Chapter 7

Strategic tillage within conservation agriculture

Mark Conyers, Yash P. Dang and John Kirkegaard

Introduction

The three pillars of modern conservation agriculture (CA) are reduced tillage, soil cover by stubble retention and diverse rotations (FAO 2015). The significant efforts to reduce tillage from the multiple passes practised in Australia up to the 1980s underpinned the publication of *Tillage, New Directions in Australian Agriculture* in 1987. Since that time Australia has led the world in the development and adoption of reduced tillage (RT) systems, but several recent reviews have questioned the drive for a complete absence of tillage (Kirkegaard *et al*. 2014, Dang *et al.* 2015a, Giller *et al.* 2015) and promoted its strategic use in cropping systems. The strategic use of tillage, primarily restricted to the surface soil and seedbed, is the subject of this chapter.

The first records of an animal drawn plough are from Mesopotamia in about 3000 BC (Hillel 1991). Tillage has been used in various forms and for various reasons over the millennia, primarily to control weeds and to prepare a seed bed (Cornish and Pratley 1987, Lal 2009). After 5000 years, has the recent progress in chemical weed control made ploughing redundant? Despite the high uptake of CA practice in Australia (Llewellyn *et al*. 2012), tillage has remained as a tool *within* CA practice (see Chapter 2). This is due to a number of factors including the need to incorporate limestone into acidic soils and the role tillage can play in integrated pest and weed management. The use of any form of tillage within CA can be controversial on philosophical grounds (Grandy *et al.* 2006, Giller *et al*. 2009), or with respect to the loss of soil C (see Chapter 16). However challenges to the complete abandonment of tillage are increasingly common (Pierce *et al*. 1994, Dick 1997, Giller *et al*. 2015) and questions about the fit of complete no-till have been asked in Africa (Giller *et al*. 2009), South America (Bolliger *et al*. 2006, Dominguez *et al.* 2010, Nunes *et al*. 2017), and North America (Baan *et al*. 2009, Wortmann *et al*. 2010) as well as in Australia (Kirkegaard *et al.* 2014, Crawford *et al.* 2015, Dang *et al*. 2015a, 2015b, 2018).

Since the replacement of the bullock, donkey and horse there have been many developments in the mechanisation of both the draft and the implement. Mechanised draft in the form of tractors has slowly increased in size and energy requirements, while implements have grown wider and deeper. The diversity of implements has also increased. The impact on the soil itself therefore came to exceed the simpler expectations of weed control and a good seed bed. Tillage machinery and purposes have evolved (see Chapter 6) along with the principles of CA. Mechanisation will continue to evolve to meet the needs of CA: modified points that cultivate below the seed rather than across the row is an example; weed sensing technology that supports spot chipping by scarifiers is a recent example. The major characteristics that we can use to best describe these various forms of surface soil tillage are their depth and degree of mixing (Table 1, see Chapter 1). Use of inversion tillage with implements such as the mouldboard plough is rare in Australia, except to ameliorate soils with significant constraints (see Chapter 8). Most growers use non-inversion, shallow tillage based on tyne and disc implements that do not fully invert the soil (Dang *et al.* 2018). The degree and depth of mixing can vary with the range of modern implements. Further, the frequency of tillage has decreased over the last two generations, as conventional tillage (CT) decreased from regular ploughing between harvest and seeding in the 1950s, to RT with just two or three passes to control summer weeds by the 1980s, at the time that Cornish and Pratley (1987) compiled their review.

In this chapter, we consider the role of various depths and degrees of tillage of surface soil within modern CA in Australia (see Chapter 2), and how this has evolved since 1987. We do not cover the placement of amendments at depth (limestone, gypsum, manure, composts) nor the displacement of clay from B horizons into sandy and/or non-wetting surface soils (see Chapter 8).

Table 1. Characterising tillage implements for varying degree and depth of soil mixing

Depth	**Increasing mixing of soil** →	**Inversion**
shallow	Diamond harrows Prickle chains Speed tillers	
Beyond-seed placement depth	Tyned implements[a] Offset discs Rotary hoe	Mouldboards

[a] Tyned implements can generally penetrate deeper than offset discs or rotary hoe but are classified here with respect to mixing of surface soil only.

The use of tillage within CA

Table 2 summarises the 'pros and cons' of tillage within CA in a broad range of agro-ecological scenarios. The usual trade-offs are evident and nearly every action can be beneficial or detrimental depending on the circumstances.

With regard to soil chemical properties, the only situation where the net benefit of tillage is clear is in the need to incorporate limestone on acidic soils. Limestone's dissolution, reaction with acidity and movement are so slow and spatially limited that in a semi-arid cropping environment (350 to 600 mm annual average rainfall), such as the southern Australian wheat-belt, liming is a poor investment without soil incorporation by tillage (Conyers *et al*. 2003a, Scott and Coombes 2006). We expand on this topic later. In addition to the need to neutralise acidifying soils, the stratification of immobile nutrients such as P (Franzluebbers 2002) and alkalinity (Paul *et al.* 2003), with high concentrations in the surface few cm of soil, can limit their availability in dry and hot conditions and may accentuate off-site effects if erosion occurs. The loss of C from soil due to tillage is also a common concern and we also expand on this topic later.

In managing soil physical conditions (Table 2), sodic soils clearly represent situations where any form of tillage needs careful consideration due to a likely increase in dispersibility (Emerson 1983). For all soils, the risk of erosion by wind or water is another area of concern (Melland *et al*. 2017, Dang *et al*. 2018), so that slope, groundcover, soil moisture and the risk of storms must be considered. Any proposed strategic tillage should be left as late as possible before sowing in the southern grain-growing region of Australia. In the northern region of Australia, where both summer and winter cropping is practised, the timing of tillage needs to consider not only the risk of storms, but conservation of stored soil water (Dang *et al*. 2018). While stored water is important throughout Australian grain cropping (Hunt and Kirkegaard 2011), winter crops in the northern region are especially reliant on stored water from the wetter summer season. The structure and porosity of compacted subsurface soils could also be ameliorated by tap-rooted crops (*e.g.* safflower) rather than ploughing (Knights 2010); surface soil crusting only requires light harrows (*i.e*. shallow working, little mixing) for amendment, and uneven seed beds might require only a shallow disturbance for levelling. Livestock compaction by sheep, although of concern to growers using no-till (NT) in mixed farming systems, may not require amendment (Hunt *et al*. 2016) as it is generally shallow and with limited impacts on water supply to crops. Controlled traffic lanes which can become compacted represent only a small proportion of a field, whatever depth or degree of mixing is selected for renovation after wet, damaging seasons. These examples demonstrate that the type of tillage and the proportion of the field covered in a strategic tillage operation should not be likened to the multiple passes of a field to 10 cm depth or more that characterised the CT of the mid-20th century. Recent data from southern NSW indicate that a one-off tillage with scarifiers or offset disc does minimal damage to wet aggregate stability and to infiltration rates, with recovery times of zero to four years (generally one to two years) depending on the severity of the tillage and the rate of addition of fresh residues (Kirkegaard *et al.* 2014, Conyers *et al*. 2019). Effects of tillage on soil physical properties are considered in more detail later.

Off-site effects from tillage practice (Table 2), other than erosion, can be beneficial or detrimental and are generally small or variable in direction (Dang *et al*. 2015b). Hence the management of off-site effects is rarely a trigger for a strategic tillage operation.

Table 2. The pros and cons of the use of strategic tillage, covering a broad range of agro-ecological considerations (based on Dang *et al*. 2015a, b and Conyers *et al*. 2019)

Consideration	**Pro**	**Con**
Soil chemical properties		
NPKS stratification	High soil surface temperature & evaporation rates means less availability of stratified nutrients; *Deep placement of nutrients & amendments to replenish depleted subsurface soils (see Chapter 8);*	Early seedling growth possibly enhanced by stratification in mild conditions
pH	Limestone has limited solubility, requiring incorporation;	
C	*Inversion (without pulverisation) improves subsurface C stores;*	Tendency to decrease profile stores of C
Soil physical conditions		
Crusting	Breaking surface crusts to improve infiltration vs run-off	Sodic soil dispersion is enhanced
Uneven seed bed	*Levelling of surface for small seeded crops*	
Compacted subsurface	Reduce compaction for improved aeration. infiltration & root growth	Sodic soil dispersion is enhanced
Wet season compaction	*Compacted controlled traffic lanes needing renovation along strips*	*Sodic soil dispersion is enhanced*
Erosion		Decreased K_{sat} on vertosols and hence increased run-off rates
Off-site effects		
P pollution	Dilution of P enriched surface strata.	No-till favours less risk of run-off
GHG emissions		
CO_2	*Removal of agronomic constraints improves net C fixation*	*Increase in short term production/loss of* CO_2
CH_4	Variable and small impacts.	Variable, small impacts
N_20	*Variable impacts reported*	*Variable impacts reported*
Plant diseases		
Crown rot (*Fusarium*), wheat	Stubble incorporation can increase decomposition	Loss of water can slow stubble decomposition
Bare patch (*Rhizoctonia),* wheat	*Minimises the spread and survival of the fungus*	Tillage can spread stubble & fungus more evenly across a field
Yellow spot (*Pyrenophora*), wheat	Minimised by stubble incorporation by discs	
Blight (*Ascochyta*), chickpea	*Burial of stubble reduces spread of spores*	
Stalk diseases (*Fusarium*), sorghum	Burial of stubble reduces pathogen build-up.	
Soil fauna		
Root lesion nematodes (*Pratylenchus*)	Reduces populations	
Helicoverpa spp.	*Reduces populations*	
Predatory insects (*e.g*. beetles, ants)		Reduces populations.
Earthworms		Reduces populations.
Molluscs (snails, slugs)	Reduces habitat and dilutes food sources.	
Pests		
Rodents, especially mice	Reduces habitat and dilutes food sources.	
Weeds		
Wind-dispersed seeds	*Prevalence increased by no-till*	
Herbicide resistance	New seeds can be buried beyond coleoptile length *e.g*. annual ryegrass (*Lolium*)	Long lived buried seeds can be brought to the surface *e.g*. fleabane (*Conyza*).

K_{sat} =saturated hydraulic conductivity, GHG = greenhouse gases

Plant diseases interact with tillage primarily through the management of stubble although they are mostly influenced by other forms of stubble management (grazing, cutting, burning, Scott *et al*. 2010, Dang *et al*. 2015a). The soil-borne fungal pathogen *Rhizoctonia solani* (AG8) which causes bare patch in cereals appears to be a disease where tillage has beneficial effects through soil disturbance alone (Rovira 1986) and this could also be true for inhibitory pseudomonads (Simpfendorfer *et al*. 2001, see also Chapter 11). Soil faunal populations are generally reduced by tillage, and this is beneficial in the case of pests such as slugs, snails (Pomeroy 1969, Voss *et al*. 1998, Glen and Symondson 2003) and plant parasitic nematodes (Rahman *et al*. 2007) but detrimental in the case of earthworms and predatory insects (Dang *et al*. 2015b, Table 2). Rodent pests burrow in soil and eat remaining grain after harvest, so tillage can assist control by both destroying habitat and burying food sources (Johnson 1986). However, baiting also needs to be used to control existing populations, so tillage is part of an integrated solution, not a stand-alone cure. The management required for effective control of standing weeds is very different to the management required for the weed seed bank stored in the soil (Table 2, Crawford *et al*. 2015, Owen *et al*. 2017). For Integrated Weed Management (IWM) where herbicide options are limited, grazing, manure crops, silage and hay cutting, harvest weed seed management and tillage are all options to be considered in the management mix (Chauhan *et al*. 2006, Edwards *et al*. 2012, see also Chapter 10).

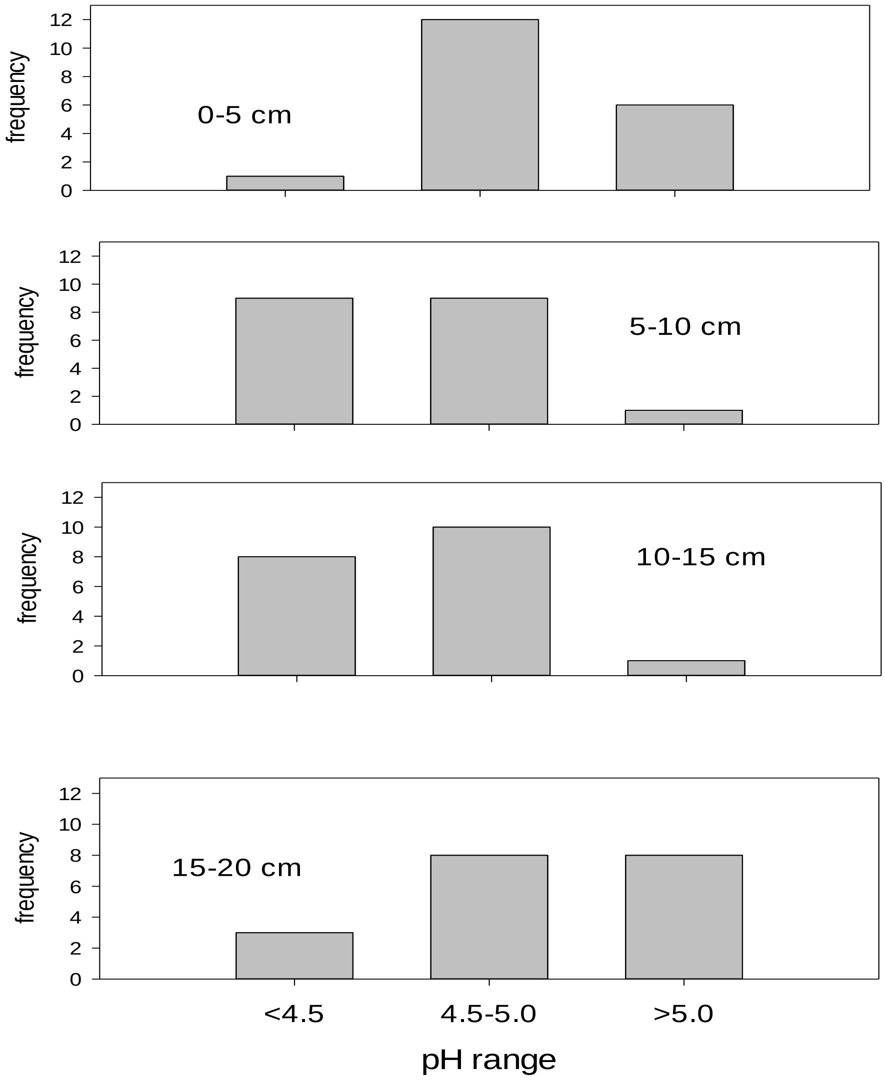

Figure 1. The frequency distribution of soil pH ($CaCl_2$) from 19 field sites over 4 depths on red kandosols near to the long-term rotation experiment (SATWAGL) at Wagga Wagga in 1996

Strategic tillage and acidity

Stratification of soil acidity (pH), together with the limited depth of penetration of applied limestone, was identified in the 1980s (Conyers and Scott 1989), shortly after soil acidity became recognised as a problem in southern Australia. The obvious influence of tillage on pH stratification was noted subsequently (Conyers *et al*. 1996) on a long-term field experiment. At this time there was concern as to how well the long-term field experiment might reflect what was occurring on commercial farms. Nineteen commercial fields were surveyed within 100 km of the experiment on the same red Kandosol soil type as for the long-term experiment reported by Conyers *et al.* (1996). Figure 1 shows the frequency distribution of soil pH ($CaCl_2$) at four depths for these 19 fields (Scott *et al*. 2017). The three pH ranges are based on where soil acidity was not likely to be a problem (pH >5) and where the acidity constraint was likely to be serious (pH<4.5).

There was a tendency for pH to be stratified and for the acidity to be worse at 5 to 15 cm depth. This implied that emerging seedlings were experiencing more stressful acidity than might be indicated by a standard 0-10 cm soil test. Over the subsequent two decades subsurface acidity under NT management has become a very common and sometimes damaging issue on commercial fields of faba beans (Burns *et al.* 2017) and possibly for other acid-sensitive species. Currently the problem is limiting the expansion of high value legumes (*e.g.* lentils, chickpeas) in some areas as the amount of limestone required to remediate the soils for adequate legume nodulation to 20 cm depth (of the order of 3.5 t/ha), combined with the need for deep incorporation (to about 15 cm), is seen as a costly investment.

Strategic tillage and soil C

It is generally recognised that tillage results in a loss of soil organic matter since it promotes mineralisation. However any improvement in plant growth, particularly for roots, is likely to increase the addition of C to soil over the season that follows. The extent of C loss from soil due to tillage varies with other management factors such as NPS inputs (Kirkby *et al*. 2014, 2016), stubble management (Heenan *et al*. 2004), as well as the proportion of pasture phase within the rotation (Helyar *et al*. 1997).

Most importantly, the rate of loss of soil C needs to be considered. In a comparison of NT by direct drilling (knife points) with annual tillage (two or three passes) by scarifiers or offset discs over 21 years, Heenan *et al*. (2004) found that the rate of loss of soil C from surface soil (red Kandosol) due to tillage was 191, 146, 189 kg C/ha/year under three different rotations. Comparing three long-term trials in the southern rainfall environment, including the trial of Heenan *et al*. (2004), Chan *et al*. (2011) found that annual losses and gains of soil C to 30 cm depth ranged from -278 to +552 kg/ha/year. In the northern grain region on a Vertosol, Dalal *et al.* (2011) found that the difference in C stock at 0-10 cm between NT and CT was < 0.4 t C/ha after 40 years. The SOC sequestration rates were initially 100-120 kg C/ha/year in the first decade but declined to an average of 45 kg C/ha/year over 40 years. At 0-30 cm depth the effect of tillage on SOC stock was not significant. These rates of change in soil C are not dramatic when compared with the large annual above-ground biomass production of the order of 10,000 kg DM/ha/year.

Given the slow loss rate of soil C due to annual tillage, involving two or three passes per year, it is likely that a single strategic tillage event implemented occasionally would have limited impact on stores of soil C (Conyers *et al*. 2015). Further, it appears that these losses of soil C due to tillage can be minimised, eliminated or even reversed by applying supplementary nutrients, NPS, to the stubble prior to decomposition (Kirkby *et al*. 2014, 2016). Adding supplementary nutrients to crop stubbles at the time of incorporation increased soil C levels over a 6-year period by 5.5 t/ha at one site, while stubble retention alone reduced soil C by 3.2 t/ha (Kirkby *et al*. 2016). The issue is considered in Chapter 16.

Strategic tillage and soil physical properties

Grandy *et al.* (2006) found a 35% decrease in mean weight diameter of aggregates in the surface 20 cm of soil following mouldboard ploughing of a grassland in Michigan. Most of the decrease was due to loss of macro-aggregates (>250 µm). However Quincke *et al*. (2007) found that a single tillage, regardless of implement (including a mouldboard) did not affect aggregate stability nor grain yield at two sites under corn or sorghum in Nebraska. Infiltration rate was increased at one site by mouldboard plough but decreased at the other. Wortmann *et al.* (2010), also in Nebraska, found that water stable aggregates were not affected by a single tillage at two sites except for an increase in aggregation at 5-10 cm depth under mouldboard inversion at one site. There were no effects on grain yield at either site. Pierce *et al*. (1994) found that a single tillage at a site in Michigan decreased bulk density and increased macroporosity but decreased microporosity. After four to five years the soil properties had generally returned to those of the NT treatment. In Saskatchewan, Baan *et al*. (2009) compared three intensities of a single cycle of tillage at three sites and found no effect on soil aggregation (dry sieving) or crop production except at one site where grain yield was decreased in one year. Conyers *et al*. (2019) in southern New South Wales found no effect of a single tillage on saturated hydraulic conductivity at three sites, but initial minor decreases in wet aggregate stability (0-14%) generally recovered within the first two years.

It appears then, with the exception of Grandy *et al*. (2006) on a grassland, that a single tillage of long-term NT system either causes no damage, or minimal damage to the various measures of soil physical properties. Recovery times, *i.e.* returning to equivalence with a NT system, generally took from zero to two years but up to four years in some circumstances.

Adoption of strategic tillage

Adoption of strategic tillage to deal with a suspected issue will be driven by profitability, which is influenced by the relative value of the perceived lost grain yield, the cost of tillage and the degree to which the yield constraint is amended by tillage. Clearly, with diseases, insect pests, molluscs and rodents, there are very specific circumstances to consider. Similarly, with herbicide resistance, the full agronomic situation of herbicide and crop rotation also needs to be assessed. Any use of tillage needs to be considered in conjunction with other practices to influence the ecology of the specific biological constraints to grain yield.

The impact of tillage on soil moisture at sowing depends on the rainfall and temperatures between the tillage event and sowing, which is beyond the control of the farmer. Previously, the risk of a dry seed bed was generally greater for winter crops in northern Australia than in the winter dominant rainfall region in the south (Dang *et al*. 2015a, b). However, the recent trend for earlier sowing systems in southern and western Australia (Chapter 18) has re-ignited interest in the need to conserve fallow rainfall and to maintain high stubble loads with minimal soil disturbance using disc seeders.

Probable drivers for strategic tillage will include soil physical and chemical properties and the need to control weeds. There are many common soil physical limitations: a surface crust that inhibits emergence, a hard pan that inhibits root exploration, surface pugging or wheel tracks that create an uneven and partly compacted seed bed. A common soil chemical constraint is acidity, especially in the subsurface soil that will inhibit root development and nodulation by N-fixing microorganisms and cannot be easily ameliorated without lime incorporation. The periodic need for *integrated* weed management is also likely to be a major driver, with around 30-66% or farmers nominating weed management as the reason for pre-sowing cultivation (see Chapter 2). The most appropriate type of tillage will depend on the nature of the main issue. For example, a surface crust will only require a superficial working with an implement such as diamond harrows; a hard pan will require a tyned implement but minimal mixing; soil acidity will require mixing of limestone into the soil to below the depth of seed placement by an implement such as off-set discs; surface pugging could be remedied by a scarifier with minor soil disturbance; and wheel tracks might require a deeper working and some mixing but only to strips across the field. No *inversion* of the soil would be required in these instances for soil management but might be necessary to bury herbicide resistant weed seeds (Chauhan *et al.*

2006). A combination of NT, limited or no grazing, and wider row spacing might favour weeds such as fleabane (*Conyza* spp). Any loss of herbicide tolerance for summer weeds would also apply pressure to a NT system. Slug, snail and mouse plagues are more episodic features of our farming systems. In future however, tillage need not always be extensive but could be spot specific and triggered by sensors.

The practical issues to be addressed then, are to determine how much disturbance is required to address the problems identified: the depth, degree of mixing and frequency of tillage that was most appropriate. The potential downsides and their persistence must be weighed against the yield constraints being addressed.

On the basis of existing Australian data, the following guidelines for strategic tillage are offered:

- Commercial application rates of 2 to 3 t/ha of limestone will last for about 10 years before re-application and incorporation is necessary (Conyers *et al.* 2003b), possibly shortened where rates of N fertiliser exceed 100 kg/ha/yr or where long-term surface applications without tillage has caused stratification and subsurface acidification. The limestone can be top-dressed onto the paddock anytime during the autumn. Discing will achieve better incorporation than scarifying (Scott and Coombes 2006).
- Small reductions in wet aggregate stability due to tillage generally can be expected to recover within two years depending on the severity of the tillage and the rate of return of fresh residues to the soil (Conyers *et al*. 2019).
- Losses of soil organic C in cultivated systems are of the order of 0 to 300 kg C/ha/yr in southern Australia, on a stock of 13 to 30 tonnes (Chan *et al*. 2011), while in Vertosols in the north the loss due to tillage can be even less on similar stocks (Dalal *et al*. 2011). Adding supplementary nutrients (NPS) to crop stubbles at the time of incorporation could enhance stores of soil C or at least minimise the loss (Kirkby *et al*. 2016). Maintaining balanced nutrition generally is required to decrease the mining of soil organic matter to provide nutrients for crop growth.
- In the northern grain region, where winter crops rely on stored summer rain, as much as 10 mm of water over 30 cm depth can be lost from the seed zone after a strategic tillage (Crawford *et al*. 2015). Such losses of water might reduce sowing opportunities. This issue might increase in importance in other regions as the issue of stored water for earlier sowings into drier seedbeds becomes more prominent.
- The purpose of the strategic tillage will determine the best timing; however, the timing and intensity of rainfall after tillage dictates the risk of erosion and/or the loss of stored soil water . Local climate data on rainfall and storm frequency are therefore critical background information (Yu and Rosewell 1996, Dang *et al*. 2015a, b).
- To minimise erosion risk we recommend the usual guidelines: the ribbon test for soil moisture, slope assessment, and pending rainfall forecasts. For southern Australia we recommend leaving the tillage as late as possible before sowing.
- Further general guidelines to implement tillage within no-till systems for the northern grains region are summarised in Table 12 of Dang *et al.* (2018).

Conclusions

Strategic tillage is a flexible option that has been adopted by Australian farmers within the context of near full adoption of NT systems. It is a sensible and pragmatic approach to maintain profitability while protecting the soil resource base. Within the context of the trade-offs outlined, best management practice should not be an uncritical adherence to a tillage or stubble management philosophy. The best approach is a field-by-field evaluation each year to take account of the stubble load, weed burden, disease history, pest history, soil physical state and soil test results. There is a wide range of implements available to optimise the tillage required, with varying depths of reach and degrees of soil mixing. Such evaluation and planning is generally within the skills of the modern farmer and their advisor.

References

Baan CD, Grevers MCJ, Schoenau JJ (2009) Effects of a single cycle of tillage on long-term no-till prairie soils. *Canadian Journal of Soil Sci*ence **89**, 521-530

Bolliger A, Magi J, Amado TJC *et al.* (2006) Taking stock of the Brazilian "Zero-Till revolution": a review of landmark research and farmers' practice. *Advances in Agronomy* **91**, 47-110

Burns H, Norton M, Tyndall P (2017) Reduced nodulation of faba bean on acidic soils; the role of topsoil pH stratification. *Proceedings of Australian Agronomy Conference*. Ballarat, Australia

Chan KY, Conyers MK, Li GD, Helyar *et al.* (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: Results of three long tem experiments. *Soil Research* **49**, 320-328

Chauhan BS, Gill GS, Preston C (2006) Tillage system effects on weed ecology, herbicide activity and persistence: A review. *Australian Journal of Experimental Agriculture* **46**, 1557-1570

Conyers MK, Heenan DP, Poile GJ *et al*. (1996) Influence of dryland agricultural management practices on the acidification of a soil profile. *Soil and Tillage Research* **37**, 127-141

Conyers MK, Heenan DP, McGhie WJ, Poile GJ (2003a) Amelioration of acidity with time by limestone under contrasting tillage. *Soil & Tillage Research* **72**, 85-94

Conyers MK, Mullen CL, Scott BJ *et al.* (2003b) Long-term benefits of limestone applications to soil properties and to cereal crop yields in southern and central New South Wales. *Australian Journal of Experimental Agriculture* **43**, 71-78

Conyers MK, Liu DL, Kirkegaard J *et al*. (2015) A review of organic carbon accumulation in soils within the agricultural context of southern New South Wales, Australia. *Field Crops Research* **184**, 177-182

Conyers MK, Scott BJ (1989) The influence of surface incorporated lime on subsurface soil acidity. *Australian Journal of Experimental Agriculture* **29**, 201-207

Conyers MK, van der Rijt V, Oates A *et al*. (2019) The strategic use of tillage within conservation agriculture in southern New South Wales, Australia. *Soil & Tillage Research* **193**, 17-26

Cornish PS, Pratley JE (Eds.) (1987) "Tillage: New Directions in Australian Agriculture". (Inkata Press: Melbourne)

Crawford MH, Rincon-Florez V, Balzer A *et al*. (2015) Changes in the soil quality attributes of continuous no-till farming systems following a strategic tillage. *Soil Research* **53**, 263-273

Dalal RC, Allen DE, Wang WJ *et al.* (2011) Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. *Soil & Tillage Research* **112**, 133-139

Dang YP, Seymour NP, Walker SR *et al.* (2015a) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: 1. Drivers and implementation. *Soil & Tillage Research* **152**, 104-114

Dang YP, Moody PW, Bell MJ *et al.* (2015b) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: 11. Implications for agronomy, soil and environment. *Soil & Tillage Research* **152**, 115-123

Dang YP, Balzer A, Crawford M *et al*. (2018) Strategic tillage in conservation agricultural systems of north-eastern Australia: why, where, when and how? *Environmental Science and Pollution Research* **25**, 1000-1015

Dick WA (1997) Tillage system impacts on environmental quality and soil biological parameters. *Soil & Tillage Research* **41**, 165-167

Dominguez A, Bedano JC, Becker AR (2010) Negative effects of no-till on soil macrofauna and litter decomposition in Argentina as compared with natural grasslands. *Soil & Tillage Research* **110**, 51-59

Edwards J, Umbers A, Wentworth S (2012) Farm Practices Survey Report 2012 (Grains R&D Corporation: Canberra)

Emerson WW (1983) Inter-particle bonding. In "Soils: an Australian Viewpoint." Chapter 31 pp 477-498 (CSIRO:Melbourne)

FAO (2015) "Conservation Agriculture" www.fao.org/ag/ca/index.html

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. *Soil & Tillage Research* **66**, 95-106

Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture. *Frontiers in Plant Sciences* **6**, 1-14

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* **114**, 23-34

Glen DM, Symondson WOC (2003) Influence of soil tillage on slugs and their natural enemies. In (Ed. Adel El Titi) "Soil Tillage in Agroecosystems" pp 208-222 (CRC Press: Boca Raton)

Grandy AS, Robertson GP, Thelen KD (2006) Do productivity and environmental trade-offs justify periodically cultivating no-till cropping system? *Agronomy Journal* **98**, 1377-1383

Heenan DP, Chan KY, Knight PG (2004) Long-term impact of rotation, tillage and stubble management on the loss of soil organic carbon and nitrogen from a Chromic Luvisol. *Soil & Tillage Research* **76**, 59-68

Helyar KR, Cullis BR, Furniss K *et al.* (1997) Changes in the acidity and fertility of a red earth soil under wheat-annual pasture rotations. *Australian Journal of Agricultural Research* **48**, 561-586

Hillel DJ (1991) "Out of the Earth" (The Free Press: New York)

Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929

Hunt JR, Swan AD, Fettell NA *et al.* (2016) Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment. *Field Crops Research* **196**, 22-32

Johnson RJ (1986) Wildlife damage in conservation tillage agriculture: a new challenge. *Proceedings of 12th Vertebrate Pest Conference*, University of California, Davis

Kirkby CA, Richardson AE, Wade LJ *et al.* (2014) Nutrient availability limits carbon sequestration in arable soils. *Soil Biology and Biochemistry* **68**, 402-409

Kirkby CA, Richardson AE, Wade, LJ *et al.* (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLOS One* **11**, 1-17

Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems and Environment* **187**, 133-145

Knights S (2010) Raising the bar with better safflower agronomy. (GRDC: Canberra). https://bit.ly/2Yx9aKL

Lal R (2009) The plow and agricultural sustainability. *Journal of Sustainable Agriculture* **33**, 66-84

Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212

Melland AR, Antille, DL, Dang YP (2017) Effects of strategic tillage on short term erosion, nutrient loss in runoff and greenhouse gas emissions. *Soil Research* **55**, 201-214.

Nunes MR, da Silva AP, Denardin JE *et al.* (2017) Soil chemical management drives structural degradation of Oxisols under a no-till cropping system. *Soil Research* **55**, 819-831

Owen MJ, Walsh MJ, Llewellyn RS, Powles SB (2007) Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. *Crop and Pasture Science* **58**, 711-718

Paul KI, Black AS, Conyers MK (2003) Development of acidic subsurface layers of soil under various management systems. *Advances in Agronomy* **78**, 187-214

Pierce FJ, Fortin MC, Staton MJ (1994) Periodic plowing effects on soil properties in a no-till farming system. *Soil Science Society America Journal* **58**, 1782-1787

Pomeroy DE (1969) Some aspects of the ecology of the land snail, *Helicella virgata*, in South Australia. *Australian Journal of Zoology* **17**, 495-514

Quincke JA, Wortmann CS, Mamo M *et al.* (2007) One-time tillage of no-till systems: soil physical properties, phosphorus runoff, and crop yield. *Agronomy Journal* **99**, 1104-1110

Rahman L, Chan KY, Heenan DP (2007) Impact of tillage, stubble management and crop rotation on nematode populations in a long-term field experiment. *Soil & Tillage Research* **95**, 110-119

Rovira AD (1986) Influence of crop rotation and tillage on Rhizoctonia bare patch of wheat. *Ecology and Epidemiology* **76**, 669-673

Scott BJ, Conyers MK, Burns HM *et al.* (2017) Stratification of acidity in the shallow soil surface – experiences in the cropping areas of southern and central NSW: doing more with less. *Proceedings of 18th Australian Agronomy Conference*, Ballarat, Australia 24-28

Scott BJ, Coombes NE (2006) Poor incorporation of lime limits grain yield response in wheat. *Australian Journal Experimental Agriculture* **46**, 1481-1487

Scott BJ, Eberbach PL, Evans J, Wade LJ (2010) "Stubble retention in cropping systems in Southern Australia: benefits and challenges." EH Graham Centre Monograph No.1 www.csu.edu.au/research/grahamcentre

Simpfendorfer S, Kirkegaard JA, Heenan DP, Wong PTW (2001) Involvement of root inhibitory *Pseudomonas* spp. in the poor early growth of direct drilled wheat in intact cores. *Australian Journal of Agricultural Research* **52**, 845-853

Voss MC, Ulber B, Hoppe HH (1998) Impact of reduced and zero tillage on activity and abundance of slugs in winter oilseed rape. *Journal of Plant Diseases and Protection* **105**, 632-640

Wortmann CS, Drijber RA, Franti TG (2010) One-time tillage of no-till crop land five years post-tillage. *Agronomy Journal* **102**, 1302-1307

Yu B, Rosewell CJ (1996) An assessment of a daily rainfall erosivity model for New South Wales. *Australian Journal of Soil Research* **34**, 139-152