PART I – CONSERVATION AGRICULTURE: THE CONTEXT

Lupin crop sown inter-row by no-till into standing wheat stubble – three pillars of conservation agriculture (Courtesy: John Kirkegaard)

Zero-till disc seeder on 250 mm row spacing, 12 m CTF system, inter-row seeding faba beans using 2 cm GPS guidance into standing barley stubble.
(Courtesy: Greg Condon and Stephen & Michelle Hatty, Matong NSW)

Chapter 1

Tillage: global update and prospects

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Introduction

Tillage refers to the mechanical disturbance of the soil primarily for planting of crops, but weed control and incorporation of nutrients are common secondary purposes. Modern primary tillage, principally mouldboard or disc ploughing, was developed in the 18th and 19th century, requiring substantial secondary tillage for seedbed preparation (the whole package being defined here as conventional tillage, CT). In response to the 'dust bowl' years in the US Great Plains in the 1940s, reduced (RT) and stubble mulch tillage, commonly called conservation tillage, that controls weeds with minimal soil disturbance and leaves at least 30% plant residue on the soil surface, was developed to combat such erosion. In the 1960s and with the development of herbicides, modern one-pass seeding systems started to appear: according to GRDC these include direct drilling (full surface disturbance), no-till (partial disturbance with narrow point), and zero-till (minimal disturbance with disc opener). These three one-pass systems approximate the definition of 'low soil disturbance no-till' in Kassam *et al.* (2019), and throughout our paper are together called no-till (NT).

At the time the book "Tillage: New Directions in Australian Agriculture" appeared in 1987, the "no-till revolution" was only a few years old, global NT area was small and there were few long-term experiments. Today, Kassam *et al.* (2019) estimate the area of conservation agriculture (CA), referring to NT planting systems with surface retention of crop residue and rotation of crops, to be about 180 Mha in 2015-16, or 12.5% of global crop area. This is an approximate estimate of world NT, approximate because there can be NT outside of CA, but it can be confidently stated that NT does not exceed 15% of world crop area. On the other hand, the world's tillage literature suggests that more than 90% of the current research relates to NT (or CA). Therefore, given that there is still at least 1,200 M ha of conventional tillage (CT), this review begins by considering some current issues with CT, before passing to NT, for which many long-term results now exist. The focus is largely at a global level, leaving Australian results to later chapters.

Conventional primary and secondary tillage (CT)

CT can involve deep (15-40 cm) ploughing, and is still widely practised in the USA, Europe, North Africa and Asia. While tradition has played a role in the persistence of this intensive tillage system, other factors remain relevant, including weed control and a need to bury the copious residues in humid situations where crops follow each other with only brief fallow periods, and in cool areas where soil warming in the spring is critical; in such cases, and assuming residue burning is no longer an option, yield is often somewhat improved with CT (see later). Relief of compaction is another valid reason for deep tillage, as is tillage for burial of fertilisers and soil ameliorants. We concentrate on tillage research in temperate North America and Europe where NT is less widely adopted, the focus being on problems of CT or comparing CT to deeper loosening tillage, or to shallower tillage (RT), or to conservation tillage.

CT and energy consumption

In modern cropping, energy inputs, and their associated greenhouse gas emissions, have received much attention lately. The total energy input per ha comprises not only fuel use but also energy embodied in other inputs and activities. Energy use is dominated by N fertiliser costs, with tillage fuel usually less than 40% of the total, so reducing tillage does not have a large effect on the total energy budget. For example, in a typical irrigated maize cropping system in Nebraska a detailed survey of farmers' energy costs found that average total input was 30 GJ/ha for a 13 t/ha grain yield (Grassini and Cassman 2012): the breakdown on energy was pumping (42%), N fertiliser (32%), grain drying (9%) and fuel for field

operations (9%), while RT saved only 6% of the total energy cost, compared with CT. The relative saving in total energy with RT (or NT) vs CT is likely to be greater in rainfed cropping, but this can be counterbalanced if herbicide use increases, since herbicides can have a high energy cost (250-500 MJ/kg a.i., compared to diesel at about 43 MJ/L), with glyphosate at the upper end of this range.

Many studies have considered reducing the energy costs of CT, which can consume 50-70 L/ha of diesel. Fuel used per ha, assuming soil moisture, tractor size and implement are optimised, is largely a function of tillage depth, soil texture and type, and degree of pulverisation of the soil, with smaller effects of speed for implements that 'throw' soil, and of the implement itself (McLaughlin *et al.* 2008; Lovarelli and Bacenetti 2017). Anecdotal evidence points to France and Russia as places where deep CT tillage was common, but Italy may have the strongest tradition of deep tillage, often reaching depths of 50 cm, but with recent efforts to reduce this. For example, Pezzi (2005) compared, in a silty clay typical of the Po Valley, a mouldboard plough to alternative PTO-driven rotary chisel and spading machines. Tilling to 40 cm required around 45 L/ha of diesel regardless of implement, but the alternative machines produced clods about half the size of the 24 cm mean diameter ones with the mouldboard. The spading machine was the best for energy cost corrected for the degree of pulverization. These are clearly extreme practices. While recent design research may allow small improvements in mouldboard energy efficiency (*e.g.* Ibrahmi *et al.* 2017), primary tillage elsewhere is not so deep (15-25 cm) and fuel cost is closer to 20-35 L/ha of diesel (Lal 2004, McLaughlin *et al.* 2008). RT systems, whether chisel or rotovator, can save up to 40% fuel used in seedbed preparation compared to CT, depending on depth of tillage and texture.

Subsoil compaction and profile amelioration through deep loosening tillage

Compaction or dense layers can be natural but are more commonly induced by repeated tillage, in-furrow ploughing, or by heavy wheel traffic, common at harvest, and under high soil moisture. The impact and prevention of subsoil compaction has been reviewed for European Union conditions by Van den Akker *et al.* (2003) and more generally by Hamza and Anderson (2005). These authors believe that soil compaction in modern agriculture with its large and heavy machines is a major cause of soil degradation and a serious challenge to sustainability. Reduced crop yield is generally via reduced subsoil rooting in drier situations and from increased denitrification in wet, cool spring soils at higher latitudes (Van den Akker *et al.* 2003). Preventing compaction is well understood and relates to the inherent susceptibility of the soil, soil organic matter content, the moisture content when trafficked, subsoil protection by the topsoil, and the pressure applied (Spoor *et al.* 2003, Hamza and Anderson 2005). Also, on-land ploughing (all tractor wheels on the unploughed surface) significantly reduces compaction arising from in-furrow wheel traffic during ploughing. But subsoil compaction is difficult to prevent with modern heavy machinery, and negative effects on crop rooting and performance can be difficult to recognize.

Subsoil compaction is expensive to alleviate. Hamza and Anderson (2005) suggest the use of deep-rooted crops and deep incorporation of organic material and gypsum as preventative strategies. However, the accepted solution is deep subsoiling or ripping to disrupt compacted zones using forward facing points on tynes or chisels with wings, which fully or partially lift and disrupt the soil at a depth just below the compacted zone. The aim is to ease rooting in and through the compacted zone without unnecessarily loosening other parts of the profile. Spoor *et al.* (2003) discusses tyne arrangements, tillage depth and speed to achieve this, with the paraplough probably the most effective implement where compaction is not too deep. Disruption is greatest when the soil profile is dry. Spoor (2006) provided more comprehensive detail on equipment for alleviating compaction*, inter alia,* attaching loosening tynes to mouldboards to break up plough pans immediately below the normal plough depth. Deep tillage is also an opportunity for the deep incorporation of fertilisers or ameliorants such as lime, gypsum, phosphorus, and organic materials (manure, compost and the like).

Deep tillage studies have recently been comprehensively reviewed by Schneider *et al.* (2017), who considered 1530 comparisons from 67 temperate sites growing cereals around the world. However, only 22% of the sites came from publications since 1990. These authors included deep inversion (mouldboard) and mixing (rotovator) tillage along with deep loosening tillage. Deep tillage was 35 cm

or more, while control tillage averaged 19 cm. Schneider *et al.* (2017) found yield responses varied but averaged +20% for sites where root-restricting layers had been identified, a response which was significantly greater when the water supply was less. This suggests only deep loosening tillage is required. Yield effects related to all types of deep tillage and included benefits due to better nutrition when no fertiliser was used, or when fertiliser or organic material was placed deep. In addition, there was an increased risk of negative effects where topsoils had >70% silt, an effect attributed to the breakdown of natural structures and biopores.

Schneider *et al.* (2017) found that many studies contained insufficient measurements for sound interpretation of results. In all the papers cited, only Botta *et al.* (2006) working with sunflower in the western Argentine pampas came close to linking subsoiling to 45 cm with the yield response; reduced cone penetrometer readings in the compacted layer (15 to 30 cm) were associated with a doubling of root growth in this layer, a doubling of crop growth, and 25% extra yield, although no evidence was presented to attribute this to greater water use. Spoor (2006) insisted that the only way to be sure of deleterious subsoil compaction in the first place, and its proper alleviation, was visual inspection of roots in soil profiles before and after deep loosening tillage. Others propose that with automatic monitoring of soil bulk density through forces on tillage tools, the inevitable patterns of variation in soil compaction across space opens the possibility to monitor and control systems for continuous adjustment of tillage machines, in order to deliver more decompaction for less energy expended (Andrade-Sanchez and Upadhayha 2019). Even if deep tillage alleviates compaction, it quickly returns in many soils when normal uncontrolled field trafficking continues, especially in humid climates. The only satisfactory measures of prevention with cropping in susceptible soils appear to be substantially lighter traffic, wider (softer) tyres, and/or controlled traffic. A move to autonomous vehicles may see lighter vehicles, but harvesters will likely remain heavy. Only controlled traffic can deal with this and it fits well with both till and NT systems, bringing many advantages as seen in the UK and Australian studies (*e.g.*, Godwin *et al.* 2015, Antille *et al.* 2019). To date controlled traffic cropping, now even more efficient with precision guidance, has not been widely adopted outside of Australia, and so is covered in Chapter 6.

Tillage erosion

A largely neglected feature of tillage until recently, is tillage erosion, soil movement down slope as a result of the tillage operation itself. It occurs regardless of tillage direction and leads to net erosion of convex slopes and upper field boundaries and net soil deposition in concave slopes and lower field boundaries, but no soil leaves the field (van Oost *et al.* 2006). The amount of soil moved in any operation depends on the slope curvature (rate of change of slope), as well as the tillage depth, implement and, to a lesser extent, speed. The latter factors are summarised in the tillage transport factor, which for mouldboard plowing to 40 cm ranged from 360 to 770 kg per unit slope tangent change per m of implement width.

Tillage erosion is obvious in the undulating crop lands of Mediterranean Europe, with subsoil appearing on the tops of rises. Van Oost *et al.* (2009) estimated average tillage erosion was 3.3 t/ha/y (and water erosion 3.9 t/ha/y) across arable lands in Europe. Tillage erosion was low (<1 t/ha/y) in the major agricultural plains, but high (>5 t/ha/y) in the undulating crop lands of Mediterranean and Central Europe. Rates are somewhat lower in the northern Great Plains of America at 1.1 t/ha/y (central western Minnesota) and 2.2 t/ha/y (south west Manitoba) for typical CT (Li *et al.* 2007). Lobb *et al.* (2007) estimated tillage erosion rate for Canada in 1996, concluding the 50% of the cropped land had unsustainable tillage erosion rates (> 6/ha/y). This was undoubtedly high because of the predominance then of CT (53%) and conservation tillage (31%); the latter was assumed to only reduce the tillage transport factor by one half. NT (16% of area) was expected by the authors to have negligible tillage erosion.

Tillage erosion is important because of net negative effects on crop yield. For example, even with a deep soil in humid Denmark, winter barley yield ranged from 6.1 t/ha (eroding areas) to 7.2 t/ha (aggrading ones) in a hummocky field with more than 100 years history of conventional tillage (Heckrath *et al.* 2005). Similar results were reported across winter wheat in an undulating field in south west England (Quine and Zhang 2002). Accumulation of nutrients in the convex low slope positions

can also contribute to nutrient loss from water overflow and drainage. Tillage erosion will remain a problem, as serious as water erosion, in all undulating lands with tillage, as there seems to be little engineering scope for its reduction, apart from shallower tillage, or NT.

Progress in no-till (NT)

The global history of NT is described by Derpsch (2016), while the most recent numbers relevant to NT come from the estimates of Kassam *et al.* (2019) of the global spread of Conservation Agriculture (CA, see above). It is assumed here that all CA involves NT, but some numbers have been adjusted to give our best estimates in Table 1. The data show that the major adopters are the Americas (mainly USA, Brazil, Argentina and Canada) but also significant acreage in Australia. The data also indicate that there has been a significant increase in area in the 7 years from 2008/09 to 2015/16 (5% p.a.), and there is a large increase in the number of countries reporting the adoption of CA (Kassam *et al.* 2019).

Table 1. No-till (NT) adoption (million ha) by region from 2008/09 to 2015/16 (adapted from Kassam *et al.* 2019, see text).

Region	NT area 2008/09	NT area in 2015/16
South America (Brazil, Argentina, Paraguay, Bolivia, Uruguay, Venezuela, Chile, Colombia)	49.56	69.90
North America (USA, Canada, Mexico)	40.00	63.18
Australia + New Zealand	12.16	22.67[1]
European Union (EU) + Russia	1.66	8.90[2]
South Asia (India, Pakistan, Bangladesh, Nepal)[1]	1.00	4.00[3]
Central Asian States (Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan)	1.30	2.56[4]
China	1.33	9.00[5]
Sub-Saharan Africa	0.48	1.48
WANA (Algeria, Morocco, Tunisia, Sudan, Turkey, Syria, Iraq, Iran, Lebanon)	0.02	0.20
Total	107.51	181.89

[1] Mostly Australia. [2] Mainly due to inclusion of Russian NT. [3] Based on recent estimates from South Asian sources. [4] Mostly Kazakhstan. [5] Much of this may not be NT, even though reported as CA (see later)

However, the question is "how much of this area is true CA (NT, permanent soil cover and rotation) and how much NT lies outside the estimated CA area?" This cannot easily be answered since many of the country statistical departments do not even collect data on NT let alone true CA. On balance, Table 1 is unlikely to overestimate the global area of NT and indicates that a significant and steadily growing number of farmers are adopting NT systems.

Advances in area of NT in last 30 years

NT in the New World NT required effective herbicides, which were developed in the UK and US in the 1950s. Chemical seed bed preparation was started in the early 1960s in Kentucky with well recognised benefits that included conservation of soil and water, and savings of time, labor, and fuel, while often producing higher yields. NT in the US increased to 2.2 million ha in 1973/74, 4.8 million 10 years later (Derpsch 2016), and just over 43 Mha in 2015/16 (Kassam *et al.* 2019).

After USA, the next push on NT came from Brazil in the early 1970s especially with the aim of reducing erosion (Derpsch *et al.* 1986). Planters were imported (from UK and Kentucky) and used to plant NT soybeans in 1972. There were initial difficulties with imported drills and limited numbers of suitable herbicides (paraquat and 2,4D) but, despite this, NT increased from 1,000 ha in 1973/74 to 400,000 ha in 1983/84. The introduction of glyphosate, a broad-spectrum herbicide in the early 1990s, and 'Roundup Ready™' herbicide-tolerant soybeans and maize in the mid-1990s, greatly facilitated NT

adoption. At the same time, Brazilian NT seeding machine manufacturers improved drills to support this revolution. Today Brazil grows soybeans, maize, wheat, barley, sorghum, sunflower, beans and green manure cover crops in rainfed agriculture using NT. Irrigated rice is also increasingly being grown with NT in southern Brazil.
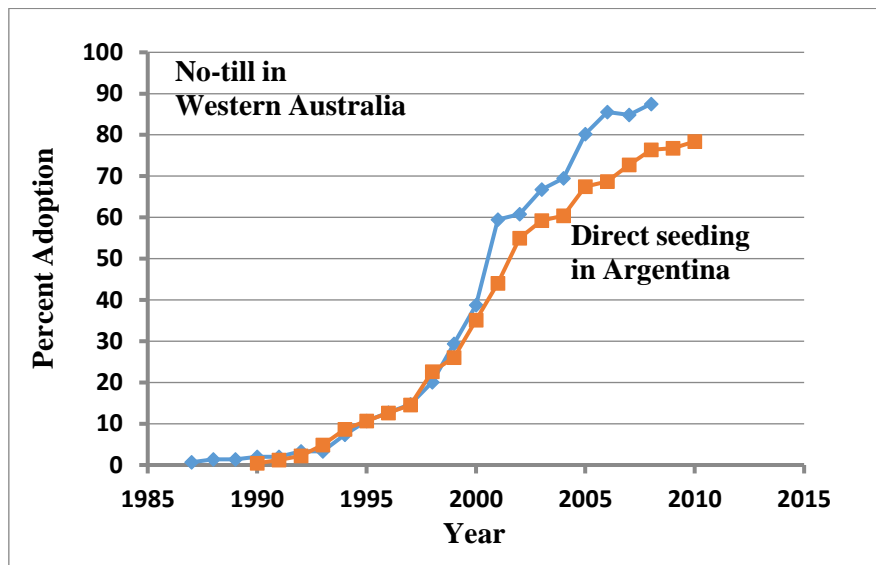

Figure 1. Adoption of no till in Western Australia (Llewellyn *et al.*2012) and in Argentina (Apresid 2012)

Under humid but more temperate cropping of maize, soybean and wheat, Argentina, then Paraguay and Uruguay, followed quickly behind Brazil, as NT (*siembra directa* in Spanish) reached 35 Mha by 2015-16, a revolution again driven by glyphosate, glyphosate-tolerant cultivars, local machinery manufacture and innovative farmers (Ekboir and Parellada 2002). Closely paralleling the rapid adoption of no-till in Argentina was that in Australia (22 Mha in 2015-16, Kassam *et al.* 2019), illustrated in Figure 1. In Australia, NT brought additional advantages when, following herbicide fallow, there was greater pre-sowing soil water storage and earlier seeding, important under the prevailing semiarid conditions (Llewellyn *et al.* 2012). Canada also adopted rapidly, so increasing fallow water storage that continuous cropping became much more common (one crop each year), while in the US Great Plains, NT permitted farmers to eliminate the fallow year prior to wheat or sorghum to reach two crops in three years. The final NT success happened a decade later in northern Kazakhstan (although not the New World), a similar cropping system and environment to that of Saskatchewan, with similar benefits for wheat cropping.

No till in the Old World Progress with NT has clearly been slower in the rest of the world, notably in Europe, West Asia and North Africa (WANA). Management of large amounts of crop residue in the wetter parts of Europe is a major issue, but there are no biophysical reasons why NT should not be successful in southern Europe and WANA as it has been in Australia. Traditional European thinking about the value of deep ploughing, however, seems to be strongly embedded, and issues of farm subsidies stifle change. In WANA, after initial efforts in Morocco in the late 1980s and Turkey in the 1990s, work by ICARDA and ACIAR, now thwarted by unrest, confirmed that NT (promoted as direct drilling) worked well in Syria, Iraq and Morocco (Piggin *et al*. 2015, Loss *et al.* 2015). It is, however, the special efforts to promote NT in South Asia, China and Sub Saharan Africa (SSA) which are of greatest current concern, for these places bring both big benefits for NT according to experiments, but special challenges: unique cropping systems (irrigated and humid subtropics and tropics) and unique farmer typology (small holdings, especially in China, with very limited on and off-farm resources and often a dependence on crop residue for fodder or other uses).

From the late 1980s, *India and Pakistan* had steady growth in NT research on wheat in the dominant rice-wheat irrigated system (over 13.5 M ha) of the IndoGangetic Plain (IGP). Traditionally, crop residue was removed during hand harvesting (sometimes then used for feeding) leaving just the

anchored straw. Rice was transplanted into cultivated (to 15-20 cm) and puddled soil at the onset of the monsoon in June-July. After rice harvest, in October-November and removal or burning of rice straw, a seedbed was prepared by irrigation and multiple cultivations and planking (levelling), into which wheat was broadcast and covered by harrowing. Local drills for line seeding (20 cm rows) of wheat came first, followed by direct NT seeding, initially based on an imported drill from New Zealand (Hobbs *et al.* 2017), soon to be followed by locally-adapted and manufactured drills. NT wheat saved water and cultivation costs and facilitated the management of some grass weeds. There was no yield loss of NT at the same sowing date as CT, but most importantly, NT permitted earlier sowing and higher yields since the wheat avoided late season heat stress. As rice straw removal declined with the spread of mechanical harvesters and as straw burning caused serious air pollution, the next challenge was seeding without removal of the rice straw, and several innovative NT seeders were successfully developed for this purpose in India (Sidhu *et al.* 2015, see later). A further imperative, driven partly by the growing cost of rural labour, was to move rice to direct seeding into cultivated or preferably uncultivated seedbeds (Landers 2018, Hobbs *et al.* 2019); transplanting into non-puddled soils was also tried. Direct seeding of rice is challenging because of weed control difficulties, the high cost of hybrid rice seed where used, and possible seedling death due to heavy early monsoon rains (Chakraborty *et al.* 2017). Advantages, however, are that NT wheat always yields more after non-puddled rice and there were significant savings in water and labour (Hobbs *et al.* 2017). At the same time NT was being introduced, a low-cost laser leveler was developed in India and Pakistan and popularised by local custom service providers; water was saved and waterlogging reduced, especially when combined with bed planting (Naresh *et al.* 2014, but see later).

The technical developments in the IGP rice-wheat system described here, according to extensive experimentation, have led to a steady increase in profit (increased yield and reduced cost), a reduction in irrigation water use, and a reduction in overall global warming potential. This is summarised in Hobbs *et al.* (2017, 2019) and highlights the development of a double crop CA package for the rice-wheat system of the IGP. To date only the laser levelling and the NT seeding of wheat have had significant adoption by farmers; estimates put NT wheat at around 4.0 M ha (Table 1, Paroda 2018). In the IGP the main drivers of early NT adoption in wheat have been fuel costs, earlier planting and better control of herbicide-resistant grassy weeds (fewer of these weeds germinate in NT); there is little soil erosion, taking away a major incentive for NT seen elsewhere.

China has around 135 M ha arable land with much intense tillage (to 15-20 cm depth) and negative consequences especially as the system became mechanised after 1970 (Wang *et al.* 2007). Erosion was particularly bad in the drier northern and western regions. Research on conservation tillage and NT began in the late 1980s with the rainfed spring maize system in the Loess Plateau soon spreading to the winter wheat system there, and the winter wheat-summer maize double crop system in the more humid North China plain (Wang *et al.* 2007). These authors summarise numerous experiments where erosion was markedly reduced under NT (with residue retention). Yields under NT were equal to or slightly higher than those from CT, especially in dry years, because of extra stored soil water at sowing; disadvantages in wet years were related to lower soil temperatures and slower early growth. The larger meta-analysis of Wang *et al.* (2018) focused strictly on NT *versus* CT: they showed on average NT yield was only 2% above CT (n = 275) for wheat and 5% higher for maize (n = 155). Standard deviation of individual responses between diverse locations appeared, however, to be quite high (27% and 31% respectively). The only significant effect of experimental conditions was a decrease in the wheat response from +7% to +5% to -10% as mean annual precipitation increased from <400 mm to 400-600 mm and >600 mm, respectively, and a tendency for the NT yield advantage to increase after 6 years of continuous NT. A similar diversity of responses to NT was seen in a meta-analysis of rice experiments across southern China by Huang *et al.* (2015): the mean effect on grain yield was not significant (+0.4%, n = 265), with 7% standard deviation of individual responses. Although this variation was unrelated to establishment method (transplant, seedling throwing, direct seeding), NT, under which plants generally tillered less, was clearly superior (+5%, n = 60) in the low radiation humid south west (CT tended to tiller excessively) and somewhat better when fertility was higher, especially early N supply.

Notwithstanding promising early results, CT dominated in China until 2006. The jump since then in CA to over 8 Mha in 2013-14 (*e.g.* Li *et al.* 2016, also Table 1) appears to be explained by confusion in interpreting official statistics on conservation tillage as CA; the true NT area is likely smaller. This reduction in tillage is undoubtedly a move in the right direction, as confirmed by small yield increases on average in the meta-analysis of Li *et al.* 2016 (+4.5% wheat, +8.3% maize, +1.5% rice) and appears to have involved shallower tillage, greater use of rotovation as strip tillage, as well as efforts to maintain residue cover. The limited move to NT, in particular CA as defined here, despite some promotion by government agencies, may reflect the diversity of cropping situations across China as emphasised in the above meta-analyses. More specifically, while most farms remain small (<1 ha), inadequate mechanisation and skills for crop residue handling continues to be a major constraint (A.D. McHugh *pers comm*). In addition, the observation of yield losses with NT (*e.g.* Wang *et al.* 2018) may be a special problem of the Loess Plateau, given the ready compactability of the generally light textured soils. For example, in an ACIAR-funded study (1992-2003) in Linfen, Shanxi Province, a single deep chiselling (30 cm), followed by NT and controlled traffic lifted winter wheat yields 10% over CT involving 20 cm deep plowing every year and no controlled traffic (Chen *et al.* 2008), with even better benefits for the yield of spring maize. A separate ACIAR project at Xifeng (Gansu), also in the Loess Plateau but without controlled traffic, found small yield reductions with NT over 10 years (winter wheat -8%, maize -7%, soybean -4%) compared with regular 30 cm chiseling, although the negative effect was less with residue retention (Li *et al.* 2018). A unique problem with crop residue in northern China is that it is used for winter heating, both in traditional houses and nowadays whole towns. Another is that plastic film mulch reduces evaporation more than residue mulch, while bringing other benefits (warming, weed control).

No-till and CA have been quite controversial in *Sub-Saharan Africa* (SSA), where some of the earliest NT experiments in the tropics were initiated at IITA in Nigeria (Lal *et al.* 1978) and in Zimbabwe and South Africa in the 1970s, mainly using tractor drawn seeding equipment, with fuel and cost efficiency as the main drivers (Wall *et al.* 2014). However, soils in SSA have had a serious decline in soil fertility and soil organic matter and become more compacted, acidic, micro- and macro-nutrient deficient and prone to erosion after many years of traditional farming (Zingore *et al.* 2005, Craswell and Flek 2013). Fallowing and opening up new land (shifting agriculture) is no longer an option. Promotion of CA on smallholder farms started in 1982/83 and intensified in 2000 (Haggblade and Tempo 2003). Tractors were not available, so CA was based on manual (jab planting into basins) and animal drawn rippers (Johansen *et al.* 2012). Crop residues are considered vital for increased soil moisture and a way to offset dry periods (Thierfelder and Wall 2009). But in much of SSA, crop residues are a scarce resource needed for animal feed or by pastoralists in the dry season (Wall 2009, Valbuena *et al.* 2012). Weed control, traditionally requiring huge labour inputs, has also been a major deterrent for adoption of CA by smallholder farmers in SSA (Muoni *et al.* 2013). Use of herbicides helped spur adoption of CA but accessibility, cost and environmental concerns led to controversies about use (Lee and Thierfelder 2017). Overall adoption of NT in SSA has been disappointingly small (Table 1).

Lessons from the global adoption experience with NT

There have been multiple drivers of farmer adoption of NT that differed between regions, and which happened rapidly after an initial lag phase in the New World (*e.g.* Figure 1). Water erosion reduction was a big driver in humid locations (*e.g.* eastern USA, southern Brazil, Argentina) while, in semi-arid areas, it was greater water conservation in herbicide fallows, which preceded NT sowing (Australia, Western Great Plains of North America, Kazakhstan), as was evident 30 or so years ago from fallowing studies (Fischer 1987). RoundupReady® varieties of maize and soybean facilitated NT adoption in the Americas.

Negative NT effects on yield were always prominent in farmers' thinking, but generally these turned out to be minor, especially with more years of NT experience and soil improvement. Yields were often higher when NT led to greater stored soil water and more timely planting of crops (Australia, South Asia and SSA). This aspect was examined by Pittelkow *et al.* (2015) in a global meta-analysis (678 studies with 6005 paired observations of NT versus CT from 50 crops and 63 countries, but dominated by high latitude, cold winter environments). They reported that latitude, crop category, aridity index,

residue management, no-till duration and N-rate were important factors influencing the overall negative yield response of 5.1%. The NT effect was greater in the tropics (-15.1%, n=521) and least in temperate zones (-3.4%, n=4824). NT yields matched CT in oilseed, cotton and legume crops but in cereals highly significant negative impacts were evident, though smaller in wheat (-2.6%, n=260) and higher in rice (-7.5%, n=31) and maize (-7.6%, n=224). NT was best under drier conditions with equal or higher yields compared with CT, when this gain was especially favoured by residue retention, at least for maize as has been also clearly shown for both rainfed and irrigated wheat-maize cropping in Mexico (Verhulst *et al.* 2009). Pittelkow *et al.* (2015) also found that, in the first two years, NT yields were lower but, from 3-10 years, tended to match CT yields, except for maize and wheat in humid climates. Moreover, these authors did find that the negative effects of NT on yields decreased with increased N-fertiliser and crop rotation. There were unraveled interactions and factor covariances in Pittelkow *et al.* (2015) and, under particular circumstances reported elsewhere in this Chapter, NT with residue retention produced consistent small positive effects on wheat and maize yields compared with CT in both Mexico and South Asia, even without benefits of extra soil stored water at planting.

A key factor in accelerating the adoption of no-till everywhere but rarely surveyed has been the steady development of appropriately-sized robust NT seed drills; the unique Indian Happy Turbo seeder is an excellent example of this. A feature especially in South America, and also Australia and India, has been the private sector working together with innovative farmers to develop a whole array of NT drills for different crops and local situations, including various versions of seeding openers (*e.g.* in Baker *et al.* 2006 and see Chapter 6). Finally, once peer pressure to stay with traditional ploughing is vanquished, and that has been a major issue everywhere, there have also been unanticipated benefits from NT, in particular farmers having more time with family and community.

Above we have described rapid NT adoption in modern agricultural situations. Its non-adoption in such situations appears related to the problem of heavy straw loads, their mechanical handling, and the depressing effect on spring soil temperature at high latitudes. The increased disease and pest problems expected with no-till and especially residue retention has not proven to be as big an issue as anticipated; this may be related to an increase in soil biodiversity and diseases suppression (see later). However regular herbicide use fostered the widespread evolution of weed resistance to herbicide, a challenge not unique to NT (discussed briefly later and in other chapters).

The slow or non-adoption of no-till in many developing countries, however, remains a huge challenge. Here cropping is characterised by small landholders, with (IGP, China) or without (SSA) substantial experience of modern agricultural technologies. A bigger role for government incentives and involvement in extension and promotion of no-till appears necessary. The closely studied IGP is illustrative. For example, Loch *et al.* (2018) explored in depth the adoption of NT wheat after rice, nowadays a well adopted NT technology, but still slower and lower adoption than expected in view of the large per ha financial benefits for adopters. They suggest that governments have not recognised the complexity of these new technologies and have failed to institute or enforce supportive policies for NT (*e.g.* enforcing no-burning laws, stopping subsidies of electricity for pumping so the extra water used in CT is felt in farmer costs). They argued that the service sector (*e.g.* custom hiring) had a key role, as it had previously fulfilled with laser levelling in the IGP. However, this was neglected by government, and the public extension services have been stretched and inadequate, especially with industry and farmer engagement, and even non-supportive of NT.

The experience in India confirmed without doubt the *sin qua non* for NT of appropriate local drills, in this case ones suited to the small four-wheel tractors of the region. The imported NZ seed drill was quickly modified by engineers from Pantnagar University in UP, India, adding its inverted-T openers to the traditional, locally manufactured wheat drill (Hobbs *et al.* 2017*)*. This simple three-point mounted NT drill worked well in the absence of trash. However, farmers shifted to hire of combine harvesters which left loose rice residue on the soil thereby creating problems with the above fixed tyne NT drill. The farmers burnt the rice residue (whether they used NT or CT) but burning of residues plus NT has been shown to be an inferior treatment for wheat yield and is now illegal due to the extreme pollution caused. This led to the development of NT seeders that could plant into loose rice stubble. This involved researchers (local and foreign), local manufacturers and, most importantly, innovative farmers. The

result was the 'Happy Turbo' seeder (Sidhu *et al*. 2015), bringing equal yields and all the benefits of residue retention. These new drills were more expensive, but are now subsidised substantially by the Government, with over 10,000 produced in 2018 (H. Sidhu pers comm). The custom hire model for such drills is becoming more common. With much poorer farmers and smaller fields found in the eastern IGP, Bangladesh and SSA, even smaller machinery such as two-wheel tractors with attached drills may be key for NT adoption (Biggs and Justice 2015). At the outset of the NT revolution in Brazil, bullock drawn NT drills and hand-operated jab planters, both for maize, were successfully developed for small farmers. There are lessons from Asia for NT adoption in SSA (Baudron *et al.* 2015, Hobbs *et al.* 2019). Key suggestions include combining CA with two-wheel tractors and other complementary agronomic practices not specific to CA, and functional markets. Also included is the development of a service provider system, since farmer ownership of tractors may not be viable.

Long term effects of no till: soil physics, chemistry and biology

Tillage is well known to have many negative effects including degradation of soil physical and biological properties, and loss of soil organic carbon (SOC) . NT systems were expected to reverse this. However, soil changes occur gradually, and careful long-term experiments were needed for their detection. Results on chemical, physical, and biological changes of long-term NT, both with and without crop residue retention, are now widely available, and it is SOC which is considered the key measure.

Soil organic carbon (SOC)

Thirty years ago, there was the expectation that NT, especially accompanied by residue retention, would build SOC, with multiple benefits, including C sequestration. This is a long-term issue, because:

- several years are necessary in order to accurately measure SOC changes; and
- effects on SOC are likely to become attenuated as new SOC equilibrium values are reached.

Measuring changes in SOC in NT vs CT comparisons turned out to be a complex task, requiring *inter alia* attention to adequate sampling depth and to bulk density changes (Baker *et al.* 2007).

Rothamsted Experimental Station, UK, has been at the centre of many efforts to quantify better SOC changes. Powlson *et al*. (2014) argued that the possibilities have been largely overestimated by the early proponents of NT and that proper soil sampling to depth suggests average sequestration rates to be no more than 0.3 t C/ha/y and possibly only half of this, even if SOC in the top 10 cm or so increases notably. A more recent meta-analysis of tropical cropping (IGP and SSA) found similar numbers (Powlson *et al.* 2016) as were assumed to prevail by Minasny *et al.* (2017) in their effort to promote annual global C sequestration at 4 ppm across all agricultural lands. Sapkota *et al.* (2017) found, after 7 years of NT with rice-wheat in the IGP, that returning a total of 2.1 t/ha/y of C in crop residues led to an increase in SOC of 0.5 t C/ha/y (0-60 cm, but predominantly from 0-15 cm). Martinez *et al.* (2016) in a detailed 20-year comparison in Switzerland of CT and NT under diverse crop rotations, with winter cover cropping where appropriate and crop residue retention in all treatments, found no changes in SOC (0 -50 cm). Perhaps surprisingly, in all the reviews, and in the comprehensive study of long term SOC changes at Rothamsted of Poulton *et al*. (2018) (which unfortunately lacked NT treatments), there is clearly no big C sequestration benefit from crop residue retention. A simple yet poorly appreciated explanation of this is that stable SOC, largely humus, has a relatively stable C:N:P:S nutrient ratio (Kirkby *et al.* 2016) and that C accumulation may be restricted in many circumstances by limited availability of the other nutrients (see Chapter 16).

Despite the general consensus above, higher rates of SOC accumulation under NT systems have been reported in Brazilian studies, as recently summarised in de Morais Sá *et al.* (2017), with C sequestration rates (0-100 cm) under NT of 1.4-2.1 t C/ha/yr for tropical cropping and 0.5 to 2.0 t C/ha/y for subtropical. Several aspects of NT are unique to Brazil – high rainfall, highly weathered oxisols, recent clearing with high doses of lime to overcome the low pH and high exchangeable aluminium, and high phosphorus applications on P fixing soils. In these soils there has been a large increase in crop residue C (and associated N, P and S) returned to the soil, with SOC increases generally proportional to this surface quantity of C. Under favourable NT conditions, soil C levels to 100 cm are returning to the

levels encountered in nearby remnant native vegetation with oxisols (de Oliveira *et al.* 2016, Corbeels *et al.* 2016) and even ultisols (Diekow *et al.* 2005). Claims of such high C sequestration with NT are recognised as controversial (*e.g.* de Marais Sá *et al.* 2017), but the question now is whether SOC, once returned to the original levels, can be raised even higher under their high biomass-return NT system, although SOC is not expected to increase indefinitely.

Soil physics

The effect of surface residue on protecting bare soil from raindrop action and crusting, thereby enhancing infiltration, is a universally recognised benefit. As for other soil physical properties, the expectations regarding improvements with NT have largely been vindicated provided adequate crop residue has been returned. For example, data from a twenty-two-year experiment looked at impacts on soil physical and carbon sequestration in Central Ohio (Kahlon *et al.* 2013) are fairly typical. The data show significant positive effects of mulch and of NT on soil physical attributes; soil porosity, water infiltration rate, saturated hydraulic conductivity, mean particle size and water stable aggregates, and negative effects on penetration resistance; there was also a tendency for a beneficial interaction between mulch and NT. They conclude that "use of NT plus mulch application enhances soil quality with respect to soil mechanical, hydrological properties along with carbon concentration in the soil". Gathala *et al.* (2011) used a 7-year rice-wheat rotation experiment in Uttar Pradesh, India, to look at soil physical properties using different crop establishment methods. Stubbles were incorporated in conventional puddling and tillage, but NT plots were seeded into standing anchored stubbles. NT treatments had lower bulk densities, lower soil penetration resistance, more water stable aggregates and higher infiltration of water compared with cultivated puddled treatments.

Soil biology

Soil biodiversity (macro and micro) is receiving more attention recently because it influences numerous ecosystem services; new molecular tools have facilitated its study (*e.g.* Kibblewhite *et al.* 2007). This is often presented under the vague label of 'soil health', but its connections to crop performance have rarely been elucidated. Govaerts *et al.* (2008) did look at tillage, residue management and crop rotation effects on selected soil micro-flora in a rainfed maize-wheat system long-term trial in the sub-tropical highlands of Mexico. Crop residue retention resulted in increased microbial biomass and respiration and increased populations of soil micro-flora that promote plant growth and suppress diseases. NT with residue showed equal or higher populations of beneficial micro-flora compared with CT, but no-till without residue did not. More importantly, Govaerts *et al.* (2006) showed higher populations of root rots and parasitic nematodes when residues were removed, confirming that zero-tillage without residue is clearly an unsustainable practice. Microbial diversity increased under NT with residue retention such that they suggest it is useful for biological control and integrated pest management). Parasitic nematodes were studied in Zimbabwe comparing CA under basin and rip NT with CT over two years (Mashavakure *et al.* 2018). NT had around 50% higher plant-parasitic nematode richness than CT, but maize yields were not related to this, being about 80% higher with NT. Other studies have shown that crop residue retention can favour diseases which sporulate on the residue (*e.g. Fusarium* in wheat, black leg in canola). Many more studies looking at specific pathogens are needed (see also Chapter 11).

Macrofauna including earthworms are an important component of the soil biota and many studies confirm that the latter are consistently favoured by NT, and usually by increased residue retention, one indirect effect of which is the development of continuous biopores, markedly enhancing water infiltration. Epigeal arthropods and beneficial soil dwelling organisms were also studied in the long term rainfed maize-wheat system using CA in central Mexico (Rivers *et al.* 2016). Higher spider populations were found in NT with residue retention and may contribute to the biological control of insect pests.

Greenhouse gas (GHG) emissions and climate change

While tillage effects on net soil CO_2 emissions are reflected largely in SOC accumulation already discussed, effects on methane and nitrous oxide (N_2O), two powerful GHGs, are less clear. Methane arises from methanogenesis of organic material under anaerobic soil conditions. Tillage systems that

encourage anaerobiosis through poor soil porosity and drainage can boost methane emissions. Thus puddled, flooded rice culture contributes approximately 1.5% of all global CO_2 emissions. Relative to this, other tillage effects on methane emissions are likely minor. N_2O, an even more powerful GHG, arises as a byproduct of both nitrification and especially denitrification, the latter favoured by anaerobiosis, associated with poor porosity and drainage and with high oxygen consumption from decomposing plant residues; anoxic microsites may also play a role. A meta-analysis by van Kessel *et al.* (2013) of experiments (excluding rice experiments) at 45 locations (239 comparisons) found that compared with CT, reduced till (62 observations) and NT (177 observations) had no significant effect on N_2O emissions (95% range of effects was from about -8% to +11%); with experiments of greater than 10 years duration N_2O was significantly reduced relative to CT (-10%); also deeper fertiliser N placement reduced NT emissions relative to CT. Chakraborty *et al.* (2017) in a global analysis of rice crops, found direct seeded NT had considerably higher N_2O emissions than CT puddled transplanted (but methane emissions were much less). Mei *et al.* (2018) conducted meta-analysis (6 out of 40 common studies with van Kessel *et al.* 2013, 9 out of 40 involving rice). Comparisons with CT showed increases in N_2O emissions with NT (+19.2%, P < 0.05, n = 167), and with reduced till (+ 12.3%, P < 0.10, n = 45). However, many factors, some interacting, appeared to influence this relative boost in N_2O emissions (*e.g.* reduced in longer term experiments, cooler soils, rainfed *vs* irrigated system, but increased with residue retention, especially where silt content was higher). A general theory for tillage, especially NT, and N_2O emissions needs more research to unravel key factors, which were likely covarying in the above meta-analyses. It is worthwhile noting that Tullberg *et al.* (2018) found N_2O emissions were reduced on average by over 50% across 6 sites in Australia with NT seeding into non-trafficked, non-compacted areas compared to the compacted traffic lane and to the randomly-trafficked control. Finally a climate component often overlooked is the cooling arising because surface residue can increase the surface albedo, commonly 0.2 for tilled soils, to around 0.3 (Davin *et al.* 2014).

New developments in no-till (NT)

Weed resistance to herbicides

In the book "Tillage" in 1987, herbicide resistance rated one page. Yet today this is probably the biggest challenge to the sustainability of modern cropping and especially NT systems (see Chapter 10); it has been exaggerated by herbicide-resistant crop cultivars but was already a growing problem before their arrival in the late 1990s, especially with fallow weed control. As well as rotating amongst suites of herbicides, use of integrated weed management (IWM) is essential, and sometimes tillage (see Chapter 7), despite the possible loss of some NT gains in useful soil traits; perhaps automated shallow precision hoeing targeting only weeds (Gerhards 2019) can lessen this need for full tillage. Sustainable cropping, especially NT cropping, will require greater weed management skills, posing special challenges for many small holders in the developing world.

Conservation Agriculture

Conservation Agriculture (CA) was a follow up to conservation tillage and then NT, having its first world congress in 2001. CA promotes the principles developed by Brazilian researchers and farmers in the latter decades of the 20th century (Kassam *et al.* 2019). CA was promoted by FAO and others to enhance the sustainability and resilience of small holder crop production systems (FAO 2011). CA counters the three components of tilled agriculture that have been shown to lead to soil and land degradation – mechanical disruption, organic matter loss, and continuous monoculture. All other components of productive agricultural systems are just as much a part of CA systems as they are of CT ones.

CA clearly represents an aspirational goal, which most agronomists would agree points to desirable outcomes, but would argue this can only be achieved gradually by applying initially only one or two of the principles. Morever, inflexible adherence to the three principles together, as appears sometimes, can distort research agendas and dampen farmer interest in adoption of its components, which is more likely to be stepwise and must always be financially rewarding in the short term (Giller *et al.* 2015). NT plus moderate residue retention is likely to be positive and acceptable as a first step if diseases permit.

Green manure cover cropping

There has been a resurgence of interest in green manure cropping, particularly in humid subtropical Brazil and humid temperate North America and Europe, but also in Australia (see Roper *et al.* 2012). Reasons differ, as reviewed by Blanco-Canqui *et al.* (2015), but green manure cover crops are ideally suited to NT because they need to be planted as soon as possible after a main grain crop is harvested (or even relay planted before harvest); planting costs need to be kept low. A common aim is to deliver soil protection from water erosion and to reduce winter-spring drainage and nitrate leaching in humid climates. They also offer N accumulation if legumes are included, as well as unique weed control options, such as knock down herbicides (brown manure) and knife rolling just ahead of the main crop, which may also be NT sown. Apart from grazing, cover crops are by definition not harvested for grain or hay.

In southern subtropical Brazil, rainfall exceeds 1000 mm, allowing two crops per year without irrigation, usually a wheat-soybean system planted with NT. However, wheat blast (*Magnaporthe oryzae)* has become a problem and farmers have found replacing wheat with cover crops increased profits through reduced costs and increased soybean yields (Calegari *et al.* 2014). Further north in the Cerrado region, annual rainfall is even higher with a wet season of 7-8 months, still enough for a double crop of NT soybean followed by NT maize; pasture species (*e.g. Brachiaria* spp), interrow NT planted with the maize, are being tested as a viable grazed cover crop option for the relatively short dry period (de Moraes Sá *et al.* 2017). Reasons for cover cropping in temperate North America and Europe are more related to environmental protection (reduce nitrate pollution of waterways), and hence are often controlled by incentives and regulation.

Permanent raised bed planting systems

Permanent raised bed planting (PB) is a variation of CA that was researched in Mexico in the 1990s by Sayre *et al.* (2005), and then introduced to South Asia as a way to reduce costs and improve water productivity in irrigated systems. Essential components are laser levelling, residue retention and NT sowing of all constituent crops into the flat top of the bed; furrows may be reformed between crops, but beds are never tilled or trafficked, automatically bringing the advantages of NT and controlled traffic. Bed planting of wheat was adopted by farmers in the Yaqui Valley, Sonora, Mexico, for easier weed and water control and water savings in the 1980s, but beds were tilled and reformed with every crop (Aquino 1998). NT and permanent beds were introduced to these farmers in the 1990s (Sayre and Hobbs 2004) but never widely adopted. This system of planting was extended, largely via ACIAR projects, to South Asia and China, where small seed drills for bed planting were developed along with narrow tractor tyres to avoid bed damage (Akbar *et al.* 2016). The compacted furrows help speed the flow of water across the field and the wetting of the beds especially if furrow diking is used. This is also an appropriate way to harvest rainwater in rainfed, arid and semi-arid situations (Govaerts *et al.* 2007). Significant yield and water saving benefits have been recorded with wheat-maize double cropping on irrigated permanent (NT, residue retained) raised beds in Mexico (Hobbs and Sayre 2004), Pakistan (Akbar *et al.* 2016), northwest India (Naresh *et al.* 2014), and China (Wang *et al.* 2004, but only wheat on non-permanent beds); a special advantage is alleviation of waterlogging damage to maize in monsoonal climates. NT and permanent raised beds also worked well for rice-maize in Bihar, India (Jat *et al.* 2019), but rice has not consistently performed well on raised beds elsewhere in the IGP, probably due to mineral deficiencies in the aerobic environments.

Conclusion

Tillage has evolved: tillage that is shallower and less intense than 30 years ago now predominates. No-till, commonly with residue retention, continues to deliver many advantages, especially for the soil. Global adoption is rising rapidly, but is still no more than about 15% of global crop area, well below potential; herbicide resistance weeds probably remain the biggest concern globally for users of NT. The lagging NT adoption by small holders around the world is a special challenge, particularly with irrigated rice culture. The impact of NT plus residue retention on soil carbon sequestration is positive but less than expected, and the exact magnitude is disputed: effects on nitrous oxide emissions appear to be

variable. Permanent raised-bed NT cropping has yet to realise its early experimental promise for irrigated field cropping.

NT is expected to continue to grow rapidly but there needs to be better attention to definitions in official statistics. Also, special farmer education, extension and policy interventions will be needed with small holders. Innovations in drilling machinery will remain critical, especially as autonomous vehicles begin to appear. Weeds will be managed with integrated systems including herbicide application and mechanical removal under precision targeting, and hopefully new knockdown herbicides. Much more research is needed on soil pathogens and biota in general, in hand with efforts to increase cropping diversity, on NT effects on nitrous oxide emissions, and on strategies to manage compaction. Excessive straw amounts are likely to be handled by removal and local processing for energy, bedding, compost and feed.

References

Aapresid (La Asociacion Argentina de Productores en Siembra Directa) (2012) Evolucion de la superficie en siembra directa en Argentina. Campanas 1977/78 a 2010/11 www.aapresid.org.ar

Akbar G, Ahmad MM, Asif M, Hassan I, Hussain Q, Hamilton G (2016) Improved soil physical properties, yield- and water productivity under controlled traffic, raised-bed farming. *Sarhad Journal of Agriculture* **32(4)**, 325-333

Aquino P (1998) The adoption of bed planting of wheat in the Yaqui valley, Sonora, Mexico. *Wheat Special Report* 17a. CIMMYT, Mexico

Andrade-Sanchez P, Upadhaya K (2019) Precision tillage systems. In 'Precision agriculture for sustainability' (Ed. J. Stafford) pp 273-284 (Burleigh Dodds Science Publishing: Cambridge, UK)

Antille D, Chamen T, Tullberg J *et al.* (2019) Controlled traffic farming in precision agriculture. In 'Precision agriculture for sustainability' (Ed. J. Stafford) pp 239-272 (Burleigh Dodds Science Publishing: Cambridge, UK)

Baker CJ, Saxton KE, Ritchie WR *et al.* (2006) 'No-tillage seeding in conservation agriculture' (Eds. Baker CJ and Saxton KE). 2nd Edition (FAO and CAB International)

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration − what do we really know? *Agriculture, Ecosystems and Environment* **118**, 1-5

Baudron F, Sims B, Justice S *et al.* (2015) Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheeled tractors, conservation agriculture, and private sector involvement. *Food Security* **7**, 889-904

Biggs S and Justice S (2015) Rural and agricultural mechanization. A history of small engines in selected Asian countries. IFPRI Discussion Paper 01443, May 2-15

Blanco-Canqui H, Shaver TM, Lindquist JL *et al.* (2015) Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal* **107**, 2449-2474

Botta GF, Jorajuria D, Balbuena R, *et al.* (2006) Deep tillage and traffic effects on subsoil compaction and sunflower (*Helianthus annus* L.) yields. *Soil and Tillage Research* **91**, 164-72

Calegari A, de Araujo AG, Costa A *et al.* (2014) Conservation agriculture in Brazil. In (Eds. RA Jat, KL Saharawat, A Kassam) 'Conservation Agriculture: Global Prospects and Challenges' pp 54-88 (CAB International: Wallingford, UK)

Chakraborty D, Ladha JK, Rana DS *et al.* (2017) A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Scientific Reports* **7,** 9342

Chen H, Bai Y, Wang Q *et al.* (2008) Traffic and tillage effects on wheat production on the Loess Plateau of China: 1. Crop yield and SOM. *Australian Journal of Soil Research* **46**, 645-651

Corbeels M, Marchão RL, Sequiera Neto M, *et al.* (2016) Evidence of limited carbon sequestration in soils under no-tillage systems in the Cerrado of Brazil. *Scientific Reports* **6,** 21450

Craswell ET, Vlek PLG (2013) Mining of nutrients in African soils due to agricultural intensification. In 'Principles of Sustainable Soil Management in Agroecosystems', Advances in Soil Science' (Eds. R. Lal and B.A. Stewart) pp 401-422 (CRC Press: Boca Raton, LA)

Davin EL, Seneviratne SI, Ciais P *et al.* (2014) Preferential cooling of hot extremes from cropland albedo management. *Proceedings National Academy of Sciences* **111**, 9757-9761

de Morais Sá J, Lal R, Cerri CC *et al.* (2017) Low carbon agriculture in South America to mitigate global climate change and advance food security. *Environmental International* **98**, 102-112

de Oliveira Ferreira A, Amado T *et al.* (2016) Can no-till grain production restore soil organic carbon to levels natural grass in a subtopical Oxisol? Agriculture, Ecosystems and Environment **229**, 12-20

Derpsch R, Sidiras N, Roth CH (1986) Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Parana, Brazil. *Soil and Tillage Research* **8,** 253-263

Derpsch R. (2016) Historical review of no-tillage cultivation of crops. www.rolf-derpsch.com/en/no-till/historical-review/#c582

Diekow J, Mielniczuk J, Knicker H *et al.* (2005) Soil C and N stocks as affected by cropping system and nitrogen fertilization in a southern Brazil Acrisol managed under no-tillage for 17 years. *Soil and Tillage Research* **81**, 87-95

Ekboir J, Parellada G (2002) Public – private interactions and technology policy in innovation processes for zero tillage in Argentina. In 'Agricultural Research Policy in an Era of Privatization' (Eds. D Byerlee and R Echeverria) pp 137-154 (CABI Publishing: Wallingford)

FAO (2011) 'Save and Grow: a Policymaker's Guide to Sustainable Intensification for Smallholder Crop Production' 112 pages. ISBN 978-92-5-106871-7

Fischer RA (1987) The responses of soil and crop water relations to tillage. In (Eds. PS Cornish JE Pratley) 'Tillage: New Directions in Australian Agriculture' pp 194-221 (Australian Society of Agronomy, Inkata Press: Melbourne)

Gathala MK, Ladha JK, Kumar V, Saharawat Y, Kumar V, Sharma PK (2011) Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice-wheat rotation. *Soil Science Society of America Journal* **75** (5), 1851-1862

Gerhards R (2019) Precision weed management systems. In 'Precision Agriculture for Sustainability' (Ed. J. Stafford) pp 399-420 (Burleigh Dodds Science Publishing: Cambridge, UK)

Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture *Frontiers in Plant Science* **6**, article 870

Godwin R. Misiewicz P, While D *et al.* (2015) Results for recent traffic systems research and the implications for future work. *Acta Technologica Agriculturae* **3**, 57-63

Govaerts B, Mezzalama M, Sayre KD *et al.* (2006) Long term consequences of tillage, residue management and crop rotation on maize/wheat root rot and nematode populations in subtropical highlands. *Applied Soil Ecology* **32**, 305-315

Govaerts B, Sayre KD, Lichter K *et al.* (2007) Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. *Plant and Soil* **291**, 39-54

Govaerts B, Mezzalama M, Sayre KD *et al.* (2008) Long term consequences of tillage, residue management and crop rotation on selected soil micro-flora groups in subtropical highlands. *Applied Soil Ecology* **38**, 197-210

Grassini P, Cassman KG (2012) High-yield maize with large net energy yield and small global warming intensity. *Proceedings National Academy of Sciences* **109**, 1074-1079

Haggblade S, Tempo G (2003) Conservation farming in Zambia. EPTD Discussion Paper No. 108. 113 pp (IFPRI, Washington DC)

Hamza MA, Anderson WK (2005) Soil compaction in cropping systems. A review of the nature, causes and possible solutions. *Soil and Tillage Research* **82**, 121-145

Heckrath G, Djurhuus J, Quine TA *et al.* (2005) Tillage erosion and its effects on soil properties and crop yield in Denmark. *Journal of Environmental Quality* **34**, 312-324

Hobbs P, Gupta R, Jat, RK, Malik RK (2017) Conservation agriculture in the IndoGangetic Plains of India: Past, present and future. *Experimental Agriculture*, Published online: 19 September 2017, pp. 1-19

Hobbs P, Thierfelder C, Wall P *et al.* (2019) The role of crop and cropping system management in Conservation Agriculture systems. In (Ed. A Kassam) 'Advances in Conservation Agriculture' Volume 1: Systems and Science.' Chapter 6, 29 pp. (Burleigh Dodds Science Publishing Limited: Cambridge, UK)

Huang M, Zhou X, Cao F *et al.* (2015) No-tillage effect on rice yield in China: a meta-analysis. *Field Crops Research* **183**, 126 -137

Ibramhi A, Bentaher H, Hamza E *et al.* (2017) 3D finite element simulation of the effect of mouldboard plough's design on both the energy consumption and the tillage quality. *International Journal of Advances Manufacturing Technology* **90**, 473-487

Johansen C, Haque ME, Bell RW *et al.* (2012) Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. *Field Crops Research* **132**, 18-32

Jat RK, Singh RG, Kumar M *et al.* (2019) Ten years of conservation agriculture in rice-maize rotation of eastern Gangetic Plains of India: Yield trends, water productivity and economic profitability. *Field Crops Research* **232**, 1-10

Kahlon MS, Lal R, Anne-Varughese M (2013) Twenty two years of tillage and mulching impacts on soil physical characteristics and carbo sequestration in Central Ohio. *Soil and Tillage Research* **126**: 151-158

Kassam A, Friedrich T, Derpsch R (2019) Global spread of Conservation Agriculture. *International Journal of Environmental Studies* **76**, 29-51

Kibblewhite MG, Ritz K, Swift MJ (2007) Soil health in agricultural systems. *Philosophical Transactions of the Royal Society Series B* **363**, 685-701

Kirkby CA, Kirkegaard JA, Richardson AE *et al.* (2011) Stable soil organic matter: a comparison of C:N:P:S ratios in Australian and other world soils. *Geoderma* **163**, 197-208

Kirby CA, Richardson AE, Wade LJ *et al.* (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLos ONE* **11** (5).

Lal R (2004) Carbon emissions from farm operations. *Environment International* **30**, 981-990

Lal R, Wilson GF, Okigbo BN (1978) No-till farming after various grasses and leguminous cover crops in tropical alfisol. 1. Crop performance. *Field Crops Research* **1**, 71-84

Landers JN (2018) Discussion paper on eliminating puddling in rice by using zero tillage. *Agriculture for Development* **35**, 23-30

Lee N, Thierfelder C (2017) Weed control under conservation agriculture in dryland smallholder farming systems in southern Africa: A review. *Agronomy for Sustainable Development* **37** (5), 48

Li S, Lobb DA, Lindstrom MJ (2007) Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada. *Soil and Tillage Research* **94**, 164-182

Li H, He J, Bharucha ZP *et al.* (2016) Improving China's food and environmental security with conservation agriculture. *International Journal of Agricultural Sustainability* **14**, 377-391

Li Z, Yang X, Cui S *et al.* (2018) Developing sustainable cropping systems by integrating crop rotation with conservation tillage practices on the Loess Plateau, a long-term imperative. *Field Crops Research* **222**, 164-179

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

Lobb DA, Hufman E, Reicosky DC (2007) Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators. *Journal of Environmental Management* **82**, 377 -387

Loch A, Cummins J, Zuo A, Yargop R (2018) Value chain and policy interventions to accelerate adoption of zero tillage in rice-wheat farming across the Indo Gangetic Plains. Final Report to ACIAR, Canberra http://aciar.gov.au/publication/

Loss S, Haddad A, Desbiolles J *et al.* (2015) The Practical Implementation of Conservation Agriculture in the Middle East. 98 pp (ACIAR and ICARDA)

Lovarelli D, Bacenetti J (2017) Seedbed preparation for arable crops: Environmental impact of alternative mechanical solutions. *Soil and Tillage Research* **174**, 156-168

Martinez I, Chervet A, Weisskopf P *et al.* (2016) Two decades of no-till in the Oberacker long-term field experiment: Part 1. Crop yield, soil organic carbon and nutrient distribution in the soil profile. *Soil and Tillage Research* **163**, 141-151

Mashavakure N, Mashingaidze AB, Musundire R *et al.* (2018) Short term impacts of tillage and fertilizer treatments on soil and root borne nematodes and maize yield in a fine textured Cambisol. *Journal of Nematology* **50**, 1-13

McLaughlin NB, Drury CF, Reynolds WD *et al.* (2008) Energy inputs for conservation and conventional primary implements in a clay loam soil. *Transactions of American Society of Agricultural and Biological Engineers* **51**, 1153-1163

Mei K, Wang Z, Huang H *et al.* (2018) Stimulation of N_2O emission by conservation tillage management in agricultural lands: A meta-analysis. *Soil and Tillage Research* **182**, 86-93

Minasny B, Malone BP, McBratney AB *et al.* (2017) Soil carbon 4 per mille. Geoderma **292**, 59-86

Muoni T, Rusinamhodzi L, Thierfelder C (2013) Weed control in conservation agriculture systems of Zimbabwe: Identifying economical best strategies. *Crop Protection* **53**, 23-28

Naresh RK, Rathore RS, Yadav RB *et al.* (2014) Effect of precision land leveling and permanent raised bed planting on soil properties, input use efficiency, productivity, and profitability under maize (*Zea Mays*) – wheat (*Triticum aestivum)* cropping system. *African Journal of Agricultural Research* **9** (36), 2781-2789

Paroda RS 2018. Reorienting Indian Agriculture: Challenges and Opportunities. Trust for Advancement of Agricultural Sciences (TAAS), India (CABI: UK)

Pezzi F (2005) Traditional and new deep soil tillage techniques in Italy. *Transactions of the American Society of Agricultural Engineers* **48**, 13-17

Piggin C, Haddad A, Khalil Y *et al.* (2015) Effects of tillage and time of sowing on bread wheat, chickpea, barley and lentil grown in rotation in rainfed systems in Syria. *Field Crops Research* **173**, 57-67

Pittelkow CM, Linquist BA, Lundy ME *et al.* (2015) When does no-till yield more? A global meta-analysis. *Field Crops Research* **183,**156-168

Poulton P, Johnston J, Macdonald A *et al.* (2018) Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology* doi: 10.1111/gcb.14066

Powlson D, Stirling CM, Jat ML *et al.* (2014) Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* **4**, 678-683

Powlson D, Stirling CM, Thierfelder C *et al.* (2016) Does conservation agriculture deliver climate change mitigation through carbon sequestration in tropical agro-ecosytems. *Agriculture, Ecosystems and Environment* **220**, 164-174

Quine TA, Zhang Y (2002) An investigation of spatial variation in soil erosion, soil properties, and crop production within an agricultural field in Devon, United Kingdom. *Journal of Soil and Water Conservation* **57**, 55-65

Rivers A, Barbercheck M, Govaerts B, Verhultz N (2016) Conservation agriculture affects arthropod community composition in a rainfed maize-wheat system in Central Mexico. *Applied Soil Ecology* **100,** 81-90

Roper MM, Milroy SP, Poole ML (2012) Green and brown manures in dryland wheat production systems in Mediterranean-type environments. *Advances in Agronomy* **117**, 275-313

Sapkota SP, Jat RK, Singh RG, Jat ML *et al.* (2017) Soil organic carbon changes after seven years of conservation agriculture in a rice-wheat system of the eastern Indo-Gangetic Plains. *Soil Use and Management* **33**, 81-89

Sayre KD, Hobbs PR (2004) The raised-bed system of cultivation for irrigated production conditions. In (Eds. R Lal, P Hobbs, N Uphoff, DO Hansen) 'Sustainable Agriculture and the Rice-Wheat System.' Chapter 20 pp 337-355 (Ohio State University: Columbus, Ohio, USA)

Sayre KD, Limon-Ortega A, Govaerts B (2005) Experiences with permanent bed planting systems CIMMYT, Mexico. In (Eds. CH Roth, RA Fischer, CA Meisner) 'Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico.' pp12-25. *Proceedings of a workshop held in Griffith, Australia* (ACIAR Proc. 121)

Schneider F, Don A, Hennings I *et al.* (2017) The effect of deep tillage on crop yield – What do we really know? *Soil and Tillage Research* **174**, 193-204

Sidhu HS, Singh M, Singh Y, Blackwell J, Lohan SK, Humphreys E, Jat ML, Singh V, Singh S (2015) Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research,* **184**, 201-212

Spoor G, Tijink FGJ, Weisskopf P (2003) Subsoil compaction: risk, avoidance, identification and alleviation. *Soil and Tillage Research* **73**, 175-182

Spoor G (2006) Alleviation of soil compaction: requirements, equipment and techniques. *Soil Use and Management* **22**, 113-122

Thierfelder C, Wall PC (2009) Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research* **46** (3), 309-325

Tullberg J, Antille DL, Bluett C, Eberhard J, Scheer C (2018) Controlled traffic farming effects on soil emissions of nitrous oxide and methane. *Soil and Tillage Research* **176**, 18-25

Valbuena D, Erenstein O, Homann-Kee TS *et al.* (2012) Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue tradeoffs in sub-Saharan Africa and South Asia. *Field Crops Research* **132**, 175-184

Van den Akker JJH, Arvidsson J, Horn R (2003) Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil and Tillage Research* **73**, 1-8

Van Kessel C, Venterea R, Six J *et al.* (2013) Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. *Global Change Biology* **19**, 33-44

Van Oost K, Govers G, de Alba S, Quine TA (2006) Tillage erosion: a review of controlling factors and implications for soil quality. *Progress in Physical Geography* **30**, 443-466

Van Oost K, Cerdan O, Quine TA (2009) Accelerated sediment fluxes by water and tillage erosion on European agricultural land. *Earth Surface Processes and Landforms* **34**, 1625-1634

Verhulst N, Govaerts B, Verachtert, E *et al.* (2009) The importance of crop residue management in maintaining soil quality in zero tillage systems: A comparison between long-term trials in rainfed and irrigated wheat systems. *Proceedings of 4th World Congress on Conservation Agriculture*, New Delhi, India

Wall PC (2009) Strategies to overcome the competition from crop residues in Southern Africa: Some light at the end of the tunnel. *Lead Papers, Proceedings of 4th World Congress on Conservation Agriculture*, pp 65-70 New Delhi, India

Wall PC, Thierfelder C, Ngwira AR *et al.* (2014) Conservation agriculture in eastern and southern Africa. In 'Conservation Agriculture: Global Prospects and Challenges' (Eds. RA Jat, KL Sahrawat, AH Kassam) (CAB: Wallingford, UK)

Wang F, Xuqing W, Sayre K (2004) Comparison of conventional, flood irrigated, flat planting with furrow irrigated, raised bed planting for winter wheat in China. *Field Crops Research* **87** (1), 35-42

Wang XB, Cai DX, Hoogmoed WB *et al*. (2007) Developments in conservation tillage in rainfed regions of North China. *Soil and Tillage Research* **93**, 239-250

Wang Y, Zhang Y, Zhou S, Wang Z (2018) Meta-analysis of no-tillage effect on wheat and maize water use efficiency in China. *Science of the Total Environment* **635**, 1372-1382

Zingore S, Manyame C, Nyamugafata P, Giller KE (2005). Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *European Journal of Soil Science* **56** (6), 727-736