrying out work on it and all funding was withdrawn. How near market was it? Well, here we are 20 years later and only now are we seeing a glimmer of hope in the form of the ASA-Lift wide span vehicle being developed in Denmark, but more of that later.

Figure 2 Mounted rolls were designed for this 12 m wide span vehicle at Silsoe. Precise firming was applied by transferring weight from the vehicle to the rolls using hydraulic pressure
Photo: Silsoe Research Institute

Research on controlled traffic has mostly been about quantifying what benefits we can achieve from non-trafficked soil. Once these data were replicated and consistent, as suggested in the reviews by Hamza and Anderson (2005) and Wolkowski (1990), the next logical research should have been on whether the benefits match the cost. A number of papers have addressed this issue (Mason et al., 1995; Chamen and Audsley, 1993; Gaffney and Wilson, 2003; Bowman, 2008; Strahan and Hoffman, 2009; Vermeulen and Mosquera, 2009), and as will be seen, a few preceded uptake of CTF systems in Australia and the start of adoption in Europe. So, even where there is consistent evidence of financial and other gains, this is no guarantee that results of research will be acted upon by growers without further encouragement.

This also applies to the recent study funded by the UK's government department "Defra" in terms of soil compaction mitigation in which they asked: "which techniques for compaction management give the greatest payback?" Basic research of course had to provide the means of prediction and surprisingly, even after all the work that has been done it was only possible to answer the question for a very limited range of crops (Defra, 2011). This is where CTF came out on top because not only were higher yields predicted from the extensive research data interrogated, but operational costs were also lower. Perhaps controversially the net transition costs to CTF were considered to be zero but where on-farm studies have been made (Chamen, 2011), the net costs were usually found to be negative. This was generally the result of selling deep working tillage equipment as well as lowering the specific draught of remaining tillage tools, both of which reduced the tractor power per unit farm area. The largest investment was in real time kinematic (RTK) global navigation satellite systems (GNSS) (Pointon, 2004) but these tend to have a large in-built payback in terms of operational efficiency, savings on inputs and operator stress as well as forming the basis for automated spatial measurements. Achieving zero cost was also about converting to CTF over an appropriate timescale that fitted in with the farm's normal machinery replacement policy; in some cases this could mean conversion over a period of five years or more. However, each farm would need to calculate whether a faster payback would justify a greater cost and this highlights the fact that almost every farm which converts to CTF has a unique system and achieves a different area percentage of permanent traffic lanes.

From Research to Adoption in Australia

Within the period of adoption in Australia, Tullberg et al. (2007) published a paper with similar objectives to those laid out here. They concluded that the research evidence on controlled traffic showed consistent and widespread benefits which were particularly pertinent to the Australian continent, such as water conservation and sustainable systems based on little or no tillage. They recognised that the complementarities of controlled traffic, zero tillage and greater cropping frequency were key to the development of farming systems that provided major economic and environmental benefits. However, although the benefits of controlled traffic had been widely demonstrated by research in many parts of the world, including Australia, these were insufficient to trigger its adoption on that continent. Adoption was mainly achieved through the dedication of two individuals (Don Yule and Jeff Tullberg) who worked closely with farmers to develop farm-based CTF systems. This was an enlightened and unique approach not only by the individuals concerned but by the Federal Government and Queensland's Department of Primary Industries with their project "Soil Compaction and Repair". Similarly, the University of Queensland under Jeff Tullberg's direction had a project on run-off and erosion, which brought Don and Jeff together. To some extent the way was paved for them by a few row-crop farmers who had introduced permanent beds, particularly for furrow irrigated cotton, but only a handful of farmers had looked at the potential of combining no-till and controlled traffic (Tullberg et al., 2007).

The research team started work in 1993 by highlighting the potential of CTF to address problems of compaction, soil erosion and poor operational efficiency. Initially six farmers agreed to trial systems which were customised to their farms and on just single fields or "paddocks". This allowed them to compare the new system with their traditional methods and also with those of their neighbours. Within 12 months all were convinced of the benefits and started to convert the whole of their farms to CTF while also "selling" the system to others. Within 5 years, more than 100,000 ha in Central Queensland had been converted to CTF and these successes were advertised through national controlled traffic farming conferences, leading to limited but widespread adoption across some parts of Australia. And this was at a time when GNSS and auto-steer were only in their infancy and when first applied to agricultural machines (Mailler, 2013). The development of this technology over the next decade certainly enhanced uptake and by 2007, Tullberg et al. (2007) estimated that over 2 Mha were now in controlled traffic across Australia. Typical farmer comments included: "it's just an easier way to farm" and "we spent years trying to do no-till, then started to control traffic; we should have done it the other way around".

In terms of research on GNSS for agricultural applications, this seems to be very sparse with only three papers being returned with the search terms "(GNSS or GPS) and auto-steer" (Pointon, 2004; Freeland et al., 2012; Vermeulen et al., 2007). Although the principles of GNSS have been well reported, achieving a reliable and accurate system on individual farms can still be challenging.

Meanwhile, in Europe and elsewhere even the term "controlled traffic farming" was practically unknown to farmers until well into the first decade of the 21st century and adoption was sporadic until this first decade had nearly passed.

From Research to Adoption in Northern Europe

In view of the Australian "story" relating to CTF adoption, it was of interest to study research in the northern part of Europe (20 different countries) on soil compaction and traffic and particularly research carried out in the 1980s and 1990s. Of about 90 documents listed only two considered the farm use of controlled traffic systems and both concentrated on the economic consequences (Stewart et al., 1998; Chamen and Audsley, 1994). Both similarly identified economic and other benefits of adopting controlled traffic but known adoption in this region was absent. This lack of uptake should also be viewed against changes to advisory services, many of which were being reduced, transferred to the commercial sector or phased out altogether. Jones and Garforth (http://www.fao.org/docrep/w5830e/w5830e03.htm, accessed June 2015) provide a background to agricultural extension up to what is estimated to be the mid 1990s. In this they view the need for extension to intensify, mentioning the requirement for improved efficiency to address increasing population and lessening reserves of agricultural land. Ison and Russell (2007) in their "review" of knowledge transfer traditions in the rangelands of Australia, suggest that the present system did not meet the needs of the farming community. Rivera et al. (http://www.fao.org/docrep/004/y2709e/y2709e00.HTM, accessed June 2015) mirror this dissatisfaction by highlighting the fact that governments at this time were revising their agriculture and rural extension services. Many in northern Europe were shifting their authority to farmer's associations or privately funded bodies such as DLV in the Netherlands and ADAS Consulting Ltd in England and Wales. In Norway, the AAS is now funded from a range of sources both private and government, as is the case for extension in Germany. There was also a move to "subsidiarity", in other words, delegating extension responsibilities to farmer's groups and encouraging participatory involvement. In England and Wales this resulted in the Agricultural and Horticultural Development Board (AHDB), which is a producer funded body and supports research projects as well as knowledge transfer. These developments are ongoing with AHDB Cereals and Oilseeds having employed regional managers in 2013 to better understand regional needs and information. AHDB Cereals and Oilseeds also has 13 "monitor farms" across the UK, three of which are farmed by CTF Europe members. The aim of these farms is to encourage like-minded farmers to share their performance information but not necessarily to promote adoption of new ideas or technologies. So, even these farms need the farmer to have taken the initiative to adopt CTF rather than having monitor farm status encouraging them to do so.

In view of these developments in extension and knowledge transfer dating back to around the turn of the century, we have to ask the question: "has adoption of CTF in Europe been any different from the Australian experience?" The answer as far as I can see is a resounding NO! AHDB Cereals and Oilseeds funded a review of CTF in 2006 (Chamen, 2006), but this was only after the first tentative steps towards farm adoption of CTF had occurred and did not result in accelerated uptake. Uptake was in reality prompted in a similar manner to how it happened in Australia but in this case I believe, by one rather than two individuals. Both these instances are in fact not unusual and follow the quote by Margaret Mead "Never doubt that a small group of thoughtful, committed, citizens can change the world. Indeed, it is the only thing that ever has" (http://en.wikiquote.org/wiki/Margaret_Mead, accessed June 2015).

Small beginnings in the UK

Since Chamen's work in the 1980s and 1990s at Silsoe (Chamen and Longstaff, 1995; Chamen et al., 1990; Chamen et al., 1992a; Chamen et al., 1992b; Chamen and Audsley, 1993; Chamen et al., 1994a; Chamen et al., 1994b), much of which revolved around development of a wide span vehicle system, he left research and was employed temporarily by an entrepreneur who wished to see the wide span controlled traffic system develop into a commercial reality. Seeking funds to help him do this, they submitted a combined research and demonstration proposal to the EU's 5th Framework programme in 2001 totalling around 4.9 MEuro. This involved 8 partners across Europe but despite winning an Exploratory Award from the EU to fund submission of the full proposal, it was not successful. Funds were therefore sought from elsewhere but despite widespread interest from the industry, the significant investment needed was not forthcoming. This put a halt on wide span activities but a conscious decision was made that to make progress with this innovative technology, farmers needed to experience the benefits of controlled traffic; and the only way was to go out and tell them about it! The extension work was supported by the Douglas Bomford Trust (www.douglasbomfordtrust.org) who funded a number of farmer meetings around the south east of England. As a result of these meetings, Chamen was invited to give a talk at a Unilever meeting involving staff from around the world. (Unilever had published a mission statement in 1998 which centred on soil protection). Some months after this in 2004, Chamen was again contacted by Unilever who offered a field on their commercial/research farm at Colworth in Bedfordshire, UK to set up a controlled traffic system. Without any resources to do this, John Deere in the USA (for whom research had recently been completed), was approached. This led to John Deere in the UK providing a tractor on a 3 m axle gauge and a combine harvester. As they were phasing out their 750 A direct grain drill in the UK at that time, an alternative was sought. This was when Edward Dale of Dale Drills stepped in and provided a no-till drill. Unilever, in addition to providing the land and management input, also funded a 5 year programme to research practicalities and to promote the system. This one field in CTF on a commercial farm turned out to be the turning point in CTF adoption and the conversion of research into practice. A small farmer focus group was set up, most of whom converted their own farms to CTF very soon after seeing the benefits of CTF in a real farm situation. There were setbacks but these were overcome and to support activities into the future a web-based CTF membership scheme was set up for farmers and others to share ideas and to run farm-based workshops (www.ctfeurope.eu). Ten years later the membership scheme has approaching 500 members, most of whom are based in northern Europe and most are farmers. Within the membership there are now approaching 50,000 ha in CTF with a further 15,000 ha planned or in conversion. This does not include others who have adopted CTF independently and about whom we know very little. Again, farmer comments have included: "farming suddenly gets easier" and "if you can convert to CTF, why wouldn't you?"

Of those who have adopted CTF, most are growing combinable crops and most are on heavier clay soils, and this despite compaction damage and its persistence being more extensive on lighter soils (Gregory et al., 2007). CTF systems in forage are mostly confined to Denmark, where large volumes of slurry are applied in the spring and in between grass cuts. CTF in these circumstances gives large and demonstrable benefits in both yield and quality, as identified as far back as the 1990s (Douglas, 1997). Uptake in root and vegetable crops has so far been limited despite greater economic benefits being demonstrated (Vermeulen et al., 2007). This reflects the greater difficulty of achievement, both in terms of complexity of operations but most importantly, through lack of appropriate machinery.

Enabling technologies, timeliness and legislation

Without doubt, adoption of CTF in northern Europe would not have happened on the scale it has without GNSS and without the real time kinematic (RTK) correction signal in particular. Even in the early days of the demonstration at Unilever's Colworth site, we believed we could run CTF with a satellite based correction. Although this would have been possible with a lot of manual input, it was obvious that we needed to move to RTK with its higher accuracy (± 2 cm) and crucially, its ability to auto-steer vehicles in exactly the same place year in year out.

The other technology that has aided adoption has been the internet. This has enabled the project to gain a higher profile and greater "visibility" than would have been possible otherwise and has been aided by social media platforms, to which a large number of farmers subscribe. Climate change predictions and water quality are also playing a role in that governments are becoming increasingly keen to promote CTF as a means of addressing carbon use, diffuse pollution and soil erosion issues. This is exampled in the UK where a government agency has sponsored farm-based workshops to promote CTF in terms of water quality, but industry has to a large extent had to match fund these events.

Research evidence is also increasing to suggest that nitrous oxide emissions could be reduced through the improved soil structure created within the non-trafficked beds of CTF systems (Gasso et al., 2013; Šima et al., 2013;

Antille et al., 2015). The benefits offered by CTF are therefore not only profitable for farmers, they are timely and appropriate to deal with environmental issues which centre on soil degradation.

The question has to be asked therefore, “would CTF have been adopted without promotion from individuals?” The answer is a “maybe”, but certainly not in the timescale that we have seen. Legislation or “inducements” in the form of subsidies could be another driver for adoption. For these to occur it must be acknowledged that governments (or more accurately, their advisors) will only be persuaded by good quality research conducted in appropriate landscapes and climates and with sufficient replication. Such is the case for the recent UK government sponsored study (Defra, 2011); what will it do with the results? As a member of the European Union and therefore governed by the Common Agricultural Policy, it may use the information to introduce incentives for farmers that improve their profitability while positively addressing environmental issues. This would have a very significant impact on uptake, particularly if similar measures were adopted across the Union.

Figure 3 Example of customised machines for controlled traffic. On the upper a chaser side extension and on the lower, widening of a trailer’s track gauge to 2.5 m to match other vehicles in the system
Photos: E.W. Davies and Neesham Farms

Constraints to adoption

Although we have seen a number of factors that have encouraged adoption there are also constraints, some of which are short term, others that must be accepted as permanent. Of the latter, inertia is one; it is much easier to continue doing what you are doing at the moment rather than entering into the effort of change and increased risk. Another permanent constraint is the need for more discipline and planning with CTF and devising ways of improving in-field efficiency, which tends to be lessened by CTF, as determined by Bochtis et al. (2010).

Short term constraints include limited belief that change can be made, something which is often termed “mindset”. Farmers and others associated with change often dwell on the obstacles rather than on solutions and never get past the stage of thinking it too difficult. Equally constraining but also probably short term, is the lack of appropriate machinery. This is a “chicken and egg” situation in that with no demand, there is nothing new offered by machinery companies, and if there is nothing available, no demand is created. There are signs however that this is changing, with companies like CaseIH, Claas, John Deere and others now offering equipment that delivers directly to the needs of CTF farmers. In some cases customized equipment is offered, as illustrated in Figure 3.

Research and Research Models for the Future

If we consider the fundamentals of CTF, the question is often asked, “does it work?” I believe this is the wrong question and completely misses the point. If we can’t get non-trafficked soil to improve in structure and to yield more, we just haven’t learnt how – it’s obvious that it should. The underlying question is not “does CTF work?”, but “is it cost effective and sustainable and if so, how can we make it work better, particularly with GNSS at our disposal?” Taylor (1994) made a similar point saying that “soil compaction is inherently neither good nor bad; it is just one more factor that must be under management’s control.”

I have often argued that we need to move on and improve controlled traffic systems rather than ask questions for which we already have the answers, but there is a certain amount of entrenchment amongst scientists. What we need to know for example is do we ever need to cultivate non-trafficked soils to grow crops profitably and for the longer term? And we need to know this for different crops and on different soils and in different climates. Can a system of this nature be sustained, particularly in terms of weed control and particularly when glyphosate for example no longer works? CTF has the advantage that due to the more amenable soil conditions, physical weed control is likely to be far more effective, and different approaches can easily be tried, as is now happening with controlled traffic farmers.

One of the things that has become fairly obvious from the history of CTF research is that there was no coordinated effort or funding to help promote adoption. This was despite widespread and consistent evidence of its benefits. As may be gleaned from the previous section, there was no guarantee that adoption would have occurred and indeed, there is still no guarantee that it will become best practice on all farms, particularly where large practical barriers still remain.

Direct experience of traditional research on CTF is that it is expensive and from a wider perspective, that it is often under-funded. Principally this relates to the preparation of experimental sites. Very often, sites are not repaired before trials are begun, i.e. good soil structure is not restored prior to the treatments being applied. This compromises any results that might be obtained, perhaps for at least the first five years of the experiments, as may be gleaned from the work of McHugh et al. (2009). Non-trafficked soil does not magically repair itself from one year to the next and the subsoil is an equally important component of the profile as the topsoil, to which repair operations are frequently confined. This fact may also be the reason why research on CTF has continued over a longer period than might be expected; the results have been positive but perhaps not as positive as they might have been had soil structure on the sites been properly restored. The trial recently started at Harper Adams University in the UK is a good example of how sites should be prepared and treatments applied (Smith et al., 2013), as was the case with Chamen et al. (1990).

It has also often been the case that due to under-investment, machinery has to be borrowed for the research and this can affect timeliness of operations in particular. Research organizations may also not invest sufficiently in the agronomy associated with the systems they are using and this is a crucial element of achieving the maximum yield potential of the site where the experiments are conducted. If the "control" treatment does not achieve the maximum yield for the site, soil and year in question, how can we hope to compare our primary treatment effects – it is likely that some other factor has been allowed to constrain yields.

Most people in agriculture will be aware that in some seasons and on some soils, better crop growth is achieved where wheels have run. This was not planned by the farmer; it was a chance effect that led to a better outcome. What CTF allows us to do is investigate the cause of the effect and then apply the right amount of firming over the non-trafficked area, which is perhaps 80% or more of the whole.

These "deliberations" bring me to the subject of further research. There is enormous opportunity to do more but it needs to be carefully planned and coordinated and carried out with close cooperation and involvement of farmers. We still don't know for example what the ideal soil structure is for delivering high and sustainable yields while at the same time providing good soil function in terms of water infiltration and drainage, gaseous exchange and a healthy environment for soil living animals – preferably of the beneficial variety! We also need a systems approach to achieve controlled traffic on farms.

I believe a good model for research is a close partnership between farmers and research scientists and field experiments that are on commercial rather than research farms. Farms using a controlled traffic system are actually ideal sites for soil structure research. Field operations can proceed in a timely and appropriate manner while experimental treatments might be applied in alternating strips. Such a methodology avoids uncontrolled compaction on the plots, an input which is largely ignored in many trials where we know that crop yields are likely to be compromised by compaction. If areas are large enough, yield assessments should be possible with yield monitors and farmers can immediately see the results as well as researchers who may be remote from the site.

Opportunities Offered by CTF

Many of the opportunities and advantages afforded by controlled traffic systems have been touched upon in the previous paragraphs and many are well known, but I list here some of the less obvious.

1. Limited need for tillage. As stated by Arndt and Rose (1966), "excessive traffic necessitates excessive tillage", so take away the traffic and the need for tillage reduces substantially. Additionally, tillage which might be required takes less draught and is more effective (Tullberg, 2000). An example of the opportunity this creates is a CTF farmer who direct sows a cover crop immediately after harvesting wheat. This grows rapidly due to early sowing into soil that has not lost moisture through tillage. Following winter kill or desiccating spray, a cash crop is then direct sown in the spring, meaning the soil is never left without protection from raindrop impact and has the maximum amount of organic matter added to it.
2. Inter-row tillage. It is inevitable that the effectiveness of existing herbicides will diminish with time and others may not be available to replace them, so a more diverse range of weed control measures will be required. Hoeing non-trafficked soil is far easier and more effective than one that has been compacted, as any gardener will attest. CTF systems already employ highly accurate guidance systems, meaning that a high proportion of the inter-row can be managed in this way.
3. Permanent stone separation. Whereas present systems separate stones on a rotational basis because subsequent operations spread them out again, controlled traffic systems should make it possible for stones to be placed in traffic lanes and for this to be a one-off operation.
4. Direct planting of tuber crops. Most crops of this nature are planted in sandy or loamy soils, many of which if nurtured and non-trafficked maintain a friable tilth throughout the cropping season. With CTF it is therefore quite possible to direct plant potatoes for example meaning that most moisture is retained and crops can be established more rapidly.
5. Highly accurate and recordable spatial information. The permanent grid of controlled traffic systems means that

automated spatial information is easy to achieve and soil texture or fertility effects are more likely to be identified.

6. Contrasts in soil texture diminish. As soils dry they become stronger but their strength increases to a greater degree if they have been compacted (Whitmore and Whalley, 2009). This is reflected in seedbed conditions which under CTF are more amenable.

Development of CTF Systems

As mentioned earlier, the further adoption of CTF systems will lead to more commercially available equipment that makes them easier to introduce. The wider the common base width of the implements, the more efficient they are and the less tracked area they create, but there are limitations. Presently the widest combinable crop systems in general use are about 12 m with associated minimum tracked areas of around 13%. There is potential for some increase in width, but it is limited for a number of reasons. First is the reach of the combine harvester's unloading auger, which can be engineered to some extent but the added complexity and strength required means that this may not be cost effective or practical much above 14 m. Additionally, the greater loads from these larger machines will either compromise the traffic lanes or wider running gear will increase the tracked area, meaning there is no net gain. For vegetable and root crops which may be rotated with combinable crops, widths much less than these are presently impractical.

So, my prediction is that we will see more widespread adoption of CTF systems and that development of the supporting technologies, services and equipment will make this much easier. At the same time however I think there will be a rising demand for something better and more efficient. This I believe will be fulfilled with wide span vehicle or "gantry tractor" systems. Not only will they lessen tracked areas significantly (to 5–10%), but they will offer numerous other advantages. Some of the unique benefits of wide span are:

1. Flexibility in operating width. With tractor-based systems all equipment has to be the same or direct multiples of a base width. With wide span any width can be used without increasing the tracked area of the CTF system.
2. Ability to avoid subsoil damage. Conventional tractors often work deep in the soil when ploughing or creating beds for vegetable crops and thus impact more directly on the subsoil – this can be avoided with the wide span technology.
3. Ability to plough within ecological/organic farming systems. As operating width is flexible any width of plough can be used.
4. Inherently stable vehicle even with high offset loads.
5. Probability that implements will cost less. This is because implement width is built up by multiple lighter units without the need for folding and in-built strength.
6. Improved lateral and vertical precision. This is afforded by an inherently stable platform from which to apply chemicals and soil contacting operations.
7. Avoidance of the need for ground-contacting depth control systems. Many cultivators and drills are equipped with multiple and costly wheels for depth control – these could be replaced by more sophisticated contactless sensing devices coupled to implement height control.
8. Ability to carry out selective harvesting meaning that several different crops could be grown within each "bed".
9. With low tracked areas there is potential to "engineer" the traffic lanes while still improving field yields.
10. Greater potential for implement control on sloping ground. This can be achieved by a combination of crab steer of the vehicle and side shift across the spanning beam.
11. Manual guidance system based on permanent traffic lanes. Because the driver is positioned over a permanent

Figure 4 The ASA-Lift WS9600 wide span vehicle loading onions on a farm in Denmark. This machine presently integrates with a tractor-based system using tractors with a 3.2 m track gauge

traffic lane, it is relatively easy to use precise manual control in the event of a GNSS failure.

It can be of no surprise therefore that we are seeing a resurgence of development of this technology in the form of the ASA-Lift WS9600 machine in Denmark (Figure 4). This was prompted by a farmer and demonstrates demand from an end user rather than a top down approach. Presently it is being used for light tillage and as an onion loader from windrows created by conventional equipment on a 3.2 m tractor-based CTF system.

There is a great deal new about this system and much to research in terms of vehicle design, control systems, revised agronomy (perhaps strip inter-cropping, relay cropping or agro-forestry to name but a few) and the ability to manage soils very precisely.

Conclusions

Controlled traffic farming addresses the increasing concern and reality of a damaging increase in stresses on soils reaching ever deeper into the profile. This is being caused by an inexorable increase in machine mass in response to economic demands but which is in an upward spiral. Extensive "establishment-based" research over the past 30 years has consistently confirmed the damaging effects of over-compaction on soil functions and the curtailment of crop yields. However, transfer of controlled traffic technology to the farming sector has relied on dedicated individuals rather than institutions, despite changes in agricultural extension. To address this issue, researchers and farmers should work in partnership in well funded projects.

Although the number of farms converting to controlled traffic will continue to rise and more appropriate machinery will become more readily available, the efficiency of these systems is constrained by existing machines. Agricultural engineers have a major opportunity to research and support the development of wide span vehicles that are inherently more efficient at delivering CTF systems.

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