

Controlled traffic for sustainable cropping

J. N. Tullberg
School of Agriculture and Horticulture
University of Queensland Gatton

ABSTRACT

Comparisons between wheeled and non-wheeled soil in terms of energy input, hydrology, health and crop performance demonstrate that field traffic is often more significant than tillage as the driving process of soil degradation. Evidence presented here has been derived largely from experiments in the vertisols of Southeast Queensland, but is consistent with data from a range of other environments. It supports the assertion that many of the current problems of reduced tillage systems can be attributed directly to the pervasive impact of field traffic.

Controlled traffic, permanent, or raised bed farming systems have provided a solution to many of these problems over more than 0.5Mha in Australia. The combination of controlled traffic with Australian developments in precision guidance provides the opportunity to achieve a further major improvement in the economics and sustainability of farming.

KEYWORDS

Traffic;Tillage;Energy;Soil;Degradation;Sustainability.

INTRODUCTION

Efficient mechanisation is a major factor underlying the high labour productivity and low cost of most Australian crop production systems. It is a given, understood and unquestioned by scientists or farmers. In discussion about planting, for instance, the focus might be on questions such as seed/fertiliser placement, seed zone conditions in relation to establishment, or the interaction between weed kill, disturbance, residue reduction and soil moisture loss. A tractor/machine operation would always be assumed.

We need to recognise the practical impact of this assumption. Each unit of planter width is associated with a broadly predictable equipment weight, power and tyre specification. In Australian extensive agriculture, for instance, one metre width of planter would typically weigh about 6kN, requiring about 0.15m tyre width to support it. It would need about 10kW of tractor power, with a weight of about 8kN, and tyre width of 0.2m. It will cover a little over 0.5ha/h, and consume fuel at the rate of about 2L/h.

These values are a simple consequence of the usual level of planter draft (23). Whilst not invariable, they are based on known and predictable physical relationships which dictate, amongst other things, that we drive tractor and implement wheels carrying 10 -- 25kN each, with tyre pressures of 80 -- 120kPa, over 25 -- 40% of crop area at planting, when the soil is in a moist and vulnerable condition. Even in minimal-input zero tillage cropping, > 50% of crop area is wheeled in each cropping cycle (16), and this percentage is usually much greater (11).

Wheel traffic is unavoidable in current crop production systems. This paper is concerned with the impact of random field traffic, and the benefits that accrue when it is controlled. The impact is often referred to as compaction, but this soil property can be difficult to define and measure. It is used infrequently in this paper, where soil is regarded as "wheeled" or subject to normal wheel traffic treatment, and compared with soil that is "non-wheeled", or managed in controlled traffic.

In controlled traffic systems all field traffic is restricted to permanent, defined traffic lanes. Traffic lanes are normally untilled and unplanted, to optimise traction and trafficability. Soil in the intervening beds is

managed to optimise crop performance, uncompromised by traffic. Runoff and drainage considerations normally determine traffic lane orientation relative to topography (26), and elevation relative to the beds (7), although controlled traffic has been successfully demonstrated on the contour in WA (1).

Traffic lane spacing is determined largely by equipment considerations. Controlled traffic systems in Northern Australia are often based on 3m traffic lane spacings for extensive grain, and 2m spacings for irrigated cotton, dictated by the harvester in both cases. In horticultural operations, and in the higher-rainfall zones of the South and West, traffic lane spacings are generally narrower, and bed drainage and traffic lane elevation is the major consideration in "raised bed" systems (7).

A variety of zone tillage and bed production systems were part of traditional practice in a number of ancient civilisations (4). These systems often provided some element of controlled traffic, but being animal-powered, they were usually abandoned early in the mechanisation process. Modern controlled traffic research started in the southern United States in the 1960s (5), but this program, and similar programs in Europe, developed cropping systems based on wide "gantry" tractors (3).

Despite its sound technical basis, this approach was unpopular with farmers and manufacturers, and most publicly funded research and development programs have been abandoned over the past ten years. Australia is the only country where significant areas (~ 0.5Mha) are managed in controlled traffic. The term "tramlining" is used in Europe to describe the system of temporary traffic lanes used for post-planting fertiliser and chemical application, but these systems normally entail annual mouldboard ploughing.

METHODS

This paper is concerned with the impact of field traffic or its control, in terms of energy input and soil deformation, hydrological parameters of soil structure, and soil health and crop performance. Experimental results quoted here are largely derived from work carried out at the University of Queensland, Gatton (14,19,20,21), or in counterpart experiments in Shanxi Province, on the loess plateau of NW China (13).

Discussion of the energy effects of traffic, and soil deformation consequences, is based on commonly available machine performance data rarely considered in this context. Direct comparisons of the energy requirements of disturbing wheeled and non-wheeled soil were made using instrumented tines mounted beside one another on a common toolbar (20).

Traffic and tillage effects on infiltration and runoff were assessed using tipping bucket units to monitor runoff from zero till and stubble mulch plots in opportunity grain cropping on a black earth, with each plot split into wheeled and controlled traffic sub-plots of 90m², replicated four times. Wheeling treatment was applied annually to the full sub-plot area, using a tractor of approximately 50kN axle load, operating at about 10% wheelslip (21). This experiment has been in place for six years, during which time crop yield has been regularly measured, and a number of other parameters have been assessed. Soil biological activity in these plots has also been monitored over the past year (U.Pangnakorn, pers. com.).

Soil structural effects have been assessed in a number of ways. The most straightforward has been the use of a set of cylindrical sieves (T. Tapaevaleu pers. com.) as a standard test of aggregate size distribution after disturbance of wheeled and non-wheeled soil by a planter opener at varying moisture content. This heavier clay soil area was regarded as seriously degraded ("a compaction problem"), and its amelioration has been monitored since a controlled traffic, zero till regime was installed in 1996 (A.McHugh, pers. com.). Monitoring has included disk permeameter transects at 3 moisture tensions, and at 100, 200 and 300mm depth on annually wheeled and non-wheeled areas.

Soil response to wheels

Wheel traffic affects soil by applying load to the surface. When this load exceeds soil strength, soil deforms until the increase in soil strength or area is sufficient to resist the load. Load and deformation are transmitted from surface to subsurface layers. The surface loading applied by transport wheels is

primarily vertical and compressive, but traction wheels also apply horizontal shear loads of up to 40% of vertical load. These loads produce vertical and horizontal deformation, examples of which have been illustrated by Horn (8). Soil is not a simple solid easily defined in terms of elasticity etc, and soil response to load is difficult to predict, even in idealised conditions.

There is an extensive literature on soil response to tillage systems, but traffic effects are rarely considered or quantified, and engineers and agronomists (e.g. 24, 15) take a distinctly different approach to this subject. Soil response to traffic is reviewed from a number of perspectives in Soane and Van Ouwerkerk (18). Despite the complexity of the situation some general principles can be distilled from the literature. While there might be important exceptions, the author has found the ideas listed below generally useful in understanding the impact of traffic on soil.

- Most of the damage caused by any given traffic event occurs on the first pass.
- Tyre pressure determines mean contact stress and surface damage.
- Axle load largely determines the depth to which wheel effects penetrate.
- Soil damage occurs largely due to plastic deformation, in both compression and shear.
- Reduced porosity and pore connectivity are the major symptoms of damage.
- Greater load and deformation result in damage to progressively smaller pores.
- Soil strength generally decreases with moisture content, and increases with depth.
- Field operations often occur after rain, when surface soil is trafficable. Subsurface soil can be wetter.

RESULTS AND DISCUSSION

Traffic energy and soil deformation

This is of fundamental importance because tractor and implement wheels normally dissipate more energy per unit area of soil, over a greater depth of the soil profile, than most tillage or planting implements (20). This energy input occurs regardless of whether or not its damaging effects are partially rectified, or simply disguised by subsequent tillage or planting operations.

It is a straightforward exercise to work out the energy dissipated in the soil by a tractor. Reasonable estimates of power transmitted to the implement, of power wasted in deforming soil vertically (rolling resistance) and power wasted in deforming soil horizontally (wheelslip) can be made with simple instrumentation. Power is energy per unit time. Power transmitted to the implement, and the area/unit time over which this is dissipated, allow calculation of implement energy input to the soil. Power wasted deforming soil in the traction tyre "footprint", and the area wheeled/unit time, allow calculation of traffic energy input to the soil.

With modern farm equipment, traffic energy input values are typically around 10kJ/m^2 . Tillage energy inputs to soil disturbance, on the other hand, are typically in the range $3\text{--}6\text{kJ/m}^2$ for broadacre planting and tillage. Only in deep tillage (subsoiling) operations does this tillage energy input to the soil approach traffic energy input, but it might similarly be argued that only in this operation does the profile disturbed by tillage approach that affected by traffic, and the wheeled width approach the implement width. It should also be noted that some authorities regard it as an ineffective response to subsoil degradation (12).

Chamen (3) and other authors have noted the influence of traffic on tillage or planting energy requirements. Tullberg (20) subsequently demonstrated that the draft of tillage tines following tractor and implement wheels was approximately double that of other tines, under a range of conditions typical of broadacre farming. The impact of preceding tractor and implement wheels was shown to increase the energy requirements of tillage or planting by 25 -- 40% in these circumstances; an increase which is itself largely a consequence of the inefficiency of the traction process.

This work showed that approximately half the total power output of a tractor can be dissipated in the process of creating and undoing the traffic effects of its own wheels (20). In plain language, half the total power output of a tractor is dissipated in soil degradation. When traffic is controlled, tractor size and fuel requirements are typically reduced by 50%, regardless of other changes, and this has been achieved in practice by some farmers.

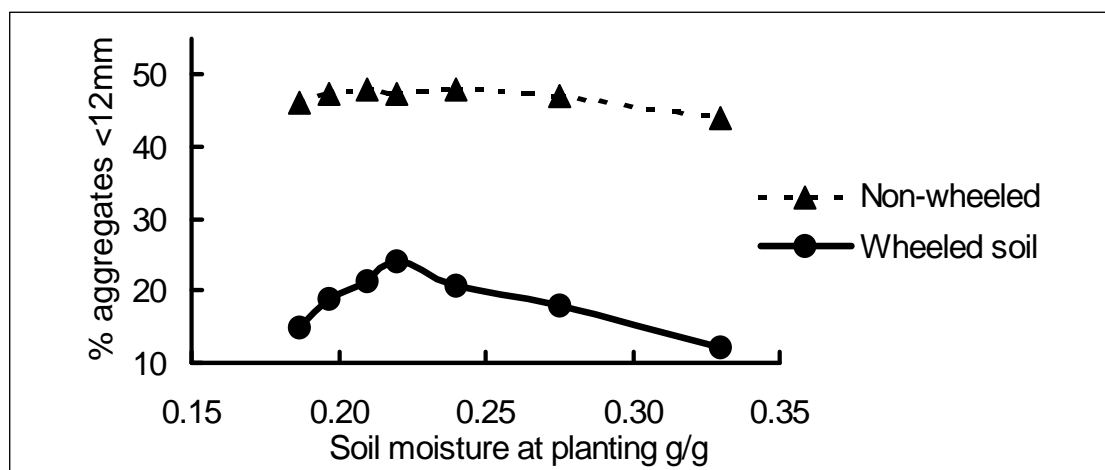


Figure 1. Wheeling effects on aggregate size in planting zone (T. Tapaevalu pers. com.).

Energy requirements are one useful measure of cost and environmental impact, but evidence from a variety of sources indicates that the tillage process rarely removes all physical soil degradation effects (18). Effects within the disturbed layer, illustrated in figure 1, demonstrate the negative effect of traffic on aggregate size distribution, and its impact on planting timeliness (T. Tapaevalu pers. com.). The practical implications have recently been commented on by Rohde (17).

Beneath the disturbed layer soil structural damage is often visible, and only in this sub-tillage layer is "soil compaction" commonly recognised. As depth of this damage increases, mechanical rectification becomes more expensive, and natural amelioration processes occur more slowly. Damage in this sub-tillage layer effect must be largely responsible for the reduction in infiltration rates discussed below.

It is interesting to note the inverse relationship between tractive efficiency and soil damage. When tractive efficiency is increased soil deformation occurring under tractor tyres must be reduced. Controlled traffic achieves this by restricting tyres to the strong, compact soil of the permanent traffic lanes. If it is necessary to traffic softer soil, the best way of increasing efficiency and reducing soil damage is to increase the length of the traction "footprint". This can be achieved in practice -- in order of increasing cost and effectiveness -- by reducing tyre pressure, replacing two wheel drive with four-wheel-drive, or replacing pneumatic tyres with crawler tracks, or belts.

Water entry

All wheel traffic on moist soil produces some soil deformation, and even light traffic will reduce the number or size of large voids and pores. The damage to soil hydraulic properties is often greater than might be expected on the basis of simple proportionality with changes in void ratio (9), and the impact on productivity depends on the extent to which different pore size classes are affected by field traffic.

Hamblin (6) has summarised the origins and functions of different pore size groups. Fissures, cracks and macropores > 50 micron diameter, are the free-draining transmission pores largely responsible for the movement of water down the soil profile. Because the largest voids and pores are physically the weakest, they are the first affected by traffic. Damage to these might be expected to affect infiltration rates, and the literature includes ample evidence of this. Rainfall simulator results from contrasting environments (heavy clay under 100mm/h in Australia, loess under 60mm/h in China) confirm that the traffic effect was greater than the tillage effect (figure 2). The cumulative effect is illustrated in figure 3 in terms of infiltration over a full season (Li Yuxia, pers. com.). The greater treatment effect apparent in the Australian data simply reflects greater precipitation rates and heavier equipment than China.

Water storage

Water in micropores of < 5 microns is held at greater potential, making it unavailable to plant roots. Water in the intermediate mesopores, in the 5 – 50 micron diameter range, is held with sufficient potential to prevent drainage by gravity, while its accessibility to plant roots increases with pore diameter. The importance of this reserve of plant available water increases with the imbalance between rainfall and crop water use, so it is extremely important in most Australian cropping systems.

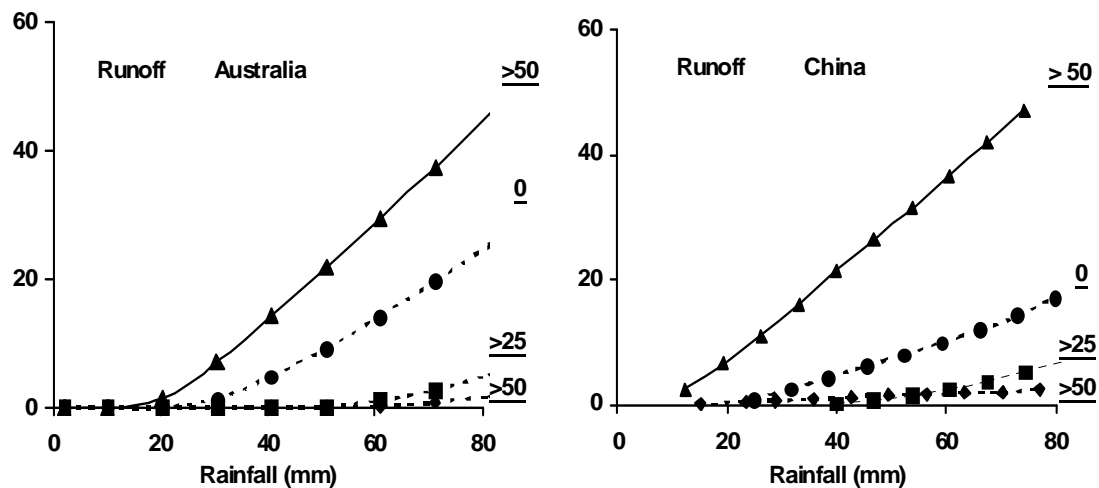


Figure 2. Traffic and cover effects on runoff of simulated rain in Australia and China (Solid lines = wheeled plots. Broken lines = non-wheeled plots. Underlined data = % residue cover)

More severe deformation progressively affects smaller soil pores, so it would appear reasonable to expect heavier traffic to progressively impact plant available water. Much of the literature (2) suggests that compaction effects on this parameter are small, but a substantial improvement in hydraulic conductivity, drained upper limit and wilting point occurred over four years in a degraded soil that was not subject to tillage or traffic (A. McHugh pers. com.). This data, illustrated in figure 4, indicated no difference between the effects of one and three annual wheel traffic treatments, and a single annual wheel pass prevented any improvement in soil structure.

The improvement in plant available water in non-wheeled soil corresponds with anecdotal evidence of controlled traffic effects but these results might equally point towards the general problem of defining a control condition for research on soil compaction. Non-wheeled, cropped soil is usually not available, so no completely uncompacted control is available to compare with compacted treatments. In practice, soil which exhibits no apparent damage must be taken as the control condition, sometimes after deep tillage, and perhaps with reference to nearby pasture or forest areas.

The control condition used in a recent study of heavy grain bin effects by Voorhees (22), for instance, was defined as soil that had not been subjected to axle loads in excess of 50kN. It is interesting to note that this was the axle load used to impose traffic treatments in the South-East Queensland work reported here (14,21), where the control condition was the absence of any wheel effects over a defined period.

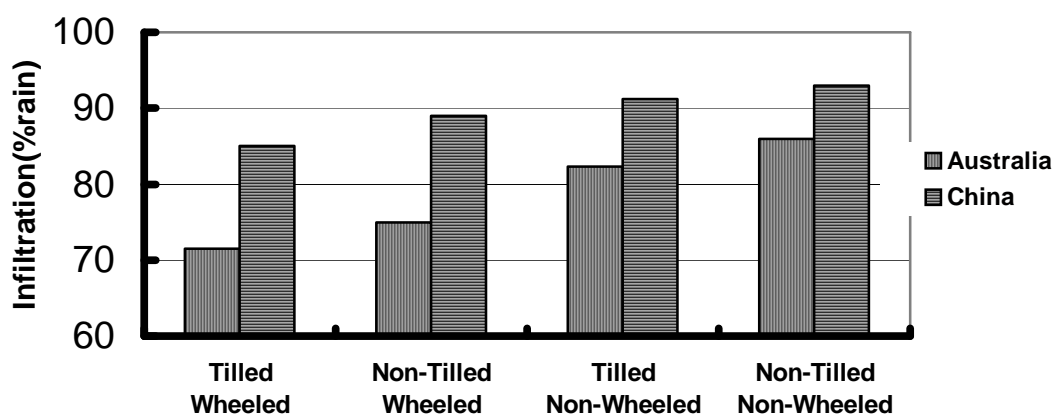


Figure 3. Cumulative effect of wheeling and tillage in Australia and China (Li Yuxia, pers. com.)

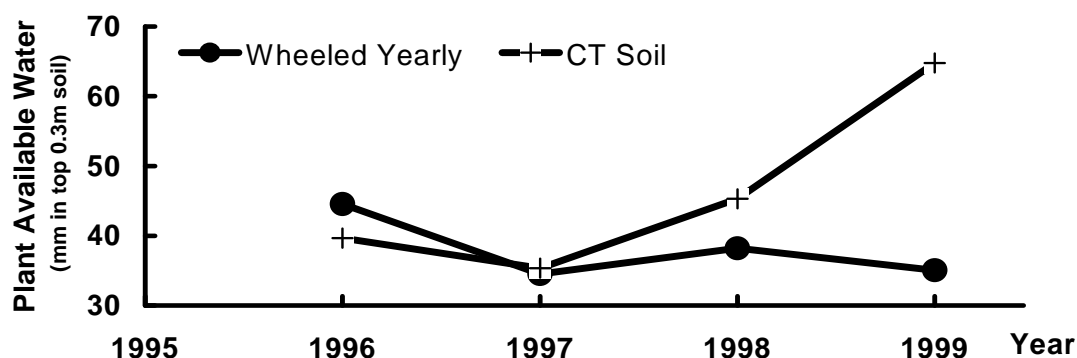


Figure 4. Effects of annual wheeling treatment on plant available water (A. McHugh pers. com.)

Soil health and crop performance

Soil health is not a precisely defined parameter, but measures of soil biological activity -- such as earthworm numbers -- are widely regarded as best available indicator. U. Pangnakorn (pers. com.) has monitored tillage and traffic effects on several groups of soil biota, and earthworm data from this work is presented in figure 5. While this illustrates the well-known advantage of zero versus conventional tillage, it also demonstrates a wheeling effect of similar magnitude. Earthworm numbers were substantially greater in non-wheeled treatments at all sampling dates when soil moisture was adequate in the sampling zone (the surface 150 mm).

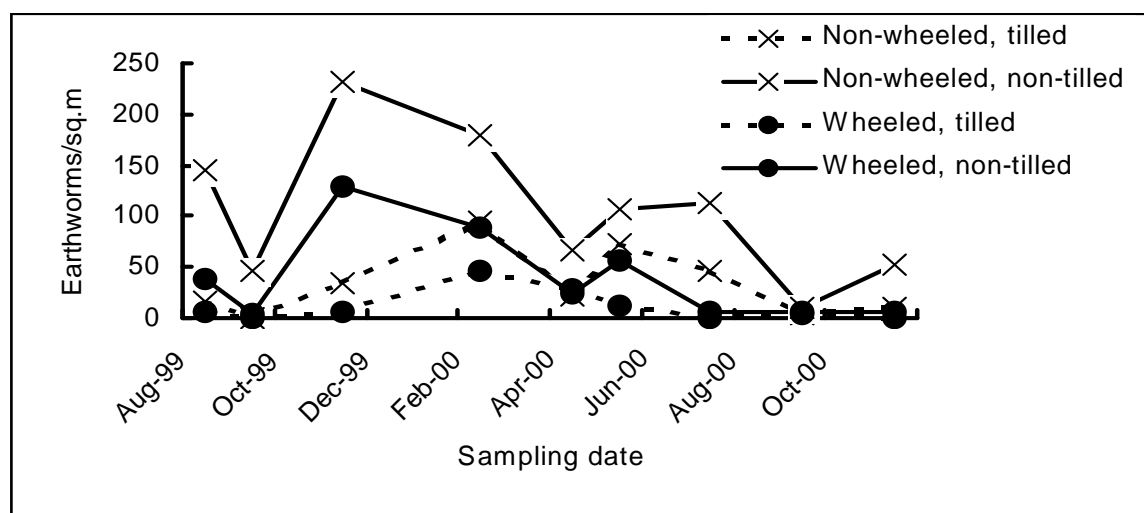


Figure 5. Traffic and tillage effects on earthworm population (U. Pangnakorn pers. com.)

Mean yield data for wheeled and controlled traffic, and tilled and zero till plots over the 6 years and 9 crops of the runoff trial are presented in table 1 (Li Yuxia, pers. com.). These data indicate that if current conventional practice is represented by wheeled tilled soil, improvements of 10% and 5% respectively can be achieved by controlling traffic and eliminating tillage, and that these two effects appear to be additive. It is interesting to note the similarity with cumulative infiltration data for these plots. Dryland data from West Australia indicates a similar yield effect (1), whilst a much greater yield response is reported when raised beds overcome post-planting waterlogging problems (7).

Table 1. Impact of traffic and tillage on crop yield

	Mean yield over six years opportunity grain cropping,t/ha	
	Wheeled annually	Controlled traffic
Stubble mulch	3.50	3.83
Zero tillage	3.63	4.04

Practical impact

Substantial areas of crop production have now been managed in controlled traffic over several years (25), so there is a growing body of information on the practical outcome of this approach. These might be categorised as those related to guidance, and those related to timeliness.

Permanent traffic lanes provide a straightforward guidance system for all cropping operations. Farmers adopting controlled traffic often report reductions in the time and material input to operations of 10 -- 20%. When permanent wheel tracks are accurately installed, the elimination of double coverage and/or gaps also has a positive effect on yield. Importantly, it makes night operation possible, which is a major contributor to effective and timely herbicide application (26). Farmer comment tends to confirm that the elimination of random wheel traffic also eliminates the major reasons for tillage. Controlled traffic farmers are using much less tillage than they used to, and several would claim that controlled traffic is a prerequisite of zero tillage.

It is easy to demonstrate that permanent wheel tracks become trafficable sooner after a rainfall event, allowing field operations to occur more rapidly. Just as importantly, zero tillage planting is not complicated by wheel ruts or surface compaction (17). The outcome in northern Australia is an increased number of cropping opportunities. Farmers generally agree that controlled traffic produces greater yields than conventional farming, but suggest that increase in cropping frequency is the most important mechanism in an environment where planting opportunities are usually short and rare.

Soil erosion

The combination of increased cropping frequency, reduced tillage and improved infiltration suggest that controlled traffic will reduce runoff and water erosion, regardless of other factors. It also provides a network of channels which can be used to control overland flow.

Yule *et al.* (26) observed the destructive effects of overland flow concentration during high intensity rainfall events. They also noted the role of tine and wheel marks in exacerbating this concentration process in both tilled and zero till cropping systems, when worked on the contour. They surmised that carefully laid out "downslope" systems would overcome this problem by preventing the concentration of runoff. Downslope systems worked over, and almost at right angles to existing broad-based contour banks have subsequently been installed by many farmers, and their operation observed over several years. This approach is controversial to the extent that it appears to be the opposite of accepted good practice. The evidence available so far -- from preliminary modelling, from aerial survey-plus-ground inspection, and from farmer comment -- all indicates a substantial reduction in damage from extreme events.

Adoption constraints

This paper has provided several examples of the economic and environmental cost of random field traffic. Almost any of these would, independently, justify the adoption of controlled traffic farming. Combined, the evidence appears overwhelming. It begs the question of how such an important factor has been unnoticed for so long in Australia and overseas. Perhaps the following is relevant:

- Tractor tyre pressures of 80 kpa or 12 lb/in², appear relatively benign to most people -- unless they have been run over by a tractor.
- People believe that soil compaction is caused by implements. The only connection between ploughs and pans is that the plough has obliterated visible evidence of traffic in the tilled layer only.
- Farmers' instant reaction to the idea of controlled traffic is "but I'll have to change all my machinery!" It also cuts across the conventional wisdom of achieving uniformity.
- Some agricultural scientists have seen controlled traffic as a competitive idea to zero tillage. Unlike zero tillage and deep tillage, no major group of multinational agricultural suppliers with large advertising and promotion budgets will profit from controlled traffic.
- Established agricultural systems work remarkably well with compacted soils. We still have much to learn about the agronomy and practical management of non-compacted soil.

The future

Controlled traffic demands and promotes the use of greater precision in field operations. A well known example is zero tillage double cropping achieved by interrow planting with a simple planter and offset hitch. Farmers can start to control traffic using very simple systems, but the benefits of greater precision

are clear. Widespread adoption of controlled traffic has been a major stimulant to the development of high-precision field guidance systems.

These DGPS-based systems (10) provide potential guidance precision of about 20mm, and will enable another revolution in farm practice as farmers exploit the benefits of reliable spatial precision and the greater accessibility of developing crops. The immediate benefits are those of precision band herbicide or insecticide application, interrow planting and split fertiliser application. It is not difficult to see the use of physical weed control and companion cropping in minimum input, organic or eco-labelled production, or the convergence of precision guidance with site-specific farming.

These developments will reduce the power requirement, weight and complexity of farm equipment. They replace brute force and uniformity with precision and information. Australian companies currently lead the world in the development of high precision guidance. It would be even better to see this commercial initiative enhanced by a major interdisciplinary project to develop the full potential of "high precision agriculture" and further improve the economics and sustainability of farming.

CONCLUSION

Controlled traffic farming avoids the situation where a large proportion of tractor power is dissipated in soil degradation. It is a system in which the management of different soil zones is optimised to provide maximum benefit in terms of:

1. Energy requirements, to allow a reduction in fuel use, tractor size and production cost.
2. Soil structure and health, to provide reduced runoff and enhance crop/soil performance.
3. Spatial precision in the soil/plant/machine relationship, to improve crop management.

Controlled traffic avoids the contradictions inherent in most mechanised farming systems, to provide substantial, demonstrable and consistent improvement in the economics and sustainability of cropping.

ACKNOWLEDGEMENTS

Much of the work reported here was supported by the Australian Centre for International Agricultural Research under projects 9209 and 96143 -- "Sustainable Mechanised Dryland Grain Production" -- with China Agricultural University.

REFERENCES

1. Blackwell, P. 1998. Proceedings Second National Controlled Traffic Conference. Gatton p 23.
2. Boon, F.R. and Veen, B.W. 1994. In: Soil Compaction in Crop Production. (Eds. Soane, B.D. and van Ouwerkerk, C.) (Elsevier Science B.V. Amsterdam). pp. 237-264.
3. Chamen, W.T.C., Vermeulen, D.G. Campbell, D .J. and Sommer C. 1990. ASAE Paper No. 90-1073.
4. Chi Renli, Zuo Shuzhen. 1988. Proceedings of the 11th ISTRO Conference, Edinburgh, (2), pp.601-606.
5. Cooper, A.W.; Trowse, A.C., Dumas, W.T. 1969. Proceedings 7th Int. Congress of Agricultural Engineering, Baden-Baden, Germany, pp.1-6.
6. Hamblin, A.P. 1987. In Tillage: New Directions in Australian Agriculture. (Eds. Cornish, P.S. and Pratley, J.E.) (Inkata Press:Melbourne).
7. Hamilton, G. and Foster, I. 1998. Proceedings Second National Controlled Traffic Conference, Gatton Qld. pp.87- 94.
8. Horn, R. 2000. Proceedings, Fourth International Conference on Soil Dynamics, Adelaide.
9. Horton, R., Ankeny, M.D. and Allmaras, R.R. 1984. In: Soil Compaction in Crop Production. (Eds. Soane, B.D. and van Ouwerkerk, C.) (Elsevier Science B.V. Amsterdam). pp. 141-166.
10. Kondinin Group 2000. Beeline Navigator Evaluation. Kondinin Group, Cloverdale, W.A.
11. Kuipers, H. and van de Zande, J.C. 1994. In: Soil Compaction in Crop Production. (Eds. Soane, B.D. and van Ouwerkerk, C.) (Elsevier Science B.V. Amsterdam). pp. 417-446.

12. Lindsrom, M.J. and Voorhees, W.B. 1994. In: Soil Compaction in Crop Production. (Eds. Soane, B.D. and van Ouwerkerk, C.) (Elsevier Science B.V. Amsterdam). pp. 265-286.
13. Li Hongwen, Gao Huanwen, Chen Junda, Li Wenlin and Li Ruxin, 1999. Proceedings International Workshop on Conservation Tillage, Beijing, pp 88- 92.
14. Li, Y., Tullberg, J.N. and Freebairn, D.M. 2000. Traffic and Residue Cover Effects on Infiltration. Australian Journal of Soil Research (in Press).
15. Passioura, J.B. 2000. Proceedings, Fourth International Conference on Soil Dynamics, Adelaide.
16. Robotham, B.G. and Walsh, P.A. 1995. Proceedings Controlled Traffic Conference, Rockhampton, Qld. pp. 123 –130.
17. Rohde, K. 2000. Australian Grains. **10** (5). p 6,8.
18. Soane, B.D. and van Ouwerkerk, C. (Eds), 1994. Soil Compaction in Crop Production. Elsevier Science B.V. Amsterdam.
19. Tullberg, J N; Murray, S (1988). Proceedings of the 11th ISTRO Conference. Edinburgh, (**1**), 323-327
20. Tullberg, J.N. 2000. J. Agricultural Engineering Research. 75(4) 375-382. Elsevier, Amsterdam.
21. Tullberg, J.N., Ziebarth, P.J. and Li Yuxia. 2000. Aust. J. of Soil Research (in Press).
22. Voorhees, W.B. 2000. Proceedings, Fourth International Conference on Soil Dynamics, Adelaide.
23. Ward, L., Rickman, J.F. 1988. Tillage Equipment. Darling Downs Institute Press. Qld. pp 84-86
24. Way, T.R., Erbach, D.C., Bailey, A.C., Burt, E.C. and Johnson, C.E. 2000. Proceedings, Fourth International Conference on Soil Dynamics, Adelaide, S.A.
25. Yule, D.F., 1998. Proceedings Second National Controlled Traffic Conference, University of Queensland Gatton, Qld. pp 6-12.
26. Yule, D.F., Cannon, R.S. and Chapman, W.P. 2000. Proceedings, 15th ISTRO Conference, Ft. Worth.