Chapter 2

TILLAGE PRACTICES FOR CROP PRODUCTION IN WINTER RAINFALL AREAS

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Crop production in the winter rainfall areas of southern Australia is based on two broad patterns of land use. The first is a rotation of one or more years of annual legume pasture, usually based on subterranean clover (*Trifolium subterraneum*) or an annual *Medicago* species, followed by a cereal crop. The length of the pasture and crop phases varies widely depending on the relative profitabilities of crop and livestock enterprises, but until the 1970s usually involved three or more years of pasture followed by one or two crops. In the early 1980s, the area cropped increased at the expense of that under pasture and 'in-out' pasture-crop systems became common, particularly in South Australia and Western Australia. The only fallow in this regime is the short period of a few weeks during land preparation prior to sowing, or 'opportunity' fallowing if rain falls during the February-April period. This system is used in Western Australia, Tasmania and the better rainfall areas of South Australia, Victoria, and New South Wales.

The second system involves extended periods of fallow, usually for moisture conservation but also for weed and disease control. Nitrogen is also mineralised during fallow but fallowing for this reason is practised mainly on the light sandy soils in south-eastern Australia (Wells, 1971). A typical rotation, used on fine-textured soils in the drier Mallee areas of South Australia, the Mallee and Wimmera areas of Victoria and drier areas of southern and central New South Wales, is pasture-fallow-wheat. The pasture may include sown annual legumes but often consists only of volunteer species. In the early 1980s cropping increased at the expense of pasture and fallow. The evolution of these farming systems has been described in Chapter 1 and in reviews by Callaghan and Millington (1957) and Sims (1977). While both systems recognise the importance of pastures in maintaining good crop yields and stabilising incomes through farm diversification, their ratio in rotations fluctuates with economic conditions. The use of grain legumes in the cropping phase allows intensification of cropping without the need for legume-based pastures to maintain soil nitrogen status.

Since the early 1970s there has been increasing need for the development of tillage techniques that allow more intensive crop production without irreparable damage to the soil resource. In the past two decades economic forces and technical advances have combined to allow the opportunity for significant changes during the fallow and crop-establishment phases. The purpose of this chapter is to describe tillage practices and associated techniques that have been used in southern winter-rainfall areas, and to outline the development of 'conservation farming' systems. Subsequent chapters will take up aspects of these techniques and discuss them in detail.

REASONS AND OPPORTUNITIES FOR CHANGE

The most striking change in land use in southern Australia has been the intensification of cereal cropping in response to the relative profitability of cereals compared with animal production. Figure 2.1 shows the growth in area cropped in Australia since 1960. Although some of this growth can be attributed to the opening up of new land for agriculture, most of the increase has arisen from intensification of cropping at the expense of the pasture and fallow periods, and expansion of cropping into higher rainfall areas previously considered to be more suitable for grazing.

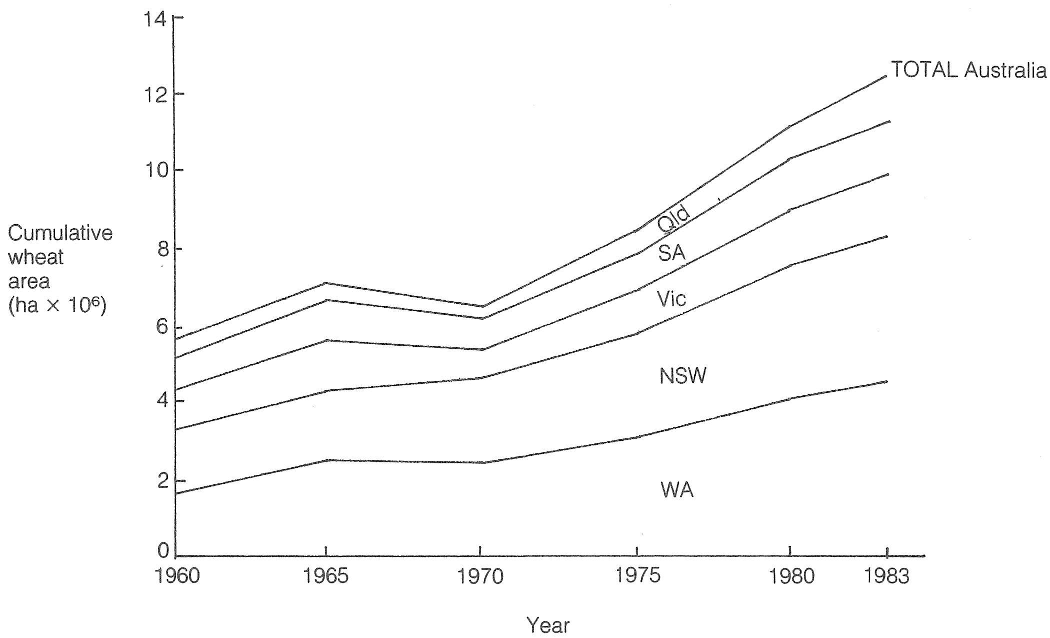

Figure 2.1 Area sown to wheat in Australia, 1960–1983 (Australian Bureau of Statistics)

The consequences of these developments have been more frequent tillage, shorter pasture and fallow periods, cropping of more fragile soils in terms of surface characteristics or slope, and an ever increasing area of crop being sown back on to cereal-stubble paddocks. It is well recognised that frequent cultivation leads to a decline in soil organic matter, loss of soil aggregates, higher soil strengths, compacted plough layers and smaller soil faunal populations (Clarke and Marshall, 1947; Barley, 1959; Smith, 1969; Greenland, 1971). On fine-textured soils this leads to reduced infiltration of water and consequently greater runoff and evaporation, soil crusting, poor crop establishment, and reduced root penetration. On sandy-surfaced soils nitrogen deficiency and wind erosion are the likely outcomes. These effects have been aggravated by a series of droughts, which have highlighted the vulnerability of many Australian soils to erosion and degradation under intensive cropping systems. It is the recognition of the threat these farming practices pose to the soil resources of Australia that has led to the increasing interest in conservation-farming techniques.

Farming methods that conserve the basic soil resource while maintaining yields have become a reality because of several economic and technical developments over the past 20 years that allow (1) large reductions in the number of cultivations required to maintain clean fallows, prepare seedbeds and sow crops and (2) the retention of surface cover on fragile soils. These developments can be briefly summarised as:

* the development of herbicides which can substantially replace cultivation for killing weeds;

* the development of cultivating, planting, and spraying machinery specifically designed for conservation-farming programmes;

* an increase in the price of energy, which allows energy-cheap herbicides to replace energy-expensive cultivation;

* the need to be able to plant large areas of crop quickly, with minimum manpower;

* the development of new crops such as grain legumes for inclusion in rotations with traditional cereals and pastures.

DEVELOPMENT OF CONSERVATION FARMING TECHNIQUES

For convenience, although they are obviously inter-related, the more important recent developments in tillage in southern Australia are discussed under seven headings: herbicides and reduced tillage; machinery; direct drilling; stubble retention; chemical fallow; deep tillage; and tillage, herbicides and rotations.

HERBICIDES AND REDUCED TILLAGE

In 1981, T.G. Reeves summarised a widely held view that

> ...there has been no greater impact on Australian cereal production during the last decade than that of the herbicide revolution. The ability to control weeds through the use of chemicals has directly or indirectly resulted in radically different tillage systems, intensified cropping sequences, an expanded cereal area and higher yields. (Reeves, 1981)

Following the development of the phenoxy herbicides (see Chapter 1) there was rapid recognition of the role they could play in reducing the number of cultivations necessary for weed control (Meadley, 1950; Myers and Lipsett, 1957). Since 1960, the number of herbicides available for a wide range of weed species has grown rapidly (Table 2.1). The most advanced state of development is in the minimum-tillage and chemical-fallow techniques described in this book, where cultivation has been almost removed from the crop-production system. It is important to note, however, that more than 90% of the southern Australian cereal crop still receives some cultivation prior to crop establishment and the main impact of herbicides on tillage practice has been the opportunity to reduce the number of cultivations during the land-preparation period.

A recent feature of the use of herbicides is the re-evaluation of some older substances either because they are becoming relatively cheap as patents expire, or they can be combined with other herbicides at low rates to give cheap effective weed control. The extent to which this is done varies between States, with substantial restrictions operating in New South Wales under the Pesticides Act, 1978.

Table 2.1 Commercial introduction of the more important herbicides into southern Australian cropping programmes

Year	Herbicide	Trade name	Main weeds controlled
1950–60	2, 4-D, MCPA	Various	Annual crucifers
1961–70	Linuron	Various	General broadleaf control
	Barban	Carbyne	Wild oats
	Dicamba	Various	Clover, emex
	Triallate	Avadex BW	Wild oats
	Bromoxynil	Various	General broadleaf control
1971–83	Paraquat/diquat	Spray. Seed	Total knockdown, annuals only
	Trifluralin	Treflan	Annual ryegrass, wild oats, wireweed
	Terbutryne	Igran	General broadleaf control
	Diclofop methyl	Hoegrass	Annual ryegrass, wild oats
	Glyphosate	Roundup	Total knockdown, including perennials
	Chlorsulfuron	Glean	General weed control, including soursob
	Trifluralin + oryzalin	Yield	Annual grasses, limited broadleaf control
	Diuron + MCPA	Mixture	General broadleaf control

It is not possible to describe in detail in this chapter the ways in which herbicides have replaced cultivation in southern Australia across the wide range of soil and climatic regions, each with its own weed spectrum. An example of a practice that has been accepted very widely is the 'cultivate-seed' system. Traditionally, land-preparation techniques across much of Australia involved an initial ploughing, followed by multiple secondary workings with tined or disc implements until satisfactory weed control was obtained, then sowing with a combine (Callaghan and Millington, 1957; Sims 1977). In 'cultivate-seed' systems the secondary cultivations are replaced with a range of pre- or post-emergent herbicides. The period between initial cultivation and sowing may be only a few days where previously it could have been weeks. The main weakness in this system is the lack of safe selective herbicides active against *Hordeum leporinum* (barley grass), *Vulpia* spp. (silver grass), and *Bromus* spp. (brome grasses).

The general adoption of herbicides in cereal programmes in southern Australia is a phenomenon of the 1970s. Reviewing weed control in Australia, Moore (1971) found that perhaps 25% of the southern Australian crop was sprayed with 2,4-D or MCPA, but use of other chemicals was minor,

Table 2.2 Acceptance of new herbicides in cereal production in Western Australia 1973–83 (G.A. Pearce and R.J. Jarvis, personal communication)

Year	Area sprayed ('000 ha)			
	Trifluralin	Hoegrass	Diuron/MCPA 2,4-D	Spray. Seed
1973	Exptl			28
1974	4			70
1975	12			27
1976	108			22
1977	370	Exptl	Exptl	25
1978	496	12	43	40
1979	749	192	780	100
1980	868	240	658	248
1981	414	690	732	565
1982	505	550	577	835
1983	970	676	643	1025

being mostly the use of triallate for wild oat control, and covering less than 45 000 ha in total. By the end of the 1970s large areas were involved, and Reeves (1981) estimated that 70% of the crop was being sprayed by that time. Since then rapid further expansion has occurred, with crops often being sprayed two or three times with different herbicide combinations. Statistics are difficult to obtain, but Table 2.2 showing the acceptance of this technology in Western Australia illustrates the point.

Accompanying the herbicide revolution has been the development of spraying equipment suitable for fast accurate application of herbicides. This is considered in detail in Chapter 10 and in reviews by Combellack (1981) and Pearce (1981). A unique feature of spraying technology in Australia is the use of low volumes of water, low rates of chemical, wide booms and high speeds. These developments were economic necessities for an Australian cereal industry based on low input, low output production methods and export dominated markets.

A further major factor in the acceptance of herbicides has been the decline in their cost, in some cases in absolute terms, but more frequently relative to other inputs such as fuel or machinery (Crook, 1984).

Problems associated with herbicide use

New problems, quite apart from the myriad questions of rates, times and methods of application of a vast range of herbicide combinations, have accompanied the introduction of herbicide technology. Many farmers, and the community at large, are wary of the widespread use of herbicides for general reasons concerning environmental impact, human health and possible residual effects in soils. Reeves (1981) has warned that 'community attitudes to all pesticide usage is hardening and even on farmer field days it is now commonplace for growers to question widespread chemical application'. Gorddard *et al.* (1982), surveying farmers in the Jerramungup district of Western Australia, found that 25% of the farmers questioned had strong reservations about the use of herbicides. Other misgivings concern phytotoxic damage to cereal crops (Elliot *et al.*, 1975), including differences between crop cultivars (Lemerle, 1981; Lemerle *et al.*, 1985) as shown in Table 2.3, and the development of weed races resistant to herbicides in

Table 2.3 Grain yields of commercial wheat cultivars sprayed with three times the recommended rates of wild-oat herbicides (adapted from Lemerle *et al.*, 1985)

Cultivar	Grain yield (t ha^{-1})					
	Unsprayed controls		Barban		Hoegrass	
	1978	1979	1978	1979	1978	1979
Condor	3.70	3.25	3.12	2.96	2.64**	2.93
Cook	3.24	2.93	2.60	2.72	3.00	2.69
Durati	1.85	2.17	0.64**	2.47	1.37	2.34
Egret	3.78	3.25	3.39	3.34	3.13	2.80**
Gamenya	3.06	2.58	2.00**	2.41	2.52	2.15
Jabiru	2.92	2.72	1.36**	2.44	2.30	2.57
Kite	2.76	2.59	1.37**	2.33	1.88**	2.44
Olympic	3.24	3.00	1.19**	2.36**	2.65	2.51**
Shortim	3.00	2.58	1.53**	2.11**	2.20**	2.37
Songlen	2.38	2.04	1.67	1.75	1.51**	1.71
Teal	3.43	3.26	1.92**	2.21**	2.34**	2.72**

** These indicate significant differences between yield of the untreated control and the herbicide treatments within each cultivar for each year. (< 0.01, LSD (1978) = 0.74, LSD (1979) = 0.45)

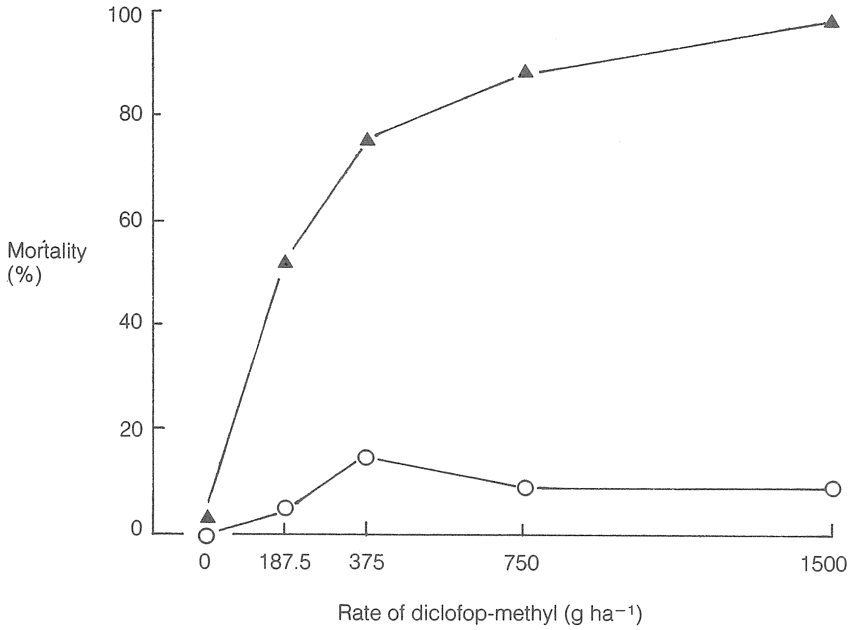

Figure 2.2 The response of two populations of annual ryegrass to different rates of diclofop-methyl; ▲ susceptible, ○ tolerant

response to selection pressures that herbicides place on weed populations (Heap and Knight, 1982). The effect of Hoegrass on a resistant population of annual ryegrass is shown in Figure 2.2.

Although herbicide use has generally led to reduced cultivation and has helped soil conservation, problems have been experienced with pre-emergence herbicides such as triallate and trifluralin, which require thorough incorporation into a fine seedbed for consistent results. This leaves the surface in a smooth, fine condition and very prone to erosion (Reeves, 1981). For this reason there has been a trend away from use of these materials.

MACHINERY

Accompanying the advances in herbicide technology have been developments in equipment for cultivating, planting and spraying, particularly in the past 10 years. At the end of the 1960s a typical farm was equipped with a 100 kW tractor, 28 tine scarifier or 20 disc plough for primary cultivation, offset disc harrows or a tined cultivator for secondary workings, and a 20 or 24 row combine for sowing. Most farmers did not have a boom spray, relying on misters or aeroplanes for application of phenoxy herbicides.

Beginning in the early 1970s, in response to increased wheat acreages, rising manpower costs, the improved availability of herbicides and widespread concern about soil degradation and erosion, a chain of technical developments began and continues today. For this overview they can be listed as the introduction of:

- four-wheel drive, 250 kW plus, maxi tractors capable of pulling large equipment under difficult soil conditions;

- * wider cultivating and sowing equipment, increasing from the traditional 4.5 m to, in some cases today, 20 m or more;

- * cultivating and sowing equipment capable of killing weeds while retaining stubble on the surface or sowing into undisturbed soil - blade ploughs, sweep or chisel ploughs, rod weeders and trash-clearing combines, and triple disc drills, were imported or manufactured for Australian conditions;

- * airseeders, which could be attached to tool bars carrying a range of tine types and configurations, including some with trash-handling capabilities;

- * large boom sprayers with superior nozzle configurations capable of delivering herbicides quickly and accurately.

Although most of these developments are compatible with a desire for conservation farming, this is not always the case. The increase in tractor power allows working of soils under conditions when damage to soil structure is likely to occur. Working of fine-textured soils when they are excessively wet, or sandy-surfaced soils at high speeds when they are dry can cause structural damage and erosion losses.

The increase in the capital cost of machinery, the cost of borrowed capital, and the increase in the price of fuel have prompted many to question the value of large tractors and cultivating equipment compared with farming systems relying on herbicides for weed control.

DIRECT DRILLING

Pioneering research

The concept of killing weeds with chemicals prior to crop establishment was first put forward in the 1930s. However, it was not until the late 1950s when ICI discovered the bipyridyl herbicides paraquat and diquat (Jeater, 1963) that the technique became a practical possibility. In 1965 the chemicals were introduced to Australia. Western Australia was found to offer special opportunities for the development of minimum-cultivation techniques (Stonebridge *et al.*, 1973) and many of the early experiments were based in Western Australia's central wheatbelt. Using European experience as a guide this early work concentrated on the susceptibility of different weed species to the herbicides, aspects of nitrogen nutrition, and testing of machinery for planting.

From this pioneering research most annual pasture species were found to be susceptible to the bipyridyls in their early growth stage, although larger weeds and subterranean clover were more difficult to kill (Stonebridge *et al.*, 1973). When the nitrogen responses of cereals sown using conventional tillage were compared with those direct drilled using a triple-disc drill, the direct-drill treatment increased nitrogen stress and reduced growth rate, nitrogen uptake and grain yield of wheat (Greenwood *et al.*, 1970). The triple-disc drill and modified combine were subsequently discarded in favour of the full combine, which gave better crop establishment, weed control and grain yields, while also increasing nitrogen uptake by the crop.

Development research

In 1966-67, field trials were started by ICI with State Departments of Agriculture and CSIRO to compare conventional tillage (ploughing and cultivating then sowing with a full combine), minimum soil disturbance (using a herbicide plus direct drilling with a triple-disc drill), direct drilling with a full combine, and direct drilling with a combine with reduced number and size of cultivating points. During these experiments a 'systems' approach was sometimes used, where each treatment was handled according to the soil and climatic conditions prevailing, rather than making strict comparisons of single-factor effects. In general, the greatest economic advantages of direct drilling related to timeliness of sowing and spraying (Chapter 16). These are only demonstrated in the 'systems' approach, but this is difficult to manage and interpret in scientific studies and was therefore not widely used.

The field trials were initially planted into annual pasture or burnt stubble and then allowed to run for several years under wheat crops. The work is described by Pearce (1969), Greenwood *et al.* (1970), Stonebridge *et al.* (1973), Reeves and Ellington (1974), Catt (1977), Rowell *et al.* (1977), McNeill (1975 and unpublished) and Jarvis (1982). The research has shown that, provided weeds are satisfactorily controlled, in broad terms the yields from direct-drilled and conventionally sown crops are comparable, usually showing a difference of less than 10%. The previously unpublished results of McNeill for southern New South Wales are given in Table 2.4. McNeill grew continuous wheat at four sites from 1969 to 1975, comparing conventional tillage (2-4 passes with a scarifier, sown with a combine) with direct drill (graze, spray with bipyridyls, sow with a full combine), with and without applied nitrogen.

Table 2.4 Wheat yields from direct drilled and conventionally sown crops on four sites in southern New South Wales (A.A. McNeill, unpublished data)

Year	Grain yield (t ha^{-1})							
	Narrandera		Grong Grong		Junee		Wagga Wagga	
	DD	CC	DD	CC	DD	CC	DD	CC
1969	1.49	2.37	1.22	1.00	1.72	2.69	0.57	1.72
1970	3.67	3.26	1.68	1.71	1.48	2.64	1.78	2.90
1971	0.30	0.17	1.16	1.27	0.82	0.86	1.25	1.58
1972[a]	0.64	0.63	0.46	0.69	1.39	1.63	1.08	1.35
1973	2.66	3.36	1.41	1.54	1.77	1.82	0.97	1.25
1974	2.33	2.22	1.02	0.79	2.07	2.38	1.84	1.79
1975	1.43	1.82	1.15	1.23	1.51	1.76	0.82	1.10
Mean	1.79	1.98	1.16	1.18	1.54	1.97	1.19	1.67

DD = direct drilled (graze, spray, sow).
CC = conventional cultivation (2–4 cultivations, sow).
[a] From 1972 onwards, tillage treatments on all sites were divided between applied nitrogen at 0 and at 20–30 kg N ha^{-1}. Yields shown are the means of the two N treatments.

McNeill found that overall, direct drill yielded 11% less than conventional tillage; that there was no interaction between tillage and nitrogen treatment; that plant establishment was approximately 20% lower on the direct-drill plots; that early crop growth was always reduced; and yield differences between tillage treatments did not change with time. The four sites used by McNeill were in a 425-550 mm rainfall zone, on similar soil types, either red earths or red-brown earths.

More recent studies by several workers in southern New South Wales have shown yield increases with direct drilling that can be attributed to changes in the seasonal patterns of water use (Chapter 8). The slow early growth of direct-drilled crops conserves water for spring, which can be an advantage in dry years. Alternatively, cultivation to prepare a seedbed will inadvertently conserve water during autumn in some years. Direct drilling will forego some or all of this

Table 2.5 Wheat yields from direct drilled and conventionally sown crops under continuous crop and pasture–crop rotations on three soil types in Western Australia (Jarvis, 1984a)

Year	Wheat yield (kg ha^{-1})											
	Clay loam (Merredin)				Sandy loam (Beverley)				Loamy sand (Wongan Hills)			
	Continuous		Rotational		Continuous		Rotational		Continuous		Rotational	
	CC	DD	CC	DD	CC	DD	CC	DD	CC	DD	CC	DD
1977[a]	199	306	332	461	1628	1728	1070	1218	582	616	1117	1242
1978	2100	1691	1727	1508	3439	3217	1064	2019	1786	1130	1968	1931
1979	1647	1777	1464	1557	2441	2668	1186	1505	1609	1465	1028	1014
1980	failed due to drought				1429	1805	2275	2169	1203	984	804	549
1981	568	1190	1071	1620	2624	2303	2005	2082	1916	1690	2964	2488
1982	582	1002	583	899	3238	3122	3326	3113	1900	1779	2324	2566
1983	602	810	769	892	2799	2863	2597	2183	1682	1524	2874	2179
Mean	814	968	849	991	2514	2529	1932	2041	1525	1313	1868	1710

Annual average rainfall: Merredin 300 mm; Beverley 450 mm; Wongan Hills 375 mm.
[a] Crops received recommended nitrogen rate each year.

because weeds are allowed to grow. Cornish (1985) argues that the net effect of direct drilling on yield depends on a balance between these effects.

Jarvis (1984a), working in Western Australia over a wider range of soil types and rainfall regions than McNeill, found consistently lower yields using direct drilling with a conventional combine on a loamy sand, an ever widening margin in favour of direct drilling on a clay loam and no differences on a sandy loam red-brown earth (Table 2.5). These data show also that some seasons favour conventional establishment, others direct drilling. This is not surprising considering the differences in soil treatment between direct-drill and conventional systems and the interactions these are likely to have with different seasons.

ICI launched its 'Spray.Seed' crop-establishment system commercially in 1970 in Western Australia. Acceptance was slow and by 1977 only 25 000 ha were being sown using the system. Adoption in other States was slow also for, despite some good results, technical and economic problems still beset the system. *Lolium rigidum* (annual ryegrass) and *Avena fatua* (wild oats), both exhibiting staggered germination patterns, were difficult to control, while control of subterranean clover often required addition of dicamba to the bipyridyls.

In the late 1970s two developments occurred, which began to turn the economic tide in favour of direct drilling. The first was the development of a highly selective post-emergent herbicide, Hoegrass, which could control *L. rigidum* and *A. fatua* in crops. The second was the escalation in the price of energy. Direct drilling uses substantially less energy than conventional cropping systems (Ellington, 1979; Poole, 1979) and farmers soon realised the value of this.

It will take many years of commercial usage to define the situations best suited to the different techniques; however, the important principles identified by research are given in Chapter 6 (soil physical factors), and Chapter 8 (crop-water relations). In the meantime farmers are adopting a flexible approach, letting the season and soil conditions dictate which practices they use in a particular year. The combined experiences of farmers and scientists are summarised in Table 2.6 in which the advantages and disadvantages of direct drilling are given.

Current developments in direct drilling

Recently, the concept of direct drilling has been extended by the development of the 'straight-in' cropping systems where there is no knockdown spray before sowing. Weed control is obtained by a combination of herbicide and grazing treatments in the season preceding the crop, and the use of an array of selective grass and broadleaf herbicides after the crop emerges. With careful weed management and paddock selection these systems are quite successful provided that weeds do not become well established before sowing. The principles underlying successful weed management are described in Chapter 9 and practical examples are given in *The Direct Drill Farmer and Grazier* (1983, published by F. Moroney and Co., Perth). Contributing to the adoption of direct drilling was the release of the knockdown herbicide glyphosate, which widened the scope of the technique as it could control weeds such as *Oxalis pes-caprae* (soursob). The development of cheap post-emergent herbicide mixtures for broadleaf control, particularly in Western Australia, has also facilitated adoption rates.

Although continuous cropping systems from which animals are excluded are becoming more common in southern Australia, integration of crop and livestock enterprises still dominates farming. Pasture re-establishment following crops is important and it influences farmer acceptance of direct drilling. The reduced amount of soil mixing associated with direct drilling compared with conventional establishment could be expected to have significant effects

Table 2.6 Some suggested advantages and disadvantages of direct drilling in southern Australia

Claimed advantages
- Reduction in time to prepare land
- Improved timeliness of sowing
- Soil trafficable in wet conditions
- Greater area of grazing prior to seeding
- Reduced risk of damage to soil structure
- Better surface structure, due to retention of organic matter at surface
- Reduced erosion hazard
- Need for less machinery
- Reduced demand for capital and energy
- Improved yields on some soil types
- More efficient use of water
- Better regeneration of clover after direct drilled crop

Claimed disadvantages
- Slower early root growth
- Less nitrogen available for growth early in season
- Slower early top growth
- Cereal root diseases more troublesome, particularly that due to *Rhizoctonia*
- Cereal pests more troublesome, particularly webworm
- Large weeds difficult to kill, vegetation mat troublesome
- Some soils too hard for tine penetration
- Uniform seeding depth difficult to maintain
- Need to burn stubbles if direct drilling a second crop
- Cost of herbicides causes cash-flow problems
- Farmers concerned about environment and health hazards associated with widescale use of herbicides
- Lack of cultivation means uneven surface causing harvesting problems
- Lower yields on some sandy soil types

on pasture re-establishment and composition and I.C. Rowland and R.J. Jarvis (unpublished data) have found significantly better establishment of subterranean clover following direct drilled crops. Gramshaw and Stern (1977) working with *L. rigidum* and Reeves *et al.* (1981) with *Raphanus raphanistrum* (wild radish) have demonstrated the importance of depth of burial on establishment of these species. Others have raised the possibility of differences in phosphate availability (Cornish, 1981) and distribution of *Rhizobium* (T.G. Reeves, personal communication).

Direct drilling can also provide the opportunity to increase stocking rate on mixed farms without reducing crop production, an important factor when comparing the economics of alternative crop establishment strategies (Chapter 16). It has been suggested that further gains can be made by considering the needs of livestock when developing a conservation-farming system. Simpson (1984) points in particular to the need to reconsider lambing time.

When direct drilling is used in a second-crop situation the stubble is usually burnt to allow the herbicides to act more effectively and to give easier passage for the combine. From the viewpoint of soil conservation, stubble burning is seen as a weakness of direct drilling because it removes the barrier to raindrop impact and removes potential soil organic matter. Consequently, research is trying to combine direct drilling and stubble retention. It should be noted, however, that the problem of water erosion in south-eastern Australia is much less than in Queensland, where stubble retention is given a high priority. This is because long fallows are less common and summer rains less frequent and less intense than in Queensland. There is some evidence that reducing cultivation is the most important step towards soil conservation in south-eastern Australia, with stubble retention providing additional protection (Packer and Doust, 1985; Packer *et al.*, 1985). In southern and Western Australia the role of stubble for control of wind erosion is well established.

RESIDUE RETENTION

Residue-mulch or stubble-retention techniques aim to retain stubble on the soil surface for as long as possible, often including through the sowing period, with the prime aim of protecting the surface from wind and water erosion. The technique was developed in North America in the 1930s to reduce erosion resulting from overcropping. The North American techniques are described by McCalla and Army (1961) and, with application to Australian conditions, by Wallens and Garland (1977).

Although for many years stubble retention has been advocated for farming the black soils of the summer rainfall areas of Queensland and northern New South Wales (Callaghan and Millington, 1957; Sims, 1977; Chapter 3) interest in the technique has only occurred in the 1980s in the winter rainfall areas of southern Australia. Burning remains the most common method of stubble removal, with less than 5% of the southern Australian cropping programme involved in comprehensive stubble-retention techniques in 1983. The main reason for disposal of stubble has been the notoriously poor stubble-handling capability of the combine drill, although other management aspects such as disease, weed and insect control have also been important. The intensification of cropping in southern Australia has led to rising interest in stubble-retention farming as a means of soil protection.

The physical, biological and management aspects of stubble farming are discussed in Chapters 3 and 7. The agronomic aspects relevant to southern Australia are discussed here. The advantages and disadvantages of stubble retention have been described by Barber (1982), Jarvis (1983a) and Coventry (1984) and are given in Table 2.7. As Coventry (1984) states:

> ...the easiest aspect of stubble retention work is listing the possible advantages and disadvantages for this system; these lists can easily be derived from work in North America and Europe. The most difficult aspect of stubble retention work is the development of a workable system for dryland farming in Australia.

Although 'systems' experiments similar in concept to the work carried out on the development of direct drilling in the 1960s and 1970s have been started in most States, definitive answers to questions as to which regions and soil types in southern Australia will benefit from stubble retention will take until the turn of the century to acquire. Commenting on stubble systems for northern New South Wales, McFarlane (1952) pointed out that:

> ...although there is widespread belief among farmers that stubble burning, as a regular practice is not desirable from a soil conservation point of view, the question of whether it is better to turn the straw under, partly cover it, or cultivate so as to leave as much as possible on the surface is still controversial. Various factors such as weed growth, soil moisture, topography, soil type and erosion danger influenced farmers' decisions.

These comments are particularly applicable today to stubble farming in southern Australia because the rate of stubble breakdown is slow due to the dry summer conditions. Incorporation may not be feasible if the soil is too dry to work or under conditions where stubble decay is slow, thus leading to poor crop establishment. Standing stubble takes longer to break down but

Table 2.7 Some suggested advantages and disadvantages of stubble retention farming systems in southern Australia

Claimed advantages
- Reduction of wind and water erosion
- Protection of soil surface against raindrop damage
- Improved water infiltration
- Reduced soil evaporation
- Increased water available to crops
- Improved levels of organic matter
- Increased numbers of soil fauna

Claimed disadvantages
- Interference with passage of machinery
- Reduced availability of nitrogen
- Pest and disease problems, e.g. • yellow spot, septoria of wheat
  • net blotch, scald of barley
- Reduced plant establishment
- Reduction of soil temperatures
- Protection of weeds from herbicides
- Interference with use of soil-incorporated herbicides
- Reduced nitrogen availability
- Interference with animal production systems
- Phytotoxic effects on crop seedlings
- Reduced pasture re-establishment

this may not be a problem in lower-rainfall areas where the low quantities of stubble can be handled with modern sowing equipment. There are difficulties with handling large quantities of stubble in the higher-rainfall, higher-yielding areas.

Falconer (1984) has questioned the wisdom of further intensification of cereal production on fragile soils, and the use of stubble-retention techniques on soils where soil erosion is not a major problem. 'Stubble is usually only a problem with multiple cereal cropping - leave the stubble to volunteer pasture, sow clover or sow a crop such as lupins or peas.'

Of over-riding importance in the development of stubble farming systems for southern Australia is the development of cultivating and sowing machinery suitable for the task. This is reviewed in Chapter 7.

The future development of systems of stubble-retention farming in southern Australia must take account of current farming practices. The basic decision to be made is whether the stubble should be incorporated or not. Benefits of soil and water conservation are much greater if it is left above ground (Chapters 6, 7 and 8). To do this and sow a subsequent crop, harvesting techniques need to be modified to cut straw shorter and to chop and spread it across the width of the machine. Grazing, an integral part of Australian farming, but almost unknown in the North American cereal belt, where stubble farming was developed, must be allowed for in any systems devised for southern Australia. The grazing of crop residues, however, may cause significant compaction of the surface layers of fine-textured soils (Packer *et al.*, 1985), consequently affecting infiltration of moisture and establishment of crop seedlings, or of looser sandy-surfaced soils, making them prone to wind erosion.

Incomplete stubble retention is an option being considered for southern Australia, particularly for high yielding crops leaving residues in excess of 6 t ha^{-1} (equivalent to a 4 t ha^{-1} grain yield). Smaller residues (less than 3 t ha^{-1}) can be handled by existing techniques following heavy grazing by sheep. In the case of heavy stubbles two options are possible: either a late burn (Pratley and Cornish, 1985), which might be difficult to achieve with green material present, necessitating a pre-burn herbicide application; or harvest of the straw for treatment with caustic materials such as NaOH or NH_4OH prior to feeding to livestock, a process known as alkalage (Kellaway, 1979; Pearce *et al.*, 1979). This latter option, however, is unlikely to be used on a significant scale because of its high cost.

CHEMICAL FALLOW

Fallowing of fine textured soils is an integral part of farming in lower-rainfall areas of South Australia, Victoria and southern and central New South Wales (Sims, 1977; Chapter 8) although it is of declining importance (Figure 8.1b). The benefits of fallows for economic cereal production in these regions in terms of moisture conservation, nitrogen supply, and disease and weed control are described by Kohn *et al.* (1966), Schultz (1971), Tuohey *et al.* (1972), French (1978a; 1978b; 1978c) and Fettell (1980). In Western Australia, which has a lower incidence of summer rains and predominantly lighter, shallower soils, little benefit is obtained from long fallows except in very dry years on clay-loam soils (Fisher, 1962; Tennant, 1980). Short 'opportunity' fallows beginning in February-March of the crop year to take advantage of early rains and to control summer weeds are common in all mainland southern States and extend into higher-rainfall areas.

Long fallows may require up to ten cultivations to keep them free of weeds. This removes all surface cover, causes decline in soil structure, and leaves the surface prone to wind and water erosion. With the development of a wide spectrum of herbicides in the 1960s and 1970s the possibility of substituting herbicides for cultivations arose. Ridge (1983a) states that:

> ...the benefits of fallowing accrue by the removal of weeds which would otherwise utilise moisture and nitrogen, host pathogens and set seed which would germinate in the following crop. Hence the large investment in conventional cultivation machinery and the costs associated with its use are directed principally at weed removal - a task which can be just as readily achieved using herbicides.

Experiments investigating chemical fallowing began at Wagga Wagga (Kohn *et al.*, 1966) and at Walpeup in the Victorian Mallee in the early 1960s. In the Mallee, investigations were aimed largely at control of skeleton weed on fallows (Wells, 1971). Herbicide mixtures of atrazine, simazine and amitrole proved effective although the atrazine component had considerable residual activity, which, while ensuring maintenance of weed control over the length of the fallow, sometimes caused emergence and growth problems in subsequent cereal crops. The non-residual knockdown herbicides glyphosate and the bipyridyls have usually proved unsatisfactory when used alone as repeated applications are required to maintain weed control. However, they have proved valuable when used for primary weed control, with residual materials used for follow-up control. Recently Ridge (1983b) has used the more selective residual materials such as Bladex and Glean with considerable success on deep clay soils of the Wimmera (Table 2.8). On the red duplex soils of north-central Victoria, Cooke *et al.* (1985) found that chemical fallowing had no effect on water or nitrate accumulation in fallows, although yields were less than with tilled fallow. From the viewpoint of soil conservation, Cooke (1985) concluded that a regimen of minimum cultivation with a scarifier and then the use of herbicides to control weeds was better than either conventional cultivation or zero tillage.

Despite this technical success with chemical fallowing, commercial acceptance is in its infancy. While most long fallows receive some herbicide treatment the area of fallow in southern

Australia that is treated exclusively with chemicals is low, probably less than 1%. However, Ridge (1983b) when discussing chemical fallowing considered that:

> ...farmers will be forced by their changed circumstances to consider more cost-effective tillage systems. They have also witnessed, in the summer of 1982/83, the worst soil erosion for 40 years. They can no longer afford the luxury of recreational tillage because of its cost and because of its damaging effects on soil structure.

Short-term fallowing of stubbles has become commonplace as cereal production has intensified in southern Australia. There has been a growing awareness that direct drilling can forego appreciable moisture conservation in some seasons, as previously discussed. Opportunity chemical fallow in the February to April period is becoming more common. In addition to conserving water for the crop, this practice spreads the workload and leads to better seedbeds in wet autumns because weeds do not grow large and bind the soil into a sod. For reasons of soil conservation chemical fallowing of these stubbles has appeared attractive to farmers. However, there are problems with stubble protecting weeds from sprays and the loss of the option to use herbicides that require incorporation into the soil. A recent development is the combination of stubble retention and chemical fallowing techniques where blade or chisel plough are used for primary cultivation, with follow-up herbicide treatments replacing multiple cultivations later in the fallow period. Large scattered summer weeds are a common feature of fallows and spray technology that will allow automated spot spraying of these weeds may eventually be developed (Chapter 10).

Table 2.8 Wheat yields following chemical fallows based on residual materials (Ridge 1983b)

Herbicide application (rate ha^{-1})		Yield (t ha^{-1})
24/8/81	26/11/81	
Glean 40 g a.i.	–	0.85
Bladex 2.5 kg a.i.	–	0.76
Bladex 1.25 kg a.i., Glean 20 g a.i.	–	0.74
Glean 80 g a.i.	–	0.74
Glean 20 g a.i.	–	0.72
Atrazine 0.6 kg a.i.	Bladex 1.25 kg a.i.	0.61
Atrazine 0.6 kg a.i.	Bladex 2.5 kg a.i.	0.57
Atrazine 0.6 kg a.i.	Glean 30 g a.i.	0.56
Atrazine 0.6 kg a.i., Bladex 1.25 kg a.i.	–	0.56
Atrazine 0.6 kg a.i.		0.47
Atrazine 0.6 kg a.i.	–	0.44
Diuron 1.6 kg a.i.	–	0.36
Conventional fallow		0.61

LSD ($P_{0.05}$) = 0.23
a.i. = active ingredient.

DEEP TILLAGE

Deep tillage (deep ploughing, subsoiling or deep ripping) involves ripping the soil below the normal cultivation layer, often to 30-40 cm, without inverting the furrow slice, with the aim of breaking up traffic-induced or naturally occurring compacted layers. The practice has been almost unknown in cereal production in southern Australia although research dates from the 1890s (*Agric. Gaz. of NSW*, December 1895). Baker (1958) had concluded that it 'has no place on normal

South Australian farms' while Sims (1977) observed that 'while some increases, generally small, have been recorded, the overall Australian situation is that little is to be gained by deeper cultivation of normal soils'. This agreed with the broad observation of Khan (1963) that, on a worldwide basis, it is only in exceptional situations that deep tillage has increased crop yields in semi-arid areas.

Recent experiments with deep ripping in southern Australia have demonstrated some spectacular improvements in wheat yield. This has revived interest in deep ripping as a soil management practice. In Western Australia large yield increases were obtained when a loamy sand was ripped to 30 cm at Wongan Hills, and later trials showed that yield responses were widespread (Jarvis, 1982; 1983b). Typical results are shown in Table 2.9. Responses have been obtained most frequently on loamy sands and sandy loams that have been cleared for more than 10 years and exposed to cultivation traffic. This is consistent with the observation of Unger *et al.* (1981) that, in the USA, responses to ripping are most frequently obtained on fine sandy loams that do not swell or shrink during wetting and drying. Tennant (1976) had earlier detected a delay in root penetration at about 20 cm in Wongan loamy sand and has subsequently found that ripping removes this effect (D. Tennant, unpublished data). The increase in yield has been attributed to faster root growth early in the season, which allows greater uptake of nitrogen, and, more importantly, deeper rooting allowing greater total extraction of water (D. Tennant, J.W. Bowden, A. Hamblin, unpublished data). The principle involved is that large responses to ripping can be obtained by removing shallow hardpans from otherwise good agricultural soils.

In Victoria and New South Wales, smaller and more variable crop and pasture yield responses to ripping have been obtained under soil and climatic conditions quite different from those in Western Australia (A. Ellington, personal communication; P. Dann, personal communication). In the high-rainfall (500 mm) north-east of Victoria on duplex podsolic soils, where traffic pans, soil acidity and waterlogging combine to give severe stunting and yellowing of wheat growth,

Table 2.9a Effect of depth and time of ripping with an Agrowplow (50 cm shank spacing) on wheat yields on yellow loamy sand in Western Australia (R.J. Jarvis, unpublished data)

Treatment	1983 Wheat yield (kg ha^{-1})	ΔY	% Increase
Direct drill with combine	1472	–	–
Conventional—scarify 10 cm	1601	129	9
Deep rip 20 cm June 1983	2207	735	50
Deep rip 30 cm Aug. 1982	2652	1180	80
Deep rip 30 cm June 1983	2472	1000	68

Table 2.9b Residual effect of ripping 35 cm deep in May 1980 with an Agrowplow (50 cm shank spacing) on wheat yields on yellow loamy sand in Western Australia (Jarvis, 1984b)

Year	Wheat yield (kg ha^{-1})			
	Not ripped	Ripped	ΔY	% Response
1980	Failed due to drought			
1981	1203	1793	590	49
1982	1500	1833	333	22
1983	1120	1399	279	25
Mean	1274	1675	401	31.5

Ellington and his co-workers have found very large beneficial effects on crop yield when lime, deep ripping and drainage are combined. Typical results are shown in Table 2.10. Treatment of sodic bands in the soil profile by ripping and gypsum addition has been effective in southern New South Wales (J. Sykes, personal communication). As a general principle, subsoiling is likely to give relatively small responses to deep ripping on soil types where the problem is due to waterlogging or to inherent high soil strength, because root growth is improved only to the depth of working. Deep working is expensive and hence the prospect of large responses needs to be high. Sodic subsoils require treatment with gypsum to prevent the return to a structureless, impenetrable condition.

Table 2.10 The effect of deep ripping, drainage and lime application on wheat yields in north-eastern Victoria (Ellington, Ganning and Bakker, unpublished data)

Treatment	Wheat yield (t ha^{-1})
No drainage, no rip, no lime	1.8
No drainage, no rip + lime (3 t ha^{-1})	2.6
+ drainage, no rip, no lime	2.3
+ drainage, no rip + lime (3 t ha^{-1})	3.5
+ drainage, rip 35 cm, no lime	3.9
+ drainage, rip 35 cm + lime (3 t ha^{-1})	4.2

Two implements, different in design and action, have been used in these experiments. Heavy-duty chisel ploughs (e.g. Agrowplow), with shanks spaced at 30-33 cm and capable of penetrating to 40 cm, have been used most widely. However, they cause considerable surface disturbance, which may be incompatible with minimum-tillage farming systems. To overcome this, the Howard Paraplow has been developed (Pidgeon, 1983). This implement relies on airfoil-shaped blades, which enter the soil at an oblique angle. Soil fracture is achieved by soil flowing over the upper surface of the blade faster than over the lower surface. Both these implements require considerable energy to drag them through the soil, depending on depth, tine spacing, and soil and moisture conditions.

The commercial acceptance of deep ripping is negligible, with less than 20 000 ha having been treated in Western Australia and Victoria combined (A. Ellington, R. Jarvis, personal communication). However, the preliminary results are so promising that rapid expansion of commercial trials and experimental programmes, including other soil types and regions in southern Australia, is anticipated.

TILLAGE, HERBICIDES AND ROTATIONS

Rotations based on pasture-wheat or pasture-fallow-wheat incorporating conventional multiple-tillage operations were practised almost without interruption until the late 1960s in southern Australia. The imposition of quotas on wheat production in 1969 and poor prices for animal products forced farmers to look for alternative crops. By 1971, 215 000 ha of rapeseed (*Brassica campestris*, *B. napus*), 13 000 ha of lupins (*Lupinus albus*, *L. angustifolius*) and 80000 ha of peas (*Pisum arvense*) were being grown. Since then the rapeseed and pea industries have stabilised, while lupin production has expanded rapidly (Table 2.11).

Pastures in the rotation, particularly if legume-based, generally give improvements in soil structure and nitrogen levels (Greenland, 1971), which are largely beneficial to subsequent crop production. The improvement in soil structure and nitrogen during pasture years and their decline under subsequent successive crops, and the effect of this on crop yields, have been documented by Ellington *et al.* (1979) and Rowland *et al.* (1980). On the debit side, as far as the crop is concerned, the pasture may host pests, pathogens associated with grass weeds, or contain plant species that appear as weeds in subsequent crops. Traditionally these have been controlled with periods of fallow and multiple-tillage operations during the weeks leading up to crop establishment.

Table 2.11 Area sown to lupins in southern Australia 1975–83 (Australian Bureau of Statistics, and others)

Year	Area of lupins ('000 ha)			
	WA	SA	Vic	NSW
1975	122			
1976	96			
1977	57	n.a.	n.a.	n.a.
1978	39	11	9	8
1979	46	14	15	31
1980	55	18	21	23
1981	93			
1982	217			
1983	319	21	16	22

n.a. = not available.

The increasing array of selective herbicides, the development of grain legumes, and to a lesser extent oilseed crops, are allowing the development of new farming systems that approach crop and pasture management from a viewpoint of the total system, considering the benefits or otherwise of the system over years rather than on the basis of a single season. Although integrated management in rotations has been the objective of farmers since Roman times, herbicides and an expanded range of crop types are offering flexibility never before possible. It should be remembered, however, that herbicides can also reduce flexibility in some circumstances (Table 2. 8). Residual herbicides such as simazine and Glean may affect crops or pastures in following years, or prevent resowing of an area with, say, wheat in the year of application, if a lupin crop is lost for some reason. Two developments are described below to illustrate how herbicides are being used in rotations.

Rotations involving lupins and oilseed rape

The merits of lupin-cereal rotations are discussed by Rowland *et al.* (1980) and Reeves (1981). In these systems herbicides such as simazine are used for general weed control in the lupin crop with follow-up sprays as required to achieve nearly complete weed control. This interrupts the life cycles of diseases such as take-all, which normally survive on grass hosts between cereal crops, and greatly reduces weed burdens in the following cereal crop. The cereal also benefits from nitrogen fixed by the lupins. In due course the cereal crop can be sprayed to eradicate weeds such as the annual crucifers which would cause problems in the following lupin crop. An example of the yield improvements possible is given in Table 2.12. In the northern wheatbelt of Western Australia (Nelson, 1984) and in north-eastern Victoria (Coventry, 1984) this has been taken a step further by incorporating stubble-retention and direct-drill techniques into the system. The commercial development of these techniques is in its infancy but they offer an exciting future.

Although oilseed rape does not fix nitrogen, it is a useful break crop in a direct-drilling programme because it tolerates relatively high levels of trifluralin. This chemical economically controls grass weeds and *Polygonum aviculare* (wireweed) in rape thereby reducing their incidence in the subsequent cereal crops. However, trifluralin requires soil incorporation. Provided the

Table 2.12a Mean grain yields and protein levels of wheat grown in rotation with lupins at Rutherglen, Victoria (Ellington *et al.*, 1981)

Rotation	Grain yield (t ha^{-1})	Grain protein (% of dry matter)
Wheat–wheat–wheat	2.5	11.3
Lupin–wheat–wheat	3.7	12.0
Lupin–wheat	4.3	13.2

Table 2.12b Mean cereal and lupin grain yields from a lupin–cereal rotation, continuous wheat, and continuous lupins for 8 years, 1975–82, Esperance Downs, Western Australia (I.C. Rowland, unpublished data)

Rotation	Wheat yield (t ha^{-1})	Lupin yield (t ha^{-1})
Lupin–cereal rotation	1794	1312
Continuous cereal	778	–
Continuous lupins	–	870

cultivation necessary for adequate incorporation is kept to a minimum and subsequent crops are direct drilled, the damage to soil structure should not be of serious concern.

Pasture manipulation

This technique involves treating the pasture with herbicides in the year before crop to remove weeds, particularly grass weeds. The ecological principles involved are discussed in Chapter 9. Spraying can take place either in early winter or spring. Early winter spraying, which is still experimental, completely removes the grass component from the pasture, allowing better growth of the clover component. Herbicides such as Kerb or Fusilade are used for this purpose. The benefits to the cereal crop are similar to those accruing from a clean lupin crop, namely removal of disease hosts, build up of nitrogen and prevention of seed set of grasses that could become weeds in the following cereal crop (Thorn, 1981). The much cheaper alternative practice of spring spraying, usually with low rates of paraquat (Chapter 5), is timed to interfere with seed set of grasses, and so reduce the weed risk in the following cereal crop. Spring manipulation is widely accepted, particularly where annual ryegrass toxicity of sheep is a problem or grass seeds are likely to foul wool or sheep carcasses.

These systems require less tillage and give better weed and disease control and crop nutrition leading to increased cereal and lupin yields. Their main drawback is poor pasture when the land is returned to pasture in the year following crop, a consequence of very effective weed control during the cropping years.

Despite the growth in interest in alternative crops, and the increasing impact they are likely to make, cereals still make up more than 95% of the area sown to crop each year in southern Australia. In addition, although in rare situations continuous crop systems without any animal enterprises are being developed, more than 98% of southern Australian farms have animal production as an important element of the farm system. Pastures therefore remain an integral part of farming in Australia and new tillage or rotation systems must take account of this.

CONCLUSIONS

This description of the changes taking place in tillage techniques in southern Australia shows clearly that excellent opportunities exist to devise farming systems that can maintain or improve productivity while conserving or enhancing the basic land resource.

In the past farmers have operated very much on a year to year basis, particularly with respect to their cropping programmes. In the future they should look at crop-production systems over spans of years, letting the practices adopted in one year complement those in the next. In some situations, particularly on fragile soils, farmers may have to accept slightly lower yields or lower immediate profits in order to protect their soil resource in the long term.

Opportunities certainly abound for the impact of new technology in the tillage field to be beneficial rather than damaging to productivity. However, it must be remembered that changes to agricultural systems are seldom wholly beneficial. Even the most promising innovations will bring attendant problems, which will require solution by science if the new systems are to be embraced by farmers. We have come a long way in the time since Hood *et al.* (1963), in their classic experiment reporting the first use of paraquat for wheat establishment, observed that 'nothing is yet known about the effect of repeated sod-seeding on soil and crops. Further experimentation is required to assess the general applicability of this technique in agricultural practice'. Many questions, however, still require answers.

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