CONSERVATION AGRICULTURE, EMISSIONS AND RESILIENCE: OPPORTUNITIES AND DANGERS

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INTRODUCTION.

Conservation agriculture (CA) has many definitions, but most refer to improving sustainability by maximising residue cover and soil health, largely by minimising soil disturbance, in contrast to soil management using traditional tillage. To date, the major focus of conservation agriculture research and extension has been on the substantial benefits achieved by reducing tillage.

Zero tillage minimises the physical loosening aspect of soil disturbance, but does not eliminate the physical compaction aspect. More recently, there has been increasing interest in controlled traffic or permanent bed cropping systems which can minimise both aspects of soil disturbance. Their common characteristic is the restriction of all heavy wheel traffic to permanent traffic lanes, so the cropping area is uncompromised by wheels. Such systems are highly compatible zero or minimum tillage.

This paper attempts to provide a concise comparison and evaluation of the impact of these systems on greenhouse gas emissions from cropping. The objective is to compare systems with and without soil disturbance, and systems with and without both compaction and disturbance. A purely theoretical comparison would not be realistic, so real systems are considered here where, (for instance) "zero tillage" is compromised by occasional requirements to deal with harvester ruts, and "zero compaction" is compromised by the need to maintain 10 -- 20% of field area as permanent traffic lanes.

A broader climatic/geographical/technological context is also required for the comparison described below. In this case, the data given is relevant to three typical systems applied to extensive dryland grain production in Australia, together with appropriate equipment and herbicide data. Despite the large differences in scale and level of technology, much of the approach would apply equally well to dryland grain production in northern China.

THE CONTEXT – AUSTRALIAN DRYLAND GRAIN SYSTEMS.

Assessments of Australian agriculture have always demonstrated high economic efficiency, based on effective mechanisation, but such assessments rarely accounted for environmental costs. These could be very large when common agricultural practice was based on ideas imported from the mild climates of northern Europe, with multiple tillage operations and “clean fallows”. In the more extreme environment of Australia ("a land of drought and flooding rains"), many years of traditional tillage resulted in wind and water erosion levels which could not be ignored.

From the 1970s onwards, soil conservation ideas drove the adoption of conservation agriculture, starting with non-inverting tillage to maintain some residue cover, and steadily replacing tillage operations with herbicide. Improvements in planting equipment, on-farm understanding of herbicides and the application, together with recognition of the harvester's role in residue management, have all been essential steps along the road towards zero tillage.

The process has been accompanied by steady development of minimal-disturbance planting equipment, able to place and firm seed accurately in hard soil through normal levels of crop residue. Robust planters with good residue clearance and individual row depth control are readily available now, although usually big, heavy and expensive, requiring powerful and heavy tractors. Adoption of controlled traffic systems (CTF) has been driven by the problems of random traffic by this heavy equipment, which compacts >50% field area per crop

Current dryland cropping systems can now be classified within three broad generic groups, each of which represents a step along the path from an (increasingly rare) traditional tillage system towards more sustainable production systems. These groups are:

> Stubble mulching, where traditional tillage has been reduced to between one and three minimum-inversion tine or sweep tillage operations, and between one and three herbicide weed control operations. (probably still the most common system).
>
> Zero tillage, with no regular soil disturbance except at planting and full herbicide weed control. Occasional chisel tillage or subsoiling is required to relieve soil compaction, or deal with surface ruts after wet harvests. (probably less common than stubble mulching).
>
> Controlled traffic farming, (CTF) with all heavy wheels restricted to permanent lanes and oriented to provide safe disposal of surface water. CTF overcomes the problems of wheel traffic in the cropping area, but requires accurate guidance and equipment systems of common working width, track width, and relatively narrow tyres. (this is the least common practice, but growing rapidly).

The impact of zero tillage with residue retention (compared with stubble mulching) is well-known and has been described by several authors. It might reasonably be summarised as one of increasing rainfall infiltration rates and soil health while reducing erosion by water and wind, tillage energy requirements and soil evaporation rates. Surface soil bulk density is greater but continuity of porosity improves, increasing soil resilience to compaction effects.

The direct impact of CTF (compared with zero tillage) includes further large increases in infiltration rate, plant available water capacity and soil health, combined with a substantial reduction in equipment energy requirements. Soil bulk density and the energy requirements of traffic and traction are substantially reduced.

Cropping system performance comparisons are summarised in Table A below.

Table A. Cropping system performance (approximated from Tullberg et al. 2007)

	Planting Power (kWh/ha)	Infiltration rate (extreme event)	Soil biota (earthworms/m^2)	PAWC (top 300mm)	Grain yield (9 crop mean)
Stubble mulch	100	100	100	100	100
Zero Tillage	100	170	400	120	105
CTF	50	260	1100	185	115

It is important to recognise the importance of difficult-to-quantify "system" impacts of practices, in addition to the direct effects. These often relate to timeliness of crop management operations. Residue cover in zero tillage systems, for instance, reduces the rate of moisture loss after rain, and increases time available for seeding. Similarly hard, unplanted permanent traffic lanes in CTF facilitate in-crop operations and improve seeding, spraying and harvesting timeliness. Better timeliness can substantially improve cropping frequency and yields in an unreliable climate where rainfall is the primary determinant of cropping.

Very large-scale equipment is not unusual in Australian broadacre grain production. A variety of equipment widths are used in stubble mulching and zero tillage operations, usually with dual-tyred tractors. CTF operations require equipment of common (or modular) width. The most common arrangements are based on a 9 m planter and harvester with a 27 m sprayer, all on a 3 m trackwidth with tyres of 0.5 m section and 2 cm RTK-GPS autosteer.

Warranted 3m track width tractors are available from all major manufacturers, but 2 m track width CTF systems are sometimes used in irrigated production in Australia. CTF systems based on much smaller track widths (Govaerts et al. 2003) have been successfully applied in other countries, including Mexico, India, Pakistan and China. These low-cost "permanent bed", or "permanent raised bed" systems usually use the furrows to provide guidance, but share the major CTF system characteristic of restricting all heavy wheels to permanent lanes.

RESULTS AND DISCUSSION

A simple Excel spreadsheet approach has been used to compare greenhouse gas (GHG) emissions from different farming systems, and a copy of this spreadsheet appears here as a Figure 1 -- a numbered series of tables. The tables follow a rational order, dealing first with those emissions that are easily quantified.

Easily quantified emissions are related to purchased inputs (fuel, machinery, fertiliser and herbicide), and for most practical purposes, energy-related. They can be assessed with a relatively small probability of error for any given system, once the system is defined.

Soil emissions -- largely nitrous oxide and methane -- are much more highly variable. They can be estimated only by inference from experiments under different circumstances. In all cases, emissions are expressed in terms of carbon dioxide or CO_2 equivalent -- “CO_2 -e”.

The assumptions used in the example and presented in these tables (Figure 1) are intended to be reasonably typical of broadacre cropping in eastern Australia, but spreadsheet input values (highlighted) can easily be changed to represent other systems. Overall outcomes are unlikely to be significantly different for other dryland systems.

Input-Related Emissions.

Fuel. Emissions from fuel use obviously relate to the operations involved in the cropping system, and the energy requirement of these operations. Operations typical of the each system are set out in Table 1. In this case, zero tillage has been assumed to require the equivalent of one tillage operation in three years. Improved timeliness permits one less spraying operation in CTF, but an additional fertiliser operation (in-crop liquid N) is assumed to improve nitrogen efficiency.

Fuel requirements for field operations are given in Table 2, based on extension service data from DPIF (2008) but modified to account for the improved energy efficiency of CTF systems (Tullberg 2000). The total field operation fuel requirement for each system -- the cumulative product of (operations x fuel requirement) -- appears in the right-hand columns of Table 2, together with the CO_2 released by burning that fuel. The results demonstrate the substantial reduction in fuel achieved by zero tillage, but another, larger reduction achieved when zero tillage is combined with controlled traffic.

Herbicides. Replacement of tillage by herbicides is often assumed to provide a large increase in energy efficiency (Wylie 1987), but the energy embodied in herbicides (incorporated in the materials, or used in the manufacture and transport to the farm) is considerable. Glyphosate is the most commonly used herbicide, and also one of the most energy intensive, according to Zentner (2004) who has tabulated embodied energy of many agricultural inputs. This is the basis of Table 3, with data for a number of common herbicides, converted into diesel fuel and its CO_2 equivalent.

Table 3 also includes the author's estimates of the relative frequency with which each herbicide is used, to allow the calculation of a "mean spray impact" -- the CO_2 equivalent of the average herbicide spray operation, set out below Table 3.

Fertiliser. Nitrogen fertiliser is usually represents the largest single anthropomorphic energy input to cropping, and nitrogen efficiency of cereal production is generally very poor, with a mean value often around 40%. In Australia fertiliser is traditionally applied at seeding, and large nitrogen losses are associated with heavy rainfall events during the period between seeding and plant uptake. Loss mechanisms include leaching and denitrification, which is associated with waterlogging, high water-filled porosity and compaction.

These are all issues for all cropping systems, but anecdotal reports of more frequent waterlogging in zero tillage appear to have a factual basis. It is certainly not difficult to envisage more frequent and extensive waterlogging of the seed/fertiliser zone when these materials are placed at the base of a narrow slot cut into the more compact soil of zero tillage systems. Infiltration rates reduced by random traffic will also exacerbate waterlogging.

Fertiliser is applied only to the highly-porosity crop bed areas of CTF where greater biological activity will tend to reduce losses, and movement into the permanent wheel lanes will be restricted by limited porosity. Leaching could occur more rapidly from beds with better infiltration, but the permanent lanes of CTF facilitate split fertiliser application, using liquid N via sprayers to achieve high workrates.

All of these factors are consistent with the anecdotal claims of "greater yield with less fertiliser" in CTF (e.g. Ruwolt 2008), but these have not been subject to proper evaluation. Long-term CTF trials with minimal N input (e.g. Li et al. 2007), have demonstrated yield improvements >10%, and data from China (Chen et al. 2008) is also consistent with improved N efficiency. The conservative assumption used in this paper is that N requirements of CTF are 10% less than those of zero tillage or stubble mulch.

This is the basis of the values quoted in Table 4, which includes the energy embodied in fertilisers (taken from Zentner 2004). The feedstock for N fertiliser production is usually gas, producing only 0.065 kg carbon dioxide per MJ energy, so emissions from embodied energy amount to approximately 4.9 kg CO_2 per kilogram of N fertiliser produced.

Constants

	Energy MJ	CO2E kg
Diesel/L	40	2.9
Gas/MJ		0.06
Nitrogen/kg	Mf E, MJ/kg	75.6
Phosphate/kg	Mf E, MJ/kg	9.5
Potassium/kg	Mf E, MJ/kg	9.9
Nitrous Oxide	CO2E factor	310
Methane	CO2E factor	23

1. Operations per crop

System	Chisel	Cultivate	Spray	Seed	Fertilise	Harvest
Stubble Mulch.	1	2	1	1	0	1
Zero Tillage	0.33	0	4	1	0	1
CTF	0	0	3	1	1	1

2. Fuel requirements, L/ha

Operation	Chisel	Cultivate	Spray	Seed	Fertilise	Harvest
Stubble Mulch	9.8	6	1.4	5	0	8
Zero Till	9.8	0	1.4	5	0	8
CTF	0	0	0.7	3	1	6

System

Fuel L/ha	CO_2 kg/ha
36.2	**105**
21.834	**63**
12.1	**35**

3. Herbicides

Commercial Product	Herbicide	Mean Frequency	Label rate kg/ha	Energy	
				MJ/kg	MJ/ha
2,4-D Amine	2,4-D	1	0.5	98	49
Atrazine	Atrazine	2	0.5	190	95
SpraySeed	Di/Paraquat	1	0.25	430	107.5
Roundup CT	Glyphosate	3	0.45	511	229.95

Fuel L/ha	CO_2 kg/ha
1.23	**4**
2.38	**7**
2.69	**8**
5.75	**17**

So mean spray impact =	148.05	3.70	10.7

Herbicide CO_2 kg/ha	
StubbleMulch	10.7
Zero Till	42.9
CTF	32.2

4. Fertiliser

System	Nitrogen 75.6 MJ/kg		Phosphate 9.5 MJ/kg		Potassium 9.9 MJ/kg		*Total Energy* (from gas)	CO_2 kg/ha
	kg/ha	MJ/ha	kg/ha	MJ/ha	kg/ha	MJ/ha		
Stubble Mulch	45	3402	5	47.5	8	79.2	3528.7	211.722
Zero Till	45	3402	5	47.5	8	79.2	3528.7	211.722
CTF	40	3024	5	47.5	8	79.2	3150.7	189.042

5. Soil Emissions

(Organic veg. cropping, Holland)

System	NO_2 during early growth - kg/ha/day		CO_2 Equivalent - kg/ha/day	
	Nitrous oxide	Methane	Nitrous oxide	Methane
Random Traffic	0.068	0.00075	21.08	0.01725
Seasonal CTF	0.047	-0.0049	14.57	-0.1127

	NO2	Methane
System	CO_2-e kg/ha	CO_2-e kg/ha
Stubble	21.08	0.01725
Zero Till	27.59	0.1472
CTF	14.57	-0.1127

(Australian dryland grain -- Speculative)

6. Assumptions

	System	NO2 Production		Methane Production		Total
		Days	CO_2-e kg/ha	Days	CO_2-e kg/ha	CO_2-e kg/ha
Same as Random Traffic	Stubble Mulch	30	632.4	150	2.59	635
	Zero Till	30	827.7	150	22.08	850
Same as Seasonal CTF	CTF	30	437.1	150	-16.91	420

7. Totals

Emissions related to Inputs

(Good Evidence)

System	Diesel Fuel kg/ha	Herbicide kg/ha	Fertiliser kg/ha	Total kg/ha
StubbleMulch	**105**	**10.7**	**212**	**327**
Zero Till	**63**	**42.9**	**212**	**318**
CTF	**35**	**32.2**	**189**	**256**

(Speculative)

Soil Emissions CO_2-e kg/ha	Grand Total Emissions CO_2-e kg/ha
635	**962**
850	**1168**
420	**677**

Figure 1. Cropping system input and emission tables

Soil Emissions

Nitrous oxide (N_2O) has approximately 310 times the greenhouse impact of carbon dioxide, so small quantities have a significant global warming effect when expressed in terms of their carbon dioxide equivalent, "CO_2 -e". Large emissions of nitrous oxide occur by denitrification when soil nitrates and a carbon source are combined under anaerobic conditions, usually produced by high levels of water-filled porosity. It can be responsible for a significant loss of N derived largely from fertilisers. (Dalal et al. 2003)

Soil compaction reduces the rainfall rate required to cause saturation and the rate of diffusion of oxygen into (and carbon dioxide out of) soil, promoting anaerobic conditions which favour nitrous oxide production. Many authors have demonstrated the association of emissions with compaction, porosity and pore connectivity (e.g. Ball et al.2008). They have also noted the extreme, apparently random, small-scale spatial variability of emissions (Ball et al.1997). The author's experience of small-scale infiltration measurement variability suggests that random traffic effects might be responsible for much of this variability.

Methane (CH_4) has approximately 23 times the greenhouse impact of carbon dioxide, but emissions from dryland cropping are small compared with those from animal production or rice cropping. Relatively dry areas of natural vegetation usually oxidise small amounts of methane, but small amounts are also emitted by cropped soils. Better aerated soil promotes the absorption and oxidation of atmospheric methane, whilst anaerobic conditions tend to encourage methane emissions.

Nitrous oxide and methane emissions are often studied together, and the impact of precise soil management on these has been reviewed by Mosquera and Hilhorst (2005). A number of authors have compared emissions from wheeled and non-wheeled rows and interrows of potatoes (e.g Ruser et al.1998, Thomas et al. 2004), but this has usually been carried out in an environment of intensive tillage and random traffic, so quantitative values are difficult to apply in the present case.

Total Soil Emissions. Research into CTF impacts on greenhouse gas emissions is rare, but Vermeulen and Mosquera (2007) compared nitrous oxide and methane emissions from random traffic and "seasonal" precision CTF (with annual mouldboard ploughing) in an organic vegetable production system in Holland. Results were obtained over three crops in two seasons, and are the basis for the values summarised in Table 5a. They demonstrate a large, statistically significant reduction in nitrous oxide emissions from seasonal CTF, and the absorbtion and oxidation of methane by seasonal CTF. Small quantities of methane were emitted under random traffic. The data also illustrates consistent and significant improvements in most crop yields, and in total and air-filled porosity of CTF.

Implications for Australian dryland production on the basis of results obtained in a European organic system must be seen as speculative and. Nevertheless the impact of varying porosity and pore continuity are consistent factors, together with the greater nitrous oxide and methane emissions from random traffic zero tillage (v. conventional tillage), demonstrated by Aulakh et al. **(**1984).

Vermeulen and Mosquera (2007) provide the only available data comparing CTF and random traffic. The wetter environment of their work (compared with Australia) would be expected to increase emissions, while the lower temperatures would tend to decrease emissions. Soil emissions from tillage-based systems are likely to be similar or smaller than those of a zero tillage system, and the manure applications used in Holland suggest that factors such as carbon availability would not limit emissions. Estimates based on different systems are clearly just estimates, but in the absence of better data, they are the only indication of likely emission effects. As such, they are might provide better indications of relative, rather than absolute, values of system emissions.

There are few indications to assist the estimation of emission rates for zero tillage systems, but if porosity is the major difference, the values of CTF and non-CTF emission rates given by Vermeulen and Mosquera (2007) might reasonably be applied to CTF and random traffic stubble mulch systems respectively. Porosity of zero till is likely to be less than that of stubble mulch, increasing emissions (Dalal et al. 2003). For current purposes, emissions from zero till are assumed to be greater than those from stubble mulch by an increment similar to that between controlled and random traffic. Values are set out in Table 5b.

The duration of emissions is also required for total emission estimates. Nitrous oxide emissions are significant only when excess nitrate is available and soil is close to saturation. This situation will occur only within a relatively short period of the growing season, assumed to be 30 days in this case. Methane and nitrous oxide emissions might occur at the same time, but methane absorption processes are likely to operate over a much longer season. A time period of 150 days has been assumed in this case for these processes.

Duration time and total nitrous oxide and methane production estimates for each system are set out in Table 6, together with the CO_2 e values.

Overall totals are given in Table 7, in which emissions related to inputs, based on good evidence, are separated from the more speculative soil emission estimates. In both cases, total emissions from controlled traffic zero tillage systems are clearly superior to those of random traffic zero till or stubble mulch. Stubble mulch appears superior to zero tillage in terms of total emissions.

Quantitative values of soil emission estimates are suspect, but the assumptions involved are conservative, so it is difficult to envisage changes which would affect system ranking. In moisture-limited environments, controlled traffic zero till systems have been shown to accumulate more plant available water, which allows them to grow more biomass with less soil disturbance. Other things being equal, this will increase the rate of soil organic matter accumulation, or reduce its rate of loss.

Developments of controlled traffic farming, such as precision interrow relay cropping (pre-harvest seeding of the following crop) will help use any excess soil moisture for biomass production. Cover crops which provide weed suppression are economically positive even when moisture is inadequate for grain crops. Precision controlled traffic farming enhances the environmental performance of productive systems by moving them closer to the systems of natural vegetation in terms of water use, biomass production and residue cover.

CONCLUSIONS

1. Greenhouse gas emissions from inputs (fuel, herbicides and fertiliser) are demonstrably smaller from controlled traffic zero till systems, compared with (random traffic) zero tillage or stubble mulch systems.

2. Evidence on greenhouse gas emissions from soils indicates that these should also be substantially smaller from controlled traffic systems. Surprisingly, emissions from (random traffic) zero till appear to be greater than those from stubble mulch tillage.

3. Further work is required to establish more precise values for nitrous oxide and methane emissions under different cropping systems.

Controlled traffic farming (CTF) is based on a self-evident truism "plants grow better in soft soil, wheels work better on roads". It has been shown to increase productivity, reduce costs and improve all measures of environmental impact.

Rapid adoption of CTF can be expensive at present given the lack of common wheel track and operating width standards for farm machinery. Adoption could be achieved over a 10-year timeframe at almost zero cost if this problem were recognised, and equipment manufacturers encouraged to move towards common track-width standards. The Australian Controlled Traffic Farming Association is considering steps towards standardisation.

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