CHAPTER 7

SMART ROTATIONS: FARMING SYSTEMS FOR THE FUTURE

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In sustainable farming systems on arable land in Australia, there are two fundamental practices: the alternation of pasture and crop phases on the same area of land; and the use of different crop types during the cropping phase. 'Rotating' crops and pastures is advocated as an alternative to mono-species cropping which, at least with cereal crops under Australian conditions, is considered unprofitable and exploitative of resources. Scientists argue that well-constructed rotations mimic nature by creating greater biodiversity, thereby providing opportunities for regulating the populations of weeds, diseases and pests, and for conserving soil, water and biological resources. Farmers recognise the potential benefits of growing a range of crops and pastures. However, they are confused by the conflicting terminology used by scientists[1], and by the contradictory messages that come from other farmers, agronomists and economists about the pasture and crop combinations that are the most productive or the most profitable. In reality, economic and operational factors frequently drive farmers toward simple rotations, which are maintained by inputs of chemicals to supply nutrients and overcome plant pests and diseases. Hence, the matter of which rotation to use on a farm or a paddock – the topic of this chapter – is both important and controversial.

This chapter comprises a brief history of research on crop and pasture rotations, an outline of the potential benefits from pasture-crop and crop-crop combinations, a consideration of both pasture leys and crop sequences, an assessment of on-farm practices in relation to scientific research findings, and comments on the strategic and tactical options for the future.

Rotations, phases or sequences?

The terms *rotation* or *crop rotation* refer to any sequence of crop (and pasture) species on the same area of land. The sequence is flexible – it is not necessarily rotated, repeated or fixed. Furthermore, depending on the farming locality in Australia, the rotation sequence may be long-phase or short phase. The long-phase rotation system involves several years of a *pasture phase* followed by a number of years of cropping (*cropping phase*). The short-phase rotation comprises alternating years of pasture → crop (e.g. medic → wheat) or cereal → pulse (e.g. wheat → lupin). In very favourable locations, the rotation of two or more crops (e.g. maize → soybean → vegetables) may occur within a year rather than extending over several years. A *ley pasture* (or *pasture ley*) refers to a non-permanent pasture phase, of one to several years duration, that has the dual objectives of providing forage for livestock and enhancing soil fertility. The ley may contain only annual species, perennials or a mixture of both. As you will realise when reading through this chapter, neither the concept nor practice of rotations is static; rotations evolve as a consequence of scientific findings and with changing socio-economic circumstances.

Crop rotations – history and benefits

Throughout recorded agricultural history (Table 7.1 - Karlen *et al.*, 1994), farmers have experienced low yields from continuous cropping. Crop rotation was found to be necessary to maintain crop productivity. For centuries in China, rice production has been associated with the culture of legumes such as peanut (*Arachis hypogaea*) and soybean (*Glycine max*). In England, a four-cycle rotation of turnips (*Brassica rapa*, a close relative of canola), barley (*Hordeum vulgare*), clover (*Trifolium* spp.) and wheat (*Triticum aestivum*) was popular during the 1780s but science had yet to explain the specific impacts of crop rotations on soil fertility. By the second half of the 19th century, when crop production was starting in Australia, a range of production systems had been tried and tested in Great Britain and Europe.

Table 7.1. A brief history of rotations – the world (Source: Karlen *et al.*, 1994)

Date	Country	Rotation types
1000 BC	China	Origin of rotations
100 AD	Rome, Greece	rich soils - barley/millet/turnip fair soils - wheat/legume poor soils - barley/legume/fallow
300 AD	Decline of the Roman Empire	Decline of crop rotations toward the crop/fallow system
Middle ages	UK, Europe	Crop/fallow system ± manure
1700s	England	Norfolk rotation – turnip/barley/clover/wheat (four- cycle rotation). Little known about the specific benefits of rotating crops
1800s	UK, eastern N America	Crop rotation, lime, minerals, animal manure.
	World	Wheat growing began in Turkey, South Australia and the prairies of USA and Canada

Scientific research and farmer experience progressively demonstrated several benefits from rotations comprising crops and pastures, or different types of crops. Prominent among these benefits (Table 7.2) was the improvement in soil fertility due to the nitrogen fixing activities of the legume-*Rhizobium* symbiosis. Furthermore, reductions in weed, disease and insect populations occurred due to the breaking of pest and disease cycles through the use of different plant families in the rotation. Crop rotation is now regarded as a fundamental tool of integrated pest management. Other benefits of biodiversity arise as a consequence of the better use of nutrients and water, the encouragement of certain classes of soil biota and the controlled use of phenomena such as allelopathy.

Table 7.2. Agronomic impacts of crop rotations

Impacts	Effects	Examples
Primary impacts	Yield increases of cereal crops due to:	
	- N fixation from pulses or pasture legumes	Impact of a subterranean clover ley on soil nitrogen, soil structure and subsequent wheat production.
	- break crop effects	Reduction of take-all in cereals due to the use of lupins (WA) and canola (southern Australia).
	- better utilisation of resources	After a crop phase, use of subsoil moisture by lucerne.
Secondary effects	Effect of break crops or pasture phases on:	
	- weed populations	Rotation of herbicide groups, reduction in seed pools, plant competition.
	- insect populations	Many pasture and crop species are unattractive to potential insect pests.
	- disease incidence	Reducing the incidence of blackleg in canola with cereals and legumes.
Other impacts	- water use efficiency	Wheat sown after a rice crop.
	- nutrient use efficiency	Different extraction rates of N, P and S by crops.
	- allelopathy	Chemical effect of plant residues on other plants, often negative.

On farms, diverse rotations extend the range of farm enterprises, thereby buffering farm income from seasonal influences and market risk. However, complex rotations can require a higher level of expertise and a more varied and costly infrastructure, so many farmers prefer monocultures or simple rotations. In these simpler farming systems, an increased use of chemicals and/or fertilisers is usually required to maintain crop yields. Farmers, and also scientists and advisers, find daunting the complexity of issues that occur in diverse rotations, such as what records to keep and what crop sequence might be most profitable.

Figures 6.1 and 7.1 present two dramatic illustrations of the impact of crop rotations. At Rothamstead in England (Figure 7.1 – Johnston 1997), the annual yields of winter wheat were greatly enhanced by a range of factors, particularly regular applications of fertiliser (1850 - 1990), the use of a rotation rather than a continuous wheat system (1973 - 1990), and the availability of new herbicides and fungicides. These factors have enabled farmers to take advantage of the favourable climate for cereals in Great Britain.

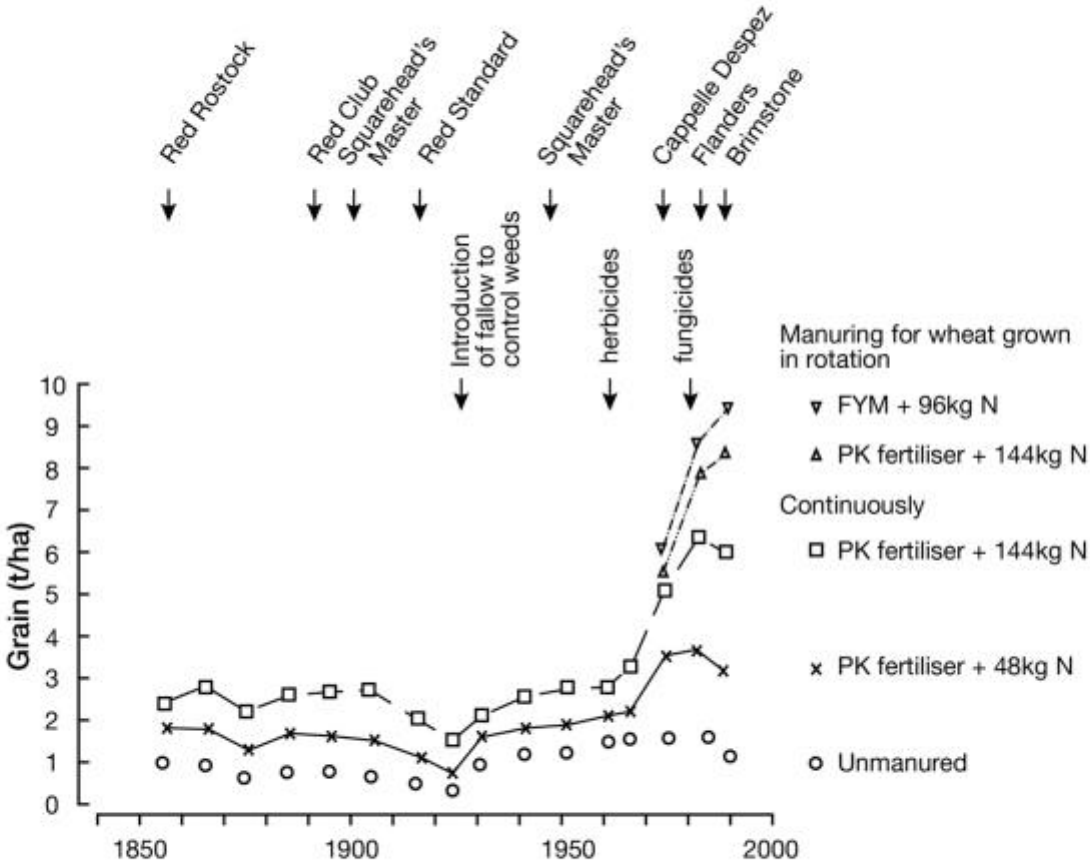


Figure 7.1.The impact of rotations (and other factors) on wheat yields at Rothamstead, UK (Johnston, 1997)

In Australia, both the natural fertility of the soils and the climate, by world standards, are unfavourable. Prior to 1900, wheat yields declined due to the lack of fertiliser and a build-up in plant diseases (Figure 6.1 – Angus 2001). The decline was arrested by new techniques of dryland farming, purposeful wheat breeding and superphosphate fertiliser. However, crop yields on the poor Australian soils were still low by world standards. Bare fallowing, a common practice that was advocated to promote water infiltration and storage, depleted the soil of organic matter and rendered it liable to wind and water erosion. Green manuring with oats (*Avena sativa*) or lucerne (*Medicago sativa*) was advocated but it was not until the 1930s that a technique of ley farming with annual pasture legumes was developed and promoted (Puckridge and French, 1983). Subterranean clover (*Trifolium subterraneum*), which had been discovered and promoted unsuccessfully by Amos Howard in the 1890s, was the basis of the ley farming system introduced during the 1930s at Rutherglen Research Station in north-eastern Victoria (Barr and Cary, 1992). On the more alkaline soils of central South Australia, at Roseworthy Agricultural College, ley farming with annual medics (*Medicago* spp.) began at much the same time.

Because of the Great Depression and then World War 2, there was little change in on-farm practices or wheat yields between 1930 and 1950, and land degradation continued. However, investments in agricultural research during this period produced some notable discoveries, including:

- the commercialisation of new varieties of subterranean clover and annual medics;
- the realisation that deficiencies of phosphorus and sulphur were widespread in Australian soils, many of which also needed one or more of the minor (trace) elements copper, zinc, molybdenum, manganese, iron and boron;
- documentation of the legume-*Rhizobium* symbiosis; and
- demonstration of the benefits in soil fertility and cereal yields from legume leys.

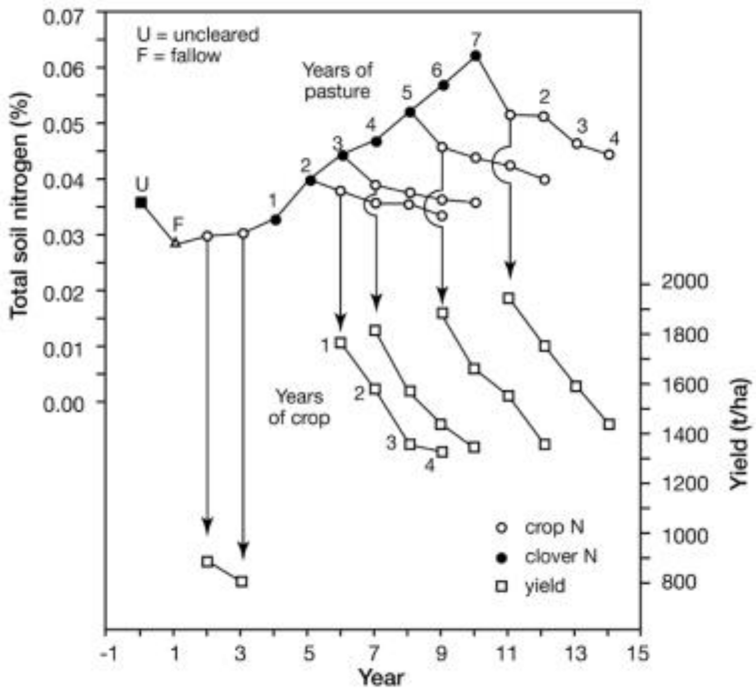
These discoveries, coupled with the availability of land, capital, labour and machinery, underpinned the rapid post-WW2 expansion of legume leys in southern NSW, Victoria, South Australia and Western Australia. This expansion was responsible for a period of strong improvement in wheat yield, from 1950 to 1980 (Figure 6.1), when cereal crops were grown in rotation with pasture legumes (subterranean clover, medics or lucerne). During a second period of improvement, starting in the 1980s and accelerating through the 1990s, several factors contributed to improved crop yields, including the availability of new crop varieties, new herbicides, liming, and the development and adoption of minimum tillage and no-tillage techniques. However the main impact, which allowed the full benefit of other technologies to be expressed, was a reduction in the incidence of cereal diseases, particularly take-all (*Gaeumannomyces graminis* var. *tritici*) in wheat and barley crops. This reduction was due to the widespread adoption of break crops such as lupin (*Lupinus angustifolius*), other pulses and canola (*Brassica napus*). From 1980, lupins became a key component of crop rotations in WA and, during the 1990s, there was a 10-fold increase in the area of canola (to a total of more than 1M ha) in all areas of the Australian cereal belt except northern NSW and Queensland.

The science and principles that underpin the success of rotations in a farming system have general application for all climatic zones and to irrigated farming. The challenges are: (1) to select or develop an array of pasture and crop species that are adapted to particular areas; (2) to organise the interactions between the pasture and crop components to achieve the production potential, not only of each component but also the whole system; and (3) to maintain the amount and quality of the farm resources (soils, vegetation, water, biota) over time. These issues are considered in the following sections.

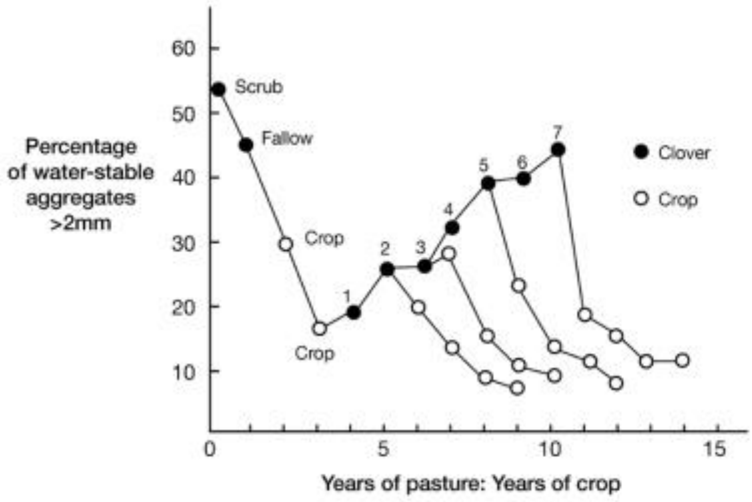
Legume leys in relation to nitrogen fixation, soil fertility and take-all

Nitrogen fixation

The most important feature of pasture legumes is their ability to 'fix' atmospheric nitrogen (produce their own protein) using a symbiotic relationship with the soil bacteria *Rhizobium* and *Bradyrhizobium* (rhizobia) harboured inside root nodules. The amount of nitrogen fixed (N_{fix}) may vary from a few kg N/ha/year to as much as 300 kg N/ha/year. Soil nitrogen is boosted by the direct accumulation of organic legume residues (tops and roots) and by the return of ingested nitrogen in the dung and urine of grazing animals. During the pasture phase, soil nitrogen increases because the quantity of symbiotically fixed nitrogen exceeds the mineralisation of organic nitrogen. Then, during the cropping phase, nitrogen mineralised from organic matter becomes available to crops. The export of grain off the farm results in a loss of nutrients to the soil-plant system.



a) Total soil nitrogen increases under pasture and decreases under crop



(b) Pastures increase soil aggregate stability (% water stable aggregate y-axis), cropping decreases aggregate stability

Figure 7.2. The improvement and depletion of (a) total soil nitrogen and (b) soil aggregate stability during pasture and cereal crop phases at Wongan Hills, WA (Rowland and Perry, 1991).

In an experiment conducted at Wongan Hills in WA during the 1960s, reported by Rowland and Perry (1991) (Figure7.2a), the alternation in total soil nitrogen that occurred between periods of pasture (N accumulation) and wheat production (N depletion) was clearly demonstrated. Furthermore, this study demonstrated the effect of the pasture and crop phases on soil aggregate stability (Figure 7.2b), an index of soil structure.

Several experiments conducted during the 1960s and 1970s provided estimates of the improvement in total soil nitrogen from pastures. The mean estimates over several years ranged from 34 kg N/ha/year (Walpeup Victoria, 0-15 cm soil depth, grass-medic pasture) to 91 kg N/ha/year (Merriden WA, 0-25 cm soil depth, grass-subclover pasture). Until recently, a benchmark value of 50 kg N/ha/year was used as an estimate of the value of legume ley pastures on farms. However, with the trend towards a prolongation of the cropping phase, plus higher on-farm yields of grain from cereal crops (Table 7.7) and canola, there is an urgent need to enhance the biological fixation of nitrogen from both pasture legumes and pulses.

Peoples and Baldock (2001) reviewed the nitrogen dynamics of pasture-crop systems and concluded that legume biomass, rather than fluctuations in the ratio of fixed N to soil N in the foliage of legumes, determined the amount of nitrogen fixed by pasture. Their benchmark value was 20-25 kg of shoot N fixed for every tonne of legume herbage dry matter produced by the pasture. They estimated that the net annual input (N_{fix}) from pasture legumes ranged between 20 and 120 kg N/ha/year when the calculations were based on the legume shoot nitrogen, or 60-270 kg N/ha/year based on estimates of whole plant nitrogen (shoots + roots). The efficiency of nitrogen fixation by pasture legumes (subterranean clover, lucerne) and pulse crops (lupin, field pea – Evans *et al.* 2001) appeared similar. However, pastures are more likely than pulses to raise soil N levels, since pasture nitrogen is recycled back to the soil by way of livestock urine and dung, and plant residues while much of the nitrogen fixed by pulses is removed from the paddock in the nitrogen-rich grain.

A simple soil N balance (ΔN_{soil}, the change in soil N) can be calculated from estimates of fixed nitrogen and the amounts removed in products (Table 7.3):

$$\Delta N_{soil} = N_{fix} - N_{product}$$

Variations in the supply (from pastures, pulses) and demand (from crops) for nitrogen, plus the potential for soil N to be leached or denitrified, mean that simple first estimates need to be refined before reliable estimates can be made of the adequacy of the soil N level for crop growth and the need for supplementary fertiliser. The taking of deep soil cores (60cm) that are tested for soil nitrogen prior to sowing are a useful objective measure of crop available N.

Table 7.3. Pastures and wheat crops – growth potential, nitrogen addition from pasture legumes and the nitrogen requirements for wheat of various protein levels

Seasonal characteristic	(1) Available water during growing season (mm)	(2) Yield potential of wheat (t/ha)	(3) N required (kg/ha) for grain protein of 9%, 12%	(4) Pasture potential yield (kg/ha)	(5) N addition from pasture (kg N/ha)	(6) N Balance (kg N/ha)
Relatively dry year (70% of normal rainfall)	270	3.20	101 135	5,000	100	-1 -35
Median year (0.5 decile)	390	5.60	177 236	8,000	160	-17 -76
Relatively wet year (120% of normal rainfall)	500	7.80	246 328	10,750	215	-31 -113

(1) Growing season available water = ¼ x January to April rainfall + May to November (inclusive)
(2) Yield potential for wheat = (growing season available water - 110mm) x 20 kg grain/ha/mm
(3) N required for grain yield of various protein levels = yield in t/ha x wheat protein ÷ 5.7 x 20
(4) Yield potential of subterranean clover = (growing season rainfall - 70 mm) x 25 kg DM/ha/mm
(5) N addition from pasture = clover yield (kg/ha) x 0.020
(6) Potential change in soil nitrogen (column 5 - column 3)

Choice of pasture legume

Of the many factors that might affect legume biomass, and consequently the amount and reliability of nitrogen fixed each year, the choice of legume genotype is one of the most potent. For example, in one study at Wagga Wagga during seasons that did not favour subterranean clover (Peoples and Baldock 2001), the addition of lucerne to the sward doubled the legume biomass and hence the annual input of fixed nitrogen. At Wagga Wagga during normal seasons, when both lucerne and subterranean clover usually grow well, average benefits of +20% could be expected from lucerne/subterranean clover leys, compared with subterranean clover alone. In addition, lucerne is capable of accessing water and nitrate-N that have moved to depths that are beyond the roots of annual pasture plants, potentially reducing both soil acidity and salinity. Finally, crops grown after lucerne instead of annual legumes are supplied with nitrogen over more years due to a larger residue of nitrogen combined with a slower pattern of nitrogen mineralisation (Peoples and Baldock 2001).

In practice, the choice of legume that is sown on farms depends on the soil type and management objectives that drive the sequence of the rotation. On sandy soils in South Australia and Western Australia, where nitrogen loss due to leaching of N in winter is rapid due to low levels of clay and organic matter, the pasture phases tend to be short, often only of one year. In these systems, pasture productivity is low relative to the potential and a more productive pasture phase could result in improved crop yields.

Table 7.4 presents the current array of popular pasture species used in pasture leys around Australia. On the deep clay soils that are typical of the areas in northern NSW and Queensland where crops are grown, lucerne is the most valuable pasture species. The use of annual legumes in pasture leys is restricted in northern NSW and Queensland because of the effects of the variable pattern of seasonal rainfall on their germination, growth, seed production and seed conservation. In southern NSW and Victoria, mixtures of lucerne and subterranean clover are recommended. In South Australia and Western Australia, the choice of annual legumes depends on soil pH, but increasing attention is being given to lucerne and other perennials because of problems with deep drainage and soil salinity. R&D activity over the last decade has produced a range of new legume species and varieties (Table 7.4) that have created considerable interest amongst farmers.

Note: In recent years, investment and R&D activity in the National Annual Pasture Legume Improvement Program has swung towards increasing the diversity of annual legumes, to suit niches not filled by subterranean clover, annual medics and lucerne. New adaptive mechanisms, not contained within the conventional species, were also sought. These mechanisms included greater adaptation to waterlogging, different patterns of hard seed breakdown, small seeds that can pass through the digestive system of sheep and cattle, aerial seeding for ease of harvesting and greater insect tolerance. An early success was balansa clover (*T. michelianum*), introduced by SARDI for sites prone to intermittent waterlogging. Other studies and selection has lead on to the commercialisation of new species and varieties, such as yellow serradella (*Ornithopus compressus*), which is adapted to the sandplain soils of WA and the Pilliga region in NSW, French [pink] serradella (*Ornithopus sativus*), which produces easily harvested seed, biserrula (*Biserrula pelicinus*), gland clover (*Trifolium glanduliferum*), and some perennial legumes such as sulla (*Hedysarum* spp.).

Table 7.4. Pasture legumes in the Australian wheatbelt

Rainfall Incidence	ZONE and LEGUME (alternatives that are less popular are shown in brackets)	pH	SOIL TEXTURE	LENGTH of PASTURE PHASE
Summer-Dominant ↑	QUEENSLAND Lucerne (Annual medics)	 Neutral "	 Vertosols "	 Nil or long "
	NORTHERN NSW Lucerne (Annual medics) (Yellow serradella)	 Neutral " Acid	 Vertosols " Kurosols	 Nil or long " Long
	Central, southern NSW & North-central VIC. Subterranean clover Annual medics Lucerne	 Acidic Neutral Neutral-acid	 Sodosols, chromosols, and kandosols	 Long Short, long Long
	Western VICTORIA & SOUTH AUSTRALIA Annual medics Vetch Balansa clover (Lucerne) (Subterranean clover)	 Neutral-alkaline Acidic Neutral Acidic	 Calcarosols (Mallee) Calcarosols (Mallee) Waterlogged Vertosols (Wimmera) Kandosols	 Short Short Short, long Short, long Short
↓ Winter-dominant	WESTERN AUST. Subterranean clover Annual medics Yellow serradella Pink serradella (Lucerne)	 Acidic Neutral Acid Acidic Neutral	 Chromosols, kandosols Calcarosols Rudosols Rudosols Calcarosols	 Short Short Short Short Long

Use of perennial grasses in crop rotations

With the exception of the Northern Slopes and Plains of NSW, there is no area of the wheat/sheep zone belt where there has yet been a significant impact of improved types of sown grasses. Grasses are, of course, either a potential weed in the cropping phase and/or a sink for nitrogen. Even though many grasses are not hosts of root diseases that affect cereals, there is concern about the carry-over of these diseases. Furthermore, there is not much agronomic evidence to justify the use of a grass/legume pasture compared with a ley containing lucerne and/or annual legumes (Wolfe and Southwood, 1980). However, there are livestock disorders (bloat, redgut) that sometimes occur when legumes are the dominant pasture component. Where lucerne is not suited to a location due to a soil problem such as waterlogging or soil acidity, or if there is concern about the development of salinity, the benefits of perennial grasses, especially their ability to use soil water more fully, may result in them taking a more important role as a component of rotations. Hence, there is currently a reassessment of the role of grasses, particularly with respect to dryland salinity.

Pastures and crop diseases

Aside from the benefits in supplying nitrogen and enhancing soil structure, a well-managed pasture is known to reduce the abundance of many soil-borne fungi and nematodes associated with crop diseases (Table 7.5). The record of research conducted on the management of take-all is well-documented (Gardner *et al.,* 1998). Wheat, barley and a number of grasses such as barley grass (*Hordeum leporinum*), bromegrass (*Ceratochloa catharticus*), silver grass (*Vulpia* spp.), ryegrass (*Lolium* spp.) and tall wheat grass (*Agropyron scabrum*) host take-all. Non-hosts for this disease include all pasture and crop legumes (although contaminant grasses in pastures and crops can sustain take-all inoculum), phalaris (*Phalaris aquatica*), wallaby grass (*Danthonia* spp.), cocksfoot (*Dactylis glomerata*) and oats. The use of broadleaf crops to break the disease cycle with a non-host pasture or crop is discussed later. Suffice to say that this tactic probably applies equally well to (1) other root disorders of wheat such as those caused by crown rot (*Fusarium graminearum*) and root lesion nematodes (*Pratylenchus neglectus* and *P. thornei*), and (2), stubble-borne diseases of crops such as yellow spot (*Pyrenophora tritici-repentis*) in wheat and blackleg (*Leptoshaeria maculans*) in canola

Table 7.5. Levels of take-all in soil and on wheat roots and grain yields in five rotations

1977 crop	1978 crop	Take-all symptoms			Grain yield of 1979 crop
		Soil before seeding - % positive for take-all presence	% plants with take-all infected roots at tillering	% white heads after flowering	
Wheat	Wheat	56	67	14	1.73
Wheat	Pasture	65	58	8	1.40
Wheat	Medic pasture	25	10	2	2.79
Wheat	Oats	16	14	1	2.30
Wheat	Peas	0	8	2	3.03
				LSD (P=0.05)	0.36

Management of ley pastures

Guidelines for the establishment and management of ley pastures are given in Table 7.6. A pure-legume pasture may seem desirable for subsequent crop production; however, a legume-dominant pasture not only is difficult to produce and maintain for the duration of the ley but also may be less desirable than a mixed grass-legume pasture for livestock production. Some of the livestock disorders that can occur on pastures with a high legume content are bloat in cattle grazing white clover or lucerne, clover infertility in ewes grazing oestrogenic cultivars of subterranean clover, and redgut (a twisting of the gut and subsequent bacterial infection). Hence, management of the pasture toward legume dominance is important only in the year preceding crop production.

Well-managed pastures are dense swards with a high potential for growth; they will suppress weeds in the pasture and, in turn, in the ley/cropping system. In southern NSW, the demise of skeleton weed, a serious problem in croplands until the 1960s, was in part a consequence of the increase in the use of subterranean clover, which competed for light with the rosette of skeleton weed, and lucerne, which was more effective than skeleton weed in acquiring subsoil moisture (Wells, 1969)

Table 7.6 Management guidelines for ley pastures
1. *Crop to pasture* • Choose an appropriate annual or perennial legume. Consider using lucerne to minimise the risk of deep drainage, the cause of dryland salinity. • Choose varieties that are recommended for the locality. • Sow pasture seed at recommended seeding rates. • If the pasture is sown under a cover crop, reduce competition from the cover crop by halving the normal seeding rate, or by sowing pasture and crop in alternate rows. • Do not sow annual legumes too late – they may not flower if sown after the shortest day (June 21, in the southern hemisphere). • Do not sow pasture seed too deeply (use precision machinery). • Be careful with herbicides, especially residual herbicides. • Control pasture insects (redlegged earth mite, blue oat mite). • Overcome constraints such as crusting (seedling emergence) and soil acidity (early root growth).
2. *Pasture phase* • Manage for the persistence (of perennials) and regeneration (of annuals). • Ensure adequate nutrition. • Control botanical composition by nutrition (moderate P rather than high P), stocking rate (moderate to high). • Choose an appropriate grazing strategy (continuous stocking of subterranean clover and medic pastures, rotational grazing of lucerne). • Consider winter cleaning in the final pasture year. • Monitor critical pasture parameters to determine the need for better management.
3. *Pasture to crop* • Minimise carryover of root disease by killing grass ('winter clean'). • Obtain a good final kill of lucerne (research work is in progress).

Many of the common weeds of crops are ruderal plants that are well-adapted to the disturbances of cultivation and grazing. However, the use of persistent pasture species that are carefully established, adequately fertilised and grazed at moderate stocking rates, are capable of reducing the seed-set and subsequent population density of most types of crop weeds. Lucerne and pastures containing perennial grasses are particularly effective in controlling weeds (Michael 1970), as they provide year-round competition for light and water. Lucerne suppresses summer growing weeds such as heliotrope (*Heliotropium europaeum)*, hairy panic (*Panicum effusum)* and black grass/stink grass (*Eragrostis cilianensis*). Hence, a grazed pasture phase is a valuable adjunct to pre-crop (tillage, herbicide) and in-crop (herbicide, plant competition) weed control methods.

Impact of broadleaf crops on cereal crops

In Australia the area of broadleaf crops has risen from a level of less than 5% of croplands prior to 1990 to greater than 20% in most production zones and a high of around 40% in the fertile Victorian Wimmera zone. However, while the area of lupins in WA and canola in southern Australia now exceeds 1M ha, the use of oilseeds and pulses in Australian wheat rotations still trails that evident in Canada (Table 7.7). In most areas in Australia, the area and production of pulse crops has been constrained by successive outbreaks of diseases, such as phomopsis (*Phomopsis leptostromiformis*) and anthracnose (*Colletotrichum gloeosporioides*) that affect lupins, or the black spot complex (*Mycosphaerella pinoides*, *Ascochyta pisi*) and bacterial blight (*Pseudomonas syringae* pv *pisi*) on field pea.

Table 7.7. Area of crops in Australia and Canada (‘000 ha, average of 3 years, 1998-00)

Crop	Australia	Canada
Wheat	12,001	11,253
Oilseeds (canola + linseed)	1,693	6,083
Pulse crops (field pea + chickpea + lentils + lupins + soybeans		

Table 7.8. Estimated benefits in the yield of wheat crops from break crops, compared with continuous wheat, due to a reduction in plant diseases such as take-all and nematodes, and/or higher soil nitrogen (from pulses)

Location	Benefit
Canadian crops (Manitoba farms – Bourgeois and Entz, 1996)	
• Wheat after flax	+16%
• Wheat after peas	+11%
• Wheat after canola	+ 8%
Australia (research trials)	
• Wheat after pulses (Evans *et al.,* 1991)	+21-24%
• Wheat after canola (Angus *et al.,* 1999)	+19%
• Angus *et al.* (2001)	
Wheat after pulses (no N applied to wheat)	+40-50%
Wheat after pulses (N applied to wheat)	+10-12%
Australia – overall increase, from a range of better practices, in on-farm wheat yields, 1987-89 to 1997-99	+35%

An important factor that has driven the increase in the areas of broadleaf crops in Australia and Canada is the break crop effect - the boost in on-farm cereal yields due to a reduction in cereal root rots (pulses, canola) and/or an increase in soil nitrogen (pulses). Recent reports have clarified the expected size of this effect. In some experiments, the benefit in cereal crops due to pulse crops was as much as 50%, but this comprised a component due to enhanced nitrogen nutrition as well as the reduction in cereal diseases. Surveys of research trials in Australia (Evans *et al.*, 1991; Angus *et al.*, 1999) and farm yields in Canada (Bourgeois and Entz, 1996) have indicated that the usual level of yield benefit (wheat grown after a broadleaf crop compared with wheat after wheat, when the economically optimum level of nitrogen fertiliser was applied) is of the order of 10-25% (Table 7.8). There is little doubt that Australian farmers are experiencing yield boosts of this magnitude from broadleaf crops because of the substantial overall increase of 30-40% in wheat yields per ha during the 1990s. However, if rotations tighten from diverse to simple, the level of benefit could decline (Figure 7.3) due to a reduction in nitrogen fixation as well as a potential build-up in the populations of diseases, weeds and pests.

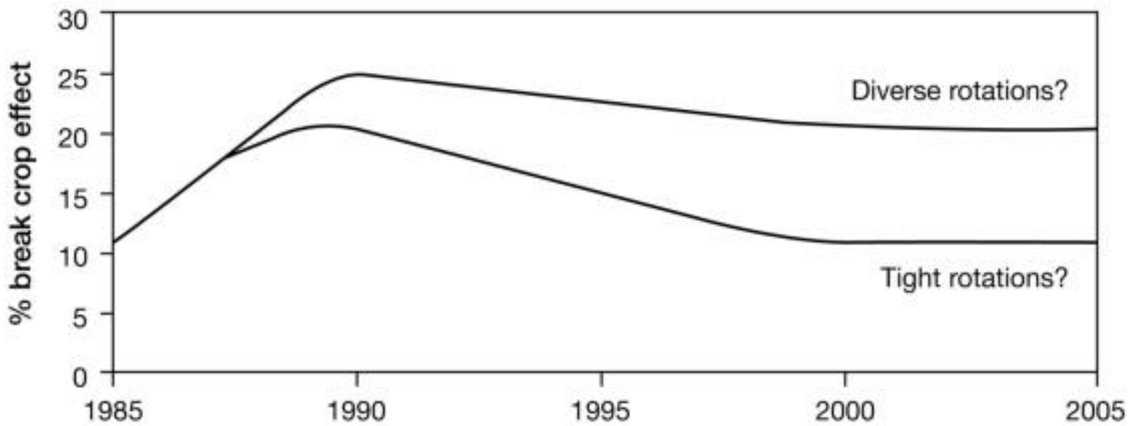


Figure 7.3. Over time, what is the trend in the size of the break crop effect (extra yield of wheat after a pulse or canola, compared with continuous wheat) for diverse rotations or for simple (tight) rotations?

Adoption of break crops in southern Australia

Interest in 'alternative crops' began in the late 1960s when quotas were imposed on wheat production. Lupin varieties were derived from early crosses (Gladstones 1970) between the WA sandplain lupin, which had become naturalised on the sandy soils north of Perth, and sweet lupin genotypes available from Germany. Rapeseed varieties were imported from Canada into NSW and Victoria. During the 1970s there occurred a mini-boom in the production of these crops, followed by a 'bust' when diseases such as phomopsis (lupins) and blackleg (canola) occurred. The 1970s and 1980s marked a period of intense plant breeding to overcome these constraints.

Another factor that constrained the early adoption of broadleaf crops was the cautious attitude of growers, who needed time to build up their 'stocks of knowledge' for growing and harvesting newer crops, experience in marketing them, and more evidence of their alleged economic and rotational worth. For example, non-cereal crops needed to be sown at optimum times that were different to cereals (lupins in late April, canola in May, mainstream wheat varieties in late May, barley and field pea in early June). Sowing machinery and methods had to be adapted to the different sizes of seed and, in the case of pulses, to the need for inoculation of the seed or soil with a suitable strain of rhizobia. Herbicides required registration and harvesting machinery had to be adjusted.

Furthermore, in southern NSW and Victoria, many soils required liming to raise soil pH and remove the potentially harmful Al^{3+} ion, which restricted the root growth of sensitive crops like rapeseed/canola. Most farmers initially grew only small quantities of canola and pulse crops (Vanclay and Lockie, 1993) until agronomic packages such as Canola Check became available, break crop benefits to subsequent cereal crops were apparent, a marketing structure was developed, and some refinements incorporated. For example, the use of lime to reduce soil acidity created soil conditions that were more favourable for the growth of take-all (Murray *et al.* 1987); where liming is practised, the control of alternate hosts such as silver grass in the rotation is essential, as a failure to do so can result in yield losses in wheat of up to 40%.

The clear benefit of lupins to the wheat rotation on sandy soils in WA, coupled with the availability of the first round of improved varieties, resulted in the Australian lupin area increasing rapidly from <200,000 ha in 1980 to 1.4 M ha in 1992. The area of rapeseed/canola was slower to respond, in part due to the need to breed varieties that were high in oleic rather than erucic acid (thought to be implicated in the occurrence of heart disease in humans), with low levels in the oil and meal of glucosinolates (an anti-nutritional factor in pigs and poultry production). The availability of good-quality, high-yielding canola varieties, plus a core network of knowledgeable agronomists and experienced growers, were the ingredients for a spectacular expansion during the 1990s of canola into all farming regions in southern Australia. The long-term impact of canola, the area of which increased by 25-fold from 1990 to 2000, had implications for the nitrogen economy of croplands, since canola not only displaced pulse crops but also increased the yield of cereal crops and their requirement for fertiliser N.

Adoption of break crops in northern NSW and Queensland

The croplands of central Queensland, southern Queensland and northern New South Wales are situated in an agro-ecological zone, termed the ‘northern region’ by the Grains Research and Development Corporation. This region is distinctly different from southern Australia (‘southern region’ and ‘western region’) in several respects. North of a line that bisects NSW from Bourke to Sydney, median rainfall is higher in the summer months (November to April) than in the winter season (May to October). This rainfall distribution contrasts with southern Australia, where rainfall is both more reliable and the pattern is either slightly winter-dominant (southern and central NSW) or truly Mediterranean (SA and WA). Furthermore, most soils in the northern region are, compared with the loams and sandy loams of southern Australia, higher in their content of clay, deeper in profile and capable of storing more water. Consequently, farmers in the northern region potentially have a choice of whether to grow a winter crop or a summer crop. However, because of the low reliability of rainfall, they must reduce the risk of crop failure by fallowing to accumulate moisture in the soil profile. Hence, the historical rotation that developed was *wheat* (May to November) → *fallow* (December to September) → *sorghum* (October to April) → *fallow* (May to April in the following year) → and then back to *wheat*.

In the northern region from the 1980s, considerable changes have taken place in crop agronomy and the rotation is now more flexible and diverse. The no-tillage system of crop production, developed during the 1980s (Felton *et al.* 1995), not only reduced considerably both water run-off and soil erosion during the fallow period but also improved the timeliness and flexibility of sowing. Regular monitoring is now undertaken to assess the depth and nutrient content of moist soil before sowing, assisting farmers to determine if they will sow a crop and what crop to sow. The options range from delaying the sowing of a crop until the next season or, if soil moisture is replenished quickly after a crop, both a winter crop and a summer crop can be sown in the same year. This is called double cropping and the crop sown in response to additional rainfall is the 'opportunity crop'. Nitrogen deficiency was originally regarded as a minor problem in cropping soils because of the high levels of soil organic matter and nitrogen after clearing the original brigalow (*Acacia harpophylla*) community. By the 1980s it had become widespread and severe, limiting both the yield and protein content of wheat (Holford, Doyle and Leckie, 1992). There is now considerable interest in the use of lucerne leys, pulses and fertiliser to counter this deficiency.

Table 7.9. Incidence of crown rot infection, additional pre-plant soil nitrate, grain yield and grain protein for wheat after chickpea compared with wheat after wheat, northern NSW (Felton *et al.*, 1998)

Experiment	Crown rot infection (on + N treatment) %		Extra soil nitrate kg/ha	Grain yield (t/ha)		Grain protein (%)	
	After wheat	After chickpea		After wheat	After chickpea	After wheat	After chickpea
Windridge 1989	n.m.	n.m.	40	2.82	1.48	9.9	10.1
Glenhoma 1990	3	20	47	2.35	1.76	12.9	10.6
Windridge 1992	2	27	19	3.77	2.67	11.9	9.7
Windridge 1993	7	35	30	0.21	0.31	12.5	12.1
Gabo 1993	34	52	21	1.15	1.04	15.2	13.2

n.m. = not measured

Of the pulses available, chickpea (*Cicer arietinum*) is the most popular in the northern region, despite the disease problems of phytophthora root rot (*Phytophthora medicaginis*), luteoviruses (various) and ascochytha blight (*Ascochyta rabiei*) that have occurred with this crop. In wheat rotations, the break crop effect of chickpea is as strong as that which occurred with pulses and canola in southern Australia. For example, Felton *et al.* (1998) demonstrated the ability of a prior chickpea crop to enhance the content of pre-plant soil nitrate-N, reduce the incidence of crown rot in the subsequent wheat crop and so boost both the yield and protein content of wheat grain (Table 7.9).

Smaller areas (< 50,000 ha) of other broadleaf crops are grown in the northern region. These include soybeans, navy beans (*Phaseolus vulgaris*), faba beans (*Vicia faba*), sunflower (*Helianthus annuus*) and canola. There are several reasons for the conservative adoption of each of these crops. Firstly, markets for each crop must be found, a difficult task during the build-up phase of a crop. Secondly, R&D funds are limited and each of the pulse and oilseed breeding programs struggles to cope with the plethora of selection objectives. Thirdly, individual crops may be less attractive: for example, sunflower is prone to bird attack and the crushed seed has a low specific gravity, discouraging the transport and use of sunflower meal. However, because of the decline in soil organic matter and the threat of diseases, especially crown rot, to cereal production, there is renewed interest in break crops for rotations. As canola is so well established in the southern and western cropping regions, it is under evaluation in the northern region in terms of its yield and oil quality, its effect on crown rot and other soil organisms, tolerance of drought and frost and impact on wheat yields.

Current issues in Australian rotations

Simplicity and diversity

In all crop production areas in Australia, there have been some general changes to crop rotations in the 1990s (Table 7.10). Chief amongst these has been a decline in sheep production and an intensification of cropping, with the pasture phase becoming either less frequent (particularly in the short rotations on the sandier soils of SA, WA and parts of NSW and Victoria) or shorter (in long rotations where the pasture phase has been traditionally of several years duration). While canola and pulses have brought potential diversity to rotations, many farmers are simplifying their cropping sequences towards a continuous alternation of wheat with a broadleaf crop, such as wheat/canola or wheat/lupins. These farmers claim that economic considerations drive the simplification of their crop rotation to the crops that are (or seem) most profitable. The pulse crop in the rotation is the component that is often regarded as the 'weakest link' because pulses are less adaptable in terms of their soil and seasonal requirements than cereals or canola, they do not compete as well as canola with weeds and, at least in the short term, they seem to be less profitable than canola. Another reason for the move to simple rotations may be the unwillingness of farmers to accept the greater degree of operational complexity that is associated with several crops in the rotation.

Table 7.10. An illustration of how a crop rotation can be used to enhance both management and herbicide weed control options

Year	Crop	Weed type		Management options
1 to 4	*Pasture* (mixed species) (4 years)	Grasses	←	Grazing management
			←	Winter cleaning
			←	Spray topping
		Broadleaf	←	Grazing management
			←	Spray grazing
			←	Pasture spraying (Selective herbicides)
		All		Fodder Conservation
5	*Canola*	Good grass control	←	Selective herbicides
	(Broadleaf)	Limited broadleaf control	←	Selective herbicides
6	*Wheat*	Good broadleaf control	←	Selective herbicides
	(Grass)	Limited grass control	←	Selective herbicides
7	*Lupins*	Good grass control	←	Selective herbicides
	(Broadleaf)	Limited broadleaf control	←	Selective herbicides
8	*Barley*+lucerne+clover (Undersown)	Limited grass and broadleaf control	←	Few selective herbicides

This trend toward simple rotations is worrying to biologists, who predict an increasing difficulty in controlling pests and weeds. Their prediction is not supported by experience in the main cropping belt of the North American continent, where at least 20% of corn (*Zea mays*) production is produced from a corn monoculture, and much of the rest is produced from a simple corn/soybean rotation. However, this simplicity is maintained only through enormous investment and R&D inputs, from private and public sources, to develop the chemicals and fertilisers that are needed to maintain the simple systems. These investments are beyond the scale of what is either possible or sustainable in Australia.

The concept of biological risk

The future of crop rotations needs to be considered in relation to the concept of *biological risk*. Risk in agriculture is generally estimated, qualitatively or quantitatively, in terms of *climatic risk* (El Nino drought or La Nina deluge?), *production risk* (what is the chance of reaching specified target yields?) and *financial risk* (what is the likely return from additional inputs of fertiliser?). Both farmers and scientists have problems in evaluating the risk of biological events, which are steadily becoming more apparent. Some examples include the increasing incidence of herbicide-resistant weeds as a consequence of overusing certain herbicides, the development of pest resistance to insecticides, and the occurrence or recurrence of crop diseases (anthracnose in lupins, sclerotinia and blackleg in canola).

Biological risk is an important component of the overall picture of risk but it is often underestimated or conveniently ignored. Biological risk is difficult to calculate because the probability of genetic resistance breaking down due to mutations cannot be estimated unless the inheritance of pest resistance is understood. In qualitative terms, all risks can be split into two components, *consequence* (how big will be the effect if a problem occurs?) and *probability* (what is the likelihood of the problem occurring?). For example, the risk of a drought can be worked out in terms of the impact on crop yields if an El Ninõ drought occurs (40% lower grain yields) multiplied by the likelihood of an event this year (say, 1 in 2 or 50%) - the risk is an expected reduction of 20% in crop yields. An example is given below of how this way of thinking can be applied to the controversial topic of simple canola-wheat rotations.

Example: The risk of blackleg occurrence in canola?

Risk of blackleg occurrence = Effect on canola crop (% loss) x likelihood of blackleg outbreak

The difficulty in this equation is estimating the likelihood of a blackleg outbreak because scientists do not know what genes control blackleg resistance/susceptibility. However, if the complexity of a rotation is halved, the likelihood of a blackleg outbreak may be quadrupled, or increased by an even higher multiple. Thus, in adopting a simple rotation instead of a complex (diverse) rotation, a group of farmers in a district may change the likelihood of blackleg breakdown from a chance in millions to a chance in hundreds (or worse). If blackleg resistance fails, plant breeders might only take 3-4 years to develop and release resistant new cultivars, or they may need considerably more time. Have we the R&D resources to recover blackleg resistance after indulging in such risky behaviour (replacing a complex rotation with a simple one)?

In presenting the above example, it must be stated that, in an investigation in WA (Khangura and Barbetti, 2001), the incidence of blackleg in canola was not related to rotation but rather to the proximity of the current canola crop to canola grown in previous years. However, the spatial distance between current and previous canola crops will be influenced by the diversity of the rotation – in simple rotations, the chance of locating this year's canola near to a previous crop will be increased.

Water use in rotations

The problem of dryland salinity, a consequence of rising water tables, is a critical agricultural and environmental issue facing Australia. Salinity not only affects agricultural land, both dryland and irrigated, but also pollutes rivers and can affect residential areas. The cause of salinity is simply an inability to use rainfall fully and so, in time, water drains through the soil to the water table, which rises to the surface bringing with it dissolved salt. Where the problem is created (the recharge zone) is not necessarily where it occurs (the discharge areas). Thus, the farming system in one location may contribute excessive amounts of deep drainage to groundwater that may, through the lateral movement of water, create a severe salinity problem many kilometres away. Water draining through the soil also represents a waste of the potential for crop and pasture growth. From both an agricultural and an environmental viewpoint, the best farming systems are those that use most of the available rainfall (some runoff and drainage is required for our rivers and drainage systems).

The connections between water use, salinity development and plant production means that, in time, rotations will be evaluated in terms of how close they come to achieving their water-limited yield potential. One rotation will be compared with other rotations in terms of water use efficiency, as well as production and profitability. This will be the logical development of the concept of crop water use efficiency, which was proposed by French and Schultz (1984) and is now widely adopted for crop monitoring (Chapter 8).

In many situations, tree production and farming may be combined to reach particular recharge targets. A number of possible systems – block planting, tree belts, alley cropping and woodlots – IS available (Stirzaker *et al.,* 2002).

Monitoring soil fertility

*Acidification of soils in Australian farming system*s

Problem acid soils, those with a pH that is low enough (pH_{Ca}<5.2) to affect plant growth, are common to large areas of soils used for rotational cropping in southern NSW and WA. Accelerated acidification (that is, acid addition at a rate higher than that from natural processes) is common to many Australian farming systems and reflects a net addition of acid to the soil. Under low rainfall conditions (400-450 mm median annual rainfall), the acid addition rates, usually expressed as the amount of lime required to be added each year to balance acid addition, are relatively low (10-20 kg of lime/ha/year) (B.J. Scott personal communication). However, in the wetter parts of the wheat belt (550-650 mm median annual rainfall), the rates may be as high as 100-150 kg of lime/ha/year (Helyar *et al*., 1997), the amount depending on:

- the use of legumes, which increase the content of organic nitrogen in the soil, a proportion of which nitrifies and is subsequently leached;
- the removal of products and waste products high in residual alkalinity; and
- the use of acidifying fertilisers containing nitrogen and elemental sulphur (Cregan and Scott, 1998).

In acid soils, toxic ions of aluminium and manganese may seriously retard the root and shoot growth of agricultural plants. Acid soils and soil acidification can be managed through two approaches:

- through the practice of farming systems that minimise acid addition, and
- by the application of lime.

The successful introduction of changes to farming practice requires an appreciation of the mechanisms of acidification that are operating in a particular paddock. In practice, soil pH should be regularly monitored and lime applied if the pH_{Ca} falls below 5.2.

Liming will also assist by increasing the availability of molybdenum and by enhancing *Rhizobium* infection and symbiosis for most temperate legumes. The lime rate that is sufficient to achieve these objectives can be determined from the pH and buffering capacity of the soil. For most moderately buffered soils used for cropping, 2.5-3 t/ha of lime will raise soil pH about one unit (1-10 cm). Heavier textured soils require greater applications while less is needed for lighter soils to achieve the same pH increase. Reapplication of lime may be necessary every 10-15 years.

The most efficient use of lime is achieved if lime is applied, and thoroughly incorporated, before sowing the most acid sensitive crop in the rotation. In many common rotations used in southern Australia, the best time is prior to the sowing of canola, which responds well to lime application on acid soil, particularly where manganese toxicity is prevalent. On the Southern Slopes of NSW, where soils are commonly acid and canola is a preferred crop, over 60% of all canola crops are now grown in paddocks that have been limed. Such use of lime has also benefited the establishment and growth of lucerne. This improved growth of lucerne has resulted in large increases in pasture growth, stocking rates and nitrogen fixation.

Phosphorus

Phosphorus is essential for successful growth of both crops and pastures. Most Australian soils are naturally low in phosphorus and they require regular applications of phosphorus fertiliser, sometimes with other nutrients such as sulfur and zinc. Traditional practice in a rotation has been to drill phosphorus with each crop at sowing time and to topdress pastures. This practice was found to be less efficient than applying all the fertiliser needs to the crop phase, because the banding of the phosphorus beneath the surface improved P uptake, particularly under drier soil conditions or when the soil had a low pH and a high P sorption capacity. Surface application during the pasture phase also favoured the dominance of annual grasses such as barley grass, at the expense of annual legumes (Ayres *et al.,* 1977). Hence, it was recommended that application of P to the pasture phase be omitted and extra fertiliser is applied during the cropping phase. In practice, the first step of this recommendation was enthusiastically adopted but insufficient extra P was applied during the crop sequence. Consequently, soil tests are now in use more frequently to monitor the status of phosphorus, nitrogen and other nutrients, and guide applications of fertiliser.

Nitrogen

The current scenario for N supply and demand in Australian dryland crops has been analysed by Angus (2001). During the 1990s, there began a strong increase in the demand for fertiliser nitrogen for wheat production, an increase that was paralleled by a decreased capacity for soil nitrogen supply. Relatively cheap fertiliser, changing land use and the success of Australian canola were the ingredients of the declining contribution of biologically fixed nitrogen to the N economy of croplands, rather than any constraint on the fixation process itself. The popularity of canola was crucial, since canola not only enhanced the demand of wheat for nitrogen (the break crop effect) but also displaced pulses from rotations in several zones. The N dynamics of wheat crops are such that, even in rotations that incorporate legumes, there is a winter-spring mismatch in the soil nitrogen supply and the crop demand for nitrogen. These trends drive the need to monitor soil nitrogen levels and estimate the nitrogen requirements of crops, and they may encourage the use of greater areas of legumes in croplands.

Herbicide management

The management of herbicides within the rotation can impact substantially on the species and density of weeds. Each crop or pasture phase presents particular opportunities for weed control. Examples of these in a rotation sequence are summarised in Table 7.11.

Table 7.11 Rotations - Past, present and future

Time	**Australia** Short rotations (WA, SA, Vic, south-west NSW)	Long rotations (Vic, southern NSW)	**US** Corn rotations
Past (1980s)	Wheat/fallow ⇒ Wheat/pasture ⇒ W / W / oats ⇒	Wheat (3 y) + pasture (5 y) ⇒	Corn/soybean/ wheat/clover ⇒
Recent (1990s)	Wheat/lupins ⇒ Wheat/canola ⇒	Canola/wheat/pulse/wheat/pasture ⇒ or Canola/wheat/pulse/wheat/canola/ wheat/pulse/wheat/pasture ⇒	Corn/corn ⇒ Corn/soybean ⇒ Corn/soy/alfalfa ⇒
Present and Future (beyond 2000) • Monoculture, simple rotations or greater diversity? • A pasture phase in each rotation or continuous cropping? • Consideration of long-term as well as short-term biological risk?			

The development of herbicide-resistant weeds is dependent on an active selection process whereby the resistant weeds survive the repeated use of herbicides (Chapter 9). Both the pasture phase and different crops provide a range of opportunities for the rotation of herbicide groups – a key strategy. A pasture phase can play a crucial role in managing herbicide resistance because it provides opportunities for non-selective weed control. These include:

- grazing pastures at heavy stocking rates to prevent seed set;
- spray grazing, the use of a low rate of a broadleaf phenoxy herbicide, such as 2,4D or MCPA, followed by heavy grazing;
- fodder conservation – both silage and haymaking are effective, non-selective methods for weed control. With haymaking hay must be made before the target species sets seed;
- the slashing of pasture to prevent weeds setting seed; and
- strategic grazing and fertiliser management that encourages the suppression of weed species.

Effective weed management in a rotation is based on the use of a range of approaches that are integrated into a weed control strategy, rather than on any particular method of weed control. The concept of IWM (Integrated Weed Management) embraces a consideration of the ecology of the weed species and the planned use of a range of methods including cultivation, strategic application of herbicides, competition from crops and pastures, biological control where available, grazing, fodder conservation, and slashing. In the future, new tools may become available through the controlled use of phenomena such as allelopathy (the release by one plant species of chemicals which affect other species in its vicinity, usually to their detriment – An *et al.,* 1998).

Economic evaluation

Historically the economic performance of crops and pastures was often evaluated according to their comparative gross margin, which is the difference between the variable costs and returns of each crop. The problem with the gross margin approach is that it assesses each enterprise in isolation, and takes no account of any inter-relationship between enterprises. For example, the nitrogen added to the farming system by a pasture phase may produce hundreds of dollars worth of extra crop production over several years but the pasture gross margin takes no account of it. Gross margins also take no account of the infrastructure and fixed costs associated with the conduct of any enterprise. These deficiencies can lead to poor decisions that may impact on the components of a rotation.

The need for a rigorous economic analysis of farming systems has led to the development of more complex economic models as tools for analysis, such as MIDAS (Model of an Integrated Dryland Agriculture) (Morrison *et al.,* 1986). This mathematical programming model was designed to evaluate farming systems in Western Australia. A similar need for better economic evaluation of the complexity of rotational farming systems in southeastern Australia resulted in the adaptation of MIDAS for southern and central NSW as PRISM (Profitable Resource Integration Southern MIDAS) (Faour *et al.* 1997).

Towards the Future

In situations where R&D backup is limited, and/or where the inputs of fertilisers and chemicals must be modest because of climatic and production risks, simple rotations could fail due to a combination of herbicide-resistant weeds, more frequent occurrence of diseases and pests, production costs and insufficient R&D back-up. This scenario applies to most of Australia. For example, in southern NSW, canola/wheat rotations are biologically risky (weeds, diseases, pests) and N depleting. N fertiliser is expensive. Even if canola/wheat is the most profitable rotation in the short term, there is a choice available of diverse rotations that are close to the economic optimum.

In Australia, diverse rotations must be seen as an essential rather than a desirable strategy of defending the benefits of break crops and improving the sustainability of production. **The basic building block of rotations suitable for dryland farming in Australia is a four-cycle combination of cereal-canola-cereal-pulse (or canola-cereal-pulse-cereal)**. This combination is the optimum for productivity, profitability and sustainability. Scientists, advisers, farmers and industry must strive to maintain and enhance this basic building block.

At least in the context of Australian dryland cropping systems, continuous cropping is unrealistic. Ley pastures (lucerne and annual legumes) also are an essential component of Australian rotations, but the minimum and optimum proportions of pastures are not clearly known for the range of cropping systems. The use of pastures and livestock in farming systems should not be constrained by current thinking. For example, livestock owners could transport and deploy their flocks in the same way as do bee keepers - to the mutual benefit of the livestock owner and the landowner. Other developments might be agroforestry, plus the retirement of patches of land from agricultural production for aesthetic, biodiversity or salinity reasons.

Rotations that satisfy most of the requirements for sustainable and productive farming are documented in Table 7.12. A risky rotation is shown for comparison. Components of future rotations include better varieties of pulses, new crops such as linseed/Linola™, and fodder legumes such as vetch and berseem clover (*Trifolium alexandrinum*). A wider range of pasture legumes will also become available.

Table 7.12. Some rotations that could be used by farmers on the southern slopes of New South Wales, where a long-phase rotation is practised

Crop/pasture sequence	**Year**									
	1	2	3	4	5	6	7	8	9	10
Intensive crop	W	C	W	PL	W	C	W	PL	B/P	P 3-4yrs
Conventional	P	P	P	P	W	C	W	PL	W	B/P
Risky	P	P	P	C	W	C	W	C	W	B/P

P = pasture, W = wheat, C = canola, PL = pulse, B/P = barley undersown with pasture

Therefore, there is a need for a greater recognition and understanding of the concept of risk (production risk, biological risk) and of the principles that apply to it. Diversification assists in buffering production and marketing risks. The risks of herbicide-resistant weeds, disease occurrence and pest outbreaks can be reduced by an integrated farm/landscape management system that incorporates diversity in time (temporal diversity) and space (spatial diversity).

Temporal diversity may be enhanced by:

- adopting a minimum four-cycle rotation;
- maintaining at least 20% of arable land as pasture;
- extending the range of crop types;
- extending the range of pasture types; and/or
- developing areas of refuge for beneficial animals and organisms by conserving, on the least productive parts of a farm, areas of remnant woodlands and permanent grasslands.

Spatial diversity may be enhanced by:

- strip cropping, a simple kind of spatial diversity;
- avoiding extremes. Eucalyptus dieback on the Northern Tablelands of NSW was a consequence of lack of spatial diversity (over-clearing and pasture improvement, leading to much higher grass grub/beetle numbers);
- the use of interlocking patches of different crop types, ley pastures, permanent pastures, grasslands, and woodlands;
- evaluating the importance of patch size and patch diversity on productivity, profitability, sustainability, property value and personal satisfaction.

These principles are equally applicable to rotations used in irrigated agriculture. In Australia, both the cotton (Hulugalle *et al.*, 2001) and rice (Ockerby *et al.*, 1999) industries are moving toward more diverse systems of production. There may never be an ideal rotation, but there is usually a better one.

PRINCIPLES

- Well-constructed rotations mimic nature by creating greater biodiversity, thereby providing opportunities for regulating the populations of weeds, diseases and pests, and for conserving soil, water and biological resources.
- During the period from 1950 to 1980 in southern New South Wales, Victoria, South Australia and Western Australia, legume leys based on subterranean clover, medics or lucerne rapidly expanded. These leys improved soil fertility, reduced the impact of some weeds and raised cereal crop yields.
- Starting in the 1980s and accelerating through the 1990s, the widespread adoption of 'break crops' (lupins, other pulses and canola) reduced cereal root diseases and disorders, producing further improvements in the grain yields.
- Currently, economic and operational factors are driving farmers back toward simple rotations, which are maintained by extra inputs of fertilisers to supply nutrients and chemicals to overcome plant pests and diseases. In situations where R&D backup is limited, and/or where the inputs of fertilisers and chemicals must be modest because of climatic and production risks, simple rotations could fail due to a combination of factors. These factors include the more frequent occurrence of diseases, pests and/or herbicide-resistant weeds, and insufficient R&D back-up particularly for broadleaf crops.
- The basic building block of rotations suitable for dryland farming in Australia is a four-cycle combination of cereal-canola-cereal-pulse (or canola-cereal-pulse-cereal). A pasture phase is also an important component of sustainable rotations.

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