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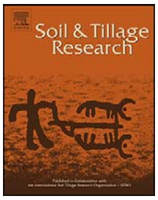

Tillage, traffic and sustainability—A challenge for ISTRO

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ABSTRACT

Tillage might be unnecessary for crop production, but no practical mechanised system can avoid field traffic, usually by wheels. Wheels can cause soil damage, but this can be limited to a small proportion of field area by restricting all heavy wheels to permanent traffic lanes. Widespread adoption of controlled traffic in Australia, and permanent raised beds in Mexico has demonstrated the effectiveness and practicability of Controlled Traffic Farming (CTF) systems in very different cropping environments.

This paper considers the system impact of wheel traffic on productivity and sustainability of mechanised cropping, citing comparisons between CTF and conventional “random traffic” cropping systems where possible. Evidence of the extent and effects of wheeling on soil structure is summarised in terms of hydrology and crop performance. Soil erosion and broader environmental effects are considered briefly.

Tillage and traffic effects on greenhouse gas emissions from cropping are discussed, including emissions from fuel, herbicide and fertiliser inputs. Soil emissions are considered in some detail, citing evidence from soil compaction studies, and where emissions have been monitored from wheeled and non-wheeled soil. Outcomes have been encapsulated in a spreadsheet comparison of emissions from cropping systems using tillage with random traffic, no-till with random traffic and CTF no-till. Using data from extensive grain production systems in Australia this indicates that CTF could provide a major reduction in cropping emissions.

CTF can improve productivity, and all measures of sustainability; it also overcomes some important constraints to the adoption of conservation agriculture. As precise guidance becomes progressively cheaper, machine system width compatibility remains the only major impediment to a significant improvement in food security and the environmental footprint of cropping.

Width compatibility is simple in principle, but complex in practice, and will occur only with the active engagement of the farm machinery industry. The paper urges ISTRO to join with regional farmer CTF groups to draw attention to this issue and provide a forum for the development of compatibility standards.

1. Introduction

The impact of farm equipment traffic on soil properties and crop production is a matter of casual observation, so soil compaction has been investigated in many soils and environments over the past century. Considerable evidence related to this topic was presented in Soane and van Ouwerkerk (1994), but this and subsequent collections of significant papers on sustainable soil management (e.g. Horn et al., 2006) all demonstrate that the impact of vehicle traffic on soil and crop production is a problem in many environments. The instances where mild soil compaction has been shown to have a positive effect usually relate to its effect on disturbed soil.

In highly mechanised systems, crop establishment is carried out using tractors with axle loads in the range 50–100 kN, and harvesting equipment axle loads in the range from 150 kN upwards. Common ratios of tyre width: operating width can be used to estimate wheel (or track) “trafficked” area as a percentage of field area, and values of ranging from 220% to 540% are quoted by Kuipers and van de Zande (1994). Where traffic is not controlled, the area trafficked (driven over) by heavy wheels in seeding, spraying, harvesting and materials handling operations is rarely less than 50% of field area, even in zero tillage grain production. When natural amelioration processes occur on a timescale of several years at depths greater than 20 cm (McHugh et al., 2009), this indicates that traffic-induced structural degradation will be almost universal in the sub-tillage soil profile of highly mechanised cropping systems.

Soil damage occurs because vehicle tyres or tracks impose loads that cause vertical and horizontal soil deformation, reducing porosity and connectivity while increasing mechanical resistance to root exploration. Reducing vehicle weight, restricting operation to times of greater soil strength, or reducing contact pressure might all reduce soil damage, but only the last option appears to be feasible when demand for greater capacity is satisfied only by bigger and heavier farm equipment.

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Investigation of contact pressure effects on soil damage in different environments has produced inconsistent results. Running gear comparisons made by Ansorge and Godwin (2006) for instance, challenge the generalisation that soil surface damage is related to contact pressure, but deeper damage is related to total load. Using grain harvester axle loads (150–250 kN), they demonstrated the beneficial effects of rubber tracks (v. tyres) in terms of cone penetrometer reading and soil displacement. They also suggested that when using rubber tracks, the hardpan beneath mouldboard plough depth provided significant benefits in preventing damage to deeper layers.

It should be noted that this beneficial outcome occurred in an environment where the best treatment (rubber track on stratified soil) still produced cone penetrometer readings in the range indicating some root growth restriction (>1.5 MPa), and vertical soil deformation levels (>5 mm at 350 mm depth) likely to have a significant impact on internal drainage. This soil condition is unlikely to be suitable for no-till planting of the next crop, and amelioration of damage at depths >350 mm will be mechanically expensive, or slow if left to natural processes.

Soil conservation research and extension to date has focused largely on reducing tillage, so minimum soil disturbance, maximum residue cover, and crop rotation are seen as the basis for Conservation Agriculture, now widely advocated in most environments (eg FAO, 2010). Soil structural degradation – compaction – has received less attention, and is sometimes claimed to be unimportant in no-till systems.

This paper summarises evidence to show that soil compaction by wheels or tracks is a major issue for many mechanised systems, and might contribute to the slow uptake of conservation agriculture. The problem can be avoided in the non-tilled cropping beds of controlled traffic farming (CTF) systems, in which all heavy wheels are restricted to permanent traffic lanes, where compaction is a trafficabillity advantage. CTF requires precise guidance of equipment with matching (or modular) track and working widths, and a layout which ensures traffic lane drainage. Ideally, tyre widths will also match.

Controlled traffic farming is often seen simply as a system to increase mechanisation efficiency. This paper demonstrates its broader advantages for productive and sustainable cropping, by comparing the performance of traditional tillage-based, random traffic zero till, and controlled traffic zero till systems (CTF). It also contends that CTF adoption will be difficult without constructive engagement of the farm machinery industry, and advocates the development of equipment track and working widths standards for different cropping environments.

2. The impacts of field traffic

2.1. Productivity

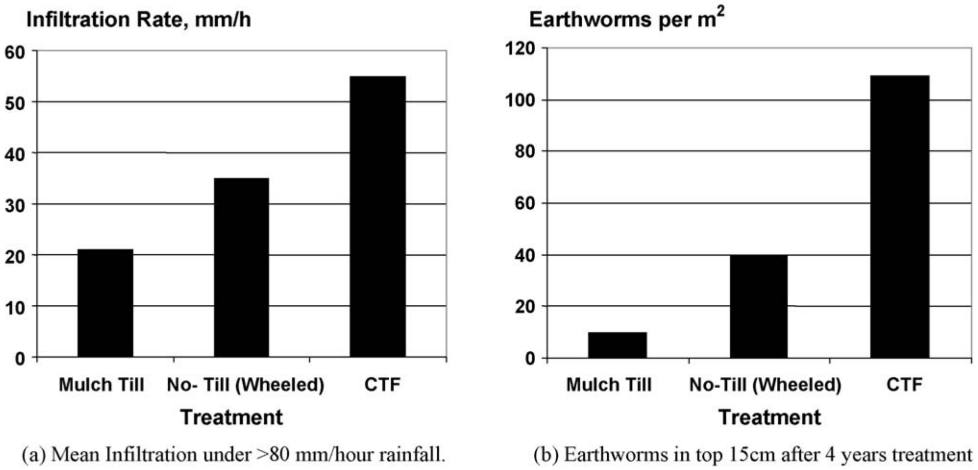
The effects of controlling field traffic have been studied on at least four continents, with a variety of crops and in a range of environments (Taylor, 1983; Tullberg and Murray, 1988; Chamen et al., 1992; Wang et al., 2009). Unsurprisingly, bulk density of non-trafficked soil has always decreased and porosity has improved, which might be expected to improve yield potential.

Crop yields have usually improved under controlled traffic (Vermeulen et al., 2010), but the relationship between yield and compaction is influenced by many system effects (Boon and Veen, 1994). Despite major variability, mean yields have often increased by 5–20% in side-by-side comparisons in grain crops (e.g. Dickson and Campbell, 1990; Tullberg et al., 2007), where field traffic was the only change. This corresponds well with the literature on soil compaction.

The effect of removing tillage and removing both tillage and traffic on infiltration rate and soil biota are illustrated in Fig. 1 from Australia. Side-by-side yield effects of 10–15% in this situation were related to increased soil moisture availability occurring as a result of greater infiltration (Li et al., 2007) and greater plant available water (McHugh et al., 2009). Both are a function of improved porosity.

The "system" effects of controlled traffic – earlier field access after rain, the elimination of harvester wheel ruts and random wheel effects on residues – are the basis of much greater yield improvements than those measured in classical "side-by-side" assessments. System effects are largely associated with improved trafficability and timeliness of field operations. A clear example occurs where permanent traffic lanes can allow planting to proceed immediately after harvest, permitting double cropping in environments where it would not otherwise be possible. Significant cost reductions and yield improvements might also be expected from improved timeliness of herbicide and fertiliser application, and major savings have been reported by a number of farmers (e.g. Ruwolt, 2008).

Demonstration of system effects is difficult, because it involves changes in soil and crop management which inhibit simple comparisons. The timeliness effect of controlled traffic was assessed by McPhee et al. (1995b), and associated with a cumulative productivity improvement of >30% over two seasons in semi-arid, subtropical crop production. This was combined with a reduction in machinery system costs of >50% (McPhee et al., 1995a). More recently a group of 16 CTF farmers in southern Queensland surveyed by Bowman (2009) reported a mean production increase of 37% combined with a 49% reduction in machinery-related costs (fuel, oil, repairs and maintenance, labour and contract harvesting).



(a) Mean Infiltration under >80 mm/hour rainfall.

(b) Earthworms in top 15cm after 4 years treatment

Fig. 1. Tillage and wheeling effects on infiltration and earthworm activity in a vertosol (adapted from Tullberg et al., 2007). (a) Mean infiltration under >80 mm/h rainfall. (b) Earthworms in top 15 cm after 4 years treatment.

Australian data often refer to a dry environment where production is moisture-limited, but rainfall can occur in high-intensity events leading to significant runoff and soil erosion. Tillage clearly increases moisture loss and erosion hazard, so most farmers understand the value of minimising soil disturbance. No-tillage and systems with infrequent tillage are increasingly common (Llewellyn et al., 2009), but compaction can be a major issue in these systems, and is obviously related to farm machinery traffic.

The situation might be different in better-watered areas where the conventional treatment includes tillage to deal with surface soil compaction, in addition to levelling, controlling weeds and burying residue. In cooler, humid environments with more frequent low-intensity rainfall, yield dependence on the soil moisture store is smaller, erosion is less evident, and immediate yield increase is less certain when traffic is removed in side-by-side trials. Unsurprisingly, no-till is rare where moist harvests often result in deep wheel ruts and compaction. In these conditions, controlling traffic should be the first step towards reducing tillage and conservation agriculture.

2.2. Runoff, erosion and pollution

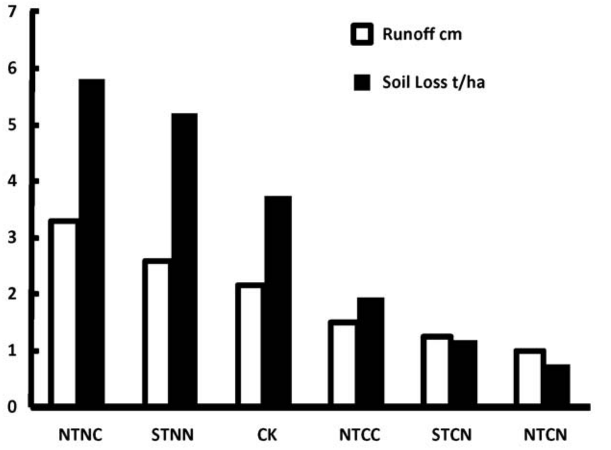
Productivity was the focus of earlier soil compaction research, but the past two decades have seen a growing interest in broader environmental effects. These include concerns for erosion, pollution, the maintenance of urban water supplies, and energy. Associations between soil management, flooding and greenhouse gas emissions have been surmised for many years, but only recently brought to public attention. Widespread soil compaction is relevant to each of these.

Community interest in these effects has been demonstrated in the proposal for a European Directive on Soil Protection (Commission of the European Communities 2006). This has not proceeded but farmers – European and worldwide – can anticipate increasing community pressure, or direct incentives to change their soil management systems to reduce degradation and environmental impact.

Wheel traffic effects on infiltration, runoff and erosion have been demonstrated in many different environments (e.g. Voorhees and Lindstrom, 1984; Li et al., 2001; Silburn and Glanville, 2002). Wang et al. (2008) measured runoff and soil loss from non-replicated plots subject to varying tillage and traffic treatments under natural rainfall for two years on the loess plateau in China (Fig. 2). Most soil loss occurred in only four major rainfall events, and was well correlated with runoff. Losses were minimised when soil was residue-protected, non-wheeled and non-tilled. Both wheeling and residue removal greatly increased soil loss. Where neither had residue protection, erosion from a mouldboard-ploughed plot (CK in Fig. 2) was less than that from a surface-tilled plot, probably as a result of greater surface and tilled layer storage in ploughed systems. Maximum runoff and soil loss occurred from compacted, non-tilled plots unprotected by residue.

Compaction effects were applied to these plots in one pass of a 3.6 t tractor, but rainfall simulator experiments in adjacent plots wheeled by 3.6 and 1.2 t tractors indicated very little difference in rainfall/runoff characteristics, despite the 3 × weight difference between tractors, and a measurable difference in the depth of bulk density change (Wang et al., 2008). It was also interesting to note that the most severe erosion occurred from a non-tilled, compacted plot from which residue had been removed. This outcome corresponds with the visual evidence of erosion and surface compaction when no-till stubbles are heavily grazed in Australia.

Traffic-induced soil compaction affects watercourse pollution from agriculture because runoff and erosion is associated with the movement of fertiliser (Silburn and Hunter, 2009) and herbicides (Silburn et al., 2002) into watercourses, either as solutions or attached to soil particles. Compaction clearly effects runoff and erosion on a small-scale, and catchment scale soil compaction by vehicles and grazing has been implicated in recent increases in flooding events in Europe (Holman et al., 2003; Boardman et al., 1994).



Tillage	No	Surface	Yes	No	Surface	No
Residue	No	No	No	Yes	Yes	Yes
Traffic	Yes	No	Random	Yes	No	No

Fig. 2. Tillage, residue and wheeling effects on mean growing season runoff and soil loss from loess plots (mean data from 1998 and 1999, growing season rainfall 250 and 274 mm respectively, adapted from Wang et al., 2008).

2.3. Greenhouse gas balances

Wheel traffic has damaging effects on greenhouse gas balances via a number of mechanisms. Compaction increases the fuel energy requirements of all soil-engaging operations, and is often a major motivation for tillage, which disrupts and aerates soil, encouraging oxidation of soil organic matter and the release of carbon dioxide. Compaction has generally negative effects on nitrogen fertiliser efficiency and soil emissions.

A simple Excel spreadsheet approach has been used to assess cropping system effects on emissions, by comparing the impact of three cropping systems which are broadly representative of current Australian practice:

Mulch tillage, where traditional tillage has been reduced to 1–3 minimum-inversion tine or sweep operations, with 1–3 herbicide operations in annual cropping. Soil is tilled and random-wheeled, with some residue retained. (The most common system until recently).

No-tillage, with no regular soil disturbance except at seeding, and herbicides replacing tillage for weed control. Occasional chisel tillage or subsoiling is required to relieve soil compaction, or deal with surface ruts after wet harvests; some opportunity cropping. Soil is random-wheeled but not tilled. Most residue is retained, but 30–50% has been crushed by wheels (increasingly common).

Controlled traffic farming (CTF), with all heavy wheels restricted to precise permanent lanes (10–15% of area) oriented for drainage and safe disposal of surface water. No tillage, maximum standing residue, usually opportunity cropping. (Least common, but increasing).

A copy of this spreadsheet appears here within Appendix 1 as Tables 1–7, which attempt to quantify the impact of emission sources in terms of CO_2 equivalent. Tables 1–4 are concerned with emissions related to inputs (fuel and machinery, herbicides and fertilisers). These are all energy-related, and not difficult to quantify for well-defined systems. Table 5 is concerned with soil emissions of nitrous oxide and methane, where system impacts are more variable and less well understood.

This spreadsheet is intended for use with farmer groups, allowing entry of locally valid inputs for different systems. The values illustrated here are default values representing typical dryland grain cropping in northern Australia.

2.4. Energy-related emissions

Fuel emissions relate to the operations involved in the cropping system, and the energy requirement of each. Operations typical of each system are set out in Table 1, where no-tillage has been assumed to need one tillage operation every three crops. Timeliness advantages of CTF are assumed to require one less spraying operation, but an additional in-crop liquid N application (via the sprayer). Average fuel requirements are given in Table 2, where fuel use in stubble mulch and no-tillage operation are based on DPIF (2008). Fuel use for CTF operation has been reduced from that needed in no-tillage on the basis of the effects noted by Tullberg (2000). Total fuel use (and CO_2 equivalent) per crop for the field operations of each system appear in the right-hand columns of Table 2.

Herbicide emissions are related to the energy embodied in material inputs, manufacturing processes and off-farm transport. Energy data for commonly used herbicides, quoted in Table 3, is taken from Zentner et al. (2004). It has been combined with an estimate (based on discussion with farmers) of the relative frequency of use of each herbicide to calculate a "mean spray impact" (the energy and CO_2 equivalent of the average herbicide spray operation), set out under Table 3. This has been used to calculate the total CO_2 equivalent of herbicide use in each system, assuming a similar range of herbicides is used in each.

Fertiliser and particularly nitrogen fertiliser, usually represents the largest single energy input to cropping. Nitrogen efficiency of cereal production is often in the range 30–40% (Raun and Johnson, 1999), with nitrogen loss occuring through volatilisation, loss in solution as runoff or leachate, and loss as gas by denitrification. Loss mechanisms are complex, and vary with soil, fertiliser type, placement and environmental conditions. When most fertiliser is applied at seeding, losses are most severe during the period prior to crop uptake, in rainfall events when available nitrate can be lost in runoff, with eroded soil, leached or denitrified. Soil compaction might reduce leaching loss, but losses due to runoff and erosion might increase, together with the frequency and duration of periods when soil moisture content exceeds the drained upper limit, promoting denitrification.

These losses should be smaller in soils with a pore structure undamaged by wheels, and with greater organic matter and biological activity. Opportunities for loss can be further reduced by minimising the period during which excess nitrate is available by splitting fertiliser applications to better match N supply with crop demand. In-crop application is substantially cheaper and easier using the permanent traffic lanes of CTF to achieve high work rates and accurate placement of liquid N with modified sprayers. A reduction of 20% in N fertiliser requirements of CTF is assumed in Table 4, where energy values of fertilisers are taken from Zentner et al. (2004), and the CO_2 equivalent based on energy production from natural gas. The 20% reduction is much smaller than that claimed by commercial farmers using CTF (e.g. Ruwolt, 2008).

2.5. Soil emissions

Nitrous oxide (N_2O) has approximately 300 times the global warming impact of carbon dioxide, so small quantities have a significant effect. It is generated in complex microbially-mediated reactions in soil when nitrate and carbon (usually organic matter) are present. Ball et al. (2008) have demonstrated the associations between emissions and compaction-related parameters such as water-filled porosity. Nitrous oxide emissions from agricultural soils are characterised by their extreme variability (spatial and temporal), and occur largely from very wet soils, usually when water-filled porosity is in the range between 60% and 80%.

Methane (CH_4) has approximately 23 times the greenhouse impact of carbon dioxide. It is often absorbed by soil in good condition, but emitted from waterlogged soil. Methane fluxes from dryland cropping are small compared with those from animal or paddy rice production. Nitrous oxide and methane emissions are often studied together, but in most cropping situations (other than those involving prolonged flood irrigation) nitrous oxide is more important in terms of global warming potential.

Individual reports of soil management effects on cumulative soil emissions show no consistent tillage system effect, but Rochette (2008) recently summarised the results from 25 reports of such work, representing 45 site-years of data. He concluded that tillage system impacts on nitrous oxide emissions were small in soils with good to medium aeration and drainage, with results evenly balanced between increased and reduced emissions. In poorly-aerated soils, on the other hand, nitrous oxide emissions from no-till systems were greater (and sometimes much greater) than from tilled systems, with a mean system impact of 2 kg $N_2O–N\ ha^{-1}$. The explanation for increased emissions from no-till soil was the increased frequency with which water-filled pore space exceeded 60% under these conditions in fine-textured, poorly drained soils.

The reports cited above rarely define the precise measurement site in relation to prior tractor and harvester wheel traffic, but in the absence of specific information it is reasonable to surmise that researchers would avoid placing emission monitoring devices in obvious wheeltracks. Wheel track effects are however a particular interest in emission measurements from potato production.

Ruser et al. (1998), working in southern Germany, presented results in terms of emissions per total hectare of potato crop (i.e. row zone plus interrow zone). In this experiment non-wheeled interrows occupied one sixth of field area, wheeled interrows another sixth, and ridges two thirds of field area. When these data are recalculated per unit area of each zone, nitrous oxide emissions from non-wheeled interrows, wheeled interrows and ridges were in the ratio 1:8:0.17, respectively. Generally similar monitoring of emissions from potato production on a well-drained soil in New Zealand (Thomas et al., 2004) reported nitrous oxide emissions in the ratio 1:6:2.4, respectively.

Fertiliser was broadcast after ridging by Ruser et al. (1998), and their soil data demonstrate ridge nitrate levels similar or less than those of the interrows, particularly after rainfall. Fertiliser was broadcast prior to ridging by Thomas et al. (2004), and concentrated in the ridge by that operation, accounting for the greater nitrate levels and greater ridge emissions found in their work. Both studies concluded that nitrous oxide emissions were driven by high levels of water filled porosity, both identified tractor wheel compaction as a major factor, and both found quite similar ratios of emissions from non-wheeled and wheeled interrows. This is entirely consistent with the conclusions of Ball et al. (2008), and also suggests the importance of fertiliser placement.

Research into CTF impacts on greenhouse gas emissions is rare, but Vermeulen and Mosquera (2008) have compared nitrous oxide and methane emissions from random traffic and "seasonal" precision (SCTF) systems of organic vegetable production in the Netherlands over a two-year period. In this situation mean nitrous oxide emissions in random traffic were 2.25 kg $N_2O–N\ ha^{-1}$, and SCTF reduced these by 20–50%. The methane balance also changed from one of small emissions to small, steady absorption, a result similar to that found by Ruser et al. (1998). Porosity of soil managed in SCTF was consistently greater than that of random traffic, and yields of most crops increased under SCTF.

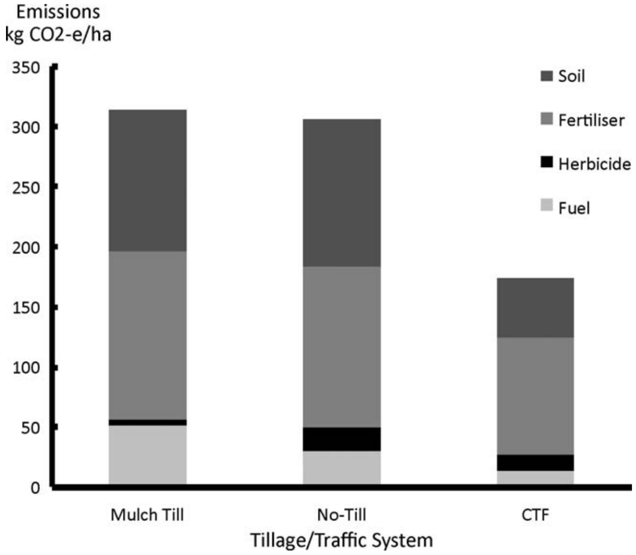


Fig. 3. Carbon dioxide equivalent emissions from conventional (mulch) tillage, simple no-till and precise no-till cropping systems.

The SCTF system used by Vermeulen and Mosquera (2007) entailed an annual overall plough tillage operation, so wheel compaction effects would still be present beneath ploughing depth. This compaction might be expected to increase the frequency and duration of periods of high levels of water filled porosity, and hence the nitrous oxide emissions measured in SCTF compared with permanent CTF. Where compaction and internal drainage is not an issue, nitrous oxide emissions are also likely to be smaller from non-tilled than tilled soil (Patiño-Zúñiga et al., 2009).

Nitrous oxide emissions measured in dryland grain production in Australia have generally been associated with the same factors of wet, anaerobic soil conditions, but emission levels have generally been less than 0.5 kg N_2O–N ha^{-1} (Officer et al., 2008), smaller than those found in the northern hemisphere, reflecting the drier climate, smaller yields and reduced fertiliser use in this environment. Default values for mulch tillage and CTF in Table 6 are based on Vermeulen and Mosquera (2008) values for random and SCTF, and no-till emissions have been assumed to be 10% greater than those from mulch till. All emission values have been reduced to account for the smaller emissions measured in Australia, using a factor of 0.5/2.25 = 0.222.

To infer CTF impacts on emissions from Australian grain production on this basis is obviously speculative, but there is no alternative at present. The assumptions used here appear quite conservative in terms of the literature-derived relationships between tillage, compaction, porosity and emissions.

The overall impact of different cropping systems on greenhouse gas emissions from all sources under these dryland conditions is summarised in Figure 3. While the magnitude of tillage and traffic impacts will vary in different systems, the general trend to reduce emissions by reducing tillage and traffic impacts is unlikely to change. No-till systems in random traffic will reduce emissions from fuel energy inputs, but increased emissions from herbicide inputs will limit the overall benefit. Compared with no-till alone, controlled traffic no-till (CTF) will further reduce energy requirements for fuel, herbicides and fertilisers. It will also substantially reduce soil emissions.

3. Discussion

A recommendation that we should deliberately drive 50–200 kN axle-load vehicles over the soil before seeding would be laughable—but it is a close approximation of current practice in much of the developed world. System productivity might be acceptable, but the evidence suggests that productivity would improve and costs decline if this random wheeling could be avoided. Sustainability would certainly be better.

In the early days of mechanisation, variable overlap by tillage machines of different width ensured that field traffic patterns were essentially random. Wheel impacts are not always obvious with small machinery, but as equipment power and weight increased, soil compaction problems became more common. The controlled traffic solution was sometimes suggested, but usually dismissed as impractical because of two major problems: the difficulty of precise field guidance, and the incompatibility of wheel track, tyre and working widths of different machines.

These problems are obsolete in no-till cropping. The cost of 2 cm precision autosteer is now <20% of the cost of a new medium tractor, and CTF-compatible tractors, seeders, harvesters and sprayers can now be purchased from major manufacturers (with only minor farmer modification required). Compatible systems usually use a 3 m track width (ie transverse distance between traffic lane centrelines) and tyres of 0.5 m section width for the tractor, harvester and all heavy loads. Machine working widths of 9 m (seeder and harvester) and 27 m (sprayer) are common (Tullberg et al., 2007). This system, with some variants, has been widely used in extensive grain production in Australia, with outstanding success in terms of costs, sustainability (reduced soil loss) and productivity (yield and cropping frequency) (Strahan and Hoffman, 2009).

As the cost of precision guidance continues to decline, width compatibility of machinery – particularly tractor and harvester track width – remains the major difficulty, particularly for farmers who have to move equipment along public roads. The farm machinery industry could make a major contribution to conservation agriculture systems by producing equipment that is compatible with permanent raised bed and controlled traffic systems. For most practical purposes this is a matter of track width adjustability, narrower tyre options and a range of working widths. Agreed sets of standard track, tyre and operating widths would be a major advantage. In the longer term, manufacturers could look towards cost reductions from modular-width equipment systems.

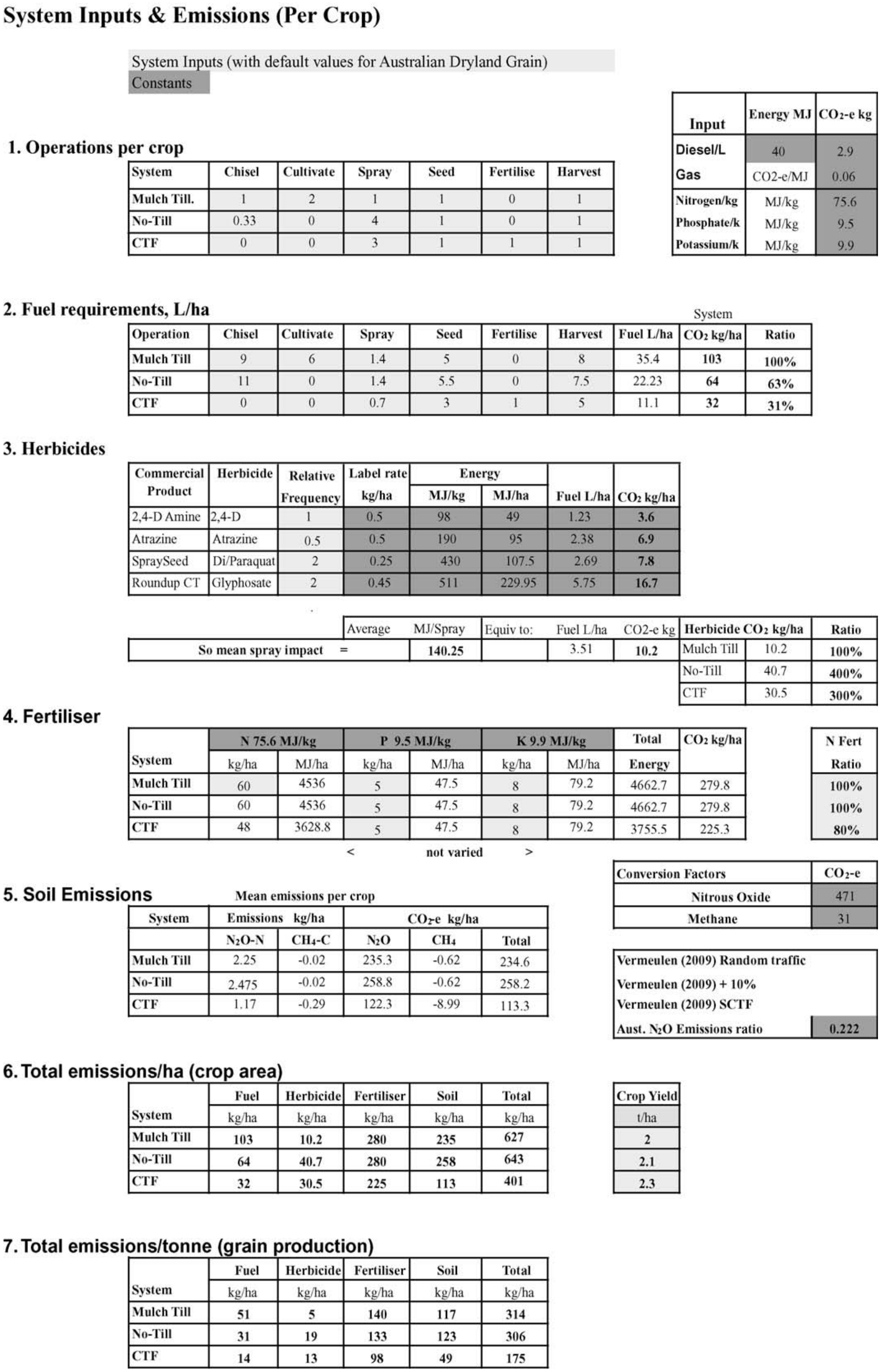
Much of the data presented here relates to highly mechanised cropping systems in sub-humid environments, but the principles and beneficial outcomes of CTF also apply in simple mechanisation systems. The productivity benefits of permanent raised bed conservation agriculture, and its large-scale application in low-resource areas using permanent raised beds has been described by Sayre et al. (2005). The same principles should be equally valid in more humid climates such as northern Europe if no-till conservation agriculture is to be used in systems where soils are often moist when seeding and harvesting with heavy equipment.

4. Conclusions

1. Conservation agriculture is widely regarded as a more sustainable cropping system, but productivity and all measures of sustainability (energy, soil and water conservation, greenhouse gas emissions) improve substantially when the principles of conservation agriculture are combined with controlled traffic.
2. Controlled traffic farming overcomes the surface rut and subsurface soil compaction problems farmers face as they move to no-till conservation agriculture, in both highly developed and low-resource mechanised cropping systems.
3. The major impediment to greater adoption of controlled traffic farming in minimum or no-till systems is the lack of compatibility in equipment track, tyre and working widths.

The lack of agreed width standards for CTF is a significant difficulty for the farm machinery industry, facing a situation where there is still not a large market for CTF-compatible equipment. Organisations such as ISTRO could have an extremely important role in joining with farmer-based Controlled Traffic Farming groups in Europe, Australia and elsewhere to draw attention to this issue and provide a forum for the development of advisory standards.

Appendix A. Cropping system inputs and emission spreadsheet



System Inputs & Emissions (Per Crop)

System Inputs (with default values for Australian Dryland Grain)

Constants

Input	Energy MJ	CO_2-e kg
Diesel/L	40	2.9
Gas	CO2-e/MJ	0.06
Nitrogen/kg	MJ/kg	75.6
Phosphate/k	MJ/kg	9.5
Potassium/k	MJ/kg	9.9

1. Operations per crop

System	Chisel	Cultivate	Spray	Seed	Fertilise	Harvest
Mulch Till.	1	2	1	1	0	1
No-Till	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	Fuel L/ha	System CO_2 kg/ha	Ratio
Mulch Till	9	6	1.4	5	0	8	35.4	103	100%
No-Till	11	0	1.4	5.5	0	7.5	22.23	64	63%
CTF	0	0	0.7	3	1	5	11.1	32	31%

3. Herbicides

Commercial Product	Herbicide	Relative Frequency	Label rate kg/ha	Energy MJ/kg	Energy MJ/ha	Fuel L/ha	CO_2 kg/ha
2,4-D Amine	2,4-D	1	0.5	98	49	1.23	3.6
Atrazine	Atrazine	0.5	0.5	190	95	2.38	6.9
SpraySeed	Di/Paraquat	2	0.25	430	107.5	2.69	7.8
Roundup CT	Glyphosate	2	0.45	511	229.95	5.75	16.7

	Average	MJ/Spray	Equiv to:	Fuel L/ha	CO2-e kg
So mean spray impact	=	140.25		3.51	10.2

Herbicide CO_2 kg/ha		Ratio
Mulch Till	10.2	100%
No-Till	40.7	400%
CTF	30.5	300%

4. Fertiliser

System	N 75.6 MJ/kg		P 9.5 MJ/kg		K 9.9 MJ/kg		Total	CO_2 kg/ha
	kg/ha	MJ/ha	kg/ha	MJ/ha	kg/ha	MJ/ha	Energy	
Mulch Till	60	4536	5	47.5	8	79.2	4662.7	279.8
No-Till	60	4536	5	47.5	8	79.2	4662.7	279.8
CTF	48	3628.8	5	47.5	8	79.2	3755.5	225.3

< not varied >

N Fert Ratio
100%
100%
80%

5. Soil Emissions

Mean emissions per crop

System	Emissions kg/ha		CO_2-e kg/ha		
	N_2O-N	CH_4-C	N_2O	CH_4	Total
Mulch Till	2.25	-0.02	235.3	-0.62	234.6
No-Till	2.475	-0.02	258.8	-0.62	258.2
CTF	1.17	-0.29	122.3	-8.99	113.3

Conversion Factors	CO_2-e
Nitrous Oxide	471
Methane	31

Vermeulen (2009) Random traffic	
Vermeulen (2009) + 10%	
Vermeulen (2009) SCTF	
Aust. N_2O Emissions ratio	0.222

6. Total emissions/ha (crop area)

System	Fuel	Herbicide	Fertiliser	Soil	Total
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Mulch Till	103	10.2	280	235	627
No-Till	64	40.7	280	258	643
CTF	32	30.5	225	113	401

Crop Yield
t/ha
2
2.1
2.3

7. Total emissions/tonne (grain production)

System	Fuel	Herbicide	Fertiliser	Soil	Total
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
Mulch Till	51	5	140	117	314
No-Till	31	19	133	123	306
CTF	14	13	98	49	175

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