Land management practices – why they are important and how we know this

Michele Barson and Rob Lesslie,
Bureau of Rural Sciences

Introduction

The purpose of this paper is to provide a brief overview of the role land management practices have in contributing to improving farmers' resource base and their productivity, and to natural resources management outcomes at the catchment scale. The focus in this paper is on some of the biophysical practices associated with cropping industries.

The changes in land cover brought about by clearing of native vegetation to establish much of Australia's agriculture have led to an acceleration of sediment and water transport processes and significant changes in landscape function, particularly in relation to catchment hydrology, hydrogeology and sediment movement. The land uses established following clearing continue to affect the quantity, quality and distribution of water and soil resources. Observation, experimental work and simulation modelling has demonstrated that the choice of land management practices (for example tillage methods, rotations used), can have a significant impact on the status of the farm resource base and farm productivity. The on farm practices chosen can also have off site impacts through significant redistribution of water, sediment and nutrients. The timing, quantities, or forms of these material transfers can result in adverse impacts such as increases in sediments, nutrients and salts in rivers, and subsequent declines in water quality and the aquatic habitat.

The move towards developing targets for catchment health, in addition to the continuing search for more sustainable and profitable farming systems, will focus on the role that modifications in land cover, land use and land management practices can play in delivering improved natural resource management outcomes at farm and catchment scales. Land management practices are of particular interest, especially where their modification can provide benefits on and off farm with minimum disruption to agriculture.

On farm impacts of tillage/residue management/fallow practices

Within the cropping industries, tillage practices, including crop residue management and length of fallow, have had a demonstrable impact on soil structure, soil organic matter and nutrients, soil erosion potential, local and catchment water balance and water quality, although responses can be variable and complex. Until the mid 1970s it was common practice to remove crop residue by inversion tillage using disc ploughs (with or without stubble burning) as part of fallow management to improve soil infiltration and aeration, raise soil water and nutrient levels, control weeds, disease and prepare the seedbed prior to sowing. In summer rainfall areas, stubble would be burnt or cultivated immediately after harvest, while in winter rainfall areas stubble would be burnt or cultivated in the autumn, after being grazed through the summer (Freebairn 1992).

1. Soil structure

Soil structure refers to the arrangement of sand, silt, clay and organic matter components and the size and shape of the pores between them. This affects water infiltration and storage capacity, soil aeration, temperature and physical stability (Geeves et al 1996). Depending on native soil characteristics and soil moisture conditions, tillage practice (along with the clearing of deep rooted perennials for cultivation, crop residue burning, and inappropriate grazing management) can lead to decline in the physical structure of susceptible soils (Moran 1998; Freebairn 1992).

Surface crusting, involving the loss of aggregation and porosity in the top few centimetres of soil, can occur when bare soil surfaces are exposed to rainfall following cultivation (Valentin and Bresson 1992). Hardsetting is a compact, hard and massive soil condition affecting the A horizon (McDonald et al 1984; Chartres 1992). Cultivation can exacerbate this condition by preventing the build up of organic matter and destroying any structure that does develop. Compaction of soil below the cultivated layer from the physical pressure exerted by farm machinery can result in a decrease in porosity and hydraulic conductivity (Gupta et al 1989).

Soil structure decline generally reduces water infiltration leading to increased runoff and potentially reduced soil moisture levels and lower water tables (Silburn and Connolly 1995). It also promotes the concentration of nutrients in fine surface materials prone to wind and water erosion (Moran 1998) and limits root growth and yield (McGarry 1989; Hamblin and Tennant 1979).

2. Soil organic matter

Soil organic matter comprises living and decayed plant and animal material and charcoal that become mixed with the mineral components of the soil. Soil organic matter is important in maintaining soil structure, as a source of nutrients for plants and micro organisms and as a source or sink for atmospheric carbon.

Significant losses of organic matter in soils have been recorded in many parts of Australia as a result of cropping (Russell and Williams 1982; Dalal and Mayer 1986; Chan *et al* 1992) through both increased *in situ* losses and soil erosion. *In situ* decline in soil organic matter under agriculture is usually promoted initially by lower returns of organic matter to the soil, and is dependent on rates of biomass production, harvesting and residue management. However, tillage also promotes the rate of mineralisation of organic matter, increasing microbial activity by soil mixing and disturbance and exposing organic matter protected by the soil matrix to the biosphere (Grace *et al* 1994, 1997).

Experimental results examining the impact of tillage practices on soil carbon stores have not always shown that conservation tillage on its own will lead to increases in soil carbon. Fettell and Gill (1995) found under continuous wheat, conservation tillage (direct drilling and stubble retention) had little long-term effect (over 14-15 years) on soil organic carbon. Under continuous cropping over 10 years involving wheat/lupin rotation, organic carbon declined by 31 percent under stubble burnt/conventional tillage when compared to stubble retained/direct drilled (Chan *et al* 1992). Freebairn *et al* (1998) found that a pasture phase (ley) between crops adds organic matter to the soil. However, its effectiveness will vary with soil type, climate, ley composition and management. Gains in soil carbon in ley phases may well be lost in the following crop phase, but a higher overall level of carbon can be maintained with ley rotation.

Burning of agricultural plant residues (stubble burning) depletes inputs of organic matter into the soil. These practices are becoming less common (Figure 1). Where stubble burning is necessary (eg. heavy stubble accumulation, weed and disease build-up), loss of soil organic carbon can be reduced by delaying the burning operation until late summer/early autumn and by practising a light burn (Chan *et al* 1992).

Long fallows (> 6 months) have been declining in importance since about 1965 (Cornish and Pratley 1991). Much of the land once fallowed is now either left in pasture or cropped. Short fallows (1-6 months) are used between successive winter crops or after a period of pasture. Management of crop residue (stubble) is important to minimise the risk from wind and water erosion during the fallow. While fallowing may increase yield and residue production through increased water storage, the increased water availability promotes greater activity of the soil biota (Grace *et al* 1997). Thus increasing the frequency of fallow phases in the cropping sequence accelerates the depletion of organic carbon stocks (Russell and Williams 1982; Grace *et al* 1994).

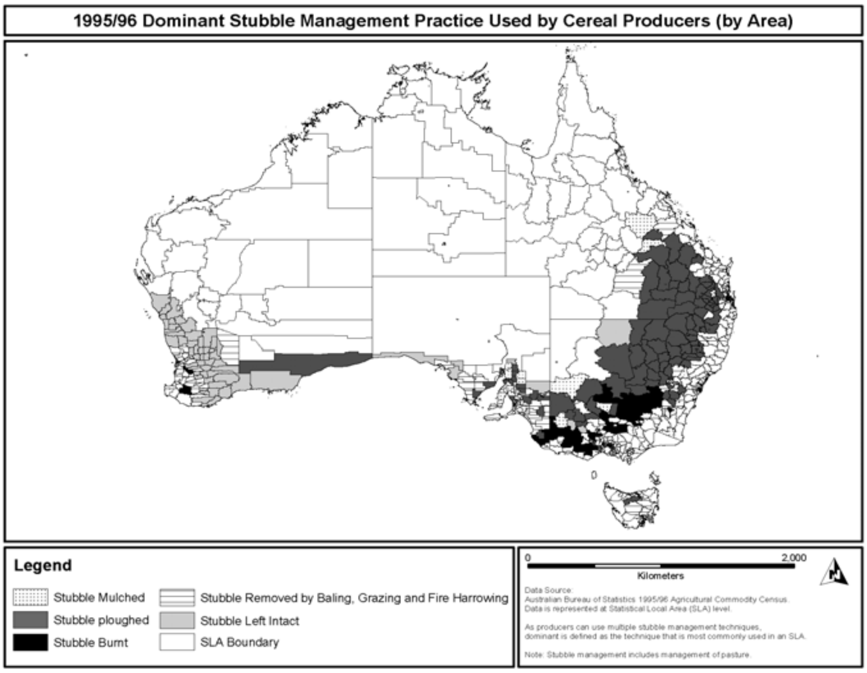
Experimental results demonstrating the impact of management practices on soil carbon have been variable because of the difficulty of controlling for the factors likely to affect the outcome. These include past management history, which is often not known, as well as rotation system, tillage method, residue management, crop species and fertiliser use, soil type, climate, incidence of weeds and disease. Simulation modelling, notably using the Rothamsted model (Jenkinson and Coleman 1994), which has been extensively calibrated for Australian conditions (Skjemstad and Spouncer 2003) has shown that reducing tillage can slow the rate of soil carbon depletion, and that practices such as incorporation of pasture phases can increase soil carbon storage in soils with low carbon contents resulting from long periods of cultivation (Skjemstad and Janik 1996).

3. Soil erosion

Soil erosion involves the detachment and transport of soil particles from the soil surface and their transport and deposition in the landscape, usually by wind and water. The extent to which these processes occur depends on soil cover, topography, the nature and condition of the soil, and the energy of the wind and water. The natural resources implications of accelerated soil erosion include soil loss, reduction in soil nutrient status (including organic matter), declines in soil structure and stream scouring and sedimentation, impacts on water quality (turbidity, nutrient and other chemical loads), soil moisture and groundwater.

Bare soil is susceptible to erosion due to its direct exposure to movement by wind and water and because there is no vegetation cover to reduce erosional forces (McLaughlin *et al* 1998). The forms of erosion principally associated with cropping include hillslope (sheet and rill) erosion, and gullying where cover is in inadequate on sloping terrain. It is generally accepted that cover is a key control over rates of soil loss, including the amount of crop residue remaining after tillage. The removal of cover and exposure of bare soil by tillage increases soil loss through an increase in runoff volume (promoted by aggregate breakdown, increased compaction and reduction in water transmissivity), increased detachment of the soil, and increased overland flow velocity (Freebairn 1992). In some cropping systems, increased soil strength associated with no-till is a major factor in reducing erosion, while cover is relatively less important. In wet tropical environments, for instance, where runoff is frequent and unavoidable, soil strength has been found to be the most important factor controlling erosion on steep canelands in north Queensland (Freebairn 1992).

(a)



(b)

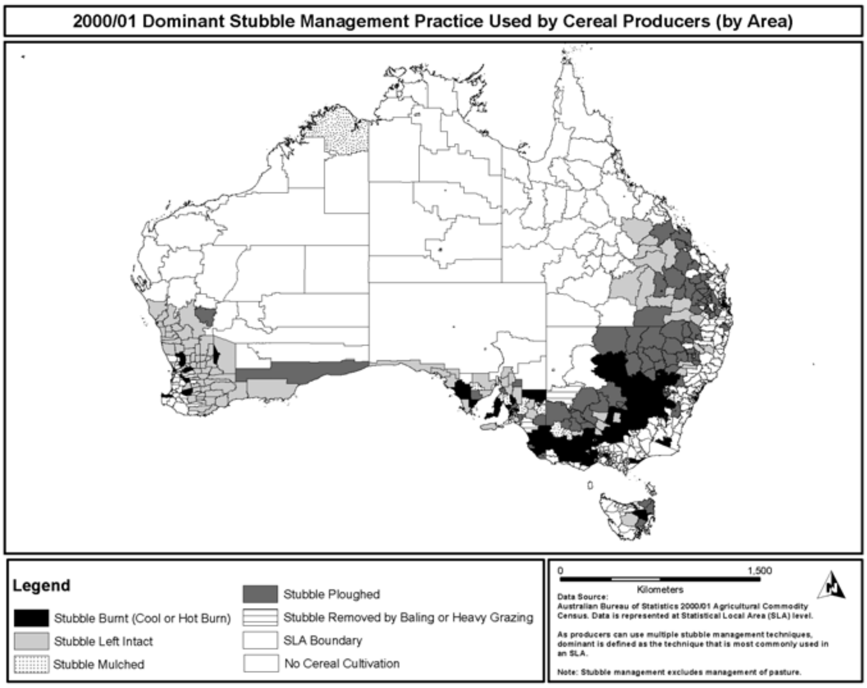


Figure 1: Dominant stubble management practices used by cereal producers (by area) in (a) 1995 and (b) 2000 (Australian Bureau of Statistics and Bureau of Rural Sciences).

The impact of tillage and cultivation practice on mean annual soil movement is illustrated in Figure 2 for five surface conditions during the summer fallow period in an experimental trial over 11 years conducted in the Darling Downs (Wockner and Freebairn 1991). Reduced soil movement is clearly evident under a zero-tillage regime.

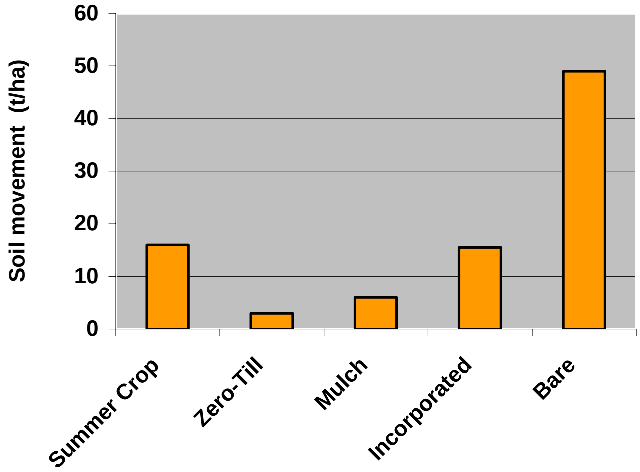


Figure 2 Impact of soil cover on soil movement (after Wockner and Freebairn 1991)
4. Water balance

Tillage is commonly used in fallowing strategies to reduce reliance on rainfall through the cropping season by building up soil water for the next crop. The efficiency of fallow is, however, influenced by the infiltration capacity of the surface soil and water holding capacity. As noted previously, tillage has been shown to be associated with decline in permeability and water holding capacity across a wide range of soil types (Wockner and Freebairn 1991; Connolly *et al* 1997). Key factors include the loss of surface cover, surface sealing and the compaction of sub-surface soil. Tillage of cracking soils can also reduce the effectiveness of water movement to lower soil layers (Freebairn 1992). There is corresponding evidence that conservation tillage generally results in improved infiltration and hydraulic conductivity (Packer and Hamilton 1993, Unger 1990, O'Leary 1996).

There are exceptions to these generalisations. For example, smooth soil surfaces associated with conservation tillage can result in higher runoff compared to tilled soil by creating surface roughness and breaking soil crusts where structural decline has occurred (Freebairn 1992; Moran 1998). Deep tillage has also been practised to improve sub-surface water storage and root growth, but results are variable (Radford *et al* 1992) with beneficial effects short lived on hard-setting soils (Mead and Chan 1988).

Research has led to a much better understanding of the impact of tillage and associated practices on the farm resource base. This understanding, coupled with farmer awareness of declines in their resource base, the advent of tillage and planting equipment suited to operation in stubble, developments in rotation and the increased availability of herbicides for pre- and post- sowing weed control is encouraging greater retention of crop residues and reduction in tillage. However, as Figures 1 and 3 demonstrate, the extent of adoption of these practices varies regionally.

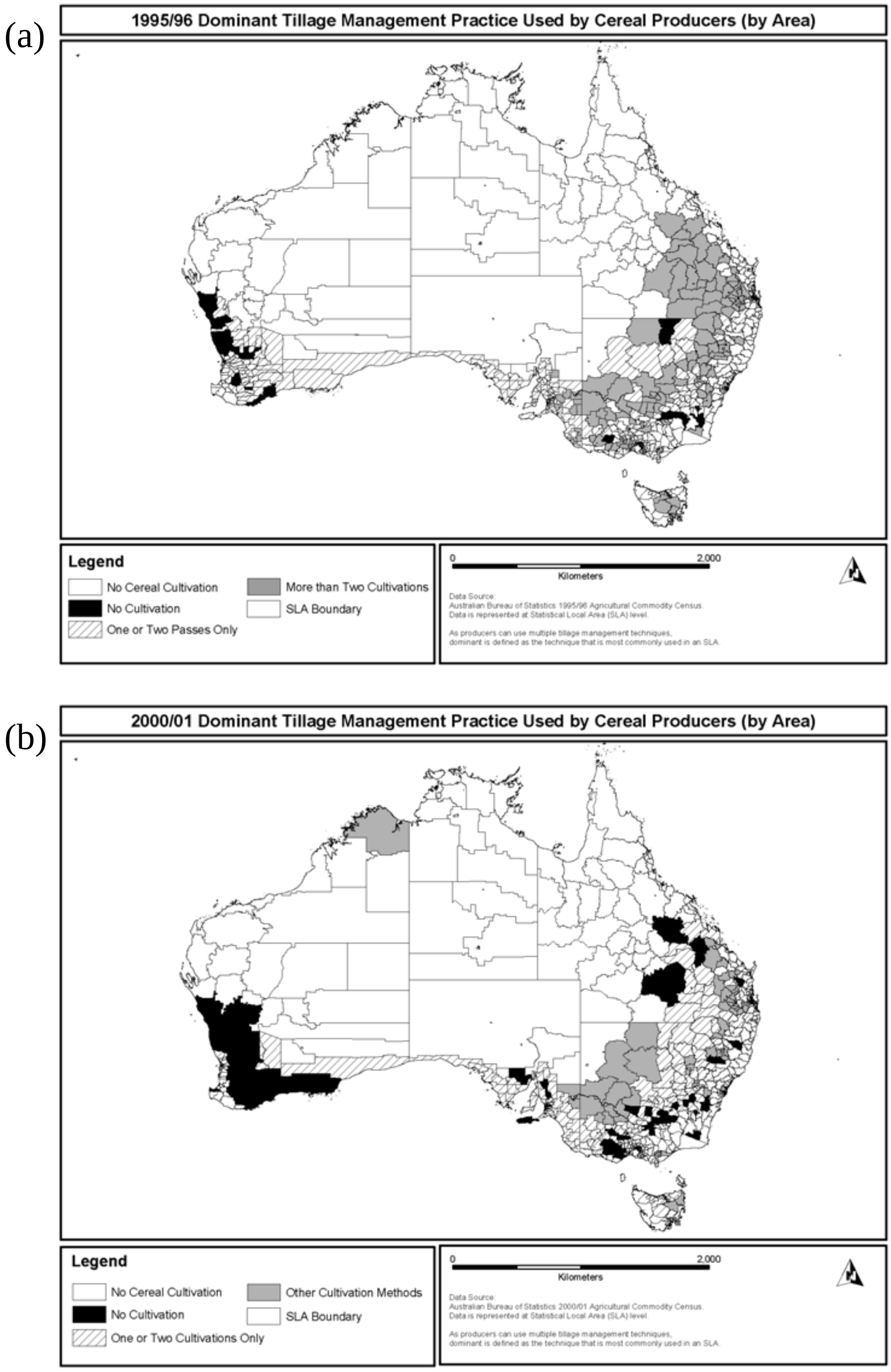


Figure 3: Dominant tillage practices used by cereal producers (by area) in (a) 1995 and (b) 2000 (Australian Bureau of Statistics and Bureau of Rural Sciences).

Impact of practices on yield and profit

Freebairn (1998) has noted that results from tillage experiments can be variable in direction and magnitude, most probably due to the effects of climate and its interactions with the soil-plant system. The inability to control or account for all the major factors affecting results, including climate and disease, also makes it difficult to demonstrate significant differences in profitability under more conservative tillage treatments. Additionally, it may take a number of years before the cumulative impacts of less conservative tillage practices and stubble burning demonstrably affect profitability.

However, using cropping system models, which explicitly consider many of the interactions between crop production, rotations, tillage management, fertiliser, water balance and soil erosion, it has been possible to demonstrate where improvements in returns can be achieved as a result of certain changes in cropping practices.

For example, in the higher rainfall part of the north western New South Wales grain growing region, changing cropping systems on vertosol soils from long fallow or winter cropping to flexible opportunity cropping with summer cropping is predicted to substantially reduce deep drainage as well as significantly improve profits from cropping (Ringrose-Voase *et al* 2003). Similarly, improvements in profitability and more effective water use with reduced erosion risk have been predicted for sites in sub tropical Queensland (Dimes and Freebairn 1993).

Impact of practices at catchment scale

Many river systems in Australian exhibit greater turbidity, increased sediment yield and nutrient loads, higher flood peaks and shorter flows (leading to damage to river banks, silting and scouring) following agricultural development in their catchments (Moss *et al* 1996). Increased soil erosion is strongly implicated these trends. However, it has been difficult to establish the role that tillage and other land management practices play without knowledge of the links between land management and catchment processes over a wide spatial scale. Agricultural land use and land management practice is only one of many factors that influences sediment and water transfer through catchments (Wasson 1998).

Catchment size is a key control. In smaller, unchannelled catchments there is evidence that catchment erosion (mainly sheet and rill) caused by cultivation practices such as tillage impacts on turbidity and downstream sediment delivery (Edwards 1987; Wasson 1994). However, relationships may be complex. The contribution of agricultural practices may, for instance, be secondary if gully erosion has developed - where this has occurred there is evidence that most eroded material in downstream sediments derives from subsoils (Olley *et al* 1993). Gullying is mainly controlled by topographic and soil characteristics and vegetation removal rather than cultivation (Wasson 1998).

The impact of agricultural practice on larger catchments has been particularly difficult to resolve because of the discontinuous nature of catchment transport systems, and the attenuation of sediment movement by storage. Evidence derived from plot studies and small catchments cannot be scaled up to larger catchments (eg > 1,000km^2) and sheet and rill erosion resulting from agricultural practice may not impact downstream water quality (Wasson 1998). Erosion resulting from cultivation may be an important influence on downstream water quality if nutrients and pesticides from topsoil are transported in solution or on fine sediment. However, if nutrients and pesticides are adsorbed into sediment, knowledge of particular conditions and locations of catchment deposition and desorption is of critical importance (Finlayson and Silburn 1996).

Recent developments in techniques for preparing spatially explicit sediment budgets for catchments (for example, Moran *et al* 2003, Prosser et al in preparation) provide methods for dealing with the high level of heterogeneity of landscape materials and their behaviour at catchment scales. This approach enables quantification of the separate contributions of sediment from hillslopes, gully and riverbank erosion, prediction of subcatchments that are the most significant sources of sediment export, and identification of sediment deposition sites. Spatially explicit sediment budgets are powerful tools for identifying where focussed erosion control will have the greatest benefits to catchments and the best return on the investment of funds.

Studies undertaken to date for the river basins covering the most intensively used third of the Australian continent (Moran *et al* 2003), the Murray-Darling Basin (Prosser et al in preparation), the Western Port Bay (Victoria) Basin (Hughes *et al* 2003), Goulburn and Broken (Victoria) catchments (DeRose *et al* 2003) and the Wingecarribee catchment (New South Wales) (Olley and Deere 2003) indicate that gully and riverbank erosion are the dominant erosion processes and sources of sediment delivered to streams in most areas. Exceptions occur in catchments in northern Queensland, much of the Fitzroy and Burnett catchments and northern parts of the Murray-Darling Basin, where hillslope erosion is dominant (Moran *et al* 2003). Elsewhere the contribution from hillslope (rill and sheet erosion) is generally modest. The pattern of gully and riverbank erosion for southern Australia is supported by radionuclide analysis of sediment sources for several regions (Prosser *et al* 2001). However, it should be noted that the finer particles derived from sheet erosion might make a disproportionately large contribution to turbidity and nutrient transfer (Ian Prosser, *pers.comm.).*

The implications of these findings for the role of agricultural land management practices in improving catchment condition and protecting downstream ecosystems from sediment deposition are yet to be examined in detail. It is likely for southern Australia, in relation to sediment and nutrient targets, that reducing gully and/or riverbank erosion rather than focussing on practices associated with hillslope erosion minimisation, may have the biggest impact. Land management practices which could contribute to meeting these targets include controlling stock access to waterways, protecting existing riparian vegetation and replanting previously cleared streamlines, as well as maintaining good cover in areas prone to gullying. In addition to encouraging on farm action, erosion control activities need to be planned across major catchments to focus public expenditure on the areas generating the most sediment, ie “hot spots”, to ensure the best returns on public investment.

Similarly the development of spatially explicit salt, water and nutrient budgets for catchments will help decide which management practices will be most effective in reducing their export to streams and rivers. The availability of this information will ensure that end of valley targets established to improve catchment condition are realistic.

Conclusions

- land management practices for cropping, including tillage, residue management and length of fallow, have been shown experimentally to affect soil structure, soil organic matter and rates of soil erosion on farm, although experimental results can be variable
- this variability has been attributed to the inability to control for all the major factors interacting with the soil-plant system
- for practices such as tillage and residue management it has been difficult to demonstrate improved profitability because a range of factors affect the outcome, and perhaps because the cumulative effects of more exploitative practices may take a number of years to demonstrably affect farm profit
- simulation modelling approaches which explicitly consider these interactions can be used to examine the relationships between land management practices and natural resources management outcomes. To date the focus of such work has been on the impact of cropping practices on the water balance
- at the catchment scale, choice of on farm land management practices which can most effectively contribute to catchment or end of valley targets, will need to be carefully considered in the context of an understanding of the storage and movement of nutrients, sediment, salt and water in the catchment.
- public investment in activities aimed at erosion control will need to focus on the larger sources of sediment to ensure best returns on investment.

References

Chan, K.Y., 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. *Australian Journal of Soil Research*, 30 pp71-83.

Chartres, C.J. 1992. Soil crusting in Australia. In Sumner, M.E. and Stewart, B.A*. Soil Crusting: Chemical and Physical processes* pp 339-65 Advances in Soil Science, Lewis Publishers, Boca Raton, Florida.

Connolly, R.D., Freebairn, D.M. and Bridge, B.J. 1997. Change in infiltration characteristics associated with cultivation history of soils in south-eastern Queensland. *Australian Journal of Soil Research*, 25, pp1341-58.

Cornish, P. and Pratley, J. E 1987. *Tillage: new directions in Australian agriculture*. Inkata Press: Sydney.

Dalal, R.C. and Mayer, R.J. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. 1. Overall changes in soil properties and trends in winter cereal yields. *Australian Journal of Soil Research*, 24 pp265-279.

DeRose, R., Prosser, I. P., Wilkinson, L. J., Hughes, A. O., and Young, W. J. 2003. *Regional patterns of erosion and sediment and nutrient transport in the Goulbourn and Broken River catchments, Victoria*. CSIRO Land and Water. Technical Report 11/03, March 2003.

Dimes, J. P. and Freebairn, D. M. 1993. Analysis for optimal water use in grain cropping systems of north eastern Australia. In *Proceedings of the Seventh Australian Agronomy Conference*, Adelaide 1993 Australian Society of Agronomy, pp240-243.

Edwards, K. 1987. Runoff and soil loss studies in New South Wales. Technical Handbook No 10. Soil Conservation Service of New South Wales. Chatswood:Sydney.

Fettel, N. A. and Gill, H. S. 1995. Long-term effects of tillage, stubble and nitrogen mangement on properties of a red –brown earth. *Australian Journal of Experimental Agriculture.* 35, 923-8.

Finlayson, B. and Silburn, M. 1996. Soil, nutrient and pesticide movements from different land use practices and subsequent transport by rivers and streams. In Hunter, H.M., Eyles, A.G. and Rayment, G.E. (eds) *Downstream Effects of Land Use*. Department of Natural Resources, Queensland, pp129-140.

Freebairn, D.M. 1992 Managing Resources - the soil resource: erosion, stubble management and catchment. In *Proceedings of the 6th Australian Agronomy Conference*. 10-14 February 1992, Australian Society of Agronomy, pp38-46.

Freebairn, D.M. 1998 Technical issues in understanding processes (researching) across scale. In Williams, J., Hook, R.A. and Gascoigne, H.L. (eds) *Farming Action Catchment Reaction: The effect of dryland farming on the natural environment*. pp 45-55. CSIRO Publishing, Collingwood, Victoria.

Geeves, G., Cresswell, H., Murphy, B. and Chartres, C. 1996. *Productivity and Sustainability from Managing Soil Structure*. Extension brochure. CSIRO Division of Soils and NSW Department of Land and Water Conservation, Canberra.

Grace, P.R, Ladd, J.N., and Skjemstad, J.O. 1994. The effect of management practices on soil organic matter dynamics. In Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R. and Grace, P.R. (eds) *Soil Biota: Management in Sustainable Farming Systems*. CSIRO Publications, Melbourne. pp172-71.

Grace, P.R, Post, W.M., Godwin, K.P. Bryceson, K.P., Truscott, M.A. and Hennessy, K.J. 1997. Soil carbon dynamics in relation to soil surface management and cropping systems in Australian agroecosystems. In Lal, R., Kimble, J.M., Follett, R.F. and Stewart, B.A. (eds) *Management of Carbon Sequestration in Soil*, CRC Press, New York. pp 175-93.

Gupta, S.C., Sharma, P.P., and DeFranchi, S.A. 1989. Compaction effects on soil structure. *Advances in Agronomy*. 42, 975-93.

Hamblin, A.P. and Tennant, D. 1979 Interactions between soil type and tillage level in a dryland situation. *Australian Journal of Soil Research* 17, pp177-89.

Hughes, A. O., Prosser, I. P., Wallbrink, P. J., and Stevenson, J. 2003. *Suspended sediment and bedload budgets for the Western Port Bay Basin.* CSIRO Land and Water. Technical Report 4/03, March 2003.

Jenkinson, D. S. and Coleman, K. 1994. Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. *European Journal of Soil Science* 45:167-174.

McDonald, R.C., Isbell, R.F., Speight, J.G. Walker, J. and Hopkins, M.S. 1984. *Australian Soil and Land Survey Handbook*. Inkata Press, Melbourne.

McGarry, D. 1989. The effect of wet cultivation on the structure and fabric of a Vertisol. *Journal of Soil Science*, 40 pp199-207.

McLaughlin, M.J., Kookana, R.S., Donnelly, T.H., and Wasson, R.J.1998. Land degradation processes and water quality effects: organic matter, soil and nutrient loss, and chemical residues. In Williams, J., Hook, R.A. and Gascoigne, H.L. (eds) *Farming Action Catchment Reaction: The effect of dryland farming on the natural environment*. pp 191-214. CSIRO Publishing, Collingwood, Victoria.

Mead, J. A. and Chan, K. Y. 1988.The effect of deep tillage and seedbed preparation on the growth and yield of wheat on a hard setting soil. *Australian Journal of Experimental Agriculture.* 28, 491-8*.*

Moran, C.J. 1998. Land degradation processes and water quality effects: decline in soil structure. In Williams, J., Hook, R.A. and Gascoigne, H.L. (eds) *Farming Action Catchment Reaction: The effect of dryland farming on the natural environment*. pp141-157. CSIRO Publishing, Collingwood, Victoria.

Moran, C., Prosser, I, DeRose, R., Lu, H., Croke, B., Hughes, A. and Cannon, G. In Preparation. *Sediments and nutrients in the rivers of the Murray-Darling Basin: targeting the future*. Report for the Murray-Darling Basin Commission.

Moss, A.J., Bennet, J., Poplawski, W., Shaw, R. and Moller, G. 1996. Land use factors affecting the condition of rivers, estuaries and bays in southern Queensland. In Hunter, H.M., Eyles, A.G. and Rayment, G.E. (eds) *Downstream Effects of Land Use*. Department of Natural Resources, Queensland, pp35-44.

O'Connell, M.G., O'Leary, G.J. and Incerti, M. 1995. Potential groundwater recharge from fallowing in north-west Victoria, Australia. *Agricultural Water Management*, 29, pp37-52.

O'Leary, G.J. 1996. The effects of conservation tillage on potential groundwater recharge. *Agricultural Water Management*, 31, pp65-73.

Olley, J. and Deere, D. 2003. *Targeting rectification action in the Wingecarribee catchment.* A collaborative consultancy with the Sydney Catchment Authority. CSIRO Land and Water. Technical Report 47/03, September 2003.

Olley, J.M., Murray, A.S., Mackenzie, D.H. and Edwards, K.1993. Identifying sediment sources in a gullied catchment using natural and anthropogenic radioactivity. *Water Resources Research*, 29, pp1037-43.

Packer, I.J. and Hamilton, G.J. 1993. Soil physical and chemical changes due to tillage and their implications for erosion and productivity. *Soil and Tillage Research*, 27, pp327-39.

Prosser, I., Moran, C., and Moran, C.J., 2003. *Assessing soil erosion and its off site effects at regional to continental scales*. Invited paper for OECD expert meeting on soil erosion and soil biodiversity indicators. 25-28 March 2003 Rome, Italy.

Radford, B.J., Gibson, G., Nielson, R.G.H., Butler, D.G., Smith, G.D., and Orange, D.O. 1992. Fallowing practices, soil water storage, plant available soil nitrogen accumulation and wheat performance in South West Queensland. *Soil and Tillage Research*, 22, pp73-93.

Ringrose-Voase, A. J., Young, R. R., Paydar, Z., Huth, N. I., Bernardi, A. L., Cresswell, H. P., Keating, B. A., Scott, J. F., Stauffacher, M., Banks, R. G., Holland, J. F., Johnston, R. M., Green, T. W., Gregory, L. J., Daniells, I., Farquharson, R., Drinkwater, R. J., Heidenreich, S., and Donaldson, S. G. 2003. *Deep drainage under different land uses in the Liverpool Plains catchment*. Report 3 Agricultural Resource Management Series. New South Wales Agriculture.

Russell, J.S. and Williams, C.H. 1982. Biogeochemical interactions of carbon, nitrogen, sulfur and phosphorous in Australian agroecosystems. In Galbally, I.E., and Freney, J.R. (eds) *The Cycling of Carbon, Nitrogen, Sulphur and Phosphorous in Terrestrial and Aquatic Ecosystems*. Australian Academy of Science, Canberra, pp 61-75. 1982

Silburn, D.M. and Connolly, R.D. 1995. Distributed parameter hydrology model (ANSWERS) applied to a range of catchment scales using rainfall simulator data I: Infiltration modelling and parameter measurement. *Journal of Hydrology*, 172, pp87-104.

Skjemstad, J. O. and Janik, L. J. 1996. *Climate change: determining the potential for carbon sequestration in Australian soils.* Final Report to the Rural Industries Research and Development Corporation. CSO-5A

Skjemstad, J. and Spouncer, L. 2003. *Integrated soils modelling for the National Carbon Accounting System*. (Estimating changes in soil carbon resulting from changes in land use). Australian Greenhouse Office. Technical report No 36. February 2003.

Unger, P.W. 1990. Conservation tillage systems. *Advances in Soil Science*, 13, 27-68.

Valentin, C. and Bresson, L.-M. 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. *Geoderma* 55, pp225-45.

Wasson, R.J. 1998. Dryland farming, erosion and stream sediments - the problem of catchment scale. In Williams, J., Hook, R.A. and Gascoigne, H.L. (eds) *Farming Action Catchment Reaction: The effect of dryland farming on the natural environment*. pp215-228. CSIRO Publishing, Collingwood.

Wasson, R.J. 1994. Annual and decadal variation of sediment yield in Australia, and some global comparisons. In Olive, R.J., Loughtran, R.J. and Kesby, J.A. (eds) *Variability in Stream Erosion and Sediment Transport*. Proceedings of the IAHS Symposium, December 1994, Canberra. International Association of Hydrological Sciences Press, Wallingford, pp269-79.

Wockner, G.H. and Freebairn, D.M. 1991. Water balance and erosion studies on the eastern Darlind Downs - an update. *Australian Journal of Soil and Water Conservation*, 4(1) pp41-47.