Productivity and Sustainability Effects of Conservation Agriculture

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ABSTRACT

The broad idea of conservation agriculture (CA) implies the use of more crop residues, less tillage, soil degradation, etc. It has been known for many years but CA practice still developing and improving.

Early development was concerned almost exclusively with residue, tillage and the maintenance of yields. More recently, there has been much work on controlled traffic and bed farming systems to address issues such as soil compaction, and allow further improvements in yield without additional inputs. The greater productivity and sustainability of controlled traffic farming (CTF) zero tillage systems is discussed in this paper, which also shows why these systems will reduce the greenhouse gas and other environmental issues of crop production. By avoiding the contradictions of earlier systems, they become closed to justifying the title "conservation agriculture".

1. INTRODUCTION

CA is concerned with cropping systems which are more productive and sustainable than traditional systems. Complete sustainability -- zero non-renewable resource use or environmental damage -- is still unachievable at acceptable levels of production, but resource use can be optimized, and environmental damage minimized. In a world where the margin between food requirements and food supply is uncomfortably small, production must continue to increase. This paper provides a short review of the productivity impacts of CA, but discusses sustainability issues at greater length. This discussion is relevant to most forms of agriculture, but the specific focus of this paper is on water-limited dryland agriculture of North-West China and Australia.

The following definitions are used for the purposes of this paper:

Traditional tillage systems use a primary operation (ploughing) to bury crop residues, level the surface, de-compact the upper root zone and control weeds. Shallower secondary tillage operations attempt to produce a fine tilth for planting, while levelling the surface and controlling weeds. Traditional tillage systems are still very productive in environments where soil erosion is uncommon, and yields are not normally moisture-limited. In drier, more erosion-prone environments, tillage promotes moisture loss, and buries protective crop residues.

Zero tillage is now widely accepted as a better and more sustainable system in most situations, but planting equipment must be larger and heavier to work effectively through residue on compacted, rutted and uneven surfaces. Zero tillage might be optimal, but some tillage is often seen as necessary to manage residue, level ruts, or undo some wheel compaction effects. Reduced or minimum tillage systems might all be seen as steps along the path to zero tillage. Zone tillage, limited to a narrow planting strip has conceptual similarities to CTF.

Controlled traffic farming (CTF) facilitates zero-tillage cropping in undamaged soil by restricting all heavy wheels to permanent traffic lanes. When traffic lanes are at the bottom of furrows which also define the cropping beds, it is called permanent raised beds (PRB). Wheels work more efficiently on permanent compacted traffic lanes, which also become a water management system. CTF and PRB systems must be designed for runoff control, drainage and/or irrigation, so proper layout is essential.

Zero tillage reduces tractor energy requirements by replacing tillage with herbicide weed control (or cover crops), so the residues of grain crops can be retained to protect surface soil against erosion by wind or water, and to improve rainfall infiltration rates. A number of studies have demonstrated that the environmental impact of zero tillage is less than that of traditional tillage.

The permanent beds of controlled traffic farming provide better aeration, rainfall infiltration and plant available water capacity. Equipment operation from firm, permanent traffic lanes improves timeliness and efficiency, while more precise guidance facilitates zero tillage planting and reduces herbicide costs. CTF needs modular equipment wheel track and operating widths, and guidance. Bed widths vary with technology, so values of 2m-3m are used in Australia, but 0.6m–1.5m are common in China, Pakistan, Bangladesh and Mexico, with harvesting equipment spanning two or more beds (Sayre et al. 2005).

2. PRODUCTIVITY

Tillage operations which expose moist soil can be expected to reduce crop yield in water-limited environments, and this effect has been seen in many situations. Most recently, Li et al. (2007) demonstrated that zero tillage with residue retention could improve yield by more than 20 per cent (compared with traditional plough tillage) in North China. In Australia, common tillage systems are non-inverting and residue is usually retained on surface, so the positive effects of zero tillage are rather smaller (e.g. Radford 1995). Research and farmer experience often record a yield reduction in the first year after changing to zero-till management, but this is usually followed by several years of steadily improving soil condition and yields. The initial yield decline is usually attributed to a temporary change in the nutrient balance, but a range of highly-practical issues of operator learning and system management are probably of equal significance.

Control of field traffic produces a further yield increase, despite the fact that no crop is planted in the 10-20 per cent of field area used as permanent traffic lanes. A review of the literature on yield loss due to soil compaction (So, 1990), concluded that the average value was around 15 per cent. This coincides well with the statistically significant yield increases of between 10 and 15 per cent recorded in controlled traffic research in China (Chen Bao, pers. com.) and Australia (Tullberg et al. 2003). Australian farmers, however, have demonstrated that much greater yield improvements occur in practice.

The difference between farmer and research results is a consequence of research procedures where valid comparisons are made by planting crops in side-by-side plots, varying only the parameter of interest. An important consequence is that no plots are planted until all are ready for planting, even though a controlled traffic plot might be ready long before a non-controlled traffic plot. Farmers do not wait, and gain a very substantial yield advantage as a result. In marginal situations, this timeless advantage is often the difference between a productive crop, and crop failure (McPhee, 1995). Timeliness is also an extremely important factor in the effective use of herbicides, and CTF growers have generally been able to produce more crops with less herbicide.

Many of these advantages can be encapsulated in the improved use of rainfall, as summarised in the following statement taken from ACIAR (2006). "Rainfall is used and stored more effectively under a no-till and controlled traffic system when compared with conventional cropping methods, as shown in Figure 1. The two major contributing factors to the total water saving under a controlled traffic system were the increase in plant available water capacity (PAWC) and an increase in rainfall infiltration into the soil, reflecting an increase in total water storage in the soil profile. Increased timeliness of operations also provides small increases in effective rainfall".

Productivity is a function of both output (yield) and inputs. In the Chinese and Australian research reported here, fertilizer inputs were uniform for all treatments. On-farm energy (or tractor fuel) requirements were substantially reduced in zero tillage, and reduced even further in CTF. Herbicide manufacture and application, on the other hand, represent a significant energy input which substantially reduces the energy benefit of zero tillage, but has a slightly smaller effect in CTF.

Unnecessary or poorly targeted inputs represent a waste of resources at best, and a pollution threat at worst, and this aspect of the topic is dealt with in more detail under the heading of sustainability. In productivity terms, however, it is clear that productivity improves (i.e., yields improve with the same or less input) with zero tillage management, and improves considerably further when zero tillage is combined with controlled traffic operation.

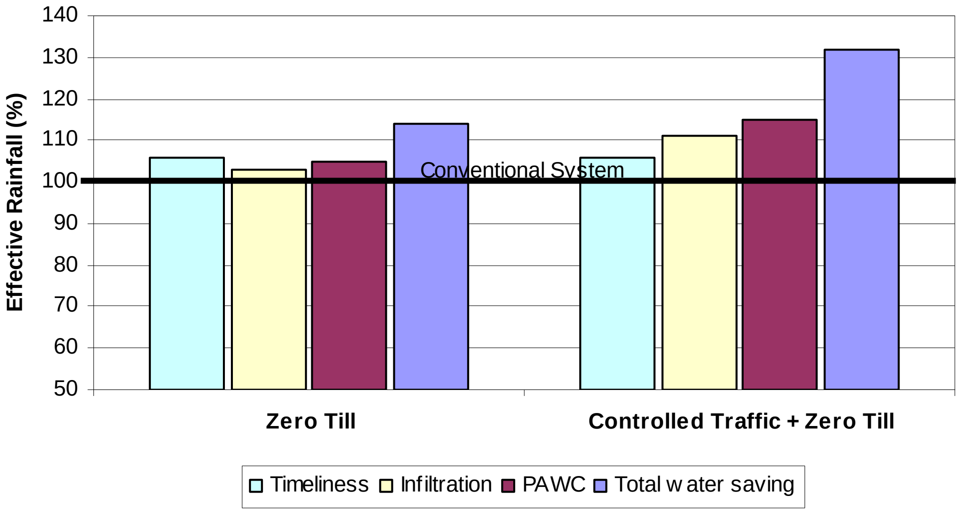


Fig. 1. Increase in the effective rainfall (rainfall available for crop production) resulting from changes in infiltration, PAWC and timeliness of operations under zero- till and controlled traffic systems (compared to a baseline of conventional tillage with uncontrolled traffic). [base = 100]

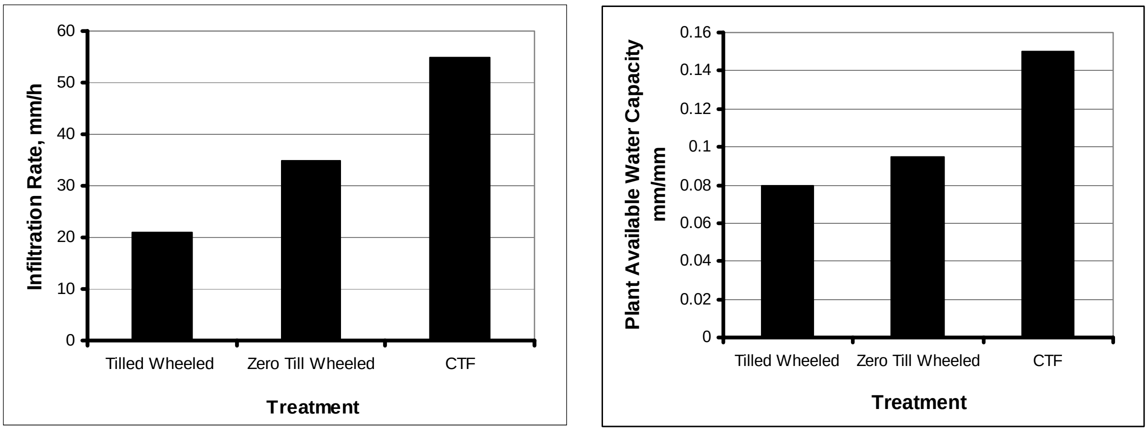
3. SUSTAINABILITY

Despite the perception of conflict between productivity and sustainability objectives, most environmental damage is a consequence of misdirected resources; so changes that improve long-term sustainability usually improve productivity. Perhaps the most valuable improvements are those which overcome systemic conflicts, such as those between residue and efficient planting, or between tillage and traffic. There are many facets to sustainability, but the major ideas relevant to cropping are the optimum use of water (rain), energy and chemicals (fertilizers and biocides), together with soil conservation. These criteria are used here to consider the sustainability effects of CA.

3. 1 Water Use

Improving water use efficiency is a matter of great importance for dryland agriculture in areas where crop yield is generally moisture-limited. In physical terms, rainfall infiltration can be maximized and the quantity of water stored in the root zone. Although tillage can be used to break up surface crusts and deeper compaction, zero tillage has been shown to be a more reliable way of increasing rainfall infiltration. Zero tillage increases surface soil permeability, but without tillage, subsurface compaction ameliorates only slowly, and can severely limit infiltration.

Unless traffic is controlled, the wheels of spraying, planting and harvesting operations cover about 50 per cent of total field area per crop, and compaction lasts several years. Elimination of wheel effects by CTF deals with this problem. The effect is illustrated in Figure 2a for the Australian situation, and similar results have been observed in China by Wang et al.(1999). This effect is extremely important in environments where a proportion of rainfall arrives in high-intensity events.



a) Infiltration rate under 80 mm/hour rainfall (Li et al 2000) b) Plant available water (McHugh 2003))

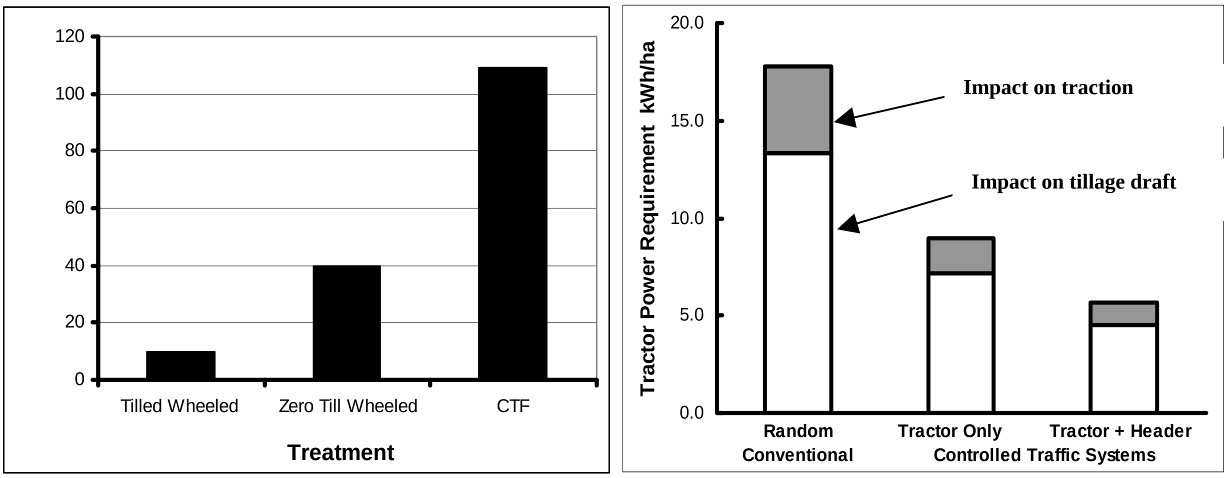
Fig. 2. The impact of tillage and wheeling on infiltration and plant available water.

In the natural situation the action of roots, soil biota and moisture will slowly increase the number of pores which retain soil moisture in a form available to plant roots (i.e., between field capacity and wilting point). In cropping environments, however, this beneficial effect can be inhibited to the depth of tillage, and inhibited both above and beneath the depth of tillage by wheel-induced soil compaction. Most of the benefit of this natural process in CTF (controlled traffic with zero tillage) can still be obtained, and it operates with reduced effectiveness under zero tillage with uncontrolled traffic.

Zero tillage and CTF impacts on plant available water are illustrated in Figure 2b, and shows one of the major advantages of CA systems (Tullberg, Yule and McGarry, 2003). Greater infiltration and greater plant available water are the basis of the improvement in water use efficiency illustrated in Figure 1. Similar effects have been observed in China by Bai Yuhua et al (pers. com.). This increase in plant available water is of critical importance were crop production depends to a large extent on water stored in the soil, but even in irrigation systems, greater plant available water capacity can save water by reducing irrigation frequency.

3.2 Energy Use

Agricultural tractors carrying out tillage or planting operations rarely provide the machine with more than 75 per cent of the power available at tractor axle. The other 25 per cent of power is used overcoming rolling resistance (compacting soil vertically) and wheel slip (compacting soil horizontally) under the tires. This is a consequence of working on relatively soft soil. Only recently, it was recognized that soil compaction by the tractor itself increases the power requirement of the operation vary significantly. For most practical purposes, about 50 per cent of the power output of a tractor is used in the process of compacting and de-compacting soil passing under its own wheels (Tullberg 1999). The situation is less serious with harvesting and spray operations, but these operations still use a significant proportion of their power to propel themselves around the field.



a) Tillage and wheel effects on earthworms (Pangnakorn 2005) b) Traffic effects on tillage/planting power.

Fig. 3. The impact of tillage and wheeling on soil life and tractor power requirements.

In controlled traffic systems, wheels are restricted to permanent traffic lanes, which can be managed as roads. Wheels operate against less rolling resistance and with greater tractive efficiency on compacted permanent traffic lanes. Planting equipment works best in soft, non-wheeled soil, which requires less power. For most practical purposes, CTF farmers in Australia have been able to reduce their tractor power by approximately 50 per cent , and tractor size on CTF farms is now often dictated by the tractor's ability to lift heavy equipment on the linkage, rather than by tractive ability. Some dimensions of this effect are illustrated in Figure 3b, for complete CTF systems (tractor and harvester on permanent traffic lanes) and systems where only the tractor operates in controlled traffic.

Power dissipated in compacting and de-compacting soil is fuel and money spent on soil structural degradation, and this represents a large proportion of the total on-farm energy use in non-controlled traffic systems. The requirement to cope with compacted soil and wheel ruts is a major issue for zero tillage planter design, and wheel ruts are a major factor convincing farmers that they still need tillage. Similarly, discussion of soil compaction problems is used as the basis for selling subsoilers (the most energy-intensive tillage implements) as “zero tillage” implements.

If tillage can be totally avoided, field power requirements will be substantially reduced, but herbicides used to a much greater extent. Manufacture of herbicides is energy-intensive and the production of the most common zero tillage herbicide -- glyphosate -- for instance requires the equivalent of approximately 9L diesel fuel (Zentner et al, 2004). Energy for field application must also be included, but improved timeliness and more precise (banded application, to crop row or interrow only) can reduce herbicide requirements in CTF.

Estimates of the overall energy impact of zero tillage and controlled traffic have to be based on assumptions about tillage frequency and herbicide choice, and the outcome can be changed substantially depending on those assumptions. The assumptions incorporated in Table 1 (Tullberg, 2006) are typical of those of dryland cropping practice, and show that in this case at least – zero tillage alone can reduce energy requirements by about 25 per cent but CTF -- controlled traffic zero tillage farming can reduce energy requirement by 67 per cent.

Table 1. Machinery, Herbicide and Total Energy Requirements for Three Tillage Systems.

Operations:	Residue Manag e-ment	Tillage Frequency			Sprays	Planting	ΣHerbicide energy MJ/ha	Σ Fuel energy MJ/ha	Total energy MJ/ha	Energy saving, % TA
Representative systems		Heavy	Medium	Light						
Traditional tillage, no herbicide.		1	2	2	0	1	0	1941	1941	/
Zero tillage, < 1 tillage./crop	1	0.6*	0	0	4	1	320	1116	1436	26
Controlled traffic or permanent bed zero/ min. till		0.25*	0	0	3	1	240	397	637	67

*Tillage frequencies < 1 represent operations occurring less than once each crop –e.g ., surface leveling, bedforming or subsoiling

The discussion of energy could be concluded at this point, but it is important to note that the manufacture of nitrogen fertilizer is usually the biggest single energy input to crop production (other than solar energy). Since nitrogen fertilizer is an important factor in the environmental impact of agriculture, including water supply pollution and greenhouse gas emissions, it will be considered separately.

3.3 Nitrogen Fertilizer

Nitrous oxide is a greenhouse gas with a global warming potential 300 times compared to carbon dioxide, and responsible for a large proportion of cropping agriculture's greenhouse impact. Nitrous oxide is produced largely by the denitrification of soil nitrate. This process can occur rapidly when nitrate is available in soil at low levels of air-filled porosity - at or approaching water logging - and occurs more rapidly at higher soil temperatures. Denitrification can involve the loss of 20-60 per cent of applied nitrogen, and represents a serious economic loss, as well as an environmental problem. It is much more common in modern agriculture than in natural systems, due to the combination of nitrogen fertilizers with soil compaction, reduced porosity and water logging (Hilton et al, 1994). Where field traffic is uncontrolled, soil compaction is universal in cropped fields as illustrated and explained in Figure 4. This random-traffic induced compaction could be a factor in the greater nitrogen requirement sometimes associated with zero tillage, where surface and subsurface compaction remain undisturbed. The topic has been explored by many authors, for instance Aulakh et al. (1984) and Six et al. (2004)

Reductions in nitrous oxide emissions might be brought about by two mechanisms

a) Avoiding soil compaction and water logging, particularly in the zone where high concentrations of nitrate fertilizer reside after planting.
b) Better matching nitrogen fertilizer application to crop demand to reduce the time when excess nitrate is available.

The current alternatives are to apply most fertilizer at or pre-planting, to soil which is often compacted and susceptible to water logging, or post-planting surface application. Both are inefficient and greenhouse-unfriendly.

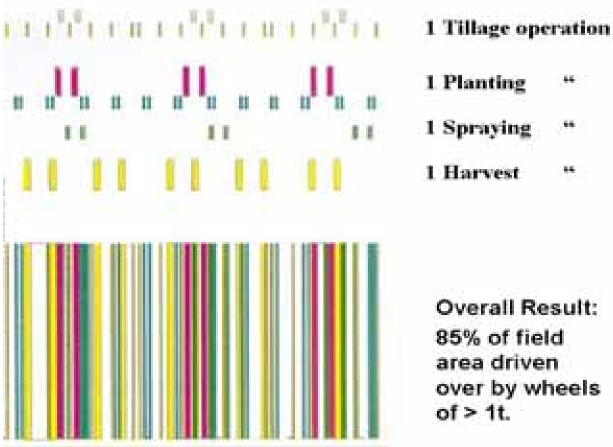


Fig. 4. Traffic impact in minimum tillage.

Farmers and scientists are usually surprised by the large percentage of field area driven over by heavy wheels. Unless traffic is controlled, a complete zero tillage system still involves driving heavy wheels over 50 per cent paddock area. As wheel compaction effects usually last several years, compaction is universal under non-CTF cropping systems. Being universal, it is difficult to demonstrate without controlling traffic.

Control of field traffic will avoid compaction of fertilized soil, and well-designed permanent bed systems can eliminate water logging. Permanent traffic lanes and precise guidance also provide a mechanism for drilling fertilizer interrow, in the growing crop. These measures should substantially reduce denitrification, and better timing would also reduce the opportunity for nitrate loss and pollution of groundwater. Both measures should increase nitrogen efficiency and so is economically attractive to farmers.

3.4 Soil Conservation

The anchored residue of zero tillage will provide effective control of wind erosion, and valuable protection against water erosion in all but extreme rainfall events. CTF ensures that more residue remains standing for longer time. Australian farmers are using CTF and precise guidance to plant a new crop in the interrow of the previous crop's standing residue, allowing most residue to remain in place until the new crop takes over the soil protection function. CTF has also allowed farmers to avoid the tillage operations which would otherwise occur in "zero till" systems after rain at harvest time, resulting in deep wheel ruts from the harvester.

Control of field traffic improves soil conservation by increasing infiltration and further reducing runoff, an effect demonstrated in China by Wang et al. (1999), and in Australia by Tullberg et al. (2003). In most climates, however, very high intensity rainfall will still occasionally produce runoff, and this can cause significant water erosion if allowed to concentrate. In Australia, layout of controlled traffic systems at right angles to the contour has been effective in preventing concentration by keeping runoff within the crop row where it was generated (Tullberg et al. 2003). In this "down slope" system, runoff remains spread across the field, at small depths and non-erosive velocity, until it arrives at a safe disposal point.

Runoff reduction is also the most effective method of reducing waterway pollution. Deep drainage can increase under zero tillage, and increase further with controlled traffic. This is not a common problem in water-limited systems, but "opportunity cropping" -- making sure that crops are available to use all available water -- is the most effective strategy to reduce deep drainage in annual cropping systems. Deep-rooted perennials are more effective, but not usually an option in grain production.

Water is also an important factor in the environmental impact of agriculture. Most pollutants are carried into watercourses by erosion, and some chemicals -- particularly nitrates -- can be carried into groundwater supplies by deep percolation of water. Increasing infiltration rate will reduce runoff, erosion and watercourse pollution (Silburn, Freebairn and Rattray, 2003). Greater water-holding capacity of the soil will only reduce deep percolation where crop production is increased to use the additional stored water.

4. CONCLUSIONS

The options available for reducing greenhouse gas-induced global warming are extremely limited. Agriculture provides an opportunity to reduce greenhouse gas emissions and increase carbon storage as soil organic matter, so it is expected that the greenhouse gas impact of agriculture become a priority. Increasing population requires increased food production, and current environmental priorities - soil erosion and waterway pollution - are also likely to increase in importance. Most agricultural scientists would suggest zero tillage as the first priority to meet these challenges.

This paper has considered the evidence on fuel energy, water use efficiency, nitrogen fertilizer efficiency and soil conservation, with particular reference to the impact of equipment wheels. This indicates that uncontrolled field traffic is a major problem for the environment, and for the productivity and sustainability of cropping. Wheel traffic induced effects - surface ruts and subsurface compaction - are also major factors inhibiting the adoption of zero tillage.

Controlled traffic farming has been demonstrated effectively in high-technology countries, and adopted on a large-scale in Australia. This process has been assisted by the development of 2cm-precision guidance systems at less than 5 per cent of tractor price. Similar advantages have been demonstrated on a smaller scale in lower-resource environments, using permanent raised beds for guidance. Although these systems usually require a minimum of 15 per cent of field area to be set aside for permanent wheel lanes, production per hectare has increased in all cases.

Controlled traffic (or raised bed) zero tillage systems appear to provide the improved environmental performance and productivity which will be required in future. Controlled traffic farming should be seen as the first step in precision agriculture for a more environmentally friendly food production system.

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