Rotation, Sequence and Phase: Research on Crop and Pasture Systems

J.F. Angus, J.A. Kirkegaard and M.B. Peoples
CSIRO Plant Industry, Canberra

Abstract

The yield of a crop is greatly affected by the preceding crop or pasture. In the past, the effects have been studied in long-term rotation experiments conducted on research stations. On farms that grow crops continuously or grow both crops and pastures, there is a decreasing proportion of paddocks managed in fixed rotations. Increasingly the sequence of crops and pastures is decided tactically each year, based on factors such as product price, input costs, soil reaction, the weed-seed bank and the residual water, nutrients, pathogens, allelochemicals and herbicides. This paper reviews research during the 1990s which has quantified the residual value of water and nitrogen and the control of pathogens using break crops. It also reviews the introduction of perennial pasture phases into cropping systems, particularly in relation to reducing groundwater recharge and nitrogen dynamics.

Selecting the crop or pasture best suited to each paddock on a farm in terms of production and resource conservation is a complex process that is one of the most challenging technical problems currently facing farmers. The prospects for providing rules of thumb and decision-support systems for crop and pasture choice are discussed.

Introduction

The general conclusions arising from research on rotations are well known. Legumes lead to increased soil organic matter and continuous non-legumes to a decrease. Fallowing accelerates the decrease. Yield is higher for crops grown after different crops, for example cereals perform better when grown after broadleaf crops and vice versa. This review traces four periods of research on crop and pasture rotations, defined broadly, which has been conducted for over 80 years in Australia. Research on long-term experiments with pastures, cereals and fallows, started at Longerenong in 1916 (1), at Glen Innes in 1921 and the Waite Institute in 1925 (2). From the 1930s to the 60s, when the value of pasture leys for overcropped soils was recognised in southern Australia, there was a period when experiments focussed mainly on pasture-crop rotations. In the 1980s, there was less interest in pastures and more interest in crop sequences, initially those containing grain legumes, and then in sequences containing canola. In the 1990s, interest in the pasture phase returned, first because of the interest in revitalising pastures which were believed to be in decline, and secondly to encourage the use of perennial pastures to reduce environmental problems of soil acidification and salinisation.

The changes in sequences and phases of crop and pastures on farms have reflected the changes in research. Donald (3) described wheat yield in relation to the changes in farming systems, as shown in Figure 1. Angus (4) extended the explanations from 1960 to 2000. Yields declined due to continuous overcropping in the nineteenth century. For the first half of the last century yields rose with new varieties, fallowing and superphosphate, before reaching a plateau when nitrogen (N) was exhausted with fallowing. Nitrogen fertility increased with the more widespread adoption of pasture-crop rotations after the 1940s. However there was a new yield plateau by the 1970s and 1980s partly due to the expansion of cropping into low-rainfall regions where yields were lower than in the older cropping regions. Yields again rose in the 1990s particularly in Western Australia and southern NSW. The timing of this yield increase coincided with less pasture area, increased use of break crops and larger amounts of N fertiliser (4).

In this paper we prefer not to refer to ‘rotations’ on farms, because there are few examples where a particular sequence of crops and pastures is repeated. Rotation, however, is important in experiments because of the increased precision through repetition. The term ‘sequence’ captures the flexibility that is increasingly apparent in the choice of crop and pasture on farms, as discussed below. The term ‘phase’ implies that pasture or crops continue to be grown for several years, and has continuing relevance for farms and experiments.

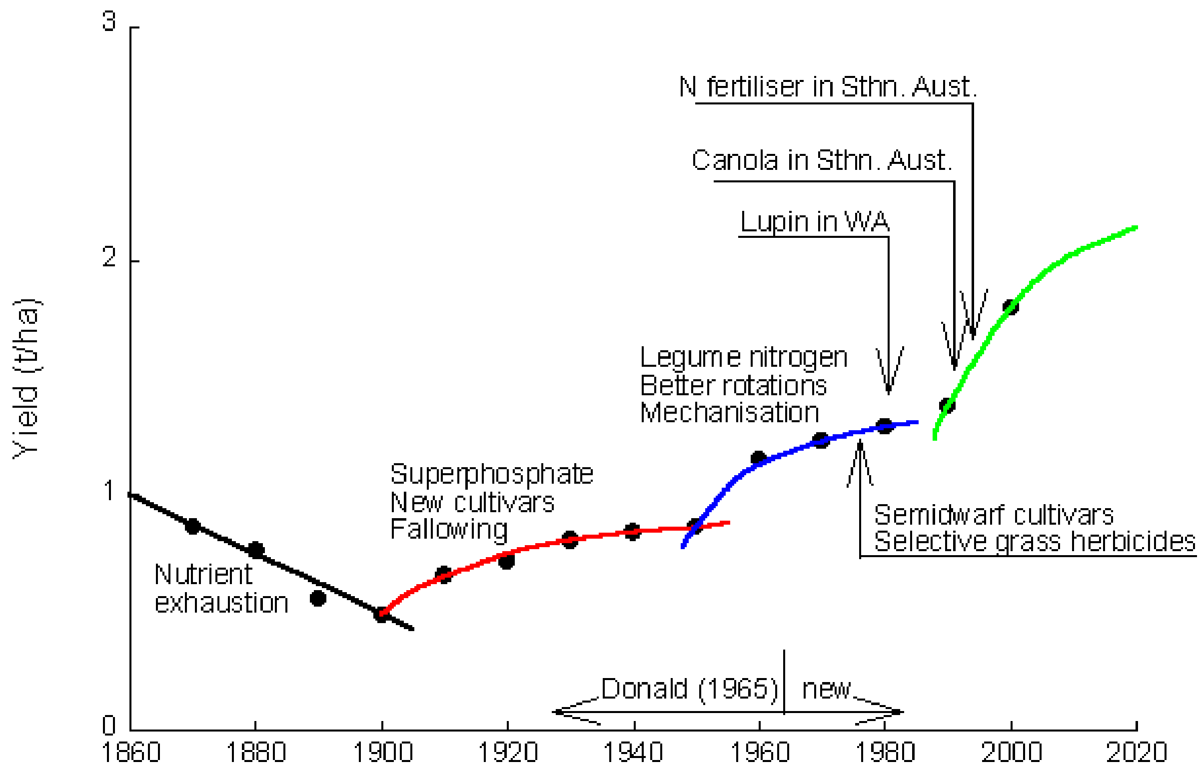

Figure 1. Changes in wheat yield each decade from the 1860s to the present. Up to 1960 the graph and explanations are from Donald (3) and after that from Angus (4).

LONG-TERM EXPERIMENTS

Papers from a workshop on long-term agronomic experiments (LTAE) were published in 1995 in *Aust. J. Exp. Agric.* 35 (issue 7). These dealt with rotations as well as the closely related issues of tillage and stubble management. Martin and Grace (5) reviewed LTAE and identified advantages and disadvantages (Table 1). They concluded that only a small number of LTAE can be justified in Australia and that their greatest justification was in studying sustainability.

Table 1. Advantages and disadvantages of long-term agronomic experiments (5)

Advantages	Disadvantages
Environmental monitoring	Mostly unreplicated or obsolete designs
Detect slow changes	Soils move between plots
More reliable than short-term experiments	Small plots are unrepresentative
Allow retrospective analyses	Treatments become obsolete
	Expensive to operate

The value of long-term experiments is not just for agriculture, but also for the community as a whole. Soil from long-term experiments, if sampled and stored carefully, provides a unique resource because it can be used to show environmental change against a background of constant management. Examples include topics that were totally unexpected at the time when the experiments were set up, such as carbon sequestration in soil and the increasing level of fallout of industrial pollutants such as PCB and dioxin (6). The value of LTAE can be realised only if soils are carefully collected and archived.

One topic which Australian LTAE have not addressed well is the long-term impact of intensification. While there has been adequate study of the consequences of low-input and extensive systems, there has been little attention to the long-term consequences of continuous cropping under conditions of economically optimum N fertiliser and weed control, combined with best management of residues and tillage, and, if necessary, lime and gypsum.

Pasture-Crop Rotations

The ley-farming system widely adopted in the southern grain-growing areas of Australia during the 1950s was studied in many rotation experiments that have been reviewed by Greenland (7), Russell (8), Puckridge and French (9) and McCown et al. (10). These leys were based on annual legumes, mostly subterranean clover and medics, and the crops grown in rotation were almost all cereals.

Briefly these studies showed that the pasture phase led to yields greater than the fallow-cereal systems they replace and to increased soil organic matter, with related improvements in soil structure shown by increased aggregate stability, reduced bulk density and improved water infiltration. The rotation of pastures and crops led to fluctuating levels of organic matter, with increases during the pasture phase and decreases during the crop phase. More recently attention has been directed to the negative aspects of annual pastures in rotations. Analysis by Helyar et al. (11) of a pasture-crop experiment conducted in the 1960s and 70s at Wagga Wagga showed the acidification during the pasture phase. Dear et al. (12) reported the unstable botanical composition of annual pastures, with the risk of erosion when plant density was low.

The cereal yields in the pasture-crop experiments described above were extremely low (~1.5 t/ha) by today's standards. Since the annual pastures almost certainly contained grasses, it is likely that cereals following pastures in these experiments were infected with root diseases such as take-all. Subsequent research by Kidd et al. (13) showed that removing grass from an annual pasture using a selective herbicide during winter ('winter cleaning') led to reduced root disease and higher yield of a cereal grown in the following year. Selective herbicides were not available when most of the research on pasture-crop rotations was conducted.

The relevance of pasture-crop rotations is decreasing along with the 30-40% decrease in sheep numbers and the increase in crop area from 16 to 20 m ha in Australia over in the past 20 years. Since the area of arable land is about 50m ha, the decrease in the area of pastures available for rotation with crops has presumably fallen from 34 m ha to 30 m ha. Much of the additional crop area consists of broad-leaf crops, which increased by a factor of 10 since 1980, while the area of winter cereals increased by 6%. While broadleaf crops made up 3% of the crop area in 1980, they made up 20% in 2000 (14).

Crop Sequences

Grain legumes and other broadleaf crops

The search for broadleaf winter crops in Australia started with the wheat quotas and low wool prices of the late 1960s. By the early 1980s, lupin started to be widely grown, followed by field pea and, by the late 1980s, by canola. The case of fieldpea is interesting because varieties released in the 1960s were not grown widely at the time, but those same varieties were grown extensively by the late 1980s. Perhaps the limitation to adoption of fieldpea before then was weed control and adoption of other broadleaf crops was also delayed by the lack of effective weed control.

The value of these new crops growing in sequence with cereals was evaluated not only in long-term rotation experiments, but also in simpler 2-year experiments, the first year of which consisted of a comparison of several crop species and the second year of wheat sown over the plots. The compilation of experimental results in Table 2 includes 135 site-years of wheat growing after wheat compared with wheat growing after at least one broad-leaf crop. In many cases experimental treatments in addition to crop species were studied, and where these included level of N fertiliser, yields for only the lowest N treatment are included here. Where there were other treatments such as sowing date, the yields were averaged over all treatments for each species. The weighted averages in Table 2 provide only a general guide to the relative benefits of the different broadleaf crops because the data are drawn from different experiments.

Table 2. Yield of wheat after wheat and the percentage yield response of wheat after broadleaf crops.

		Yield of	Percentage wheat yield increase after:				
Reference	Experiments	wheat after wheat (t/ha)	Lupin	Field pea	Faba Bean	Chick pea	Canola
Reeves (15)	Rutherglen, 1 year	3.94	36	22	8		17
Marcellos (16)	Tamworth, 1 year	1.67	58		68	81	

Rowland et al. (17)	WA, 26 site-years	0.85	41				
Evans et al. (18)	Sth. NSW, 15 site-years	2.09	44	32			
Rowland et al. (19)	WA, 17 site-years	1.37		41			
Heenan et al. (20)	Wagga, 12 years	2.50	32				
Heenan (21)	Wagga, 4 years	2.76*	72	67		73	72
Schultz (22)	Tarlee, 14 years	1.61	53	45			
Felton et al. (23)	Nth. NSW, 9 site-years	1.57				54	
Asseng et al. (24)	East Beverley, 1 year	1.6	131		31	50	38
Dalal et al. (25)	Warra, 8 years	2.11				39	
Angus, unpublished	Junee, 1 year	3.7	68	65	58	51	32
Angus et al. (26)	Sthn Aust, 26 site-years	3.29					19
Weighted means		1.98	46	42	42	53	19

* the control treatment was wheat after barley.

The means indicate a 40-50% yield benefit for wheat growing after grain legumes and about 20% for wheat after canola. The advantage of legumes is that they provide residual N, as well as a disease break, while canola is presumed to provide a disease break with no N-benefit.

An alternative way of estimating the relative value of the N contribution and the disease break is with N fertiliser applied to wheat grown after wheat. In the lupin-wheat sequences reported by Rowland et al. (17), the yield increase by wheat following lupin was 41% in the absence of applied N, but 12% when the economically optimum level of N was applied. In the fieldpea-wheat sequences reported by Rowland et al (19), the corresponding yield responses were 41 and 10%. The low value for the non-N contribution in these studies compared to the value for canola in Table 2 may be related to the relatively greater importance of a disease break in south-eastern Australia, where most of the canola studies were conducted.

An assumption often made is that the N contributed by legumes to following cereals is primarily from biological fixation by the legume. Another contribution may be N-sparing, i.e. less soil N taken up by a legume than a non-legume (27). Green and Blackmer (28) suggested another possible contribution from a comparison of a soybean – maize rotation with a maize monoculture in the US midwest. In these systems, the presence of soybean leads to more mineral N becoming available for maize, but the source of the N was attributed to *less immobilisation* of soil mineral N by the soybean residues, because their C:N ratio is less than for cereal residues, rather than from residue N remaining after N fixation. Green and Blackmer (28) conclude that the presence of soybean actually leads to faster rundown of soil organic N than continuous maize cropping. The importance of this process has not been tested in Australian cropping systems.

Despite the lower yields of wheat after canola than after legumes in experiments, there has been more recent adoption of canola than grain legumes (except in the northern sandplain of WA, where lupin is well adapted) presumably because the gross margins for canola is greater than for the grain legumes used for feedgrains. Even though returns for canola are relatively high, the economic value of substituting canola for wheat was made up of 27% from the canola itself and 73% for the following wheat (26). Another benefit of canola is the more reliable response to fertiliser N by the following wheat crop (29). There has been a large increase in the amount of N fertiliser used in Australia since the early-mid 1990s, particularly in south-eastern Australia. It is likely that the increase was because there were reliable yield and protein responses to N applied to wheat growing after canola, as well as to the canola itself (4). The timing of the adoption of break crops and the efficient use of N fertiliser also explains the rapid rise in wheat yields during the 1990s (Fig. 1).

Break-crops and biofumigation

The term ‘break crop’ implies that the level of cereal pathogens decreases during a period without a host. If that is the case, then cereal yields after different non-legume broadleaf crops should be similar. However, in several comparisons there were higher wheat yields after Indian mustard than after canola, leading to the hypothesis that brassicas were capable of actively suppressing pathogens, such as the fungi that cause cereal root diseases (29,30).

Further studies suggested that isothiocyanates (ITC) and other breakdown products of glucosinolates, were released from *Brassica* residues in a process of biofumigation, and were capable of inhibiting the growth of fungal pathogens as well as weeds, insects and nematodes (31). Not all pathogens are equally susceptible to control by biofumigation; for example the take-all fungus is highly susceptible while *Pythium* is less susceptible (32,33). In addition, the different side-chains on isothiocyanates confer different toxicities; for example, propenyl ITC is toxic to several fungal species at relatively low concentration while 4-pentenyl ITC is less toxic (33). Indian mustard roots contain propenyl glucosinolates, leading to release of propenyl ITC from the root residues, while canola roots release no propenyl ITC (34). There are known to be a wide range of glucosinolates contained in different organs of members of the *Brassica* and related genera, leading to the prospect of breeding for increased suppression of soil-borne pathogens. Fortunately there is little correlation between the concentrations of glucosinolates in seed and other organs, so it should be possible to breed the low seed glucosinolates required by the market, while maintaining levels in other organs that will inhibit pathogens. The opportunities for using brassicas for pathogen control are in both broad-acre cropping and for horticultural systems where there are possibilities for specialty biofumigation cover crops to replace fumigation by obsolete products such as methyl bromide.

In the case of broad-acre cropping the prospects for increasing disease control using different brassicas are not as encouraging as suggested by the first results indicating higher wheat yields after Indian mustard than after canola. A recent compilation of all 26 available comparisons conducted in southern Australia showed no difference between the yields of wheat after Indian mustard, canola and linola (26). While it appears that the process of biofumigation leads to rapid control of susceptible soil pathogens, in the annual cropping cycle this confers little or no advantage over the control provided by absence of host (35, 36). Nevertheless there is still no clear explanation for results of significantly higher yields of wheat after Indian mustard than of wheat after canola. The possibility remains of improving the break-crop benefit of brassicas by genetic changes to the profile of isothiocyanates and other biologically active constituents of residues.

Control of root disease appears to be the main mechanism by which brassicas lead to increases in the yield of following crops. There have been suggestions that the root channels left by brassicas may provide some advantage for subsequent crops, but the results of Cresswell and Kirkegaard (37) did not confirm such effects. There is some evidence that canola provides more N for following cereals (38-40). Possible reasons are the breakdown of microbial biomass during biofumigation and that brassica residues break down more rapidly than wheat residues.

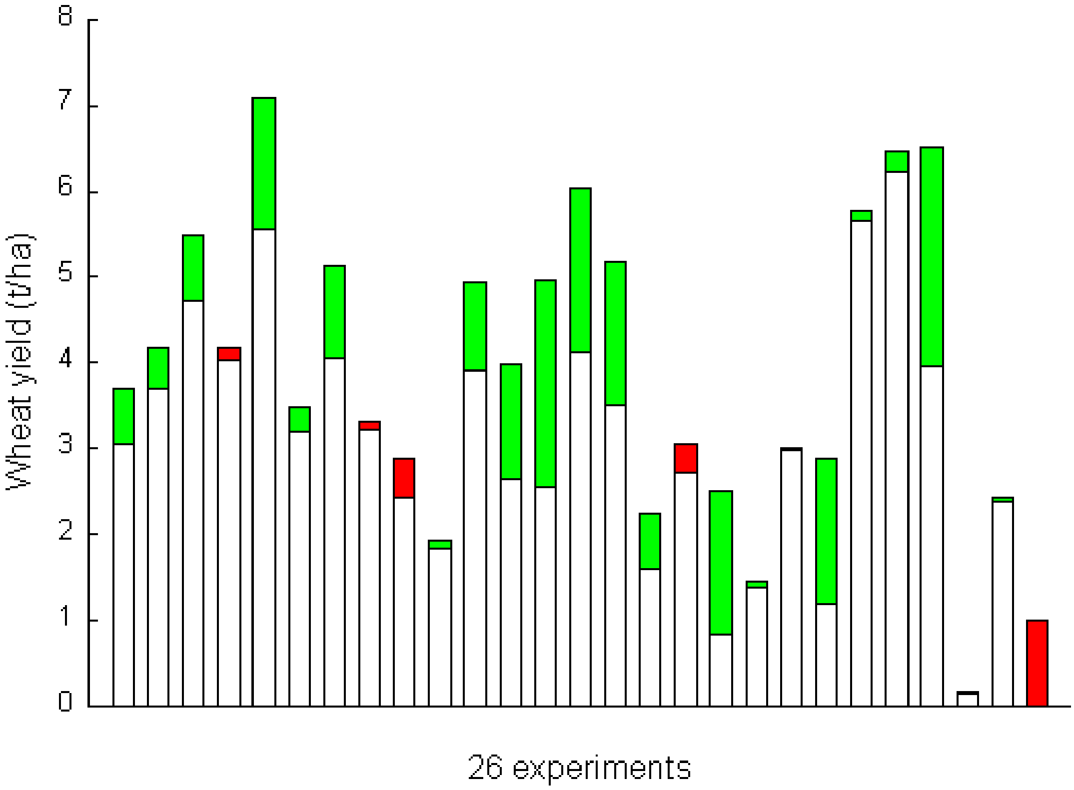

Fig. 2. Yield of wheat growing after wheat (open bars) and the increase (green bars) or decrease (red bars) of yield for wheat growing after canola in 26 experiments in southern Australia (26)

Besides evaluating the break-crop benefit and the mechanism for disease control, research on brassica-wheat sequences has led to insights into the water and N relations of subsequent crops. Averaged over 8 comparisons, dryland wheat growing after canola extracted 23 mm more soil water than wheat growing after wheat, leading to subsoil drying to matric potentials down to –5 MPa in comparison to values of –3 MPa after wheat (41). Over 26 comparisons wheat after canola contained 17 kg N/ha more than wheat after wheat (26). While the additional N may have been due in part to more soil N mineralised after canola, it was also associated with less mineral N remaining in the soil at the time of wheat maturity. The main reason for the additional extraction of soil water and mineral N was greater demand by healthy plants and continued uptake by healthy wheat roots. The consequence is less potential for groundwater recharge and nitrate leakage.

There are reports of poor wheat growth after canola in southern Australia, with symptoms resembling long-fallow disorder of wheat in Queensland. The cause of long-fallow disorder is reduction in the levels of mycorrhizal infection in the roots, leading to low uptake of Zn and P (42). However, it is not clear whether problems reported in southern Australia have a similar cause, since Ryan et al. (43) showed reductions in mycorrhizal infections in wheat growing after canola, but with no accompanying yield decrease.

Phase Farming

Research conducted during the 1990s began to re-examine the pasture phase, because of dissatisfaction with the perceived low productivity of annual pastures, their unstable botanical composition, soil acidification and leakage of water and nutrients (12, 44). There was also concern about the generally low yields and grain protein of wheat growing after annual pastures.

The changes from previous pasture-crop research were the shorter intended duration of experiments and more emphasis on measurement of processes related to N dynamics and soil water rather than yield and long-term changes in soil organic matter. In addition, research addressed perennial species as well as relatively new management practices such as winter cleaning of annual pastures.

Dewatering

An important function of a lucerne phase in cropping systems may be in dewatering landscapes where annual crops and pastures allow groundwater recharge. The Salinity Audit (45) predicts that dryland agriculture will be an increasing source of salt in the Murray River and its tributaries, because current farming systems have used insufficient rainfall. Perennials pastures, particularly lucerne, have longer growing seasons and deeper roots than annual crops and pastures, so have the capacity to extract soil water that would otherwise drain to the water table. Several studies have now compared the soil water dynamics of lucerne, annual crops and pastures. Research by Crawford and Macfarlane (46), Lolicato (47), Ridley et al. (48), Dunin et al. (49) and Angus et al. (50), shows a 'buffer' of dry soil of about 200 mm i.e. the amount of water that can be accepted before there is rapid drainage below the effective root zone of lucerne. In the comparisons of Angus et al. (50) the difference in the size of buffer between lucerne and annual crops was about 100 mm, with another 100 mm between annual crops and annual pastures. In this example the soil under poor annual pastures remained close to the drained upper limit when sampled in winter and summer each year from 1993 to 1998. The target for recharge reduction is the amount that currently drains below the root zone. Measurements of water loss below a lysimeter at Wagga Wagga (annual rainfall 550 mm) suggest that the average drainage is about 10-30 mm per year under annual crops (51,52). The increased water use possible with lucerne (and more productive crops) is therefore capable of greatly reducing or preventing groundwater recharge.

Lucerne however occupies no more than about 5% of the mixed-farming area where it is most widely grown in southern NSW. Its more widespread adoption depends on its profitability compared to crops, and what it can contribute to crop profitability. Holford and Doyle (53) found reduced yield of crops following lucerne because of low reserves of residual soil water. Angus et al. (54) overcame this problem by removing lucerne in the year before cropping and allowing time for soil-water accumulation. McCallum et al. (55) showed that soil-water recharge after removing lucerne was in the root-zone of annual crops and that the subsoil remained dry in the Victorian Wimmera, at least until the next period when rainfall exceeded the storage capacity of the topsoil. However in most locations there is a risk of insufficient soil water stored at the end of a lucerne phase for subsequent crops. Research is needed to seek a balance between reducing groundwater recharge and storing sufficient water for subsequent crops.

Nitrogen aspects

New techniques involving the natural abundance of ^{15}N are now used to estimate N fixation within a single year rather than the decades needed to measure changes in soil total N in long-term experiments. For example Peoples et al. (56) and Peoples and Baldock (57) reported much higher inputs of biologically fixed N from pastures containing lucerne than from those containing annual legumes in south-eastern Australia. The additional N-fixation was related to the additional growth by lucerne which was due to a more rapid start of growth in autumn, prolonged growth in late spring and summer growth in response to rain. Despite the additional N fixation there is not necessarily increased supply of soil mineral N at the start of the following cropping phase, apparently because the high C:N ratio of lucerne residues leads to slow mineralisation (58).

Recent research on pasture phases has thrown new light on annual pastures as well as perennials. Winter cleaning of subclover based pastures leads to high yields of subsequent crops. Previous research by Kidd et al. (13) indicated that the yield benefit of winter cleaning was control of cereal root disease. However, Scammell and Harris (personal communication) compared the effect of grass removal from a mixed subclover-based pasture on the yield of subsequent wheat and canola crops. They found large yield increases, suggesting that control of cereal root disease was not the only effect of grass removal. Peoples et al. (56) reported that the yield responses were associated with large (~100 kg/ha) increases of mineral N in the soil during autumn in response to winter grass removal from a mixed pasture in the previous winter. In some cases the additional soil mineral N is as large as the increased N fixation. The consequence is that only 1 or 2 crops benefit from the net N mineralisation after subclover, while there may be a longer period of N supply after lucerne, possibly after an initial period of transient immobilisation. The timing of N release from all residues is affected by the environmental factors of temperature and soil water, so the period is likely to be faster in summer-rainfall environments, as suggested by the relatively high crop yields after lucerne at Tamworth reported by Holford and Crocker (59). In winter-rainfall environments the reserves of mineral N in the soil after lucerne can be increased by removing the lucerne in the previous season (54).

These results open many possible ways to include lucerne and other perennial pastures in cropping systems to take best advantage of their benefits for production and the environment. Examples may be 1 or 2 year pastures to dewater a subsoil after a flood or more regular phases. In wet regions there may be scope for intercropping, with the lucerne placed either randomly or in rows, for example under wheel tracks as markers for controlled traffic. The end of a phase of perennial pasture may involve removal of lucerne but retention of annual legumes that decompose rapidly to provide mineral N for the early parts of the cropping phase

The course of research into pastures in northern Australia, particularly in the top end of the Northern Territory, bears a parallel but shorter path to that in southern Australia. In the 1950s and 60s, research was directed at developing a ley-farming system based on the annual legume, Townsville stylo (*Stylosanthes humilis*), analogous to the ley-farming system then dominant in southern Australia. Within a few years it was clear that the compositions of annual pastures were unstable and that a pasture containing a perennial component was superior (60).

Crop Choice as a Tactic

Since there is about 16 m ha of cereals and 4 m ha of broadleaf crops in Australia, it is clear that many cereals are still grown after other cereals. Based on the widespread yield increases of cereals after broadleaf crops, there is still scope for expanding their area. For some graingrowers, particularly in semi-arid regions, there are no well-adapted broadleaf crops while in other regions, suitable species are available but are not yet widely grown. At the other extreme, in wetter regions, graingrowers can choose between 4 cereals, 6 broadleaf crops and at least 2 pasture types (annual and perennial). In these regions, there are probably over 100 possible sequences. With this range of options, the prospects for a return to fixed rotations are slight, and flexible systems are needed to select the best crop or pasture for each paddock in each year, within the context of the whole farm. The approach of selecting a crop as a tactic based on current prices and costs has been tested using the MIDAS model and shown to be more profitable than fixed rotations (61).

There is little prospect of conducting routine experiments to test all different sequences as thoroughly as for the broadleaf crop – wheat sequences summarised in Table 2. Equally it cannot simply be assumed that there are no surprises; for example Kirkegaard et al. (62) found that wheat grown after oats did not outyield wheat after wheat, despite the reputation of oats as being a good break crop for wheat. The most efficient way to examine sequences is by means of the mechanisms by which one crop affects later crops, for example whether they share diseases in common and from the residual water and nutrients.

At present graingrowers and consultants perform the mental gymnastics of making a good choice for each paddock as well as taking account of whole-farm considerations such as cash flow, labour peaks and stock numbers. The difficulty arises because not only must the selection of a crop or pasture take into account the effect of the previous year's crop and its residues, but also of the next year's crop because of the options opened or closed by decisions of the present year.

So far agronomic research has not developed methods to assist this process, other than provide information about components of the system. Most farmers and consultants want to continue to make these complex decisions, and it is not clear that formal methods would be capable of making any improvement over their intuition. However a collection of relevant data and an attempt to assemble it into a decision support framework would be worth the effort, if only to compare with intuitive decisions. It is not clear what such a system would look like. A linear programming framework alone is inappropriate since it normally deals with rotations, and not with annual decisions for individual paddocks. Equally, current simulation models dealing with a crop sequence in a single paddock through residual water and N are inadequate since they do not deal with important but poorly understood factors such as disease, allelopathic interactions (63) and weed/herbicide interactions. Combining information about these processes with an existing simulation model would violate the generally accepted rule of modelling, that different parts of a model should be balanced. Perhaps the best that could be done with existing knowledge is a simple rule-based system to calculate profitability of different crop and pasture sequences, based on processes by which one crop is known to affect later crops, and which can include new information from this rapidly expanding field. In view of the likely environmental benefits of perennial-pasture phases in mixed farming systems, and the community interest in rising groundwater under farmland, a decision support system for crop choice should also include information about likely recharge.

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