Achievements and Future Challenges in Conservation Tillage

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Abstract

Conservation tillage (CT) is a key tool in sustainable production systems throughout the world. It has been particularly effective at sustaining crop production in semi-arid rain-fed regions. Wherever potential evaporation exceeds precipitation during most months of the year, proper application of water-conserving CT technology is critical. This paper reviews the progress made in CT management, with particular focus on the U.S.A. and Australia, two temperate developed countries with a long history of using CT. Parallels are drawn to other regions of the world when appropriate. Data on farmer's use of CT are provided, as are some reasons for lack of adoption by farmers. Despite decades of research and education on the benefits of CT, a majority of farmers in the U.S.A. and Australia do not practice CT on their farms. In some regions, adoption of CT is high for one crop in rotation but low for another crop in the same sequence on the same soil. The unwillingness of farmers to adopt CT, or to adopt it continuously, implies that it is either perceived to be unprofitable or that other significant constraints to adoption exist. The paper finishes with a discussion of the perceived challenges to further adoption of CT and the opportunities to overcome barriers to greater adoption. It is imperative that CT retains a flexible approach to addressing challenges while maintaining the common goal to sustain the soil resource and produce food for an ever-growing world population.

Media summary

Despite the many benefits of conservation tillage, and numerous advances over the last three decades in associated technologies from pesticides to seeding equipment that have improved its relative performance, a majority of farmers do not practice it. We identify why and what can be done to increase adoption.

Key words

No-till, soil water storage, summer fallow, cropping systems, wheat, crop residue management, soil compaction.

Introduction

Conservation tillage is variously defined around the globe. In the USA, the definition includes a minimum of 30% soil cover after planting to reduce soil erosion by water, or where soil erosion by wind is the primary concern, a minimum of 1,120 kg ha^{-1} of flat, small grain residue equivalent on the soil surface throughout the critical wind erosion period (CTIC 2004). However, precise definitions of conservation tillage can only be made in the context of the crop species and varieties, soil types and conditions, and climates (Carter 1994). For example, in parts of southern Australia conservation tillage is practiced in the absence of stubble due to problems with establishing crops in high stubble loads (a result of dry summers and slow stubble breakdown). Most of the soil conservation benefit from no-till in this region comes from reducing tillage in the structurally fragile soils, and only a minor additional benefit comes from stubble retention because rainfall is of low intensity and is winter dominant. Despite this variation in definitions, a common characteristic of conservation tillage is its potential to reduce soil and water loss relative to conventional tillage practices. Since all tillage operations bury crop residue to a lesser or greater degree, CT implies reduced frequency of tillage operations, the use of non-inverting tillage implements, and greater reliance on herbicides for weed control.

The benefits of maintaining crop residue on the soil surface are well documented and include reduced soil loss as a result of water or wind erosion, as well as increased water infiltration and soil water storage efficiency (Mannering and Meyer 1963, Woodruff *et al.* 1972, Greb 1979). Other benefits of CT systems include reduced labor, fuel, and machinery wear, improved soil tilth, increased soil organic matter, improved water and air quality, and increased wildlife (McLaughlin and Mineau 1995). Some less obvious advantages, as well as some disadvantages, accompany a CT regime, and these will be discussed later in this paper. At this point, it should be stated that the advantages of CT have resulted in its widespread adoption over the last 50+ years since such tillage regimes were first tested in mechanized farming. Although definitions of tillage practices vary, an indication of the wide-spread adoption of CT was the recent global estimate that 72-million ha were under no-tillage management in 2001-2002 (Derpsch and Benites 2003). This estimate includes approximately 50% of the cropland in Brazil and Argentina, 45 % in Australia, and 20% in the USA (Table 1). Areas of adoption are much lower in South Asia, but are not insignificant and lately have been increasing rapidly.

Table 1. Countries with at least 250,000 ha of land under no-till management in 2001/2002[a].

Country	Area under no-tillage (ha)
USA	22,410,000
Brazil	17,356,000
Argentina	14,500,000
Australia	9,000,000
Canada	4,080,000
Paraguay	1,300,000
Bolivia	417,000
North India, Pakistan	561,000
South Africa	300,000
Spain	300,000
Uruguay	250,000

[a] Amended from Derpsch and Benites (2003).

This paper will focus on CT developments in the temperate latitudes of developed countries with a long history of exposure to CT research and development. Because climate and soil conditions greatly influence the adoption and adaptation of CT, we will separately describe CT in three major agroclimatological regimes: 1) a summer rainfall-dominant, semiarid rain-fed region, represented by the Great Plains of North America and with parallels in eastern Australia, 2) a winter rainfall-dominant, sub-humid region represented by southern and western Australia, with parallels in the US Pacific Northwest (PNW), and 3) a humid region represented by eastern North America. Following description of the current situation with CT in these three key environments, constraints and challenges to such tillage, many arising in several or all environments, will be delineated and discussed.

Conservation tillage in dry summer rainfall environments.

The Great Plains.

The Great Plains is an expansive temperate semi-arid region that was once dominated by vast grassland ecosystems (Thornewaite 1941). The principal soils are Mollisols, Entisols, Aridisols, Vertisols, and Ustalfs (Aandahl 1982). The Great Plains extends in a continuous belt 500 to 650 km wide from Mexico (latitude 25°N) into Canada (latitude 55°N). Mean annual rainfall ranges from 635 mm in south Texas to 300 mm in northern Montana. Summer rainfall dominates in the region, with the majority of the highly variable annual precipitation generally received during the months of May, June, and July. High temperatures and low relative humidity occur at this same time, which results in a high evaporation potential. Much of this summer rainfall occurs as a result of convective storms, which can be of strong intensity. Extended periods of drought are common. Drought may be the key climatic parameter of the Great Plains because it determines the production capacity of the region.

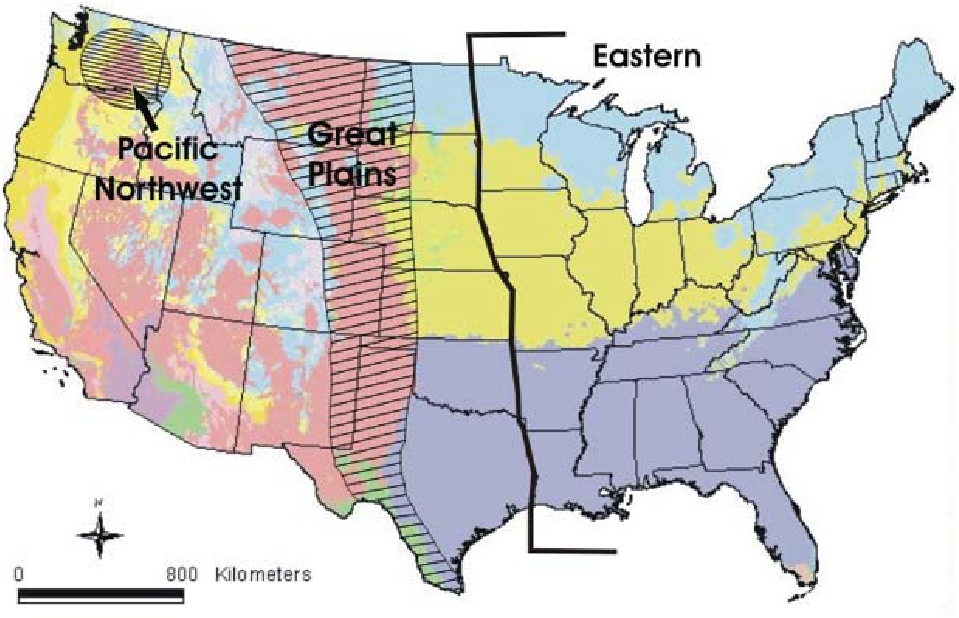

Figure 1. Köppen climate classification for the conterminous U.S.A. as adapted from the Idaho State Climate Services and available at: http://snow.ag.uidaho.edu//Clim_Map/koppen.htm**.**

In the Great Plains, dryland agriculture developed around wheat (*Triticum aestivum* L. emend. Thell.) production. Summer fallow, the practice of controlling all plant growth during the non-crop season, was quickly adopted to stabilize winter wheat production in the region. Wheat-fallow was the predominant crop rotation in the Great Plains during most of the twentieth century. Fallow periods in this rotation vary in length from 14 to 21 months depending on whether it is a spring or winter wheat system, and thus the actual time wheat plants are growing in the field is only 3 to 10 months out of the 24-month cycle.

The initial interest in CT technologies for the Great Plains began during the Dust Bowl era of the 1930s, when 60 to 80 million ha of land were scarred by wind erosion from Texas to the Dakotas (Miller *et al.* 1985). Prior to the Dust Bowl, fallow tillage typically involved use of inversion tillage, which buried most crop residues. During the 1940s and 1950s, non-inversion sub-till techniques replaced inversion tillage on the more erosive soils (Johnson *et al.* 1983). Over the past 40 yr, herbicides have replaced some or all tillage operations in many crop production systems.

Fallow water storage efficiency improved as knowledge about residue maintenance and water conservation expanded. Greb (1979) chronicled progress in winter wheat-fallow systems from the early 1900's through to 1977 and then projected progress through to 1990. Changes since 1916 in fallow tillage systems improved water storage, fallow efficiency (% of fallow precipitation stored as soil water), winter wheat yield, and precipitation-use efficiency (PUE = grain/total precipitation during entire rotation cycle). The number of tillage operations per fallow period decreased from a high of 7 to 10 in the dust mulch systems of the early twentieth century to 0 to 4 with today's CT systems. Precipitation-use efficiency doubled from 1916 to 1975, increasing from 1.22 to 2.78 kg of wheat ha^{-1} mm^{-1}. This was largely due to improved fallow-period soil water storage efficiency, which increased from 19 to 33% over the same time period. Greb (1979) projected that fallow efficiency could increase to 40% by 1990, resulting in a PUE of 3.25 kg ha^{-1} mm^{-1}. Unfortunately, there have been no improvements to the 35% storage efficiency Greb achieved for his environment in the early 70's. Fallow efficiency reports from the 1980's and into the 1990's are generally less than 42% (Table 2), regardless of the climatic zone where the data were collected (Peterson *et al.* 1996).

Table 2. Modern soil water storage efficiencies of no-till and reduced till summer fallow systems over a range of environments, ordered from north to south, in the Great Plains of North America (Peterson *et al.* 1996).

Water storage efficiency		State or province	Reference
Mean	Range		
(%)			
18[a]		Saskatchewan, Canada	Campbell *et al.* 1987
31[a]	26-36	North Dakota	Diebert *et al.* 1986
37[a]	32-42	Montana	Tanaka 1989
49		Colorado	Smika 1990
22	17-28	Colorado	McGee *et al.* 1997
25	10-37[b]	Kansas	Schlegel 1990
30	25-35	Kansas	C.A. Norwood[c]
10		Texas	Jones and Johnson 1993

[a] Spring wheat (21-month fallow) all other data winter wheat (14-month fallow).
[b] Reduced tillage.
[c] Personal communication - Southwest Kansas Research Center, Kansas State University, Garden City, Kansas 67846 USA.

Conservation tillage systems were used on about 15.5 million of the 46 million ha of cropland in the Great Plains in 2002 (Table 3). The adoption of CT, particularly no-till, is much less in the southern Great Plains than in the cooler climates of the central and northern Great Plains. The use of no-till systems in the northern and central Great Plains grew from 1.8 million ha in 1992 to 6.5 million ha in 2002, an increase of > 250%. However, these data are for no-till use in a single year and should not be considered an accurate measure of the extent of continuous no-till production systems.

Table 3. Use of conservation tillage systems in crop production in the states of the Great Plains during 2002[a]. No-till use is provided as a subset of all conservation tillage use.

Region	Total planted	Conservation tillage		No-till	
	(ha)	(ha)	(% of planted)	(ha)	(% of planted)
Northern	17,107,164	6,318,614	36.9	3,339,527	19.5
Central	17,070,130	6,773,901	39.7	3,141,612	18.4
Southern	12,263,066	2,414,208	19.7	423,061	3.4
Total	46,440,360	15,506,723	33.4	6,904,200	14.9

[a] Source: 2004 CTIC Crop Residue Management Survey System (Conservation Tillage Information Center). www.crmsurvey.org.

Despite the many benefits of CT, adoption of CT, particularly no-till, has been slow to develop in the Great Plains. In 2002, only about one-third of the land in crop production was in a CT system, and less than half of that was in a no-till system (Table 3). Many wheat growers have seen a decrease in plant growth and grain yield with CT compared to conventional tillage practices. This was partly the result of winter annual grass weeds such as downy brome (*Bromus tectorum* L.) that were difficult to control without plowing. The cost of herbicides also increased the annual out-of-pocket cash costs of CT systems compared to conventional systems that relied solely on mechanical tillage for weed control. Growers can continue to use tillage implements during years of low profitability and put off machinery replacement to profitable years; however, chemical purchases are required every year.

In the southern Great Plains, the value of the wheat crop for winter grazing by cattle (*Bos taurus* L.) is frequently greater than the value of the grain. Low adoption rates of CT in this region are related to reduced weight gain by cattle resulting from the slower crop growth in CT versus conventional systems. Grazing winter forage with cattle also compacts the soil and many growers feel that tillage is required to alleviate the problem. Higher temperatures in the Southern Great Plains also makes it more difficult to produce and retain sufficient crop residues to improve soil water storage efficiency compared to traditional systems involving inversion tillage.

The unfulfilled expectation for greater wheat yields with conservation tillage was likely a major contributor to lack of farmer adoption. In a summary of two long-term winter wheat-fallow tillage experiments conducted in western Nebraska for more than 25 years, Lyon *et al.* (1998) found no differences in mean grain yields between plow, stubble-mulch, and no-till fallow systems, despite increased soil water in stubble-mulch and no-till systems compared to the plowed system. Other researchers in the Great Plains have reported similar results (Peterson *et al.* 1996). Despite the assertion that water is the most limiting resource for dryland crop production in the semiarid Great Plains, other environmental or cultural factors must be more limiting to no-till winter wheat grain yields than available soil water. Possible explanations include greater N immobilization with no-till (Doran *et al.* 1998; Power and Peterson 1998), a decrease in root function due to root impedance or greater root disease, or slower vegetative growth due to cooler soil temperatures when compared with tilled treatments (Wilhelm *et al.* 1998).

In 1968, Smika and Wicks reported that CT altered the time when water was stored as much as it did total water storage. After only 8 months of fallow (out of a total of 14 months) the plow tillage had stored only 16% of the precipitation (56 mm of water), while the minimum till and no-till systems had stored 40% (140 mm of water) and 60% (210 mm of water), respectively. For spring wheat-fallow systems, Haas and Willis (1962) reported similar findings. As the soil profile begins to fill with water and the surface soil nears field capacity, soil water storage efficiency falls regardless of the tillage system used. Therefore, when using CT systems, the fallow period could be terminated at an earlier date to allow the planting of a summer crop. The summer crop will use the stored soil water and rainfall via transpiration rather than lose much of it to evaporation as a result of extending the fallow period another several months. Intensifying the cropping pattern, by shortening the summer fallow period and using the precipitation nearer to the time it is received, creates the potential to increase the overall system PUE and ultimately increase soil productivity via the increased annual amounts of residue added to the soil.

Intensifying the cropping systems using no-till and rotations such as winter wheat-maize (*Zea mays* L.)-fallow (W-M-F), winter wheat-maize-proso millet (*Panicum miliaceum* L.)-fallow (W-M-P-F), and continuous cropping (CC) [crops grown over the years included maize, sorghum (*Sorghum bicolor* (L.) Moench), winter wheat, foxtail millet (*Setaria italica* (L.) P. Beauv.), and sunflower (*Helianthus annuus* L.)] has increased annualized grain yield by more than 75% relative to the yield of the winter wheat-fallow (W-F) system (Peterson and Westfall 2004) (Table 4). These yield increases have translated into 25-40% gains in net income for farmers (Kaan *et al.* 2002). The largest step gain in annualized yield was achieved with the addition of maize or sorghum to the system (2 crops in 3-year system). Increasing cropping intensity to 3 crops in 4 yr only resulted in small yield increases relative to the 3-year system. Adding diversity to intensified cropping systems has also shown promise for improving weed control in CT systems.

Table 4. Annualized grain and total biomass yield as affected by cropping systems averaged over climate and soil gradients and years (1986-1998) in eastern Colorado, USA.

Variable	Cropping system				
	2-yr (kg ha^{-1})	3-yr	4-yr	Continuous[a]	LSD (0.05)
Grain yield	1030	1770	1950		200
Total above-ground biomass	3100	4750	4760	5810	250

[a]The continuous system was compared with the other systems on a total biomass basis because it included forage crops that do not have a grain component.

Cropping intensification also has had positive impacts on soil physical and chemical properties. Cropping system intensification under no-till management decreased bulk density of the surface soil layer, increased total porosity, and increased effective pore space (Shaver *et al.,* 2002). The causal agent for the improvement in physical properties has been the addition of more crop residue biomass to the soil relative to the wheat-fallow system (Shaver *et al.*, 2003). Coupled with the lack of soil disturbance in a no-till environment, the additional residue C has promoted aggregation and has increased aggregate stability. This example demonstrates that more intensive agriculture is sometimes more sustainable than low input agriculture.

Changes in U.S. federal farm policy in 1996 decoupled farm support payments from historical base crop production and allowed growers in the Great Plains to plant nonconventional crops like maize and sunflower and adopt cropping intensification without having to give up federal farm payments. For example, in the Nebraska Panhandle, dryland maize production went from just 2710 ha in 1991 to over 27 900 ha in 2001. Increased cropping intensification combined with better-designed crop rotations has increased grower interest in CT, particularly in no-till systems. Rotations that include summer crops such as maize and sorghum in sequence with winter wheat and fallow allow for alternative weed management strategies that reduce weed density, improve effectiveness of herbicides used, and minimize herbicide resistance (Daugovish *et al.* 1999; Anderson 2004). Unlike the wheat-fallow rotations, these more intense systems respond positively to the increased soil water storage potential of CT and effectively deal with the winter annual grass weed problems that prevented many growers from adopting CT systems in wheat-fallow rotations.

Some of the perceived obstacles to adoption of these more intensified cropping systems include a paucity of adapted crops and cultivars, a lack of established markets for new crops, increased costs associated with growing a crop on more land, a large population of ageing farmers unwilling to learn and adopt new practices late in their careers, and a risky production environment that has favored low input, low risk farming strategies.

Summer rainfall dominant eastern Australia.

Like the Great Plains, northern New South Wales and southern Queensland in Australia is a summer rainfall-dominant region. Fallow is commonly practiced to store water in the soil. The soils in this region are cracking clays with high water holding capacity, but with slow infiltration rates once they are wet and the surface cracks have closed. Unlike much of the Great Plains, this region is subtropical, which provides a long growing season with many choices in crop selection and planting dates. Many farmers in this region practice opportunity cropping, where they will fallow until the soil water profile is full and then they plant a crop adapted to planting at that time of year. The region is strongly influenced by the ENSO (El-Nino Southern Oscillation), which causes rainfall to vary over periods of 2 to 10 years in a pseudo-cyclic manner (Freebairn *et al*., in prep). During the warm phases, eastern Australia can become drought affected and during the cold phase these areas are wetter than average. During wet years this region tends to have a defined period of rainfall onset, commonly referred to as the break. These characteristics have allowed researchers to develop some climate forecasting skill to allow farmers to make better-informed decisions related to crop management (Freebairn *et al*., in prep). Unlike their counterparts in the U.S.A., Australian farmers do not have their cropping choices confounded directly by government farm programs, which allows them to make their cropping decisions based on the markets and sound agronomic principles. Use of conservation tillage systems in this region is greater than in the Great Plains. In 2001/2002, farmers used minimum tillage on 50.1%, and direct drill (no-till) on 30.2%, of the cropland (ABARE 2004).

Conservation tillage in dry winter rainfall environments.

Southern Australia.

The winter rainfall zone extends across southern Australia and includes part of southern New South Wales (NSW), Victoria, Tasmania, South Australia and Western Australia (Figure 2). Average annual rainfall ranges from 300 to 600 mm and occurs in association with long periods of dry and wet spells. Farming practices have evolved to capture and make progressively improved use of the rainfall resource. In southern Australia, the climate has often been described as Mediterranean, but this is misleading as in the eastern states the summers are hotter and have more rainfall than in typical Mediterranean environments (Steed *et al*. 1993). In contrast, the western cropping region of Western and South Australia has a distinct winter rainfall season (Figure 2), low winter evaporation, and rainfall exceeding evaporation in some months. In the eastern cropping region of Victoria, NSW, and Tasmania only about two-thirds or less of the rain falls between April and October (Figure 2), and in many areas evaporation exceeds rainfall during this period. The chances for spring frost damage to flowering winter crops determines the earliest available planting date for crops, and soil temperatures are low enough to restrict growth for part of the time in winter.

In southern Australia, in little more than a century, natural ecosystems with trees and perennial grasses have been transformed into farming systems with winter crops [e.g., wheat, canola (*Brassica napus* L.), and oat (*Avena sativa* L.)] in rotation with introduced cool-season perennial or annual pastures, with periods of summer fallow. The significance of this ecological shift is that the native, perennial-based warm-season active ecosystems used water predominantly in summer, drying soil profiles to great depth, so that during the winter-effective rainfall season, there was little or no drainage beyond the root zone. The contemporary winter-active, mainly annual systems do not always use all the water available to them, resulting in drainage in some areas and leading to rising groundwater and salinity.

The length of the pasture and crop phases of the contemporary systems varies widely depending on the relative profitability of the crop and livestock enterprises. Summer cropping is generally not practiced in southern Australia due to the unreliability of the summer rainfall and the high summer temperatures. Besides, in some situations, there is benefit from using fallow to store winter-spring accumulated soil water for the following season's winter crop.

The length of the fallow is partly dictated by the need for moisture conservation. In the western cropping regions, the length of the fallow ranges from a short period of a few weeks during land preparation prior to sowing, up to a few months over summer if rain falls during the February - April period (Poole 1987). The eastern cropping region typically uses periods of summer fallow (< 6 months) from the harvest of the previous crop until sowing the following year and in some rare instances long fallows (> 6 months) are used. Fallowing also occurs for weed and disease control and to accumulate available nitrogen. Kohn *et al.* (1966) found long fallows to be uneconomic for soil water storage where growing season rainfall exceeded 380 mm/year; however, the practice still exists in some areas where rainfall is less than 500mm/year on soils with high water-holding capacity. In addition, recent evidence from the Mallee in Victoria has shown that any yield advantage obtained by long fallowing is mostly due to the control of grassy weeds and disease and not to the amount of water stored (Cornish and Pratley 1991, Incerti 1989).

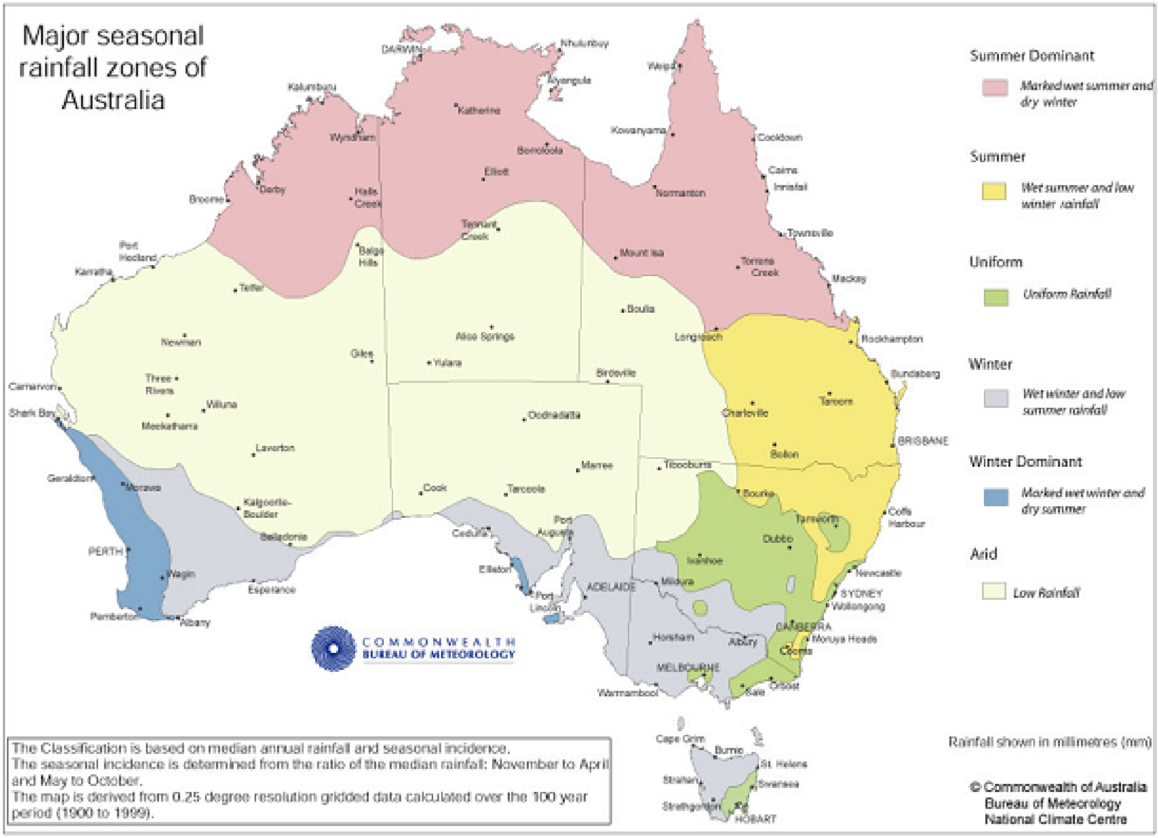

Figure 2. Köppen climate classification showing seasonal rainfall patterns for Australia. The winter rainfall zone extends across southern Australia and includes part of southern NSW, Victoria, Tasmania, South Australia and Western Australia (Bureau of Meteorology Web site, http://www.bom.gov.au/climate/environ/other/seas_all.shtml**).**

A striking change in land-use in southern Australia has been the intensification of cereal cropping since the 1960s in response to the relative profitability of cereals compared to animal production enterprises. Increased frequency of tillage, decreased length of pasture and fallow phases combined with the age and fragility of the Australian soils led to soil structural decline over the next 20 years. In particular, on the fine-textured soils these practices led to reduced infiltration of water and thus increased runoff and evaporation and soil crusting, and for the sandy-surfaced soils, nitrogen deficiencies and wind erosion were common (Poole 1987). As a consequence, there was a move toward CT practices, particularly no-till and stubble retention (reviewed previously in Steed *et al.* 1993 and Poole 1987).

In southern Australia, direct drilling and stubble retention are now widely promoted as key parts of CT systems. The benefits of CT systems are well understood and include reductions in erosion, increases in soil fertility, improvements in soil surface physical characteristics, reductions in sediment loss and bulk density (reviewed in Poole 1987; Steed *et al.* 1993). Despite these benefits adoption has been slow. Recent surveys have found that a high proportion of farmers have adopted some form of CT (ABARE 1998 unpubl., cited in Chan and Pratley 1998). Approximately 36% of farmers in southern Australia use no till and 80% retain stubble to some extent. Other data is conflicting. According to Bruce (2003), 60% of farmers in southern Australia retain all stubble, retain some stubble after grazing or a cool burn, or incorporate stubble.

There are differences in the adoption of CT between regions in southern Australia, which is likely a result of the soil type and the perceived yield penalties associated with the technology. Walters and Rovira (1994) found that in the Central West of NSW, where soils are generally less susceptible to erosion, only 2% of farmers practiced no-till farming while in the southwest of Western Australia, where most soils are sandy and prone to erosion, the adoption of CT has been relatively high (69% in 2002-2002, ABARE 2004). In addition, no-till in the southwest of Western Australia has been a revolution in improving timeliness of planting. No tillage prior to sowing means that sowing can occur on average earlier than in conventional systems, which is a great advantage in this region where spring rains drop off quickly and the risk of spring frost damage to crops is lower than in the eastern states.

Many factors may be contributing to the slow adoption of CT practices in the southeastern region of southern Australia. The reported improvements in soil characteristics creates the expectation that over time the yield of crops in these systems will increase relative to conventional practice, yet results from short- and long-term field experiments show that overall yield of wheat with CT may be either higher or lower than with conventional tillage, and that there is considerable year to year variation both within and between sites (Kirkegaard 1995). These results imply that either soil condition is not important in determining yield or that physical, chemical, or biological factors of the CT practice or the variable seasonal conditions or an interaction of these are contributing to poor crop growth (Kirkegaard 1995). For example Bruce (2003) found that yields of canola in retained stubble were higher, no different or lower compared to no-till plots at three sites in NSW and that this was directly related to temperature above the stubble layer. Also Cornish and Lymbery (1987) found that early wheat growth is sometimes reduced in the absence of tillage, but the ultimate effect of this on grain yield was dependent on rainfall. In years with low rainfall and high post-anthesis water stress, the early check in growth increased yields by making more water available for grain filling. The negative impact on yield from high stubble loads, the result of low summer decay of stubble, and the carry-over of disease are likely to limit adoption of stubble retention in southeastern Australia, especially where the risk of soil erosion is low.

Pacific Northwest.

Unlike the southern Australian climate, the Pacific Northwest (PNW) has more reliable rainfall, a more dominant winter precipitation pattern (Figure 1) and winter snowfall and freezing temperatures in some areas (Papendick and Miller 1977; Papendick 1995). Because of the presence of mountain ranges to the east of the region, orographic influences are significant. On the western edge, the climate is semi-arid and on the eastern edge, close to the Rocky and Blue Mountains, the climate is sub-humid. Winters are wet and cold, with snow in some areas and the summers are dry and hot. Sixty-seventy percent of precipitation falls between November and April. Snowfall makes up 20-25% of precipitation at higher elevations.

Soils may be frozen to a depth of 40 cm, especially in the absence of snow cover and soil may freeze and thaw several times per winter season. There is evidence to suggest that the number of freeze-thaw cycles may be a very important factor in reducing the shear strength and hence increasing the erodibility of the soil surface, especially in tilled soils with little vegetation cover (Formanek *et al.* 1984). Diurnal thawing of the soil surface can lead to evaporative loss, which over a winter season can significantly decrease water storage. In addition, when soils freeze, infiltration rates decrease and run-off increases.

High winds occur in the spring and autumn, which is a problem in the drier areas where soils are sandier than the silt-loams in the higher precipitation zones. In the higher precipitation zones water erosion is a problem as the topography is steeply rolling with tillage occurring on slopes up to 45% (Papendick 1995).

In general, the PNW has medium-textured loessal soils containing little organic matter, with poor structure and few stable aggregates (Sojka and Carter 1994).

The cropping systems of the PNW are dictated by annual precipitation, which ranges from 200 to 1100 mm. The wheat-fallow system dominates in the semi-arid areas where the annual precipitation ranges from 200 to 400 mm, and where long fallows (up to 20 months) are used to increase water storage (Papendick 1987, Papendick 1995). Winter wheat-spring crop rotations with short periods of summer fallow are common in the sub-humid areas where annual precipitation ranges from 400 to 700 mm. Tillage practices during the fallow season include chisel-plowing in the autumn to increase infiltration and reduce winter run-off from frozen soils, spring and summer tillage in the drier zones to control weeds and minimize evaporation from the seed zone.

Conservation tillage in the PNW, like southern Australia, has been greatly influenced by soil degradation (Sojka and Carter 1994), but particularly by the high rates of erosion and the need for water retention in the drier areas. Freeze-thaw events and the associated problems with soil water storage and erosion have also been drivers in the adoption of CT practices in the PNW. Increased aggregate stability due to CT practices has been found to increase resistance to freeze-thaw events (Angers *et al.* 1993), which has potential to decrease the erodibility of the soil surface; and retention of crop residues reduces the likelihood of freezing of the soil surface providing increased probability of infiltration from seasonal precipitation. Other benefits of CT are similar to those of the southern Australian cropping zone and have been extensively reviewed for the PNW (see Papendick and Miller 1977; Papendick 1987, Papendick 1995). Like southern Australia, the rates of adoption have been low. In 2002, just 27% of the cropland in the states of the PNW was managed with CT, and only 7.5% was managed with no-till systems (CTIC 2004). The constraints to adoption are similar to those mentioned for southern Australia, with the exception of concerns over inadequate seed-zone water for crop establishment under CT. In the PNW, early seeding, often ahead of the first substantial winter rains, is vital for early establishment of the winter wheat to ensure adequate winter survival.

Conservation tillage in humid environments.

Eastern U.S.A.

During the past 30 years, the use of CT systems has increased most rapidly in the central and eastern sections of the Corn Belt of the United States. Conservation systems in this region are particularly beneficial for providing protection from soil erosion resulting from high intensity rainfall events on fields whose soil and (or) slope characteristics increase soil loss potential. Thus, systems that leave more than 30% residue cover are desirable, whether that is achieved by no-till, strip-till or even by full-width mulch tillage systems following crops – such as grain maize (*Zea mays* L.) or winter cereals – that leave high residue cover after harvest.

By 2002, total no-till plus mulch-till adoption exceeded 36% of all crop area in the Northeastern and North-Central regions of the Eastern United States (Table 5). But adoption of conservation tillage has lagged in the Southeast, where only 21% of the crop area is in either no-till or mulch-till systems. The latter reduction is at least partially the result of differences in crop species in these three zones of the Eastern United States. No-till adoption is highest for soybean [*Glycine max* (L.) Merr.], and especially so for double-crop soybean, and lower for cotton (*Gossypium hirsutum* L.), maize, and small grains (Table 6). The majority of the soybean crop is in the North-Central zone, and the majority of the cotton crop is in the Southeast zone for this Eastern region.

Table 5. Use of conservation tillage systems in field crop production in various regions of the Eastern U.S.A. for 2002. Derived from CTIC, 2004.

Region	Total planted[a]	No-till[b]		Mulch-till[c]	
	(ha)	(ha)	(% of total)	(ha)	(% of total)
Northeast	3,736,900	1,025,800	27.4	423,300	11.3
North-Central	49,745,700	10,333,900	20.8	7,771,500	15.6
Southeast	21,939,900	3,825,700	17.4	748,000	3.4
Total	75,422,500	15,185,400	20.1	8,942,800	11.9

[a] Includes all grain, oilseed and forage crops other than permanent pasture.

[b] Includes strip tillage.

[c] Full-width tillage systems that leave over 30% surface residue cover after planting.

Table 6. Use of no-till in annual crop production in the Eastern U.S.A. during 2002. Derived from CTIC, 2004.

Crop	Total planted	No-till	
	(ha)	(ha)	(% of total)
Maize	22,682,100	4,161,000	18.3
Spring small grain	2,670,200	133,700	5.9
Autumn small grain	3,359,000	792,700	23.6
Full-season soybean	22,284,700	7,802,200	35.0
Double-crop soybean	1,756,400	1,129,000	64.3
Cotton	2,876,000	795,800	27.6

Adoption of no-till has been particularly rapid for soybean in the last 10 years because of the introduction of superior no-till drill seeders in the late 1980's, acceptance of narrow-row planting systems (where no-till yield reductions, relative to conventional-till, are less likely), and widespread adoption of glyphosate-resistant soybean varieties that became commercially available in 1996. In addition, soybean plants generally compensate for slow early growth, gaps in plant stands, and early-season nutrient deficiencies (factors that might develop in a no-till situation) far better than maize and without significant yield declines. However, the proportion of no-till maize in states like Indiana and Ohio has declined somewhat from its peak in the middle 1990's. Most of the concerns about no-till maize are that cool and wet soil conditions in spring will delay planting, possibly reduce plant populations, and lower yields relative to those with conventional tillage. Thus in many states, no-till maize is less popular than no-till soybean even when these two crops are commonly grown in rotation. In 2002, for instance, no-till was used on 60% of the soybean production area but only 20% of the maize production area in Indiana (CTIC 2004).

A rather unique phenomena in the humid Eastern crop production region of the U.S.A. is that there is less land that is in continuous no-till (i.e., for periods of 5 years of more with no periodic tillage) than there is land which has regular, but not continuous, no-till (i.e., where no-till systems might be used for one crop in a rotation, or for 1 to 3 years in succession, but where the land is subjected to disturbance by moderate to intensive tillage systems periodically). Hill (1998) observed that just 16% of the surveyed fields in Indiana and Illinois were in continuous no-till, while some 30% of the surveyed fields were involved in rotational tillage (e.g., no-till soybean followed by intensive and full-width tillage systems before maize in areas that are primarily in a maize-soybean rotation). In fact, the longest average time that the 1999 surveyed fields in Illinois were maintained in continuous no-till was slightly less than 2.5 years (Hill, 2001).

Researchers have readily acknowledged that no-till maize is best adapted to soils that are well drained (Dick et al. 1991, Griffith et al. 1988). No-till is often less likely to result in maize yields equal to those with conventional tillage (whether moldboard or chisel plowing) on fine-textured and (or) poorly drained soils (Dick et al. 1991, Griffith et al. 1988, Opoku et al. 1997). Yet, even then, the long-term advantages of continuous no-till to soil structure, plus the equipment and labor cost reductions associated with no-till, may still be sufficient reasons to justify maintaining a field in continuous no-till through its entire cropping sequence.

No-till soybean yields are less likely to be lower than those with conventional tillage, even on poorly drained soils. Thus, for instance, research in Iowa (Brown et al. 1989) and Indiana (West et al. 1996) have generally found few instances of soybean yield reductions with no-till relative to moldboard plowing. Soybean yield reductions are most apt to occur if soybean varieties are susceptible to disease, which is more prevalent in no-till (Adee et al. 1994), and if soybean are planted no-till into high residue cover situations in regions with shorter growing seasons (Vyn et al. 1999).

No-till maize is most likely to succeed when planted in rotation with other crops such as soybean (Dick et al. 1991, Chase and Duffy 1991, West et al. 1996, Vyn et al. 2000), or even whole-plant silage maize (Janovicek et al. 1998) relative to continuous grain maize. In one 29-year study on a dark prairie soil, average maize yields with no-till maize after soybean were only 2% less than conventional tillage, while no-till maize after maize was 13% less (Vyn and West unpublished). The extent of the no-till maize yield reduction following maize on poorly drained soil was affected by the positioning of the previous crop residue relative to the row area (Kaspar et al. 1990). Surface residue placement has also influenced no-till maize yields following winter wheat (Opoku et al. 1997).

Strip tillage is preferable to no-till for many maize producers because it results in warmer, dryer, and looser soil conditions in the intended seed row area early in the growing season (Arends et al. 2000). In addition, maize yields with strip-till have consistently been similar to (i.e., not significantly different from) those with conventional tillage when maize follows soybean in rotation. Thus, while maize yields may not be significantly better with strip-till than with no-till when maize is planted on the same day, strip-till enables a much longer planting season duration on finer-textured and poorly drained soils. Furthermore, strip-till ensures warmer conditions in the row area after planting than with no-till alone. The other key advantage of strip tillage is that it provides a convenient tool to incorporate fertilizer materials in bands below the intended row zones. Such deep nutrient banding may be beneficial to maize and soybean when nutrient stratification has occurred on long-term conservation-tilled fields, and when exchangeable K levels are low (Vyn et al. 2001, Yin and Vyn 2003). Strip-till is a particularly promising CT system in the more humid areas with cool springs and fine-textured soils because it combines the surface-residue conserving benefits of no-till with the planting flexibility and yield consistency of conventional tillage systems. In fact, surveys taken after planting cannot generally distinguish a no-till field from a strip-till field, and so these two systems are combined (Tables 4 and 5).

Challenges and opportunities in conservation tillage.

Many factors may be contributing to the uneven adoption rate of CT practices. The unwillingness of farmers to adopt the practices implies that CT is either perceived to be unprofitable or that other significant constraints to adoption exist (Kirkegaard 1995). Many researchers have identified the various constraints to CT (e.g., Bruce 2003; Carter 1994) and an overarching view is that constraints are imposed by climate, soil characteristics, and an interaction of these factors. Many of these soil and climatic constraints manifest themselves in poor growth and yield of crops and a reduction in total profitability of the system. The prevalence of some diseases, weeds, and pests in CT systems has also constrained adoption in some situations. In addition to biological constraints, institutional and social constraints also influence CT adoption rates. Constraints to CT invoke the need for strategies to overcome or circumvent these obstacles if CT practices are to be adopted on a larger scale. This section attempts to characterize some of the challenges to adoption and some of the possible opportunities to overcome or circumvent the constraint.

Residue management.

In some locations (for example NSW in southern Australia and the high rainfall zones of the PNW) where summer rainfall is low and thus residue breakdown is slow, high stubble loads can impede the sowing operation and if successfully sown through can reduce growth and yield of the crop (Bruce 2003). The high cost of drills with the ability to handle heavy stubble is an impediment to adoption of CT systems in these locations. In contrast, in drier regions where yields of crops are typically lower (for example Western and South Australia), stubble loads rarely impede the sowing operation and equally have little impact on the growth of the following crop (Bruce 2003). Burning is commonplace where stubble loads are between 5 and 10 t/ha in southern Australia (Bruce 2003). This practice is typically comprised of a late burn, after the potential summer storm period and after the ‘autumn rainfall break’ so it can kill weeds and save on herbicide and cultivation costs, both of which are environmentally desirable. In the PNW, yields of stubble are typically between 10 and 15 t/ha (Sojka and Carter 1994). The once prevalent practice of burning has been largely discredited in the PNW due to high erosion problems and air quality concerns, however, moldboard plowing, disking or chiseling is used to reduce winter wheat loads before winter. Crop sequencing or intercropping may provide opportunities to balance crop residue inputs as part of a dynamic cropping systems approach (Tanaka *et al.* 2002) to managing residues in CT systems.

As crop yields and, therefore, residue levels increase, superior planting systems will be needed to consistently place seed in desired positions in soil. Indeed, there have been many planting capability improvements since the first no-till coulters were introduced in the 1950s and these improvements are expected to continue. However, residue displacement from the row area by planter modifications alone may not always be sufficient; strip tillage or other very shallow residue/soil disturbance operations in advance of planting may be necessary in more humid regions to maintain the benefits of residue cover close to those with no-till alone without impeding planting date or seed placement capability.

Soil compaction.

Many soils require tillage to prevent or ameliorate excessive soil compaction caused by natural consolidation, livestock grazing, or vehicular traffic (Soane and Pidgeon 1975). For example, high contents of silt and sand can lead to soil instability and poor structure and a high content of non-expanding clay minerals can limit the ability of the soil to restore structure after compression by vehicular traffic (Carter 1994).

Amelioration of the soil compaction followed by controlled vehicular traffic and reduced tillage techniques could be employed in situations when excessive soil compaction is caused by vehicular traffic (Carter 1994; Chamen *et al.* 1992). For instance, Chamen *et al.* (1992) found from a series of experiments conducted in northern Europe that reduced vehicular traffic in a CT context was associated with maintenance of soil porosity and a reduction in soil strength and density. Yields of crops in these experiments were similar to yields in a conventionally tilled treatment as long as they were timed appropriately within a given rotation. Controlled vehicular traffic has provided a solution to soil compaction over more than 1Mha in southern and south-eastern Australia (Tullberg *et al*. 2003). It has improved crop production, soil structure and health, while reducing inputs, and the economic viability of controlled traffic farming has been demonstrated in enthusiastic farmer adoption (Tullberg *et al.* 2003). The combination of controlled traffic with precision guidance provides the opportunity to achieve a major improvement in the sustainability of farming.

Cropping systems that include row crops plus strip or ridge tillage systems allow tillage practices to accommodate both soil and crop requirements since different tillage methods can be adopted in the inter-row and row zones (Carter 1994). These systems have been successfully combined with CT practices; for example, ridge tillage systems involve the formation of elevated ridges with residues removed over the seed zone (Carter 1994).

Weed, disease, and insect control.

The adoption of CT is often limited by the inability to control weeds and other pests. In the Northern Great Plains, herbicides comprise approximately 85% of the pesticides used (Derksen *et al.* 2002). Control of weeds in a CT system generally involves greater use of nonselective knockdown herbicides such as glyphosate or paraquat in preference to the use of tillage. Differences in tillage practices can influence the number of viable weed seeds in the soil, their vertical distribution in the soil profile, weed emergence patterns and the type of weed species (Carter 1987).

The importance of using a diverse range of weed management techniques, particularly in CT systems, is highlighted by the development of herbicide resistance in Australia. Resistance to herbicides is prevalent in annual ryegrass (*Lolium rigidum*), wild oats (*Avena fatua*), silver grass (*Vulpia bromoides*), capeweed (*Arctotheca calendula*) and barley grass (*Hordeum leporinum*) and can be expected in others due to the selection pressures imposed on weed populations caused by herbicide applications (Steed *et al.* 1994). Weed management strategies include rotating herbicides through different chemical groups, management of weed populations when in the pasture phase through grazing to reduce seed set, or the judicious use of tillage to stimulate weed germination, which can then be controlled through the use of a knockdown herbicide. Derksen *et al.* (2002) discussed the principle of varying selection pressure to keep weed communities off balance and thereby reduce weed densities, minimize crop loss, and inhibit adverse weed community species changes. The principle uses a diverse cropping system where crop seeding date, perennation, and species and herbicide mode of action and use pattern are inherently varied.

In the USA and Canada, the advent of herbicide-tolerant crops has given farmers additional weed control options (Fawcett and Towery 2002). With herbicide-tolerant crops, herbicides are applied after emergence of the crop to control weeds and should mean that fewer applications of herbicide are required, reducing the selection pressure on weeds for herbicide resistance (Fawcett and Towery 2002). However, this technology may need to be managed carefully as it may encourage over-use of the herbicide in the system increasing the potential for herbicide resistance. Lyon *et al.* (2002) discussed the pest management implications of glyphosate-tolerant wheat in the western U.S.A. One of their concerns with this new technology was that without an equally effective and affordable herbicide to control glyphosate-tolerant volunteer wheat, growers that have relied on glyphosate for volunteer wheat control might have to return to using tillage in order to control volunteer wheat, which serves as a green bridge for several important wheat diseases. While herbicides and herbicide-resistant cultivars are very useful tools in CT systems, they are not a panacea. They cannot and will not replace the need for good agronomic practice, but will remain an essential part of CT systems into the future.

The severity of some cereal root diseases has increased under CT practices resulting in decreased yields (Rovira 1987), for example the severity of rhizoctonia root rot has been shown to increase with the introduction of no-till in southern Australia and the PNW (MacNish 1985, Cook *et al.* 2000) and bacteria belonging to the genus *Pseudomonas* have been implicated as inhibitory organisms in no-till systems in south-eastern Australia (Simpendorfer *et al.* 2002). The mechanisms underlying seedling crop response to no-till soils is not well understood, however, recent research by Watt *et al.* (2003) has found that slow root elongation associated with greater soil strength in a no-till system was associated with an accumulation of *Pseudomonas* species. Cultivar selection, nutrition, and sowing methods that optimize root elongation rate may help reduce the build-up of deleterious *Pseudomanas* on the root tips. Indeed, the adoption of sowing methods in southern Australia and the PNW that disturb the soil below seeding depth are important in the control of rhizoctonia through the disruption of hyphal networks and propagule formation (Roget 1996; Cook *et al.* 2000) and removal of grass weeds and volunteer pastures well in advance of sowing reduces the amount of inoculum available to infect the crop (Cook *et al.* 2000).

Allelopathy.

The concentration of crop residues at the soil surface in CT systems has been implicated, worldwide, as leaching water-soluble toxins (e.g., phenolic acids) deleterious to crop growth (An 1996; Kimber 1967; Guenzi and McCalla 1962). Despite an extensive body of literature documenting the allelopathic activity of extracts of plant residues (see Bruce 2003), very few have examined the phenomenon in a field environment, raising questions over the likelihood that allelopathy is playing a role in reductions in crop growth. Indeed, research by Bruce (2003) using intact cores and a rainfall simulator providing conditions similar to a field environment, found that leachates from wheat residues were not responsible for the poor growth of canola. The leachates collected had a phenolic acid concentration 20 times lower than those derived from a laboratory procedure typical of those used in most allelopathy research, indicating that caution should be exercised when drawing conclusions about the role of allelopathy in growth reduction based solely on laboratory data.

Managing the microclimate.

In the eastern United States and eastern Canada, early season soil temperatures have been reported to be lower in no-till systems compared to autumn plowed treatments and was implicated as a possible reason for inferior growth and yield reduction (Van Wijk *et al.* 1959; Stone *et al.* 1989). Further research has found that soil temperature does not totally explain the differences in early season growth and grain yields (Bruce 2003; Janovicek *et al.* 1997). Janovicek et al. (1997) found that soil GDD only explained a relatively small proportion of the variability in early growth of maize sown in various crop residues. This is further supported by a study on canola growth in wheat residue in south-eastern Australia, where the suppression in early season growth was not only associated with cooler soil temperatures but also with cooler average temperatures on the surface of the stubble (important because the meristem of canola sits above or close to the surface of the stubble) and a reduction in photosynthetically active radiation (PAR) and the red:far red ratio of incident light caused by the residue (Bruce 2003).

In both the east of North America and south-eastern Australia, modifications to the conservation farming systems have provided a more suitable growing environment; the removal of in-row surface residue in particular has generally improved the micro-climate of the growing seedling. Studies in eastern Canada have found that the removal of residue from the seeding row increased soil temperature (Janovicek et al. 1997), and maize yields by as much as 9% (Vyn *et al.* 1994).
In southeastern Australia, clearing in-row residue led to increases in average soil and air temperatures (air temperatures measured 2 cm above the soil surface) and increases in PAR and was associated with increases in canola seedling growth and yields (Bruce 2003).

Managing soil water to reduce deep drainage.

Within the context of concerns for the sustainability of agricultural practices, the challenge is to evaluate CT practices as part of the broader farming system. It has been demonstrated that CT systems can reduce erosion, increase soil water holding capacity and in some instances have benefits for soil structure; however, in some areas increased leaching of water and nutrients is also a result of these practices. Black *et al.* (1981) suggested the establishment of a perennial deep-rooted crop, such as alfalfa (*Medicago sativa* L.), or the use of flexible cropping systems (a similar concept to opportunity cropping) that respond to soil water conditions to control saline seeps in the Northern Great Plains.

In parts of Australia, CT has been successfully integrated with pasture management systems in order to maintain the benefits of CT systems while addressing some of its shortfalls through the retention of deep rooted perennial pasture species over summer that replace the typical fallow of the CT systems (Bruce pers. comm. 2004, Dorrough pers.comm. 2004). Typically, an annual winter crop is sown using no-till into dormant summer growing pastures. The summer growing pastures are suppressed either through heavy grazing or chemical application just prior to sowing. Competition from pasture species, post-dormancy, may occur during flowering and seed-fill of the crop and may lead to yield penalties; however, grazing benefits over summer, reduced costs through the lack of need to re-establish pastures, and lower input costs have led to a more profitable system for the practitioners (Seis pers. Comm 2003; Barton pers. Comm. 2003). Currently, this system is being practiced by a small group of farmers in southern Australia, where summer-growing perennial pasture is common and rainfall is equal year-round. In regions where rainfall is strongly winter-dominant this practice may not be suitable.

In the low precipitation zone of the PNW, many farmers do not practice CT because of the perceived increases in evaporative loss of seed-zone soil water during the summer months, instead a fine dust mulch is often used (Papendick 1996; Schillinger 2001). Recent research has found that seed-zone water at the end of a fallow is no different between CT and conventional tillage practices (Schillinger 2001) and suggests that the dust-mulch may not be as important for retarding soil water loss as previously thought. Creating an abrupt layer between the tilled and non-tilled layer (common in most CT systems in the PNW), which severs capillary channels from the subsoil to the surface, appears to be the dominant factor regulating over-summer evaporative loss (Schillinger 2001).

Long-term soil changes.
What happens over time with greater return of residue and continuing limited or no tillage? Research by Wilkins *et al.* (2002) found that initial increases in soil strength in no-till treatments disappeared with time in a silt-loam soil. The phenomenon documented by Watt *et al.* (2003) where slow rate of root growth in hard soils of a no-till system was associated with an accumulation of deleterious *Pseudomonas* may become less of a problem over time as soil strength decreases. If dependent on soil type, the use of faster growing roots may reduce deleterious impacts.

Microbial biomass in the surface 7.5 cm of soil reached a maximum after only one year in no-till in Ohio, and after 10 years an equilibrium level about 30% greater than that for conventional tillage was reached (Staley et al. 1988). In a long-term winter wheat-fallow system in western Nebraska, biological activity and organic C and N reserves were concentrated near the soil surface with no-till, resulting in greater potential tie-up of plant available N in organic forms Doran *et al.* (1998). However, soil organic C losses from surface soil ranged from 12 to 32% for no-till and plowing, respectively. They concluded that soil organic matter losses would only be slowed by increasing C inputs through use of more intensive cropping systems that reduce time in fallow.

Chan (2001) reviewed the literature on the effects of tillage on earthworms as it relates to their roles in agroecosystem functioning. There was little information on the long-term changes in earthworm populations under CT, and what was available, was inconclusive. Seemingly conflicting observations on the effect of tillage on earthworms might have resulted because researchers seldom provided details related to the tillage operations and the conditions under which they were carried out. In many studies, researchers failed to identify the earthworm species, presumably not realizing that different earthworm species might respond differently to the same tillage operations. The existing literature does suggest that optimal earthworm population abundance and diversity does not automatically occur with the adoption of CT. Chan identified three areas for future research requiring well designed field studies: 1) factors controlling the abundance and diversity of earthworms, 2) the functional role of earthworms in improving plant growth, and 3) improved techniques for the introduction of ‘beneficial’ species.

Acidification of surface soil in no-till systems, resulting from surface application of N fertilizer, has been identified as a potential problem in long-term continuous no-till systems (Wicks *et al.* 1988). This and other soil-related problems can be alleviated by occasional inversion tillage, sometimes referred to as rotational or strategic tillage, but the effects on soil quality are mixed (Kettler *et al.* 2000; Pierce et al. 1994). More research is needed on the tactical use of tillage in CT systems, especially no-till systems, to ascertain the long-term benefits and risks of such use.

Institutional constraints.

Government policies can constrain adoption of CT. In the U.S.A., the federal farm program encourages production of just a few primary crops and discourages growers from incorporating a diversity of crops in their production systems. This bias in farm program policy is supported by a few large commodity groups that fight for programs that support their specific commodity, but not necessarily for what is best for the total farm enterprise. Seed and chemical companies offer their customers' savings for early purchases of inputs, which tends to lock farmers into early cropping decisions and discourages the adoption of opportunity cropping, which can be an important strategy for CT systems, particularly in water-limited environments.

Conclusions.

Conservation tillage has made a significant contribution to the sustainability of cropping systems throughout the world. In water-limited environments, CT increases soil water storage efficiency, which allows for cropping system intensification and diversification. System intensification and diversification allow growers to better manage various aspects of the cropping system, e.g., the leaching of water and nutrients below the root zone or the control of a specific pest, that have constrained the adoption of CT in systems with a low level of crop diversity. Despite many decades of research and education on CT, adoption rates by farmers in some regions of the U.S.A. and Australia are low. Adoption rates in other countries such as Brazil, Argentina, and Paraguay have been much greater (Table 1). We must better understand the constraints that prevent adoption and focus resources to address these constraints. Because the world is a diverse place and farmers face different constraints imposed by soils, climates, financial wealth, customs, and national policy, it is imperative for CT systems to retain a flexible approach to addressing challenges while maintaining the common goal to sustain the soil resource and produce food for an ever-growing world population.

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