Chapter 3

TILLAGE PRACTICES FOR CROP PRODUCTION IN SUMMER RAINFALL AREAS

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The farming systems and cultural practices used in the summer-rainfall region of Australia (north of 32° S) are determined largely by rainfall characteristics. The proportion of rain falling during the summer months increases towards the northern coast of Australia. Total yearly rainfall also tends to increase towards the northern and eastern coasts in northern Australia. Winter crops in the region depend heavily on water stored during the previous summer, and this dependence on fallow-stored water increases towards the north and towards the drier interior. Summer crops are also grown after fallow but towards the north they rely less on fallow moisture. Compared with southern Australia, pastures and livestock play only a minor role in farming systems in the summer-rainfall areas in which cropping is most widely practised. Continuous cycles of crop-fallow are therefore common.

The requirement to till the soil to control weeds during the fallow period has led to widespread serious soil erosion, particularly during the summer rainfall period. Less severe erosion can still result in a substantial loss of productivity, which cannot be overcome by nutrient application alone (Saffigna *et al.*, 1984). Improved tillage systems in this environment have had as a primary goal the maintenance of crop residues near the surface to afford protection from erosion. A more recent additional goal has been to reduce soil disturbance to a minimum, leading to no-till fallows in which weeds during the fallow are controlled by herbicides, and the only soil disturbance is that necessary to sow the seed.

In the tropical northern part of the region, summer crops are often grown without fallowing, but even here soil erosion is a serious problem because of the high erosivity of summer rains. In this environment, as well, the development of cultural systems is turning to minimal and no-till practices in which cultivation is replaced by herbicides.

Four broad agricultural systems or agricultural areas can be identified in the summer-rainfall areas. They are:

* rainfed cropping in the wheatbelt of northern New South Wales and Queensland;
* rainfed cropping in tropical Australia;
* irrigated cropping throughout the summer-rainfall zone;
* rainfed cropping on the coast of northern New South Wales and southern Queensland.

The range of tillage practices now used for crop production in the summer-rainfall zone is considered here in the context of these four agricultural systems, with emphasis on the wheatbelt where most of the tillage research has been done.

DRYLAND CROPPING IN THE WHEATBELT OF NORTHERN NEW SOUTH WALES AND QUEENSLAND

The region extends from about 25° S to 32° S, between the 500 mm and 700 mm isohyets of average annual rainfall. It is by far the largest crop-producing area in the summer-rainfall zone. The main soil types used for cropping are: the cracking black earth and grey clays, which occur mainly on the north-western plains of New South Wales and the Darling Downs of Queensland; the red-brown earths, which are found mainly on the north-western slopes of New South Wales; and, to a smaller extent, non-calcic brown soils and prairie soils (Hubble and Isbell, 1983). The black-earth soils are inherently very fertile and have a high water-storage capacity but they were not generally cropped until the introduction of the disc plough (Hallsworth *et al.*, 1954), in the 1920s.

Wheat (*Triticum aestivum*) is the principal crop in the region, while barley (*Hordeum vulgare*), sorghum (*Sorghum vulgare*) and sunflower (*Helianthus annuus*) are the major crops used in rotation with wheat. Peanuts (*Arachis hypogaea*) are grown in the Burnett region of Queensland and other minor crops, such as dryland cotton (*Gossypium hirsutum*), are grown in the warmer parts of northern New South Wales and the Darling Downs.

In the absence of a legume-ley rotation or significant areas of grain legumes, soil nitrogen levels in the region are declining, even on the high-fertility black-earth soils. Consequently, recent tillage research has taken a 'farm systems' approach, in which crop rotations have been explored in order to restore soil fertility as well as improve the management of soil and water resources.

Rainfall and fallowing practices

The region receives from more than 700 mm of rainfall annually on the eastern edge to less than 500 mm on the western margins. Generally, between 60 and 70% of total rain falls in the period October to March inclusive. Rainfall is increasingly summer dominant to the north of this region. A feature of the summer rainfall is its unreliability, and its occurrence in high-intensity storms.

Both summer and winter crops have traditionally been grown after fallow for water conservation. The dependence on stored fallow water increases westward into the drier regions, with reports of wheat-yield increases of 10 to 26 kg ha^{-1} for each additional millimetre of available water stored at planting (Waring *et al.*, 1958; Fawcett *et al.*, 1976). The length of fallow varies between 5 and 19 months. A fallow of 6 months commonly precedes wheat and 6-10 months is common for sorghum. There is evidence that such long fallows, with the attendant risk of erosion, may not be necessary, as most of the water stored is present in the soil within 3 months of commencement, either in summer or winter (Berndt, 1972). Options for fallowing and crop rotations are discussed later (Table 3.8).

To maximise storage of water, the fallow period begins immediately after harvest of the previous crop. Burning of residues was originally advocated as the first step in land preparation for a fallow (Anon, 1925). Erosion was rampant between the two world wars following the introduction of the tractor, particularly on sloping country (Skinner *et al.*, 1977). Since the Second World War, there has been a move to larger tractors, the virtual elimination of the mouldboard plough, and a trend away from disc ploughs to tined implements. This has been accompanied by a steady advance of farming into the drier western areas, through the conversion of grazing lands to farming. Severe erosion has continued. The factors causing soil erosion are considered more fully in Chapter 6.

Towards better techniques of crop-residue management for soil conservation

The development and application of better residue management practices occurred in three stages. The first was the dawning awareness that burning was wrong. While controversy raged over the advantages and disadvantages of burning, farmers who attempted to retain residues did so by incorporating them. The second stage saw an appreciation of the fact that residues retained on the soil surface afforded better protection against erosion. This period was marked by developments in tillage and sowing machinery (Chapter 7) and the first serious research on stubble retention. During this time, tillage practices to leave residues above the ground were widely adopted. At the same time, a new era in research began when herbicides were used to replace tillage and the no-till fallow was devised. Research on this expanded greatly in the late 1970s and early 1980s, constituting the third stage of development. These three stages are discussed below.

Stage 1: Erosion awareness and stubble incorporation

The severe problems of soil erosion have long been recognised. Powell (1948) prophetically pointed out that:

> ...wind and water erosion on undulating cultivated land is so extensive and is increasing so rapidly that change in cultural practice is essential and in most cases inevitable, whether the change be to stubble mulch farming or to some other method.

By the late 1940s, many farmers recognised the value of retained residue as an aid to erosion control, but saw difficulty in efficient handling of the residue between two successive wheat crops with the machinery then available (Anon., 1950).

By the early 1950s, surveys in New South Wales revealed that crop residues were always grazed on the red-brown earth soils, with half the farmers subsequently burning the residues and half ploughing them in with disc ploughs and disc harrows (Hallsworth *et al.*, 1954). Those who adopted the practice of not burning did so due to an awareness of erosion. In contrast, 80% of farmers on the black earths burnt the residues. Of these farmers, 40% used a scarifier in preference to the disc plough, except where burning was incomplete. Where residue was not burnt, heavy grazing followed by use of a disc implement was seen as the only practicable management method for the heavy black soils (Anon., 1950).

Residue burning was still common in north-western New South Wales in the late 1950s, but the trend was to burn less (Walkden Brown, 1958). Residue burning was also widespread in Queensland at this time (Anon., 1962a; McGetric, 1968) though it was considered undesirable. The difficulty of handling heavy residues dominated farm practice. Primary cultivation with a sundercut or disc cultivator was normally followed by three to five secondary cultivations prior to sowing, depending on rainfall and weed growth (Anon., 1962a).

Even in the early 1960s, burning was advocated to control cereal root diseases (Butler, 1961; Anon., 1962b) although limited burning was advised where pasture-legume rotations were not used or where erosion was a serious problem. Burning was strongly advocated for the north-western plains of New South Wales as late as 1968 (Darley, 1968).

Thus, to the late 1960s, tillage techniques were dominated by the conflict over retention of residues - valued on the one hand for erosion control, but on the other hand creating problems through disease carryover and through the inability of machinery to pass through heavy residues.

Stage 2: Surface retention of residues

The first detailed tillage research in the region began at Warwick, Queensland, in 1968 (Littler and Marley, 1978), in New South Wales at Narrabri in 1967 (Fawcett, 1975), and by the Soil Conservation Service at Gunnedah in 1970. These experiments compared a wide range of residue management and tillage options. Farmers also were showing interest in trying different methods of handling residues.

In a parallel development, a range of conservation tillage machinery was imported for evaluation under Queensland conditions, following a report on a study tour of the United States and Canada (Swartz, 1969). A Queensland Machinery Evaluation Committee was set up to consider modification of existing machinery or importation of new equipment to allow the management of crop residues for maximum erosion protection.

The Machinery Evaluation Committee found that disc implements were unsuitable because of the amount of residue incorporated into the soil (Kamel, 1975). Although tined implements had been developed overseas with the capacity to handle substantial levels of crop residues, nearly all locally available tined implements had poor residue-handling capacity. Consequently, most farmers attempting stubble-retention systems conducted at least one slashing or discing before using a tined implement.

In addition to tillage problems, locally available planting equipment was inadequate (Kamel, 1975). The Australian combine (i.e. seeder and cultivator) could handle only very small amounts of residue. Planters with disc openers had been discarded because of excessive soil adherence to the discs. Compromise solutions were being developed by farmers building or adapting their own machinery for sowing by removal of cultivating tines or by placing seed and fertiliser boxes on top of tillage implements such as scarifiers. The addition of press wheels was seen to considerably improve crop establishment (Kamel, 1975; L. Ward, personal communication).

Research and farming experience in this period showed clear advantages in complete surface residue retention. Despite this, adoption of the practice was limited. A survey of the erosion-liable eastern uplands of the Darling Downs in 1980 (Chamala *et al.*, 1983) showed that 78% of farmers owned a disc plough and 68% owned a chisel plough. Only 6% owned a blade plough, 7% a scariseeder and 8% had trash combines, the equipment needed for surface retention. Farmers were therefore not set up to handle heavy stubble residues.

The survey by Chamala *et al.* (1983) showed that burning was not a significant pre-cultivation practice except where double cropping from a winter to a summer crop was practised. Most farmers used a disc or mouldboard plough in preference to a chisel plough for the first cultivation. The use of the chisel plough was for ripping plough pans rather than leaving residue on the surface. It is particularly revealing that some 48% of farmers had not changed their winter crop to winter-crop fallow techniques in the previous 12 years.

A survey conducted in 1980 in the northern shires of the northern New South Wales wheatbelt indicated that some 24% of farmers in the western plains still burnt residues, although only 5% of farmers in the undulating country to the east did so (Watt, 1983). In total, 42% ploughed-in the crop residue while some 46% claimed to practise some form of surface residue retention. There was, however, no indication of how this retention was achieved.

In the central highlands of Queensland there has been a greater adoption of techniques of residue-retention tillage than in other summer-rainfall areas due largely to the very severe erosion problems experienced in this region (Gilmore, 1982).

Stage 3: Developments of the no-till fallow technique

Many new and effective herbicides were released during the 1960s and 1970s (Chapter 1), which meant that fallowing could be accomplished without tillage. Although developments in farming practices during Stage 2 concentrated on tillage for weed control, each of the experiments mentioned earlier had some treatments in which herbicides fully replaced cultivation, and residues were left above the soil surface - the 'no-till fallow'.

More recently, a no-tillage project team based at Tamworth began research in 1978. Their programme differs from the others in that crop rotation has been an integral part of the study in an attempt to reverse the decline in soil fertility and to overcome the disease problem, which occurs when wheat is grown in a monocultural rotation, particularly when residue is retained. Other recent work has explored the possibility of increasing farm profitability by opportunity cropping using no-tillage techniques. All these projects have had as a main goal the development of tillage and stubble-handling systems to reduce soil erosion and maximise utilisation of rainfall.

Chemical companies have also undertaken considerable research aimed at partial or complete replacement of tillage by herbicides. Although the use of herbicides has increased rapidly since 1980 there has been little adoption of the complete no-till fallow.

Development of no-till planters has also taken place by government agencies, private enterprise and by farmers themselves (Chapter 7).

Herbicide technology for fallowing

The increasing range of knockdown and residual herbicides enhances the possibilities of replacing tillage by herbicides for weed control.

Partial replacement of tillage by herbicides occurs:

* where a fallow is maintained with herbicides over the erosion-prone summer-rainfall period, and tillage is done during the autumn - this system allows incorporation of fertilisers and herbicides before the following crop is sown;

* where tillage controls hard-to-kill weeds such as regrowth of grain sorghum (*Sorghum vulgare*), large weeds present at harvest time of winter cereals, or weeds under severe moisture stress - subsequent weed control may be achieved with herbicides;

* in cultivated fallows, where herbicides may be used to control weeds when soils are too wet and there is a greater risk of transplanting weeds and of damage to soil structure from cultivation;

* in cultivated fallows, where the final cultivation may be replaced by a herbicide to help conserve sowing moisture, and to improve timeliness of sowing.

In the full no-till fallow, the only soil disturbance is that required to sow the crop. To achieve such fallows, both knockdown and residual herbicides may be used. For example, in a wheat-to-grain sorghum fallow (normally 10 to 12 months in duration - Table 3.8), atrazine applied immediately after wheat harvest can control weeds for the full length of the fallow, and replace from five to eight cultivations. Knockdown herbicides are used to kill any weed escapes from the atrazine-based no-till fallow. Residual herbicides normally are more cost-effective than knockdowns but they restrict flexibility in cropping systems, as susceptible crops may be damaged if sown into treated soils. This can be important, particularly if the originally intended crop is not sown because of lack of sowing rains, or the crop fails for any reason. Residual herbicides can also restrict the possibilities of opportunity cropping, as discussed later in this chapter.

No-till techniques restrict the range of herbicides available for in-crop weed control. For example, herbicides that require incorporation for activation are virtually excluded from such systems. However, with most crops, a sufficiently wide range of herbicides is still available to control weeds within the crop.

Summary of tillage practices in the 1980s

Although in the mid-1980s there is widespread recognition by farmers of the desirability of residue retention for soil structural improvement and for soil-erosion control, adoption is still restricted by the practical difficulties of farming with retained residues. There is also some concern over disease problems. A wide range of systems is practised by farmers, but in most cases there is a distinct trend towards a reduction in the number of tillage operations. There is widespread interest in no-till cropping but little commitment to it is evident. Current tillage practices are summarised below.

Burning Where crop residues are burnt, primary cultivation is usually with a chisel plough or a scarifier followed by three to four cultivations with a scarifier. The final cultivation is sometimes done with the combine seeder. This is the easiest system and allows maximum weed control, but creates maximum erosion liability and soil structural breakdown. A combine seeder is used to plant small-seeded cereals, but there is a strong trend to row crop planters, incorporating presswheels, for planting all summer crops and larger-seeded winter crops.

Incorporation The incorporation of residues with disc ploughs allows stubble to decompose. Secondary tillage can then proceed with little modification to conventional machinery. However, only limited residue levels remain for erosion protection.

Surface retention Where surface residue retention is tried, there are many variations in methods adopted. Blade or sweep ploughs have not found wide acceptance, and chisel ploughs fitted with sweeps are more common. Visitors to farm machinery exhibitions become very conscious of the increasing amount of residue-handling machinery becoming available.

Current winter-cereal-crop seeders are limited in the amount of trash that can be handled. This is important with surface retention of residues. Seed boxes are at times fitted to trash-handling scarifiers. The use of air seeders fitted to 'wide line' machinery increases the speed of sowing in a given field, but planting depth is often inaccurate. A further approach to sowing through stubble is to increase row spacing, but the wider the row spacing, the greater the probability of incurring a yield penalty in winter crops (Chapter 7). In contrast, large-seeded crops and summer cereals are sown as spaced row crops, and residue clearance is not such a problem.

No-till fallow This technique has attracted widespread interest but little adoption. Partial substitution of herbicides for tillage is more common.

Strip cropping An important development in farming systems during the 1970s was the introduction of strip cropping. This allowed less-than-ideal tillage practices to be continued with a greatly reduced risk of soil erosion. This system also lends itself to minimum-tillage and no-till systems of production.

Conservation farming systems

Criteria for evaluation

It has become clear from research in the 1980s that systems of conservation farming must entail more than stubble retention and the simple substitution of herbicides for cultivation although these techniques are the mainstay of conservation farming. Crop rotations, crop agronomy (such as nutrition, sowing rates, choice of cultivar), fallowing and other aspects of water management, pest, disease and weed management, and the place of structural works for erosion control, are all important. These 'farm system' considerations are introduced here as a background to the detailed discussion of sub-systems in Chapters 6 to 15.

Whatever system is promoted for the summer-rainfall zone it must be judged by:

* its capacity to reduce the risk of soil degradation and arrest the decline in soil structure;
* its effectiveness in capturing, storing, and using rainfall;
* the crop yields achieved.

Comparative performance of alternative systems

The above criteria will now be used to compare a range of tillage options. (Economics are also important, but are considered in Chapter 16.)

Soil erosion Calculations using the universal soil-loss equation (D. Marston, personal communication) indicate a reduction in erosion with a change from burning to incorporating, a further reduction with surface retention and a large additional benefit from deletion of tillage in a no-tillage fallow (Table 3.1). The estimates point to the value of structural works in conjunction with conservation farming methods, particularly where tillage is practised.

Table 3.1 Soil erosion based on the universal soil-loss equation (D. Marston, personal communication)

Treatment	Soil loss (%)[a]	
	No structural works	With structural works
Residue burnt	60	25
Residue incorporated	30	10
Residue mulched	18	6
No-till fallow	3	1

[a]Soil erosion in continuous bare fallow = 100%.

These predictions are confirmed by measurements of soil loss due to natural rainfall in south-east Queensland on a range of soil types (Table 3.2) (Cummins, 1973), and in northern New South Wales from simulated rainfall on a black-earth soil at Gunnedah (Table 3.3) (Marston, 1980).

Table 3.2 Soil loss from various management practices and soil types in south-east Queensland (Cummins, 1973)

Soil type and situation	Soil loss ($t\ ha^{-1} yr^{-1}$)		
	Bare fallow	Residue incorporation (average management)	Residue mulch, contour cultivation (good management)
Alluvial, fertile self-mulching clay soil, 1–2% slope	60	24	12
Colluvial clay, red–brown colour, 1 m deep, 1–3% slope	76	31	(without contour banks) 12
Colluvial clay, red–brown colour, 1 m deep, 5–8% slope	270	110	(with contour banks and crop rotation) 10

Table 3.3 Total soil and water loss from a simulated rainfall of 50 mm at 115 mm hr^{-1} on three tillage systems (Marston 1980)

Treatment	Soil loss ($t\ ha^{-1}$)	Water loss (mm)
Residue burnt	9.04	22
Residue incorporated	1.36	13
No-till fallow	0.32	8

In detailed studies at two sites on the Darling Downs, Freebairn and Wockner (1982) compared a residue mulch treatment (retained on the surface using sweeps for cultivation) with burnt residue, residue incorporated, and no-till fallow treatments. Residue-mulch treatments produced substantially less soil movement and less runoff than did the residue-incorporated or residue burnt treatments (Table 3.4). As with Marston's (1978) data, the reduced erosion was associated with reduced peak runoff rates. No-till-fallow treatments had more total runoff than the residue-mulch treatments, but there was less soil loss under no-till. The authors attributed

Table 3.4 Mean annual runoff and soil movement from four tillage treatments on the Darling Downs 1978/79–1980/81[a] (Freebairn and Wockner, 1982)

Tillage treatment	Runoff (mm)	Soil movement (t ha^{-1})
Greenmount (black earth):		
Residue burnt	82.1	85
Residue incorporated	53.4	29
Residue mulch	37.3	3
No-till fallow	44.0	1
Greenwood (grey clay):		
Residue burnt	82.3	48
Residue incorporated	56.2	12
Residue mulch	42.6	5
No-till fallow	54[b]	2

[a]Water year 1 October–30 September.
[b]Weighted 1 year value.

this reduced erosion to the greater residue cover under no-till treatments, rather than the reduced cultivation.

Results throughout the region thus support the principle of using tillage methods that retain a maximum amount of residue to reduce soil erosion. Residue mulching is a major improvement on residue burning and residue incorporation. However, under rapid flooding the whole of the cultivated layer, with the detached residue, can be moved, with drastic erosion consequences. Results therefore indicate that elimination of fallow tillage (no-till fallow) is best for erosion control.

Soil structure Cultural practices can influence soil structure through the amount of soil disturbance (tillage) and the amount of organic matter returned to the soil (residue management). The effect of both of these variables on soil structure has been studied in systems-type experiments in northern New South Wales and southern Queensland. In general, the amount of tillage has had more influence on soil structural changes than has residue management.

Elimination of fallow tillage on a black-earth soil on the Darling Downs in Queensland improved soil structure as measured by soil aggregate stability (Hamblin 1980). On a similar soil at Gunnedah, New South Wales, D. Marston (personal communication) found improved structural stability after 3 years of no-till fallow. In a subsequent trial at Gunnedah, however, no significant improvement in structural stability was recorded after 4 years of no tillage, although organic carbon was slightly higher where stubbles were not burnt (Thompson and Marschke, 1984).

In experiments at both Gunnedah (Marston and Hird, 1978) and Warwick (Loch and Coughlan, 1984) there was little or no effect of residue retention on surface organic carbon levels of the soil. Similarly, at two sites after three years and one site after two years in northern New South Wales, Thompson, Marschke and Harte (1984) detected no difference in organic carbon levels between no-till fallow, residue burnt and residue retained treatments. However, in a fourth experiment on virgin soil, organic carbon declined less under no-till fallow than under residue burning or residue retention.

Most tillage research in the north-eastern wheat belt of Australia has been on the black earths and grey clays. By contrast, Harte (1984) compared red soils in northern New South Wales having a continuous cropping history of at least 15 years with adjacent virgin sites. He concluded that on a red-brown earth and on a calcareous red earth, cultivation had substantially reduced water stable aggregation, increased soil bulk density to 15 cm and reduced infiltration. In fact, a discrete hard pan had formed on these two soils. The effects of cultivation were not as pronounced on a Euchrozem. Infiltration was improved by deep ripping with the effects still evident 12 months after treatment (Harte and Armstrong, 1983).

Effects of tillage on organic carbon levels and structural stability take some years to become detectable. Therefore more long-term research is needed to give firm conclusions. At present, however, it appears that residue retention may not improve soil structure if soil tillage is practised for weed control.

Soil water storage Although the problem of soil erosion has been the dominating influence in the trend to new tillage systems in the region considered here, improvement in soil moisture storage has been shown to be another advantage of these new systems. A summary of these findings is given here but they are considered in greater detail in Chapter 8.

On the swelling black and grey clay soils of north-western New South Wales, Fawcett (1975) compared soil moisture at sowing in cultivated and no-till fallows of 6-18 months duration, with and without burning, at seven sites over 3 years. He concluded that, although weed control was the most important agronomic factor affecting fallow water accumulation, both stubble retention and chemical control of weeds could increase water storage compared with burning and cultivation. Although the benefits of stubble retention and chemical weed control were generally small, they were additive, resulting in substantially more stored water (average 20 mm) in the no-till fallow in 14 of 37 comparisons with other management strategies. The difference was greater in long fallow (28 mm) than in the short fallow (9 mm).

J.F. Holland (unpublished data) confirmed these results for similar soils in northern New South Wales but found the reverse effect on a soil with a hard-setting surface. It remains to be seen whether continuous residue retention under no-till cropping will improve this soil, since no-till fallow is reported to be suitable for most soil types (Osborne, 1984).

In work reported by Holland and Felton (1983), higher yields of grain sorghum after a no-till fallow were associated with increased water storage at sowing time. They commonly found about an extra 25 mm available water in the soil at sowing, and yield increases in grain sorghum of about 500 kg ha^{-1}. This is in contrast to wheat, which has produced remarkably similar yields from no-tillage and cultivated fallows (Holland, Felton and Doyle, 1982). While about 50 kg^{-1} nitrogen was applied in the sorghum studies, lower nitrogen fertiliser rates have been used with the wheat. Yield responses to no-tillage may be obtained with higher fertility levels (J.W. Littler and J.M.T Marley, personal communication).

On a black-earth soil on the Darling Downs, Littler and Marley (1978) measured moisture accumulation during fallows for annual winter cereal production in a long-term experiment. The average fallow efficiency (percentage of fallow rainfall stored in the soil) of each of the various tillage and stubble treatments is given in Table 3.5. An increase in pre-sowing available soil moisture of the no-tillage, stubble-retained treatment over the mechanically cultivated treatments was recorded in six of the ten seasons.

Table 3.5 Effects of residue and soil management on fallow efficiency over 10 years at Warwick, Queensland (Littler and Marley, 1978)

Residue Management	Soil Management	Fallow Efficiency (%)
Burnt	Cultivated fallow	16.8
Burnt	No-till fallow	20.1
Retained	Cultivated fallow	22.7
Retained	No-till fallow	25.8

In more recent work on eight sites in southern Queensland, Somervaille *et al.* (1984) reported that minimum tillage increased water storage at sowing by 17 mm compared with a cultivated fallow, while no-till increased storage by a further 11 mm.

A major practical benefit with residue retention is increased soil water content near the soil surface. Fawcett (1975) drew attention to the frequent occurrence in the summer-rainfall zone of dry soil-surface conditions which can prevent sowing even when substantial reserves of subsoil water are present. It has now been shown that the extra moisture held in the seedbed under a residue mulch compared with unmulched seedbeds can usefully extend opportunities for planting after rain has fallen (Radford and Nielsen, 1983). For example, about 2 t ha^{-1} of wheat residue effectively extended the sowing time of sunflower by 4 days at one site. The effect can be even greater when intact residues are maintained on the surface of the soil and this is combined with no-tillage. Littler and Marley (1978) estimate that, in their experiment, in three seasons the no-tillage, residue-retained treatment could have allowed sowing to be carried out at the optimum time, whereas there was insufficient seedbed moisture in most other treatments to sow at this time. These authors delayed sowing until all plots could be sown, thus penalising the no-till fallow, since wheat-grain yields fall by approximately 6% for each week that sowing is delayed past the optimum time (Goyne, 1972; Doyle and Marcellos, 1974; McDonald *et al.*, 1983). In the extreme, it can mean the difference between a crop being sown or not sown in a particular season.

Crop yield Although water storage has been increased with residue retention or no-till techniques, this has generally not been reflected in greater crop yields compared with burning of residues (A. Doyle, D. Freebairn, personal communication; Fawcett, 1975; Marston, 1980; Felton, 1984). Where differences do occur they usually favour residue retention, except in long-term experiments, where residue burning may be favoured, largely due to the effects of diseases including yellow leaf spot and crown rot (Littler and Marley, 1978). These diseases are

Table 3.6 Response of wheat to nitrogen under a cultivated and a no-till fallow (Holland, 1980)

Nitrogen rate (kg ha^{-1})	Wheat yield (t ha^{-1})	
	Cultivated fallow (residue retained)	No-till fallow (residue retained)
0	1.3	1.3
20	1.4	1.4
40	1.4	1.6
60	1.4	1.6
80	1.4	1.6
100	1.4	1.7

LSD ($P < 0.05$) = 0.2 t ha^{-1}

discussed in Chapters 13 and 14. Thompson *et al.* (1983) have more recently concluded that root lesion nematodes associated with the residue retention and no-till treatments may have also restricted the grain yields of wheat.

Other work suggests that additional nitrogen may be required for no-till crops compared with cultivated (residue retained) production systems (Doyle, 1977; Strong, 1981). Thus, increased fallow water may not always be reflected in yields. This is clearly illustrated in Table 3.6 and is discussed more fully in Chapter 11.

Equal yields have been achieved with wheat in other experiments even when nitrogen deficiencies have not been adequately corrected and diseases have built up in continuous wheat systems (Table 3.7).

Table 3.7 Wheat yields in cultivated and no-till fallow in three studies in northern New South Wales and southern Queensland

Research team	Years	Wheat yield ($t\ ha^{-1}$)	
		Cultivated fallow (residue retained)	No-till fallow (residue retained)
Fawcett (1978)[a]	1967–68	1.89	1.97
Littler and Marley (1978)[b]	1969–78	2.70	2.69
Northern NSW No-tillage[c] Research Team, Holland (unpublished), Felton (1984)	1981, 1983	2.76	2.72

[a] Seven sites in 1967, six sites in 1968.
[b] One experiment for 10 years.
[c] Seven sites in 1981, five sites in 1983.

In contrast to wheat, summer crops, particularly grain sorghum and soybean (*Glycine max*), have produced higher yields when grown under no-till fallow compared with cultivated fallows (Felton and Holland, 1983). Data from six experiments show a yield advantage of about 500 kg ha^{-1} under no-till fallow compared with cultivated fallow. Dryland soybeans produced 400 kg ha^{-1} more grain under no-till fallow than cultivated fallow in two seasons (Herridge and Holland, 1984; Holland and Herridge, 1984). In these latter experiments, pigeon peas (*Cajanus cajan*) had higher yields under a no-till long fallow compared with a cultivated fallow in both years, cowpeas (*Vigna unguiculata*) were superior under no-till fallow in one season only, and mungbeans (*Vigna radiata*) produced similar yields for the two tillage systems in both seasons.

The above summer crops were planted into winter cereal residue after a 10-12 month fallow, so there was little risk of disease carryover from the previous crop. In addition, the sorghum had been supplied with adequate nitrogen fertiliser (usually 50 kg ha^{-1} N), and the soybeans could provide their own nitrogen via fixation, so nitrogen fertility should not have limited yield in these experiments.

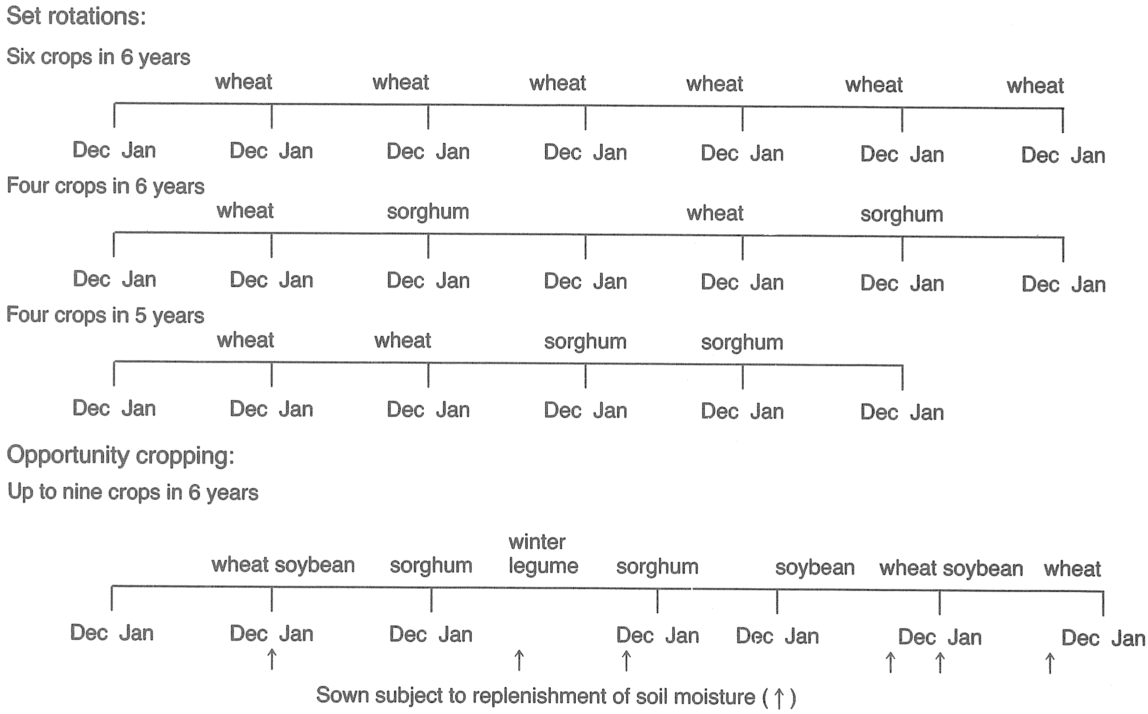
The fact that no-till fallowing generally increases water storage, but only increases yield in summer crops, very clearly demonstrates the need for a multidisciplinary approach to conservation farming, in which pest, disease and weed management are considered together with nitrogen and water management and soil conservation - conservation farming entails much more than the simple substitution of chemicals for cultivation in order to obtain satisfactory yields. Economic analyses in Chapter 16 show that the simple approach can also increase costs and reduce profitability. Any increase in costs with no-till techniques can be offset, however, by significant increases in farm productivity, particularly through changes in rotations. The following section outlines some of the changes to crop rotations that are made possible with no-tillage techniques and may even be necessary for profitable implementation.

Rotations and cropping frequency

Rotations

Littler and Marley (1978) have indicated the disadvantage of continuous wheat production, particularly where residues are not burnt, thus emphasising the need for crop rotation. Fortunately, in southern Queensland and northern New South Wales, there is a wide diversity of crops that can be grown in rotation with wheat. Besides the other winter cereals (barley, oats, triticale and rye), other crops that can be grown include: the winter grain legume crops (lupins (*Lupinus angustifolius*, *L. albus*), chickpeas and faba beans (*Vicia faba*)), the winter oilseed crops (rapeseed (*Brassica napus*, *B. campestris*), safflower (*Carthamus tinctorius*), linseed (*Linum usitatissimum*)), the summer legumes (soybean, cowpeas, mungbean and pigeon peas) and

Table 3.8 Examples of possible rotations in northern New South Wales and the Darling Downs of Queensland



Notes on opportunity cropping:

- Opportunity cropping is facilitated with no-tillage techiques, with improved timeliness of operations and preservation of soil moisture.
- The level of soil moisture replenishment at which the decision is made to sow depends on the farmer's willingess to take risks, and the expected rainfall on that crop in his environment.
- Opportunity cropping is more feasible in high rainfall environments (Berndt and White, 1976).
- Income variability is greater with opportunity cropping (Berndt and White, 1976).
- Soil erosion is minimised with opportunity cropping (Berndt and White, 1976).
- Because fallow periods are shorter, fallowing costs are less than with set rotations.
- Where possible, legume crops and cereals should be alternated in the crop sequence.

other summer crops (sunflower, grain sorghum and several millets). Table 3.8 gives examples of set rotations that vary in erosion risk (length of fallow) and crop sanitation value.

In the South Burnett region of Queensland, conservation cropping systems are now actively promoted to growers to protect the rich kraznozem soils from erosion (Bateman and Rowlings, 1980). The preferred rotation is a summer legume crop (peanut, soybean or navy bean (*Phaseolus vulgaris*)) followed by a winter cereal (wheat or barley), then summer grain crop (maize (*Zea mays*) or grain sorghum), followed by winter fallow and back to summer legume. This rotation results in three crops in 2 years. The aim during all tillage operations is to maintain stubble on the soil surface for maximum protection, and this is primarily achieved with chisel ploughs, using a range of ground tools, from narrow chisels to sweep tools. This system appears to be working satisfactorily on commercial farms, with large savings in establishment costs as well as affording the desired erosion protection in comparison with conventional systems. There may be an advantage in incorporating a no-tillage system within this rotation.

Cropping intensity

The use of no-tillage techniques has implications for cropping intensity as well as rotation. For example, Berndt (1972) showed on self-mulching soils of the Darling Downs that 70% of the total available water stored after 19 months of bare fallow had been stored 3 months after the start of the fallow. Similarly, 3 months after a fallow began in May, 70% of the total water available at the end of 14 months had been stored. These figures include available water stored at the start of the fallow averaging about 50 mm, which had not been used by the previous crop. Fawcett (1975) also highlighted the large reserve of moisture that can be present at the start of a fallow in seasons with substantial rains late in the previous growing season.

The dominance of the first few months of a fallow in terms of moisture storage is consistent with the rapid entry of water through open cracks in cracking clay soils. When cracks in the soil close after the soil is wet, slaked (Chan and Hodgson, 1981) or cultivated (Stirk, 1954), the rate of infiltration slows dramatically.

Opportunity cropping

Berndt and White (1976) have demonstrated how to exploit this rapid early wetting phenomenon by a technique called opportunity cropping, illustrated in Table 3.8. Crops are planted when a predetermined level of soil moisture is present rather than on the basis of set rotations. They showed two main advantages of opportunity cropping in comparison with set rotations; these are:

* less runoff and erosion hazard; and
* higher returns per unit area (almost doubling returns in some areas), even though yield per crop was often lower and income more variable; the higher return was associated partly with reduced fallowing costs.

Berndt and White showed on the basis of simulation techniques that in high rainfall areas (about 670 mm) this system resulted in about three crops every 2 years. This is in contrast to the situation in northern New South Wales, where a common rotation is wheat-10 month fallow-grain sorghum-14 month fallow-wheat, resulting in two crops in 3 years, even in high-rainfall environments (up to 700 mm). This results in needlessly long fallow periods with high erosion risk.

Berndt and White (1976) based their work on cultivated fallows, using the crops wheat and sorghum. More recently, Holland and Herridge (1984) have shown the benefit of using similar systems but incorporating no-till techniques and growing grain legumes. They sowed six summer crops at Tamworth in December 1983 on three cropping systems, namely no-till long (10 month) fallow, cultivated long fallow, and double crop (opportunity crop). Wheat yield from the double crop treatment was 4.5 t ha^{-1}, and the summer crops were planted 3 weeks after harvest following herbicide treatment only. Wheat, soybean and sorghum yields, and financial returns, for the different systems are shown in Table 3.9.

Table 3.9 Effect of tillage and cropping system on yields of soybean and grain sorghum and on financial returns (Holland and Herridge, 1984)

Farming system	Grain yield (t ha^{-1})			Total return[a] (\$ ha^{-1}) Jan 1983–June 1984
	Wheat 1983	Soybean[b] 1983–84	Sorghum[c] 1983–84	
Cultivated long fallow	–	2.75		825
No-tillage long fallow	–	3.15		945
Double crop (opportunity crop)	4.5	2.62		1281
Cultivated long fallow	–	–	5.75	574
No-tillage long fallow	–	–	5.80	580
Double crop (opportunity crop)	4.5	–	4.74	969

[a]Wheat \$110/t, Soybean \$300/t, Sorghum \$100/t.
[b]Mean of two cultivars: WIC 36 and Forest.
[c]Mean of + and – nitrogen.

The traditional system in this comparison is cultivated long fallow into sorghum, returning a gross of \$574 ha^{-1}. With this system, sorghum depletes soil nitrogen, and the cultivated fallow is very susceptible to erosion. At the other extreme, the double (or opportunity) cropping system involving wheat in 1983 with soybeans in 1983/84, both grown without tillage, returned a gross of \$1281, during which the soil was protected from erosion by growing crops and residue cover, and the soybeans fixed more nitrogen than was removed in the grain. The use of no-till techniques also increases the storage of water and should lead to more timely planting, both of which would increase yields over an opportunity cropping system using conventional tillage techniques.

RAINFED CROPPING IN THE TROPICS

Cropping constraints

Although crop production has occurred for some time in parts of the tropics of Australia, such as on the Atherton Tableland inland from Cairns, the region as a whole is still in the development phase, with considerable potential for expansion of cropping areas (Wood and Fukai, 1982). In particular, areas of Australia's semi-arid tropics with potential for rainfed agriculture are in the northern end of the Northern Territory, Cape York Peninsula of Queensland and the Kimberleys of Western Australia, with rainfall between 750 mm and 1200 mm annually (Peake *et al.*, 1983).

Rainfall comes predominantly between December and March, and the zone experiences one of the highest rainfall intensities in Australia, with most of the region receiving in excess of 15 mm per wet day (Leeper, 1960). By contrast, much of southern Australia receives less than half this amount per wet day. The annual rainfall erosion index increases at a more rapid rate than rainfall intensity, and areas of Cape York Peninsula of Queensland have indices in excess of 1000 compared with about 200 on the Darling Downs of Queensland (Rosenthal and White, 1980).

The main soils with cropping potential in the semi-arid tropics are the red earths, which are highly erodible (Peake *et al.*, 1983). This, in combination with the high rainfall intensities and rainfall erosion indices, has meant that soil erosion is a major problem, particularly when these soils are cultivated.

A major limitation for cropping in this zone is the short growing season confined to the December to March rainfall peak. Fisher *et al.* (1977) concluded that the main constraint to farm production with cropping is the available sowing time. Tillage systems that facilitate sowing operations and allow maximum use of the growing season should have distinct advantages.

The semi-arid tropics - research at Katherine, NT

Although cropping has been studied at the Katherine Research Station since about 1946, the only rural enterprise of consequence is the extensive beef cattle industry (Peake *et al.*, 1983). This is despite the fact that yields of dryland grain sorghum of up to 7.7 t ha^{-1} have been obtained experimentally (Myers, 1978). Several commercial cropping ventures have failed for many reasons, discussed by Fisher *et al.*, (1977). These include managerial difficulties, high costs of labour and export facilities, marketing problems and lack of agronomic knowledge. These authors highlight the problems of soil erosion faced by most schemes. They recommended research on residue mulching and minimum tillage as a means of reducing these problems.

With the objective of maximising the use of the limited growing season, Phillips (1959) studied the influence of timing of land preparation on the yield of several crops at Katherine. Although he did not study minimum tillage or no-till systems, he did compare the traditional system of waiting until the soil was thoroughly wet before ploughing with a mouldboard plough to a depth of 7-10 cm, with that of ploughing in the dry season and also with a deeper ploughing to 15-20 cm. He concluded that, in general, the highest yields of peanuts and sorghum were obtained after a deep dry season ploughing plus a deep wet season ploughing. Deep ploughing brought about greater vegetative development in cotton, but not necessarily higher cotton yields. Ploughing treatment influenced the depth of penetration of early season rainfall and it also influenced total root mass and root distribution in sorghum.

Basinski *et al.* (1964) also concluded that deeper ploughings were profitable for peanut production at Katherine. However, Arndt (1966a and 1966b) and Arndt and Rose (1966a and 1966b) showed that soil compaction associated with tillage operations had a deleterious effect on moisture infiltration. Norman and Begg (1973), in reviewing this work, concluded that for any given soil, the effect of traffic compaction on infiltration depends on the nature of the rainfall. The detrimental effect is potentially more serious if rain falls in intense storms. They postulated that in minimum-tillage systems, the infiltration could be increased by providing banks to increase the retention time and reduce runoff to a minimum. By using herbicides for weed control, they saw the aim of tillage simply to adjust the bulk density of the soil. They also suggested a possible advantage of rolling in order to develop a stable tilth in that environment.

An alternative answer to the erosion problem is to plant crops into uncultivated land covered by vegetation that has previously been chemically killed. A programme to investigate this strategy was initiated at Katherine in the late 1970s (McCown *et al.*, 1980). In terms of crop establishment, these workers have shown a large benefit from a mulch (in this case, hessian cloth), which improved the establishment of both maize and grain sorghum. For example, final sorghum establishment was about 70% under mulch compared with about 25% under bare soil. Maize establishment was about 27% under mulch compared with virtually nil under bare soil. Mulching was also associated with lower temperatures in the seed zone, decreasing soil temperatures by as much as 5-7°C at certain times at 1 cm depth, and by as much as 3°C at 5 cm depth (McCown and Peake, 1980). Elevated soil temperature is obviously linked with more rapid soil drying in tropical environments.

The Atherton Tableland

The Atherton Tableland has been used for grain cropping since about the turn of the century, and the dominant crops grown in the area are maize and peanuts. Recently, tillage research has been conducted at the Kairi Research Station to investigate crop response to reduced tillage and direct-sowing methods of crop production, in comparison with conventional cultivation systems. There have been no significant differences between these tillage systems (when residue was retained) as measured by maize grain yield in three seasons (Younger, unpublished data).

Crop rotations

As well as being susceptible to erosion, the red-earth soils common in tropical Australia have low fertility. Gross deficiencies of nitrogen and phosphorus can be accompanied by shortages of copper, zinc and molybdenum (Peake *et al.*, 1983). In an attempt to integrate legume pastures into cropping systems and improve nitrogen status of the soils for following cereal crops, the effect of 1-3 years of a Caribbean stylo (*Stylosanthes hamata*) ley on maize or grain sorghum planted into the pasture using no-till techniques has been studied. This legume has previously been shown to fix 80-150 kg N ha^{-1} (Wetselaar, 1967). Grain yield of maize and sorghum direct drilled after 3 years of Carribean stylo as standing hay averaged about 3.7 t ha^{-1}, whereas following 3 years of grass as standing hay the grain yield averaged about 1.0 t ha^{-1}, both without added nitrogen. With 100 kg N ha^{-1}, the grain yields were about 5.2 t ha^{-1} and 3.6 t ha^{-1} respectively. Results to date indicate that large amounts of nitrogen are being obtained by the cereal crops following Caribbean stylo and a number of other pasture legumes (Jones *et al.*, 1982).

No-till planters are being developed to allow sowing of such crops in tropical conditions. The most successful planter over a wide range of conditions has been a narrow tine preceded by a rolling coulter, to cut surface mulch, followed by a narrow in-furrow press wheel (McCown *et al.*, 1983).

IRRIGATION AREAS IN THE SUMMER-RAINFALL ZONE

Irrigation areas in this context include the major irrigation systems on the Gwydir and Namoi rivers in New South Wales, and at St George, Emerald, Biloela and on the Darling Downs of Queensland. As well, several irrigation schemes have been attempted in the tropics of northern Australia, foremost among these being the scheme on the Ord River.

Of the field crops grown, cotton provides the highest financial return. Most farming systems are based on cotton as the principal crop, and discussion of tillage in this section relates to the cotton crop.

In the irrigation areas of northern New South Wales and southern Queensland, the traditional method is furrow irrigation. The tillage system employed prior to sowing the crop depends on the crop rotation employed. In the case of cotton following wheat harvested the previous summer, a 'normal' land preparation might include chisel ploughing or discing the wheat stubble followed by deep ripping, land planing, further surface cultivation to control weeds, hilling-up or listing, and use of a sled cultivator to properly form beds.

There is an awareness of increasing soil compaction associated with use of heavy machinery during cultural operations on irrigated soils. The problem is exacerbated when operations are carried out while the soil is in a wet, plastic state. Investigations have been carried out to assess the effect of soil moisture status at the time of tillage on cotton yield and on soil physical conditions. McGarry (1982) reported an experiment in which cultivation was done when soils were 'dry', 'moist', or 'wet'. He found that plant height was greatest in the dry-tilled treatment, lowest in the wet-tilled treatment and intermediate in the moist-tilled treatment. By week 18 of the cotton crop, the land prepared when dry had produced approximately twice as many green bolls per plant (which reflects potential yield) as either the moist-tilled or wet-tilled treatments. Soil compaction (higher bulk densities), less moisture extraction by the cotton plants and poor soil structure were all associated with the wet-prepared treatment.

With traditional furrow irrigation, beds and furrows must be formed to allow irrigation water to be applied. Tillage is therefore required to provide an amount of loose soil for bed formation, but techniques to minimise tillage have been proposed. One possibility is to spray irrigate the cotton, reducing the need for expensive land-forming operations. Another option is to form beds as usual, but to use herbicides as much as possible to control weeds during the fallow period prior to planting cotton (Evans, 1983; 1984).

A third suggestion to minimise tillage is to maintain the hills and furrows of the previous crop (R. Chisholm, personal communication). This has the advantages of allowing the land to be replanted to cotton without the risk of compaction due to working the wet soil, of minimising the expense of tillage, and perhaps of conserving moisture that otherwise would be lost in cultivation.

There is, overall, a trend to reduced cultivation (R. Chisholm, personal communication). This has been motivated by an awareness of soil compaction problems associated with conventional techniques, and permitted by the recent availability of superior herbicides and of trash clearance seeders for planting crops grown in rotation with cotton.

RAINFED CROPPING ON COASTAL NEW SOUTH WALES AND SOUTHERN QUEENSLAND

Coastal eastern Australia, including the north coast of New South Wales and southern coast of Queensland, is characterised by abundant rainfall, averaging over 1000 mm annually, and mild temperatures.

With the exception of small areas of maize on the fertile, alluvial soils, little grain cropping has been conducted in this area. The dominant soil types are podsols and solodics on undulating topographies, which are low in nitrogen and phosphorus.

In the early 1970s it was shown both experimentally and commercially that soybeans could be grown successfully without irrigation on both the alluvial and 'hill' soils. However, cultivation of hill soils in particular leads to massive erosion problems following high-intensity storm rains of the summer months. This has led to the development of direct-drilling techniques for growing both soybeans and subsequent crops of winter cereals on these soils (Desborough, 1981). In fact, Desborough strongly recommends that cropping on erosion-liable soils of the region be undertaken using only these techniques.

Rainfall during the growing season is usually sufficient to produce soybean yields between 2-3 t ha^{-1} in a direct-drilling system without a preceding fallow to store water. In this system, soybeans are sown into a pasture recently sprayed with herbicide or into residue of a recently harvested winter cereal crop. Desborough (1981) has recorded yields of 1.5-3.5 t ha^{-1} with wheat and triticale sown immediately after soybean harvest in a double-crop system. In this situation, nitrogen fixation by the soybean is considerable, as evidenced by the lack of grain yield response from application of fertiliser nitrogen to winter cereal crops sown directly into soybean residue over two seasons on soils that were extremely deficient in nitrogen (Desborough, 1981; Hughes and Herridge, 1984).

Desborough (1981) has found that certain soybean varieties yield more when direct drilled than when sown into cultivated seedbed conditions. The reasons for this are still under investigation. The general question of plant selection for new tillage systems is considered in Chapter 15.

The technique of direct drilling soybeans into highly erodible soils of coastal Queensland may also have potential (Harbison, 1981).

CONCLUSIONS

Soil erosion is a major factor in crop production in summer-rainfall areas of Australia. The intensity of summer storms tends to increase towards the northern coast of Australia, and tillage systems therefore need to be devised to minimise the erosion risk in each environment.

In the established cropping areas, there has been a trend towards retention of crop residues, the use of tillage equipment that leaves residues on the soil surface, and the replacement of some tillage operations with herbicide applications. This has been made possible by the advent of a range of herbicides that can be used for fallow weed control, and the availability of planting equipment with the ability to pass through heavy residues. No-till fallow production systems have been shown to afford excellent protection against soil erosion, and to give at least equal and in some cases better yields than cultivated fallows. There seems little doubt that further research on crop nutrition, crop rotations, and disease, pest and weed management, will lead to both yield increases and greater profitability.

In the semi-arid tropics of Australia, where erosion and high soil temperatures are problems for crop production, systems that maintain residues on the soil surface, and particularly no-till systems, have been shown to be beneficial.

In irrigation areas, there has been a trend towards reduced-tillage systems and the re-use of existing beds and furrows as a response to the problems of soil compaction and the high cost of reforming beds and furrows each year.

On the coast of northern New South Wales and southern Queensland, conservation-farming technology offers the potential to transform extensive cattle grazing enterprises on poor soils into highly economic double cropping systems.

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