This paper was peer-reviewed for scientific content.
Pages 821-826. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Potential of Conservation Tillage to Reduce Carbon Dioxide Emission in Australian Soils

H.B. So; R.C. Dalal; K.Y. Chan; N.M. Menzies and D.M. Freebairn*

ABSTRACT

Organic matter content is one of the major determinants of soil quality, and degradation of soil organic matter is well recognized as an adverse effect of cultivation. However, the consequent release of CO_2 and resultant contribution to the global greenhouse gas problem has received less attention. In the context of the need to reduce CO_2 emission, to reduce the global greenhouse gas problem, and to maintain soil quality to sustain food production, the role and relevance of current soil cultivation practices and their impact on soil organic matter need re-examination.

Approximately 47 Mha of land is cultivated in Australia each year. On the basis of the limited data available, it is conservatively estimated that a single cultivation of this area will release 9.4 Mt of CO_2 into the atmosphere. In many situations, adoption of conservation tillage, or farming systems, can reduce CO_2 emission from the soil and effectively retain C in the soil. The current use of conservation tillage on approximately 50% of Australia's cultivated land is estimated to reduce CO_2 emission by 4.3 Mt y^{-1}, relative to the release that would occur under conventional tillage. Adoption of conservation tillage on each additional 5% of cultivated land a year would provide an additional reduction of 0.43 Mt

INTRODUCTION

In traditional agriculture, the aims of tillage can be summarized as to (1) create a suitable seedbed, (2) kill weeds, reducing competition and conserving water and (3) remove restrictions to infiltration, drainage and root growth within the root zone. Tillage loosens the soil, increasing the exposure of soil organic matter and hence speeding oxidization. This results in a reduced soil organic matter content with a consequent release of CO_2 into the atmosphere (Chan et al, 1998; Dalal and So, 1998). The associated decline in soil quality is a major concern, not only in the context of maintaining food production, but also with regard to the quality of the environment as part of the global greenhouse gas problem. The magnitude of CO_2 emission resulting from tillage operation, and the opportunities for managing soils to maintain soil productivity but minimize greenhouse gas emissions are not adequately understood.

The Australian Greenhouse Gas Problem

The 1995 National Greenhouse Gas Inventory reported that the net annual emission of greenhouse gases in Australia was 402.4 million tonnes of CO_2 equivalent, of which Agricultural activities contributed 18 % and Land Use Change and Forestry 12 % (Fig. 1) (NGGIC, 1997). The reported agricultural activities emitted mostly CH_4 and N_2O, primarily from livestock (12%), flooded rice cultivation (0.1%), application of fertilizers (1.9%) and burning of savannahs and agricultural waste (2%). Emissions reported under Land Use Change and Forestry are primarily CO_2 from activities such as forest clearance and grassland conversions (17.9%), while CO_2 sinks are associated with growth of trees in managed forest, regrowth after land clearing and pasture improvements (-4.3%). Although the methodology for estimation conforms to the IPCC guidelines, there is a high degree of uncertainty associated with emissions from agricultural activities and very high degree of uncertainty for Land Use Changes and Forestry. This uncertainty reflects the scarcity of data available and the constraints in the methodology used. Emissions from tillage operations were not included in the 1995 Inventory, and the figures should be viewed as current best estimates.

Estimated CO_2 emissions steadily increased from 1988 to 1995 (excluding Forest and Grassland clearing) (Fig. 2) and the projected growth in emissions by the year 2010, under a 'business as usual' scenario, will be 28 % over the 1990 emissions. Constraining the increase in emissions to 8 % above the 1990 levels by the year 2010, as agreed under the Kyoto protocol, is going to require serious changes in management (Jackson, 1998) as this is an equivalent reduction of ~20 % over the current rate of emission growth, or an equivalent annual reduction of ~ 80 Mt of CO_2. We ask "Can Australia's 47 million ha of cultivated land be managed to make a significant contribution to the reduction in CO_2 emission? Can a change from conventional cultivation to conservation tillage contribute to this reduction?" In its National Greenhouse Response Strategy (Commonwealth of Australia, 1992), the Australian government is seeking to encourage agricultural practices that reduce greenhouse gas emission and conserve or enhanced greenhouse gas sinks. Recommended actions include reduced soil disturbance and soil erosion through improved soil tillage, thus maintaining the effectiveness of the soil as a sink for greenhouse gases.

*H.B. So and N.W. Menzies, School of Land and Food Sciences, The University of Queensland, St Lucia, Q 4072, Australia; R.C. Dalal, Queensland Department of Natural Resources, Indooroopilly, Q 4068, Australia; K.Y. Chan, Wagga Wagga Agric Institute, NSW Agriculture, Wagga Wagga, NSW 2650, Australia; D.M. Freebairn, Queensland Department of Natural Resources, Toowoomba, Q 4350, Australia. *Corresponding Author: h.so@mailbox.uq.edu.au

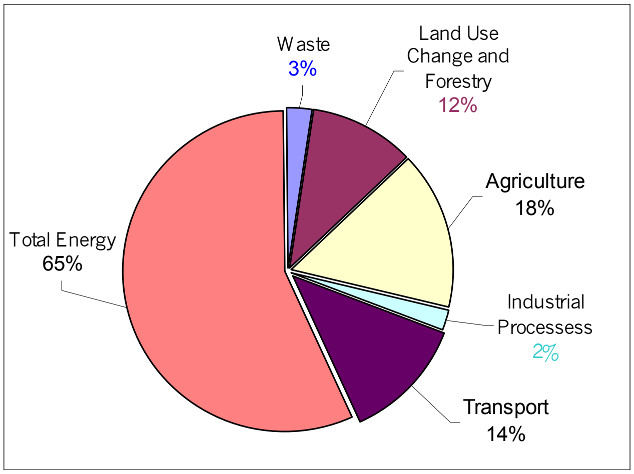

Figure 1. Contribution to total CO_2- equivalent emissions by sector 1995 (NGGIC, 1997).

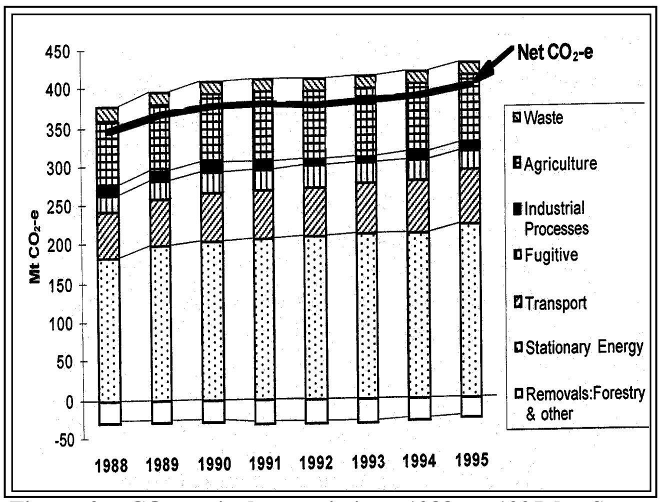

Figure 2. CO_2-equivalent emissions 1988 to 1995 by Sector, excluding Forest and Grassland Clearance (NGGIC, 1997).

In formulating its response strategy, the government has emphasized so-called 'no regrets' actions, those, which provide industry net benefits in addition to addressing the greenhouse gas effect, or at least those that have no net cost (Commonwealth of Australia, 1992). It seems logical that a similar no-regrets policy will also be essential to convince farmers to adopt new practices, and the linking of emission reduction through conservation tillage with improvement of soil quality will be essential. Using the model SOCRATES, the potential of changes in tillage practices towards reducing CO_2 emissions has been estimated at 5.94 million tons of CO_2 per annum from an estimated existing 9 million ha of wheat under conservation tillage, and 1.3 Mt y^{-1} from an estimated 2 Mha of new fields expected to be brought under conservation tillage (Carter et al., 1997, Grace et al, 1997; Jackson, 1998). Reductions of this magnitude would have a significant effect on Australia's greenhouse gas emissions (Greenfield, 1998). This paper will review the current information available and provide an independent estimate of potential reduction of CO_2 emission from conservation tillage in Australia based on consideration of known soil processes.

Tillage in Australia

The objectives of tillage necessitate the use of multiple cultivations, the frequencies of this cultivation being dictated by the prevailing climatic conditions and experience of the farmers. Although the traditional tillage practices in Australia were originally imported from European agriculture, they have evolved into a range of locally adapted practices (Pratley and Rowell, 1987). The number of cultivations adopted has been greatly reduced from its European origins, and today, conventional cultivation under dryland farming typically consist of 1 to 2 primary cultivation (75-150 mm deep depending on the perceived need) followed by 2 to 4 light cultivation (50 to 100 mm deep) and sowing (Poole, 1987). This reduction in the frequency of cultivation represents an adaptation to, and recognition of, the fragile nature of Australian soils and the value of stored water in an arid environment.

The necessity to conserve and accumulate adequate amounts of water in the root zone resulted in the introduction of clean fallow periods prior to cropping. The requirement to cultivate and kill weeds during the fallow periods has resulted in widespread degradation from erosion, particularly in the summer dominant rainfall areas with the intense summer storms (Freebairn and Wockner, 1986; Holland et al, 1987). In many areas adoption of minimum and no-till systems has been driven by the need to maintain stubble as surface protection. However, the adoption rates remained low for a long time due to the unknown impact on farm profitability (Ward et al, 1987).

In more recent times, there is increasing awareness that the soil is not only an important component of our production system, but that it plays an important role in the maintenance of local, regional and global environmental quality. At the farm level, conservation tillage as an integral component of conservation farming has become increasingly accepted, and it is estimated that some form of this system is practiced on ~ 50 % of land across all states (Burgiss and Willshire, 1998). In Queensland, the 1996 data shows that stubble was incorporated on ~ 53% of cropping land, stubble mulching employed on 20 % while 9 % was left with stubble intact (Australian Bureau of Statistics, 1996). Knowledge of the potential effect that tillage may have on the emission of CO_2 by the soil, and hence the quality of the global environment, may increase the push towards greater adoption of conservation tillage in Australian agriculture.

The Effect of Tillage on CO_2 Emission

Recent measurements showed that 221 g m^{-2} of CO_2 was released over a 4 day period following one summer tillage operation on a moist Sodosol (sandy loam soil), compared to 27 g m^{-2} from an untilled soil (Watling, 1998). Similar measurements on a Vertosol showed CO_2 release rates of 34.5 g m^{-2} after tillage and 20 g m^{-2} with no tillage (Thornton, 1998). These figures equate to equivalent losses over untilled soil of 928 kg ha^{-1} of soil organic matter in the Sodosol and 69.6 kg ha^{-1} in the Vertosol as a result of one cultivation of moist soil to approximately 100mm depth. These results indicate that the effect of tillage on soil organic matter degradation is potentially much greater in the sandy than in clayey soils. Reicosky (1998) reported cumulative CO_2 losses of 244 g m^{-2} from silty loams over 80 hours following fall moldboard plowing to a depth of 250 mm. In the spring the reduced release rates of 95 g m^{-2} was attributed to the colder soil temperatures. While soil organic matter losses associated with single tillage operations are high, it appears that when measurements are made over longer periods, the net loss over other potential organic matter additions may not be so great (Reicosky, 1998; Loch and Coughlan, 1984).

Since the 1980's, ~10 % of Australia's agricultural lands, or approximately 47 Mha, is cultivated each year (McLennan, 1998). Most of Australia's arable regions are dominated by coarse textured soils characteristic of the dryland environments (Carter et all, 1997), and have low organic matter contents. Hence, we adopt a conservative stance by assuming a low average CO_2 emission of 20 g m^{-2} (69.6 kg ha^{-1} soil organic matter loss) and that most cultivation are done on moist soil. On the basis of these figures, we estimate that a single tillage operation of Australia's arable land can potentially release 9.4 Mt of CO_2 into the atmosphere.

Losses from soil cultivation need to be balanced against organic matter additions, from residues, roots and litter, to arrive at a net loss or gain in soil organic matter over a cropping season. However, as difference in biomass production between conventional and reduced tillage is relatively small (Chan et all, 1998), the number of cultivation undertaken during a season will largely determine the rate of soil organic matter losses. Heenan et al (1995) reported net average annual rates of soil organic C losses of 50 to 400 kg ha^{-1} from a long-term rotation experiment in Wagga-Wagga, NSW (Figure 3). It is clear that the lower frequency and intensity of cultivation with direct drilling (no-till) reduced the rate of soil org C loss relative to conventional tillage. Organic matter additions are influenced by the crop rotation employed, with pasture/wheat providing the highest input, and a wheat/wheat rotation provides the lowest input, and hence results in the highest rate of org C loss. Dalal and So (1998) reported mean annual soil organic C losses ranging from 0.2 to1.4 t ha^{-1} y^{-1} in vertisols of Southern Queensland.

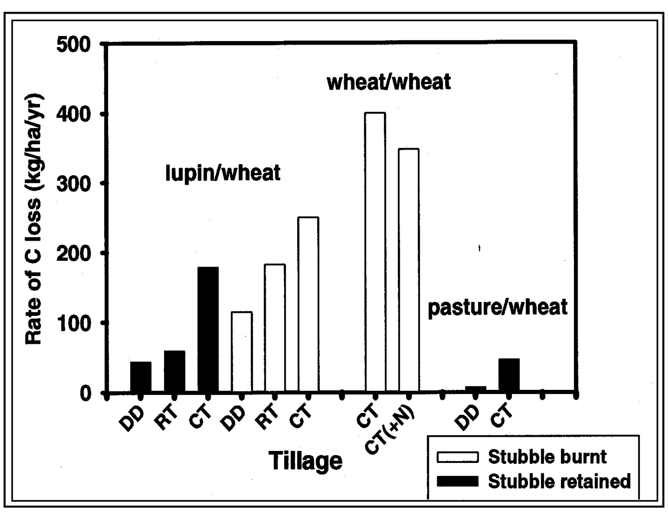

Figure 3. The rate of carbon loss under different tillage, stubble management and rotation in a long term rotation experiment in Wagga Wagga, NSW, Australia (Chan et. al 1998). DD= direct drill; RT = reduced tillage; CT = conventional tillage; CT (+N) = Conventional tillage with N fertilizer application.

The Potential of Conservation Tillage to Reduce CO_2 Emissions From Australian soils

In the Australian context, conservation tillage is increasingly and appropriately practiced as part of conservation farming, which may include crop rotations, particularly with legumes or pastures. The net gain or loss in soil organic C from the balance between organic matter inputs and losses through oxidation associated with tillage is dependent on the prevailing temperature and rainfall combinations. The ratio of C storage between conventional and conservation tillage systems is significantly correlated with annual rainfall (Chan et all, 1998). The ratio may remain constant at 1.00 in areas with less than 500 mm annual rainfall and in those cases the prospects of C sequestration through conservation tillage alone may be very limited. Approximately half of Australia's cropping lands (23.5 Mha) receive annual rainfall of less than 500 mm. Cropping under these climatic conditions tends to reduce the soil organic C contents irrespective of the tillage practices adopted (White, 1990); though conservation tillage may be of benefit by reducing the rate of degradation. Approximately half of these low rainfall areas are already under conservation tillage, and will continue to provide the benefit of a reduced rate of degradation of soil organic C. In contrast to the ineffectiveness of conservation tillage, the use of rotations with legumes or pastures can significantly increase soil organic C (Fettell and Gill, 1995) (Table 1). A legume/wheat rotation increased soil organic carbon from 0.96 % under continuous wheat to 1.46 % after 15 years, a mean annual increase of 0.033% or 330 kg ha^{-1}. Carbon sequestration under low rainfall conditions appears to be more assured if a combination of conservation tillage and legume pasture/crop rotations is practiced.

The annual rate of soil organic C increase, when conventional cultivation is replaced by direct drilling or no-till, ranges from 0.011 to 0.157 % or 110 to 1570 kg ha^{-1} (Table 1). It would be reasonable to assume a low value for the mean rate of increase in organic C of 50 kg ha^{-1} for all cropping soils in Australia (47 Mha), if conservation tillage or farming is adopted. This rate of increase will probably continue for a period of 20 to 25 years when an equilibrium maximum organic C content in the soil will be reached. Therefore, the potential annual increase in soil organic C can be approximated as 47 Mha x 0.05 t ha^{-1} organic C or 2.35 Mt org C, equivalent to a reduction in CO_2 emission of 8.61 Mt CO_2 $year^{-1}$. Currently, approximately half the cropping areas are already practicing some form of conservation tillage and these practices should be preserving carbon at a rate equivalent to a CO_2 reduction of 4.3 Mt annually. If new

Table 1: The rate of Soil Organic Carbon increase when conventional cultivation is changed to direct drilling or no-till practices.

Source (author & year)	Location Rainfall, Soil Type & Percent Clay	Duration (years) & Crop Rotation	Treatments	Soil organic carbon (% at 0-10cm)	Rate of SOC increase[c] ($\% \, yr^{-1}$)
Chan et al., 1992	Wagga Wagga, NSW	10, wheat-lupin	Stubble burnt		
	550 mm		CT(3 cult)	1.68	
	Red Earth (Chromic luvisol) 27 %		RT(1 cult)	1.74	0.055
	clay		DD(0 cult)	2.23	
			Stubble retained		
			CT(3 cult)	2.06	
			RT(1 cult)	2.06	0.036
			DD(0 cult)	2.42	
Packer & Hamilton, 1993	Cowra, NSW	7	TT (1-3 cult)	0.57	
	564 mm, Red duplex (Xeralfic		RT (1 cult)	0.83	0.041
	alfisol) 8 % clay		DD (0 cult)	0.86	
Packer et al., 1984	Ginnendera, ACT	6, wheat-pasture	CT (>3cult)	1.7	
	664 mm		RT (2 cult)	2.0	0.133
	Red Podzolic		DD (0 cult)	2.5	
	Wagga Wagga, NSW	6, wheat	CT (>3cult)	1.9	
	550 mm		RT (2 cult)	2.1	0.05
	Red Brown Earth		DD (0 cult)	2.2	
Thialingam et al., 1996	Katherine, NT	8, sorghum	CT	0.63[a]	0.0525
	996 mm		NT	1.05[a]	
	Red Earth, < 30 % clay				
	Pinnarendi, N Qld	4, mixed	CT	0.84	0.102
	Red Earth (Typic Eutrostox) 13-24	rotation	NT	1.25	
	% clay				
Fettell & Gill, 1995	Condobolin, NSW	14, wheat	Stubble burnt[b]	0.95	
	430 mm		Stubble retain[b]	0.97	
	Red Brown Earth		legume/crop rot	1.46	
			verano pasture	1.8	
			natural woodland	2.38	
White, 1990	Avondale, WA[a]	3	CT	1.37	
	389 mm, Brown Earth		DD	1.62	0.083
	(Xeralfic alfisol)	6	CT	1.35	
			DD	1.55	0.033
		9	CT	1.30	
			DD	1.40	0.011
	Wongan Hills, WA	3	CT	0.84	
	345 mm, Yellow Earthy Sand		DD	0.84	0
		6	CT	0.70	
			DD	0.80	0.016
		9	CT	0.51	
			DD	0.62	0.012
	Merridin, WA	3	CT	0.94	
	307 mm, Red Brown Earth		DD	1.02	0.026
		6	CT	0.92	
			DD	1.03	0.018
		9	CT	0.85	
			DD	0.92	0.007
Grabski et al., 1997	Grafton, NSW	14	CT	1.8	
	1057 mm, Brown Earth (Kurasol ultisol)	wheat - soybean	NT	4.0	0.157
Cavanagh et al., 1991	Forbes, NSW	3	DD	1.52	
	527 mm		CC	1.02	0.166
	Red Brown Earth				
Loch & Coughlan, 1984	Warwick, Qld	-	Stubble burnt[b]	1.6	0.0
	527 mm, Vertisol		Stubble retain[b]	1.7	
	(Ustic Pellustert)				

[a]% org C in 0-5 cm
[b]Average of CT, RT and DD where no differences were measured
[c]Calculated as (DD-CT/duration)

adoption of conservation farming of 5% can be achieved annually, additional CO_2 reduction of 0.43 Mt y^{-1} can be obtained in the first year rising to 4.3 Mt y^{-1} within 10 years. Additionally, fossil fuel consumption in cropping can be reduced through reduced tillage and controlled traffic systems (Tullberg and Wylie, 1994; Freebairn et al, 1998).

The figure for mean annual increase of soil organic C used in this calculation is low compared to data shown in Table 1 and the estimation of 180 kg ha^{-1} arrived at by Carter et all (1997). The real potential for CO_2 reduction from conservation tillage will depend on a number of factors such as soil types, cropping systems, current status of soil carbon pool, areas under cultivation (conventional vs. conservation tillage) and the actual rate of CO_2 emission as affected by temperature and water content. As climate varies greatly across Australia's agricultural areas, these estimates need to be validated against actual measured data.

CONCLUSION

In conclusion, we have shown that the potential reduction for CO_2 emission from the adoption of conservation tillage under Australian conditions can be substantial. Further investigations should be undertaken to validate these estimates. The estimates in this paper have a high degree of uncertainty associated with the scarcity of relevant data available that can be used for this exercise.

REFERENCES:

Australian Bureau of Statistics (1996) Agriculture Queensland 1995-1996. ABS Catalog no 7133.3.

Burgis, M. and B. Willshire. 1998. Adoption of conservation tillage in Australia. Paper presented to the Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?', The University of Queensland, April 1998, p

Carter, J.B., J.W. Lowe, C. Jubb, P. Grace, M. Freer, G. Farquhar, J. Zeitsch and J. Woodhill.(1997. Greenhouse gas implications of sustainable land management practices. Report prepared for the National Landcare program, Commonwealth Dept Primary Industries and Energy.

Cavanagh, P.P, A.J. Koppi and A.B. McBratney. 1991. The effects of minimum cultivation after three years on some physical and chemical properties of a Red Brown Earth at Forbes, NSW. Aust. J. Soil Res. 29: 263 - 270.

Chan, Y.K., D.P. Heenan, A.S. Grabski and H.B. So. 1998. Soil organic carbon sequestration and changes in soil quality under conservation tillage on lighter-textured soils in Australia. Paper presented to the Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?', The University of Queensland, April 1998.

Chan, Y.K., Roberts, W.P. and Heenan, D.P. (1992). Organic carbon and associated soil properties of a Red Earth after 10 years of rotation under different stubble and tillage practices. Aust. J. Soil Res. 30: 71 - 83.

Commonwealth of Australia (1992). National Greenhouse Response Strategy. Australian Government Publishing service, Canberra.

Dalal, R. and H.B. So. 1998. Soil Quality and the Effect of Continuous Cultivation. Paper presented to the Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?', The University of Queensland, April 1998.

Fettell, N.A. and H.S. Gill. 1995. Long term effects of tillage, stubble, and nitrogen management on properties of a Red Brown Earth. Aust J Exp. Agric. 35: 923 - 928.

Freebairn, D.M. and G.H. Wockner. 1986. A study of soil erosion on Vertisols of the Eastern Darling Downs, Queensland. I. The effect of surface conditions on soil movement within contour bay catchments. Aust. J. Soil Res. 24: 135 - 158.

Grace, P.R., W.M. Post, D.C. Godwin, K.P. Bryceson, M.A. Truscott and K.J. Hennessey. 1997. Soil carbon dynamics in relation to soil surface management and cropping systems in Australian agoecosystems. In Lal, R.; Kimble, J.M.; Follett, R.F. and Stewart, B.A. (Eds). Management of Carbon Sequestration in Soil, pp 175 - 193.

Greenfield, P. 1998. The National Greenhouse Response Strategy. Paper presented to the Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?', The University of Queensland, April 1998.

Heenan, D.P., W.J. McGhie, F.M. Thompson. and K.Y. Chan. 1995. Decline in soil organic carbon and total nitrogen in relation to tillage, stubble management and rotation. Australian Journal of Experimental Agriculture 35, 877-84.

Holland, J.F.; A.D. Doyle and J.M. Marley.(1987. Tillage Practices for Crop Production in Summer Rainfall Areas. In. Cornish, P.C. and Pratley, J.E. (Eds.) Tillage: New directions in Australian Agriculture. Australian Society of Agronomy monograph. Inkata Press, pp. 48-71.

Jackson, M. 1998. The Greenhouse Challenge for Australia. Paper presented to the Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?', The University of Queensland, April 1998.

Loch, R.J. and K.J. Coughlan. 1984. Effects of zero tillage and stubble retention on some properties of a cracking clay. Aust. J. Soil res. 22: 91 - 98.

McLennan, W. 1998 1998 Year Book Australia Number 80. Australian Bureau of Statistics, Canberra.

National Greenhouse Gas Inventory Committee. 1997. National greenhouse Gas Inventory 1995 with methodology supplement. Environment Australia, Canberra.

Packer, I.J. and G.J. Hamilton. 1993. Soil physical and chemical changes due to tillage and their implications for erosion and productivity. Soil and Tillage Research 27: 327 - 339.

Packer, I.J., G.J. Hamilton and I. White. 1984. Tillage practices to conserve soil and improve soil conditions. NSW Journal of Soil Conservation 40: 78 - 87.

Poole, M.L. 1987. Tillage Practices for Crop Production in Winter Rainfall Areas. In. Cornish, P.C. and Pratley, J.E. (Eds.) Tillage: New directions in Australian Agriculture. Australian Society of Agronomy monographs. Inkata Press, pp 24-47.

Pratley, J.E. and D.L. Rowell. 1987.. From the first fleet – Evolution of Australian farming systems. In. Cornish, P.C. and Pratley, J.E. (Eds) Tillage: New directions in Australian Agriculture. Australian Society of Agronomy monographs. Inkata Press, pp 2-23.

Reicosky, D.C. 1998. Effect of Tillage on the release of CO_2. Paper presented to the Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?', The University of Queensland, April 1998.

Reicosky, D.C., W.A. Dugas and H.A. Torbert. 1997. Tillage induced soil carbon dioxide losses from different cropping systems. Soil and Tillage Research 41: 105 - 118.

Thialingam, K., N.P. Dagleish, N.S. Gould, R.L. McGowan, A.L. Cogle and A.L. Chapman. 1996. Comparison of no-tillage and conventional tillage in the development of sustainable farming systems in the semi-arid tropics. Aust. J. Exp. Agric. 36: 995 - 1002.

Thornton, C. 1998. Carbon dioxide release from a tilled Vertosol under Australian conditions. 4th Year project report, The University of Queensland.

Tullberg, J.N. and P. Wylie. 1994. Energy in Agriculture. Saving energy for more profit, reduce greenhouse gases and farm fuels for the future. Conservation Farming Information Center, Dalby.

Ward, L.D., J.P. Brennan and I.C. Crook. 1987 Effects of tillage systems on farm management and profitability. In. Cornish, P.C. and Pratley, J.E. (Eds) Tillage: New directions in Australian Agriculture. Australian Society of Agronomy monographs. Inkata Press, pp 380-399.

Watling, K. 1998. Measurements of CO2 release from a Sodosol following tillage under Australian conditions. 4th Year project report, The University of Queensland.

White, P.F. 1990. The influence of alternative tillage systems on the distribution of nutrients and organic carbon in some common Western Australian Wheatbelt soils. Austr. J. Soil Res. 28: 95 - 116.