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Effects on whole farm water use efficiency of lucerne-crop transitions

Andrew P. Smith & Andrew D. Moore

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Executive Summary

Lucerne or alfalfa (*Medicago sativa* L.) is a crop valued by producers with mixed farming systems. The multiple benefits to both livestock and crop production have been widely reported; however there are also some reports of negative effects on crop production when lucerne is included in ley pastures due to competition within the farming system for resources such as water. Consequently, an assessment of the value to different farming systems using lucerne leys is best carried out using a whole of system modelling study. This paper reports a simulation study aimed at better understanding the mixed farming systems that include short-term (3-year) phases of lucerne. The effects of removing lucerne plants at different times prior to cropping; the variable effects of "biological drilling" by lucerne roots; and the effects of different crop rotations on production as well as water and nitrogen (N) use efficiency were studied at a temperate site (Hamilton).

Crop production was increased by early removal in the final phase, mostly as a result of increased N at sowing. There were also some minor effects on water use; however, as this was a high rainfall site, water was not a primary limiting factor for production. Livestock production, on the other hand, was improved by later removal of lucerne with higher stocking rates (dry sheep equivalent basis, DSE) and turnoff weights for spring lambs presumably due to availability of summer feed. When these sometimes positive and sometimes negative effects were evaluated at the whole of farm scale there was little difference on the gross margins, as the area of land each year in transition from lucerne pasture to cropping was small relative to farm area and the system was in excess to plant requirements in terms of water.

There were no detectable effects due to biological drilling, again because water deficit was not a major limitation to crop production. The best choice of crop after the lucerne ley was canola as it is a high value crop and has poor tolerance to waterlogging.

1 Introduction

Lucerne or alfalfa (*Medicago sativa* L.) is highly valued as forage for livestock production in Australia, as it is in many regions of the world. The reasons are that multiple benefits arise from including lucerne forages in farming systems, such as higher livestock turnoff weights; reduced reliance on supplementary feeding in summer and autumn; high livestock reproductive potential; and the maintenance of ground cover at crucial times of the year (Lodge, 1991; Ransom, 2004). Lucerne provides capacity to capitalise on summer rains, to improve water infiltration and alleviate waterlogging (McCallum et al., 2004). As well, the importance of ley phases has been recognised as break crops for controlling weeds and disease (Dalal et al., 2004), augmenting soil N and C stocks (Angus and Peoples, 2012), providing a period for soil structure to recover from cultivation and wheel traffic (Hanley et al., 1964). Mixed farms, that is to say farms acquiring income from crop and livestock production, have incorporated phased rotations including lucerne pastures for these reasons.

Some crop-livestock farmers, however, remain unconvinced about the overall value to the farming system of including lucerne leys (Ransom et al., 2003a). Despite the multiple benefits to the farming system, many producers with mixed farms find that once lucerne is included in the farming system, it can be troublesome to manage its establishment, optimal defoliation management, stand persistence and removal. Also, the lucerne sometimes has negative effects on the yields of following crops compared to crops grown after annual pastures (Dalal et al., 2004; Latta and Lyons, 2006; McCallum et al., 2001). Angus et al. (2000) showed the effect of different removal strategies of lucerne on the production of subsequent crops could be profound, but that early removal was sometimes at a cost to livestock production from grazing and to accumulation of N inputs. In environments with low rainfall, vigorous dewatering of the soil profile by lucerne can occur over summer (Crawford and MacFarlane, 1995; Ridley et al., 2001), in which case there may be too little soil water accumulated to buffer the yield of a crop against a dry season. However in some soils, dewatering over summer and autumn is important to lessen the effects of winter waterlogging. Lucerne has been shown to significantly reduce soil water available at sowing and yields of subsequent crops in the subtropics (Murray-Prior et al., 2005) and Mediterranean areas (Dolling et al., 2005; Latta and Lyons, 2006); this effect may last for a number of seasons (Ridley et al., 2001).

It is unclear what might occur in high rainfall environments where crops are grown and where the inclusion of lucerne is more recent. The impacts of lucerne leys on water and N use efficiency are complex, depending on rainfall amount and timing not only in the current but in subsequent crops (Ward et al., 2002). The degree to which this loss available soil water used by lucerne is offset by the increase in plant available N as a result of symbiotic fixation is difficult to disentangle experimentally, and remains poorly understood. Therefore, although there is little doubt by graziers as to the value of well managed lucerne to livestock in pastoral systems, the value of lucerne leys on the profitability of mixed-farming systems is less clear. Clearly a whole of farm perspective is required to assess the role of lucerne in mixed farming systems.

Another advantage of lucerne occurs as a result of its strong, deeply penetrating root system. The ability of lucerne roots to grow into soils with physical limitations has been termed the “biological drilling” effect (Cresswell and Kirkegaard, 1995). The term refers to the formation of stable pores in the subsoil by plant roots during their growth, which then decay to leave open biopores that can be exploited by the roots of subsequent crops. Cresswell and Kirkegaard (1995) concluded from their review that there was not any clear experimental evidence to pin-point the exact effects of biological drilling in annual crop rotations. In the case of field experiments this is possibly because of the difficulty of isolating a biological drilling effect amongst the various interconnected effects and feedbacks of the ley phase. Nevertheless, some authors (e.g. McCallum et al., 2004; Meek et al., 1992) have found various lines of evidence to suggest that a phenomenological approach may be warranted in modelling studies until the mechanisms are elucidated from experimental studies.

Over recent years there has been an increase in the area of land cropped as well as the use of lucerne in regions that have not traditionally been considered as suitable for either land use, for example areas of south west Victoria in Australia. As Ransom (2004) pointed out, a barrier to more widespread adoption of

lucerne leys in crop-livestock systems has been the lack of whole farm biophysical and economic analysis. Angus et al. (2000) also supported this idea concluding that a modelling approach is needed to evaluate strategy and tactics for time of lucerne removal, considering the amount of lucerne growth forgone, crop yield, and potential groundwater recharge, in relation to weather variability. Therefore, this was the purpose of this study: to use whole-farm systems analysis to investigate the effects on water use efficiency and farm profit as a result of different ways of managing lucerne in farming systems. Specific questions as they relate to farming systems with a rotation constituting of a lucerne phase followed by several years of annual cropping are:

1. What are the water and N balance consequences of killing the lucerne at different times in the final year?
2. Which crop sequence (especially first crop) maximizes profit after lucerne?

A secondary aim was to investigate what might be the benefits, if any, as a result of biological drilling by the lucerne root system.

2 Methods

2.1 Overall modelling approach

In order to fully evaluate the responses of farming systems to different lucerne management, large and complex datasets spanning many years are required. Therefore comprehensive, whole-farm simulation models were constructed using the AusFarm software (version 1.7). There models were built by linking the APSIM (version 7.5, Holzworth et al., 2014) crop and soil models, and GRAZPLAN (Donnelly et al., 2002) pasture and animal management models. A mixed-farming system was simulated with a lucerne ley phase that lasted for 3 years. The variations in farming systems were lucerne ley phases of different lengths, rotations of different crop and varying degrees of biological drilling. The systems simulated are theoretical, however they were developed using regional statistics (*e.g.* DEPI, 2014) and are therefore representative of an average mixed farm system in the region.

2.2 Climatic data

Simulations were conducted for a site located at Hamilton (37°50′ S, 142°04′ E) (Figure 1). The long term climatic statistics are shown in Table 1. For the site, daily climatic data (rainfall, solar radiation, pan evaporation, maximum and minimum temperatures) were extracted from the SILO Patched Point Dataset (Jeffrey et al., 2001); http://www.bom.gov.au/silo/) for the period 1950-2013 inclusive for the climate station number 90173 (Table 1). At Hamilton 16% of rain falls in the 3 summer months and 33% in winter. Other details of the long term climatic dataset are shown for the period 1950 to 2013 in (Figure 2).

Figure 1 Location of the study site.

Table 1 Long term climate data for Hamilton for the period 1950-2013.

LOCATION/STATE	CLIMATE TYPE	CLIMATE STATION	ELEVATION (M)	RAINFALL (MM)	AVERAGE TEMPERATURE (°C)
Hamilton, Vic.	Temperate	90173	241	654	13

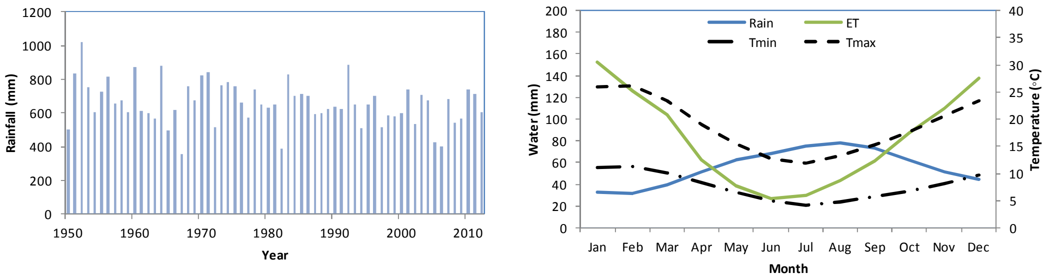

Figure 2. Annual rainfall (left), average monthly rainfall and potential evapotranspiration (ET), and average daily temperatures (°C) at Hamilton for 1950 – 2013.

2.2.1 FARMING SYSTEM

A prime lamb enterprise with autumn joining and spring lambing was simulated. The farm size was 1250 hectares of which was evenly split into 17 paddocks (73.5 ha each) as well as a feedlot. A portion of the farm was used devoted to only grazing of pastures – therefore termed 'permanent'. Each year permanent pastures (64% of area), and a phase-farming of six years of annual crops and three years of lucerne pastures (36%) occupying a fixed proportion of the farming area. Therefore at any one time, around three-quarters of the farm was in pasture (*i.e.* permanent perennial or lucerne).

2.2.2 CROPPING

Annual crops were grown on raised beds with drainage in order to alleviate the effects of waterlogging (Riffkin and Evans, 2003). Following Lilley et al. (2008), raised beds were of 1.5 m width and 0.2 m height, and 0.5 m wide furrows between the beds. Water above the drained upper limit in the uppermost 0.2 m of the soil was assumed to flow laterally across the beds at the same rate as it drained downward, and any water reaching the furrows was taken to be lost immediately as runoff. The beds were assumed to relieve any negative effects of waterlogging on plant growth however their effectiveness declined over time. The crop paddocks were cultivated and raised beds formed on once each cycle 16 March, prior to the sowing of the first crop in the sequence.

Table 2 Treatments simulated

INITIAL PLANT REMOVAL DATES (DOY)[1]	ROTATION[2]	INCREASE IN WATER EXTRACTION EFFICIENCY[4]
1 Oct (274)	CWB[3]	0%
1 Nov (305)	CBW	10%
1 Dec (335)	WCB	25%
1 Jan (1)	WBC	50%
1 Feb (32)	BCW	
1 Mar (60)	BWC	

[1] DOY refers to Julian day of the year; [2] the sequence of the rotation is repeated twice; [3] C refers to canola, W refers to wheat, B refers to barley; [4] increase in the "kl" factor in APSIM

The six years of annual crops consisted or rotations with different sequences of canola (*Brassica napus* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), as shown in Table 2.

Crops were sown after 1 April when rainfall of at least 15 mm over 5 days was received. (Other than the cultivation at the initial bed formation, crops were sown using no-till.) Crops were sown into paddocks with the most moist soils first. If no sowing opportunity occurred by 15 June they were sown dry. Canola (*var.* Hyola42) was sown at rates that resulted in emergence of 80 plants/m^2, whereas wheat (*var.* Mackellar) and for barley (*var.* Gairdner) were both sown at 250 plants/m^2. Grass weeds in the crops were sprayed within the rotation phase by complete removal from 1 April to August 31.

N fertiliser was applied to all crops at a rate of 50 kg at sowing (nitrate-N as a fertiliser blend) and on 2 August a further 20 kg N was applied as urea.

Crops were harvested when mature. Paddock-scale crop yields were reduced by 5% assuming that yield in the furrows was 80% of that on the beds due to the effects of waterlogging and compaction. Grain split during harvest (and so available to livestock grazing the stubbles) was assumed to be 1.5% of the total grain production.

2.2.3 PASTURES

Pastures in the phase-farming part of the farming system were based on a typical mix of lucerne and annual grass weeds, such as barley grass (*Hordeum murinum*). Winter-active lucerne (*Medicago sativa* SARDI-7) was sown (at 6 kg/ha) if 15 mm of rain was received after the middle of April. If these sowing conditions had not been met by the middle of June 15 then the lucerne was sown dry. Lucerne was sown into the remnant raised beds without any further cultivation.

Permanent pasture swards were composed of perennial ryegrass (*Lolium perenne*), phalaris (*Phalaris aquatica*) and sub-clover (*Trifolium subterraneum* var. Seaton Park). It was assumed that the pastures were oversown every 8 years, as part of a 'rolling' pasture renovation program (*i.e.* one paddock each year). No N fertiliser was applied to permanent pastures or lucerne.

2.2.4 LIVESTOCK

A replacement-ewe, prime lamb enterprise with autumn joining and December shearing was simulated. Crossbred ewes (Border Leicester and Merino) were mated to a Dorset ram. Joining occurred from early February (starting day 39) until the end of March (day 81). Lambing occurred in spring and the average weaning age was 14 weeks. Therefore by the end of November all spring lambs were consuming only pasture, and breeding ewes were dry.

In preliminary model runs, the ewe numbers were adjusted in order to achieve a stocking rate of more than 16 DSE/ha in order to represent regional farming systems (DEPI, 2014) and achieve a pasture utilisation rate of over 50%. The lamb sale strategy aimed to efficiently use the plant biomass. At the start of December an assessment was made of how much green feed is available on the permanent pastures and lucerne. The number of lambs to be retained over summer was calculated using a herbage allowance of 40 kg of green pasture per lamb, and the remainder of the lambs sold (lighter lambs and ewe lambs were sold first). Retained lambs were sold when they run out of forage on the perennial pastures (the herbage allowance declines to 10 kg/lamb). Ewes were removed from the farm (and simulation) when they were either 6 years of age (cast for age), were losing significant amounts of weight or were empty 12 weeks after the start of joining. These ewes were replaced with purchased purebred maiden ewes (1.5 years old). The livestock were configured with high lambing rates that reflect the higher reproduction observed on lucerne-based pastures in the MLA *EverGraze* program.

Sheep grazed permanent and lucerne pastures, crop stubbles or were fed with supplementary feeds in the paddock or a feedlot. Pastures were rotationally grazed with animals being allocated to the paddocks with the best available feed. Sheep were set to graze the permanent pasture paddocks at durations of 10 days during winter and 4 days at other times of the year. Animals were moved to the paddock with most feed in an order of priority. From weaning until the sale of the last lambs, lucerne paddocks were allocated to the heaviest mob of lambs still in the system.

Stubbles were made available for grazing by only the replacement and dry ewes. All stock grazing stubbles occupied a single paddock. Animals grazed stubbles once they became available (at harvest) for a maximum of 28 days in total and only while the cover in the stubble paddocks remained above 0.75. Spilt grain formed part of the diet of animals grazing stubbles (although it was typically quickly exhausted). Animals were moved from one stubble paddock to the next when the replacement ewes cease to gain weight. Stubble grazing ended when all stubble paddocks had been grazed or on 1 April in any case. If the ground cover in all paddocks fell below 75%, all animals were moved to confinement feeding. Sheep were moved out of feedlot when the average cover across all pasture paddocks started to increase substantially. At

other times, weaners and ewes in late pregnancy were fed in their current paddock if their body condition score fell below 2.0; other ewes were fed if their body condition score fell below 2.5. In-paddock feeding was at a rate of 1 kg wheat grain per head per day.

2.3 Lucerne removal

In its third year, that is to say at the end of the ley phase, lucerne was removed or killed in a three-step process in order to simulate farmer experiences removing lucerne (Angus et al., 2000; Falkiner et al., 2013; Ransom and Egan, 1998). First, a so-called “crash grazing” was carried out: 35 days prior to the nominated removal date, all animals grazed the target lucerne pasture until a residual biomass of 500 kg/ha remained. Secondly, on the nominated date of removal (Table 2), lucerne was sprayed with herbicides which achieved an 80% kill rate. Surviving lucerne plants were then completely removed by re-spraying 35 days later at a time when there was translocation from the shoots to the roots, which achieved a 100% kill rate. Between the first kill and cultivation, lucerne regrowth and weeds were controlled aggressively during the fallow period, in that they were immediately and completely removed. With cultivation at the formation of the raised beds all lucerne was finally considered as completely removed.

2.4 Representation of biological drilling

As outlined in the introduction, following the review of Cresswell and Kirkegaard (1995), the precise effects of biological drilling are still being elucidated as are when, where and the extent to which they occur. Cognisant of this of this a simplified, phenomenological approach was taken similar to Lilley and Kirkegaard (2011). In the APSIM-Plant model, kl is an attribute of a plant in a given soil that represents an efficiency of uptake which in turn is related to soil diffusion and root density. It includes the effect of root length density (l) and soil diffusivity (k). However, it does not treat k and l separately, but rather combines kl as one soil–crop parameter. To reflect biological drilling, the kl of the crop was notionally increased during the cropping phase between 0-50%, so modifying the proportion of available soil water that could be extracted each day. The effect of increased kl was assumed to gradually decline over the cropping phase.

2.5 Soil parameterisation

The farm spanned three different soil types – a Brown Sodosol which was a fine sandy loam over clay subsoil; a brown soil and a brown basalt. Details of each soil were taken from Victorian Resources Online and McCaskill and Kearney (2012).

The simulated farm area was composed of three soil types: a Brown Chromosol derived from basalt, (35% of area), a lunette soil (12% of area) and a basalt soil (53% of area). Soils were parameterised using data measured by McCaskill and Kearney (2012) and from the Victorian Resources Online website (vro.depi.vic.gov.au/dpi/vro/glenregn.nsf/pages/glenelg_soil_rises_pvi8). The maximum rooting depth was limited to 2.2 m.

2.6 System efficiency

The efficiency of resource use compared between the different systems based on the framework proposed by Moore et al. (2011). A number of different aspects of water use efficiency were examined:

- Total water transpired by crop plants (in units of mm), which reflects the capacity of the larger farming system to provide plant-available water
- Crop transpiration efficiency for grain, i.e. grain yield per unit of water transpired (in units of kg/ha.mm), which will reflect differences in the capacity of crops in a given system to convert available water into product; and
- Pasture utilization rate, i.e. the ratio of pasture dry matter consumed to aboveground net primary productivity of pastures (in units of kg/kg).

Within-crop N resource use efficiency was expressed as the N use:

N use (kg/ha) = N at sowing + fertiliser N – N at harvest

and the N use efficiency for grain production:

N use (kg/ha) = total grain yield/N use

2.7 Economic analysis

Gross margins (*i.e.* total gross income less input costs) were calculated by taking into account variable costs and income for the crop and the livestock enterprises using item prices typical for this region of Victoria. Data sources included the Livestock Farm Monitor Project (DEPI, 2014) and the Livestock Gross Margin Budgets produced by NSW DPI (www.dpi.nsw.gov.au/agriculture/farm-business/budgets/livestock). Data from these sources were used per unit of production (*e.g.* per tonne), per animal or per hectare as appropriate. The prime lamb enterprise income is made up of lamb sales, wool sales, sheep sales and livestock inventory change (*e.g.* ewe sales). For cropping, the cost of forming the raised beds was also taken in to account. The decision of when to sell lambs influences both the value of lambs sold however for simplicity in the analysis this has been standardised here. The assumptions and values are summarized in Table 16 in the Appendix.

3 Results

The majority (76%) of the 1250 ha farm area was utilised with the objective of maximising livestock production by prime lamb from grazed pastures (65% permanent pastures, 12% lucerne pastures). Therefore, a relatively small area of the farm (4%) made the transition from lucerne pasture to cropping in any one year.

A typical time course for pasture dry matter production is shown in Figure 3. Over the 60 years of simulations, the highest average growth rates were in December and January at 80 kg/ha/d, and the lowest were in June and July at less than 2 kg/ha/d.

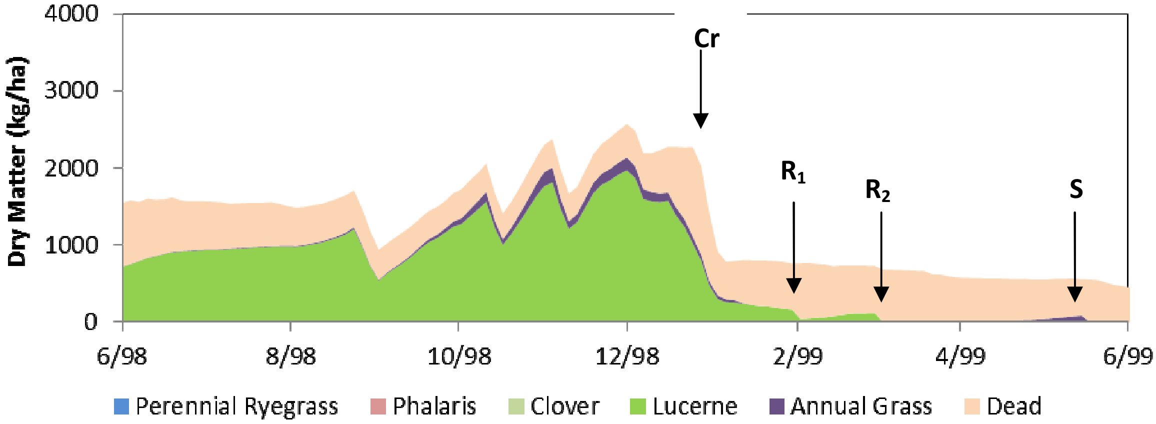

Figure 3 Pasture dry matter production for two ley phases and cropping phase (above) and the two stage removal of lucerne (below)

The example is for 1 February removal. Cr shows the time of crash grazing, R_1 is the first removal of lucerne, R_2 is the second removal and S is crop sowing on 16 May.

3.1 Effect of variable biological drilling

The effects of four levels of biological drilling - none, low (10% increase in KL), medium (25%) and high (50%) increase in KL water extraction efficiency of the roots on the main elements of the farming system (*i.e.* crop and animal production, as well as soil and water) were assessed.

Focussing on a farming systems with an initial lucerne kill on day 32 (1 February), across a range of climate years (58-year period from 1955-2013), there was an insignificant effect of varying intensity of biological drilling on the yield of the first crop after lucerne (Figure 1).

The lack of response was not influenced by crop type, however there was slightly more overall variation in wheat, for example about the median, than canola or barley. The slope of the line between the 90^{th} and 10^{th} percentiles indicates that wheat is more susceptible to changes in soil moisture/rainfall than canola overall.

For canola, there was no difference in the long term average yield (2.85 t/ha) and no difference due to phase of the rotation (between 1^{st} and 2^{nd}). For the first canola crop after lucerne there were no differences in the grain yield nor overall crop biomass production, nor water use efficiency of crop biomass or grain production, plant available soil inorganic N at sowing or soil water at sowing or anthesis.

Assuming that the most significant effect of variable water extraction efficiency (*i.e.* kl) was on crop transpiration, the effects were investigated by focussing on a crop rotation of CWB for a very low (10^{th} percentile), average (10^{th} percentile) and high (90^{th} percentile) total transpiration year or 1994, 1981 and 1956 respectively (Figure 5).

The effects of variable kl during the post-anthesis period, when crop moisture stress often occurs, were of minor significance on transpiration. However, in general the lucerne was highly effective in dewatering the soil profile. As shown in Figure 7 from the start of October 2005 to end of March 2006, the profile was dewatered by about 190 mm of water or by 88% of the starting moisture and then it took three years to fully recharge the profile.

Note that even during the period shown in Figure 7 when there was a drought, the soil water content during the cropping phase was not limiting.

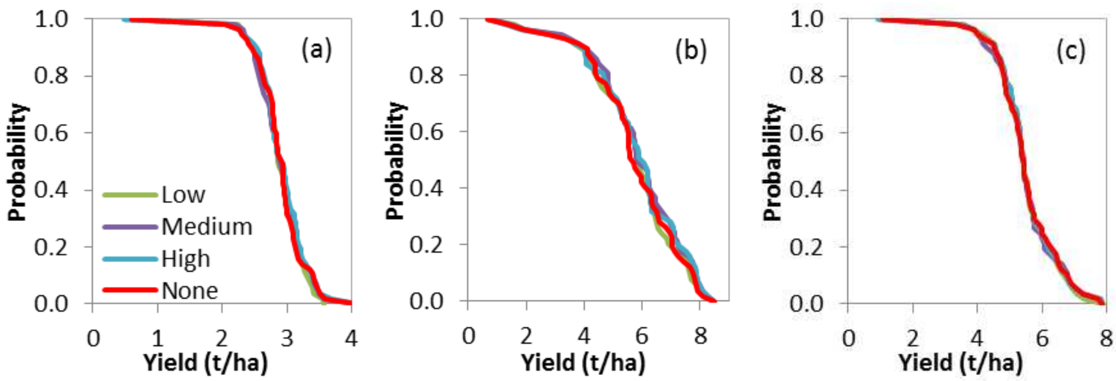

Figure 4 The effect of variable degrees of biological drilling on annual grain yield of the first crop after lucerne at Hamilton for the rotations (a) CWB, (b) WBC, (c) BCW.

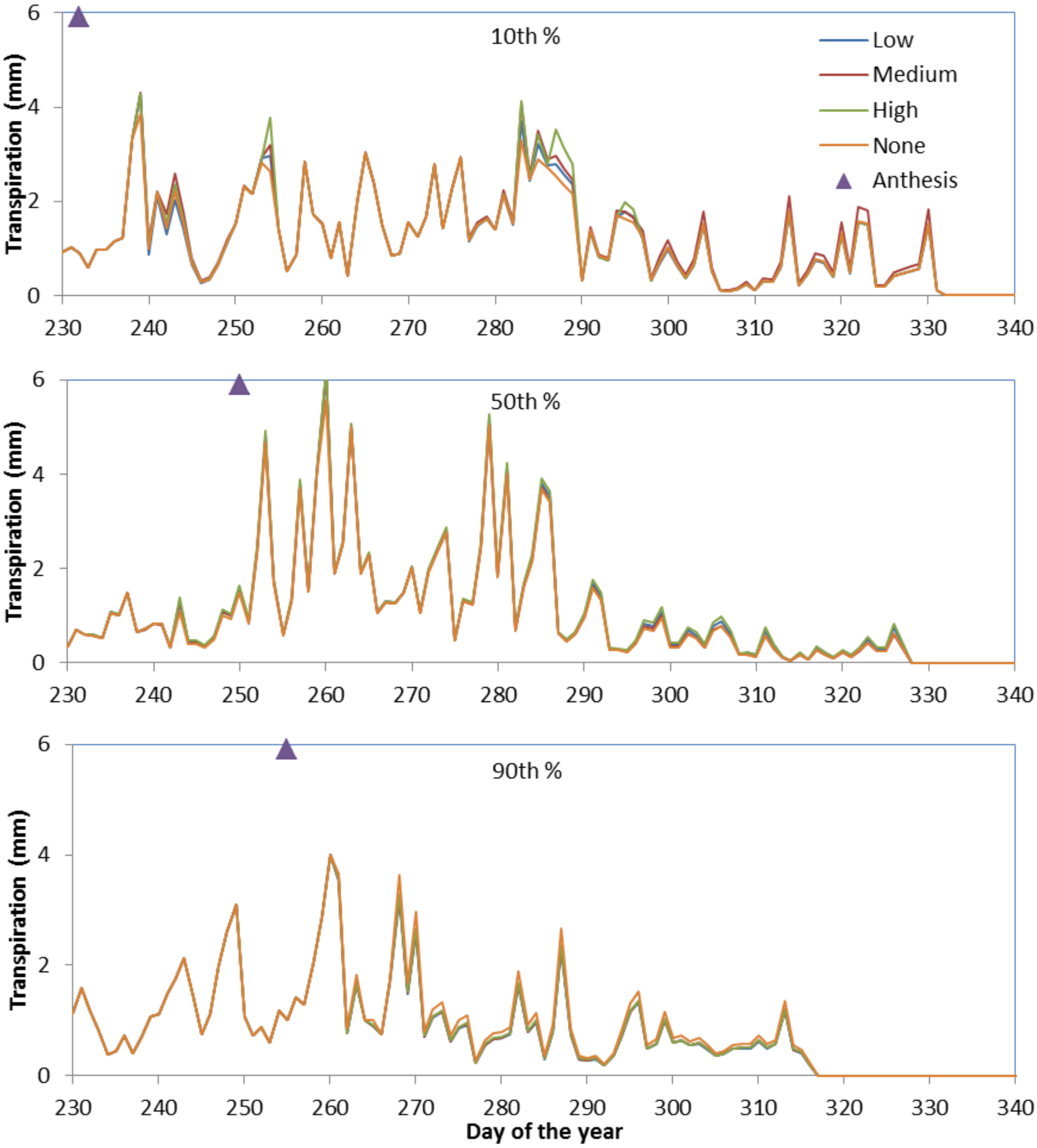

Figure 5 Daily transpiration by canola (the first crop after lucerne, for a lucerne removal date of 1 Feb) in the post-anthesis period at Hamilton for high (10th percentile), medium (50th) and low (90th) transpiration years.

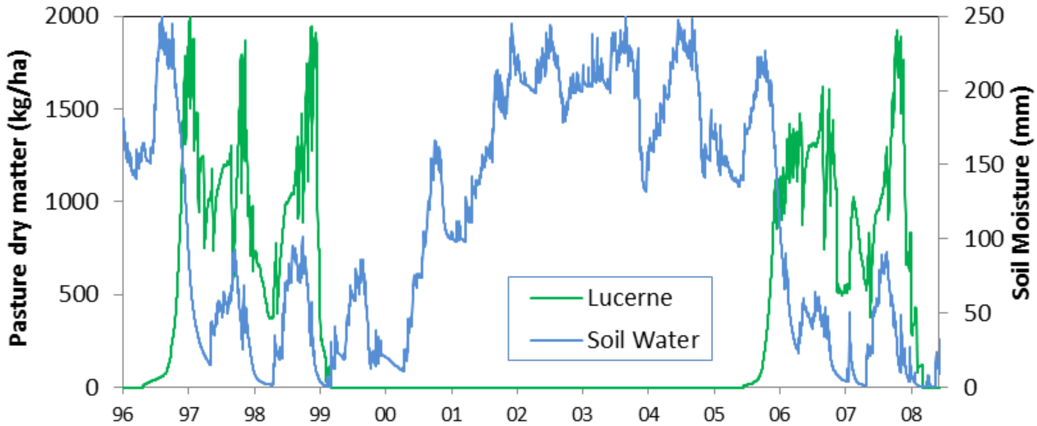

Figure 6 Soil moisture during lucerne and cropping phase for paddock with lucerne removal on day 32 and a rotation of CWB

3.2 Effect of different removal times of lucerne

In order to compare the effects of six different dates for the removal of lucerne before entering the crop phase, the systems' responses of the CWB rotation and with a 25% increase in kl due to biological drilling was assessed. The effects were clearest comparing grain yields, where the yield decreased relative to the lateness of the lucerne removal (Figure 7).

Comparing canola yields, the differences due to variable removal dates were still detectable for average yields of canola in the second phase, although by the fifth year of the rotation (*i.e.* wheat in the second phase) the effects were no longer detectable (Table 3).

For the first year canola crop there was a 22% difference in total crop water use between the earliest and latest removal or 0.26 mm per day. As there was no difference in crop-water use efficiency, the difference in water use can be attributed to the difference in available soil water at sowing (Table 4).

Figure 7 The long term average effects of different removal dates (given in the legend as days-of-year) of lucerne on the following first crop of canola

The day-of-year is the date of the first removal of lucerne, with complete removal 30 days later.

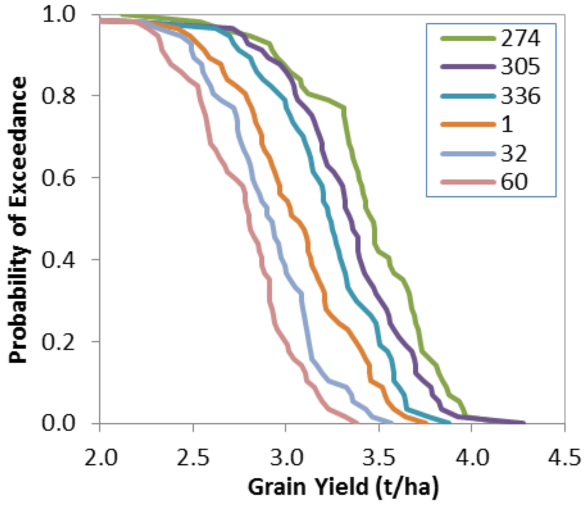

Table 3 The long term average effects of different removal dates (DOY, day of year) of lucerne on subsequent crop yields for a CWB rotation.

REMOVAL DATE	TOTAL	PHASE (TOTAL)		PHASE 1			PHASE 2		
		1	2	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	26.2	13.1	13.2	3.43	4.46	5.16	2.51	5.32	5.34
1 Nov (305)	26.0	12.8	13.2	3.31	4.31	5.19	2.53	5.29	5.34
1 Dec (335)	25.8	12.7	13.2	3.19	4.42	5.04	2.47	5.30	5.42
1 Jan (1)	25.6	12.5	13.1	3.02	4.47	5.00	2.49	5.22	5.43
1 Feb (32)	25.3	12.1	13.1	2.85	4.35	4.91	2.46	5.33	5.35
1 Mar (60)	25.5	12.2	13.3	2.74	4.57	4.90	2.46	5.34	5.49

Table 4 The long term average effects of different removal dates (DOY, day of year) of lucerne on plant available water (mm) at sowing.

REMOVAL DATE	PHASE 1			PHASE 2		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	110	125	143	164	175	152
1 Nov (305)	85	116	142	164	175	153
1 Dec (335)	67	108	136	162	176	151
1 Jan (1)	51	104	135	161	177	152
1 Feb (32)	41	100	131	161	173	150
1 Mar (60)	31	103	131	162	177	153

Table 5 The long term average effects of different removal dates (DOY, day of year) of lucerne on plant available water (mm) at anthesis and harvest for the first phase of the CWB crop rotation.

REMOVAL DATE	ANTHESIS			HARVEST		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	179	158	206	124	126	156
1 Nov (305)	161	157	205	115	125	154
1 Dec (335)	145	153	205	107	122	157
1 Jan (1)	134	154	205	106	123	156
1 Feb (32)	125	149	204	104	118	156
1 Mar (60)	120	150	205	103	118	157

Table 6 The long term average effects of different removal dates (DOY, day of year) of lucerne on N at sowing (kg/ha).

REMOVAL DATE	PHASE 1			PHASE 2		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	136	35	38	49	39	45
1 Nov (305)	120	36	40	51	38	46
1 Dec (335)	107	37	34	45	39	48
1 Jan (1)	81	35	33	45	40	50
1 Feb (32)	65	37	31	44	40	46
1 Mar (60)	50	39	31	43	41	51

Table 7 The long term average effects of different removal dates (DOY, day of year) of lucerne on plant available N (kg/ha) at anthesis and harvest for the first phase of the CWB crop rotation.

REMOVAL DATE	ANTHESIS			HARVEST		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	38	15	18	5	21	17
1 Nov (305)	29	14	19	5	20	17
1 Dec (335)	26	14	19	5	20	17
1 Jan (1)	20	15	19	5	21	17
1 Feb (32)	19	14	18	5	19	17
1 Mar (60)	19	15	18	6	20	17

Field capacity was about 240 mm therefore this was about half full. The trend of decreasing amounts of available soil water with later removal of lucerne was also evident at anthesis, however the effects were only clear for the first canola crop (Table 5).

There were also benefits for the available soil N as a result of removing the lucerne earlier compared to later (Table 6). Between the earliest and latest dates there was a 63% difference or 0.39 kg N/day. This

effect continued until anthesis of the first crop however by harvest there were no significant differences in the residual amounts of soil N (Table 7).

Therefore, it seems that in the period of grain filling between anthesis and maturity, more N was taken up by canola growing in paddocks with earlier removal of lucerne compared to the later plots.

Over the long term data, across all treatments, there was a stronger relationship between long term average N at sowing (R^2=0.99) and long term average harvested grain yield, water at sowing (R^2=0.95), or than N at anthesis (R^2=0.84) or water (R^2=0.94). Figure 8 clearly shows that available N at sowing has a larger effect on final yield than N at anthesis. Overall, 44% of the harvested grain yield was explained by available soil N at sowing whereas soil water explained on 18% of the grain yield variation, however the relationships varied between the different removal dates (Figure 9).

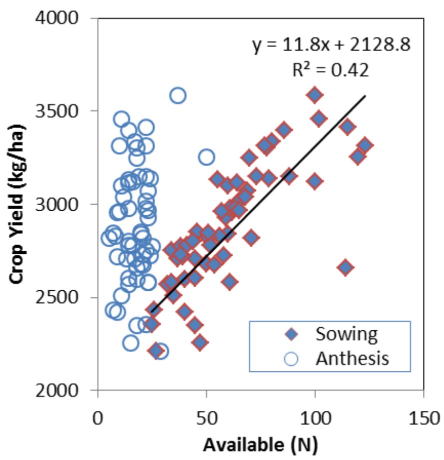

Figure 8 Linear relationship between soil N at sowing crop yields and between N at anthesis and crop yields. The values shown are for 1 February lucerne removal and canola in the CWB rotation.

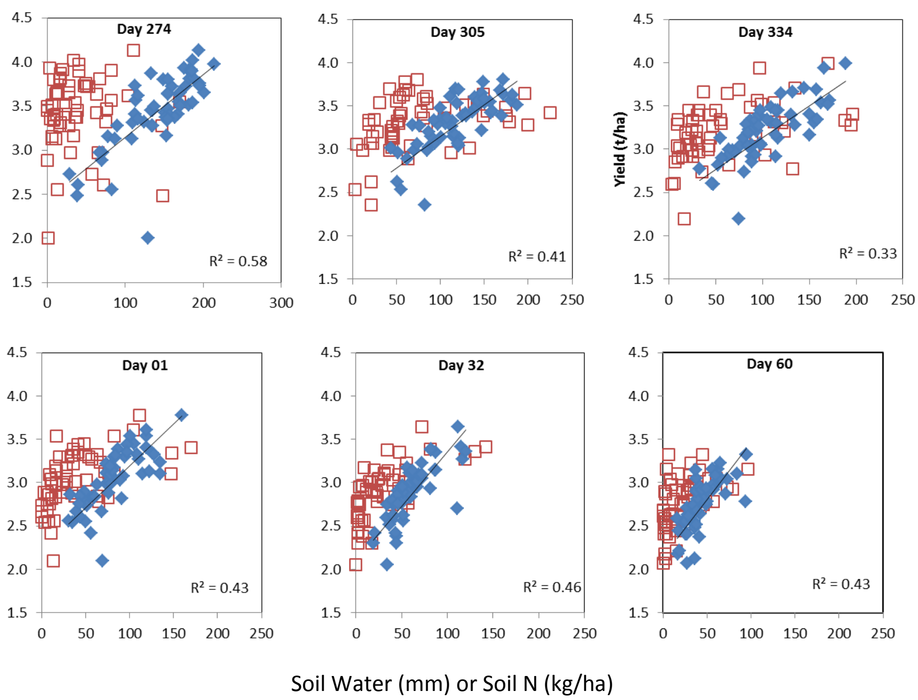

Figure 9 Linear relationship between soil water (open squares) and available soil N (closed diamonds) at sowing due to differing dates of lucerne removal (shown in the title).

Coefficients of determination (R^2) shown are for the relationship between available soil N and crop yield.

Even though the area of land use in transition was small from year to year, it was still possible to detect changes in the livestock aspects of the enterprise according to different removal times of lucerne. More lambs were sold in spring with earlier removal, due to the sale policy whereby some lambs are sold at a fixed date, with the number to be retained calculated according to a herbage allowance of green perennial on that date (Table 8).

Pasture utilisation improved with increasing stocking rates (Table 8), but was consistent between 50-60% indicating that the stocking rate is within a sustainable range. Although the animal numbers were the same between all treatments the there was a difference in the overall stocking rate measured in dry sheep equivalents (DSE) owing to the differences in the time that lambs were retained. The condition of the ewes at joining did not vary between treatments (the average condition score was a high 3.9).

Although the pasture utilisation increased with a later removal date, so too did the amount of supplementary feed consumed, increasing by 4.3 kg/ewe from October removal to March (Table 10).

Table 8 The long term average effects of different removal dates (DOY, day of year) of lucerne on stocking rates (SR) per grazed ha, pasture utilisation and the number of ewes and lambs sold.

REMOVAL DATE	DRY SHEEP EQUIVALENTS PER HA	PASTURE UTILIZATION RATE	EWES SOLD	LAMBS SOLD
1 Oct (274)	17.6	0.54	1283	10001
1 Nov (305)	17.7	0.55	1309	10067
1 Dec (335)	17.9	0.55	1311	10010
1 Jan (1)	18.4	0.57	1296	9902
1 Feb (32)	18.5	0.57	1319	9786
1 Mar (60)	18.4	0.57	1274	9825

Table 9 The long term average effects of different removal dates (DOY, day of year) of lucerne on different classes of crossbred animal weight (kg/animal) sold. (live weight or LWT and carcass weight or CWT).

REMOVAL DATE	EWES	LAMBS (LWT)	LAMBS (CWT)
1 Oct (274)	64.2	37.5	16.9
1 Nov (305)	64.3	37.6	16.9
1 Dec (335)	64.0	38.1	17.1
1 Jan (1)	64.0	39.2	17.6
1 Feb (32)	63.6	39.5	17.9
1 Mar (60)	63.9	39.2	17.6

Table 10 The long term average effects of different removal dates (DOY, day of year) of lucerne on use of supplementary feed by different animal classes.

REMOVAL DATE	MAIDENS (T/FARM)	EWES (T/FARM)	LAMBS (T/FARM)	EWES (KG/EWE/YR)
1 Oct (274)	24	100	4	17.5
1 Nov (305)	22	98	5	17.1
1 Dec (335)	22	104	6	18.0
1 Jan (1)	33	125	11	23.0
1 Feb (32)	29	116	10	21.3
1 Mar (60)	31	116	13	21.8

3.3 Effect of different crop rotations

In order to compare the effects of six different crop rotations following the lucerne ley the systems responses of crops following lucerne initially removed on day 32 and with a 25% increase in crop water extraction efficiency due to biological drilling was assessed. In all cases except the CWB rotation and BWC rotation there was higher production in the second phase compared to the first, however there was no advantage of variations in crop rotations on yield – except for CWB which yielded 800 g/ha less productivity the first phase (Table 11).

For each crop, the highest yield was in the first year following lucerne, and the lowest yield was the second year. For canola there was a clear benefit for being first in the rotation (Figure 10). This was the same for wheat – where there was a benefit in the lower 50% of years from being first, and as for canola, a clear and consistent disadvantage of being the second crop compared to the other rotations (Figure 10).

Barley showed the same trends as the other crops – but there was no clear difference for the first place but again a distinct disadvantage of being second crop in the sequence (Figure 10).

Table 11 Grain yield (t/ha) from different crop rotations (Note: the crop rotations are repeated such that CBW is CBWCBW).

ROTATION	TOTAL	PHASE		YEAR					
		1ST	2ND	1	2	3	4	5	6
CBW	26.2	12.9	13.3	2.89	4.54	5.49	2.16	4.96	6.20
CWB	25.4	12.2	13.2	2.85	4.48	4.91	2.47	5.27	5.42
WCB	26.2	12.7	13.5	5.70	2.01	5.01	6.15	2.26	5.10
WBC	26.2	12.7	13.5	5.70	4.65	2.36	5.38	5.41	2.68
BWC	26.5	12.7	13.8	5.46	5.20	2.08	5.24	6.20	2.32
BCW	25.5	12.6	12.9	5.41	2.28	4.93	5.14	2.43	5.32

(C=canola, W=wheat, B=barley)

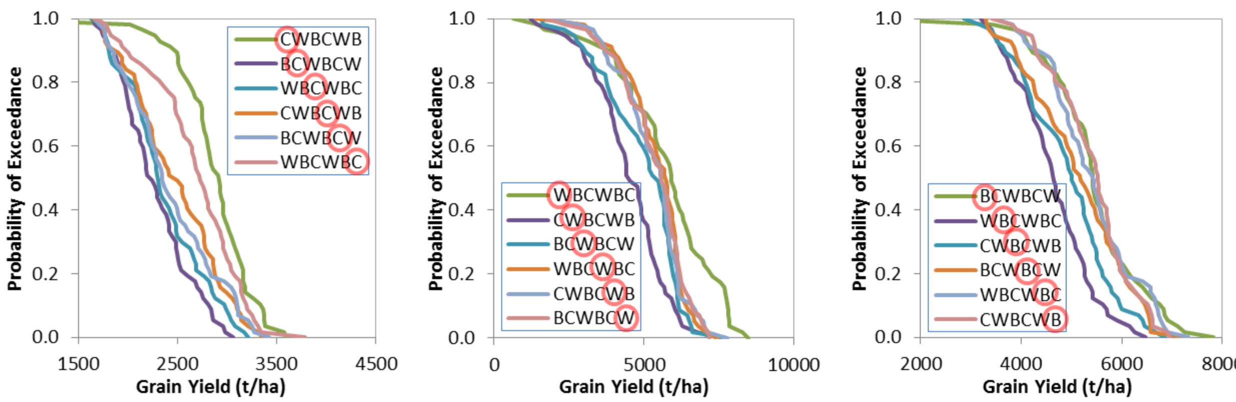

Figure 10 The average effect of position in the crop sequence on grain production of canola, wheat and barley.

In each case the letter that is circled is the crop and sequence position for which data are shown.

3.4 System efficiency

3.4.1 WATER

There was a slight increase in longer term average, crop transpiration efficiency for the production of grain of first year crops due to the later removal of lucerne - however overall the differences were minor and the trend was not detectable by the second year (Table 12).

Table 12 Transpiration efficiency for grain production (kg grain/mm water transpired) for the different removal times for different crops.

REMOVAL DATE	PHASE 1			PHASE 2		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	19.5	28.0	33.3	20.2	28.8	33.2
1 Nov (305)	19.8	27.2	33.3	20.2	28.6	33.4
1 Dec (335)	19.9	27.6	33.4	20.1	28.5	33.4
1 Jan (1)	20.1	28.4	33.3	20.2	28.6	33.3
1 Feb (32)	20.2	27.6	33.2	20.1	29.1	33.3
1 Mar (60)	20.2	28.2	33.3	20.1	28.9	33.4

Table 13 Total water use (mm) by different crops in the CWB rotation due different removal times.

REMOVAL DATE	PHASE 1			PHASE 2		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	178	162	154	124	185	162
1 Nov (305)	166	157	156	123	183	161
1 Dec (335)	161	158	151	124	184	160
1 Jan (1)	149	157	150	125	183	161
1 Feb (32)	141	160	148	122	188	164
1 Mar (60)	136	163	150	122	187	164

An explanation for the differences, in part at least, relates to the differences in total crop transpiration due to different removal times (Table 13) which was reflected in the grain yields shown above (Table 3).

The same trend in the soil water at anthesis and at harvest (Table 5) indicates that there was still yield potential to be realised and that there was some other reason for the limitation to higher yields.

3.4.2 NITROGEN

N use, calculated as the N removed or exported in grain appeared to be promoted by the earlier removal of lucerne (Table 14). Although the later lucerne removal promoted greater N use, it came at the expense of efficiency of N use for grain production (Table 15).

As for water and N use, nitrogen use efficiency of fertiliser for grain production as influenced by the different lucerne removal times effects were only detectable for the first crop.

Table 14 Total N use (kg N) for the different removal times for different crops in the CWB rotation.

REMOVAL DATE	PHASE 1			PHASE 2		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	201	84	91	113	84	98
1 Nov (305)	185	86	93	115	84	99
1 Dec (335)	174	87	88	105	86	100
1 Jan (1)	146	84	85	109	87	103
1 Feb (32)	129	87	85	111	89	100
1 Mar (60)	114	87	84	108	87	103

Table 15 N use efficiency for grain (kg grain/kg N use) for the different removal times for different crops in the CWB rotation.

REMOVAL DATE	PHASE 1			PHASE 2		
	CANOLA	WHEAT	BARLEY	CANOLA	WHEAT	BARLEY
1 Oct (274)	17	53	57	22	63	55
1 Nov (305)	18	50	56	22	63	54
1 Dec (335)	18	51	58	23	61	54
1 Jan (1)	21	53	59	23	60	53
1 Feb (32)	22	51	59	23	61	54
1 Mar (60)	24	51	59	23	61	53

3.5 Gross margins

A main aim of the analysis was to determine the effects of lucerne management on the profitability of the whole farm. At Hamilton, as there were very little difference between the livestock and crop production of the different farming systems there were also very small differences in the gross margins (Table 15). For a CWB rotation with an initial removal taking place on day 32, the operating profit was $584,000 per farm or $467/ha on an area basis (Table 16).

This was made up of 84% for the livestock enterprise and 16% from cropping. A large part of this can be attributed to the fact that 76% of the farm area was pasture in one form or another for grazing. Although the income from both enterprises was fairly similar, on a per hectare basis the costs for cropping are roughly three times the costs for livestock. With livestock the largest item costs was the selling costs (11%) and the contract services (*e.g.* shearing) (12%) as well as the buying costs (42%) associated with from the purchase of a maiden ewe ($115) compare to a cast for age ($54) – which was affected by treatment. Therefore, there was a clear correlation between the gross margin of the livestock enterprise and stocking rate (Table 8) and between grain yield and gross margin of the cropping enterprise.

Table 16 Gross margins ($/ha) in relation to date of removal of lucerne prior to cropping. Values are for the UUUCWBCWB rotation.

ELEMENT	REMOVAL DAY	LIVESTOCK [1]	CROPPING [2]	WHOLE FARM
Costs	1 Oct (274)	375	579	424
	1 Nov (305)	378	579	426
	1 Dec (335)	381	579	428
	1 Jan (1)	375	579	424
	1 Feb (32)	381	579	429
	1 Mar (60)	383	579	430
Income	1 Oct (274)	884	935	896
	1 Nov (305)	892	912	896
	1 Dec (335)	897	902	898
	1 Jan (1)	908	892	904
	1 Feb (32)	900	882	896
	1 Mar (60)	900	882	896
Margins	1 Oct (274)	509	356	473
	1 Nov (305)	513	333	470
	1 Dec (335)	516	324	470
	1 Jan (1)	533	313	480
	1 Feb (32)	519	303	467
	1 Mar (60)	518	304	467

[1] and [2] for only those areas used for livestock and cropping.

Although the greatest impact of variable lucerne management was to the cropping component of the farm business, there was very little overall gross margin benefit across the farm due to removal date. The benefit to crop production due to early removal was 15% from $356 per hectare to $304 for the latest removal, where as for livestock the opposite trend occurred and there was only a slight overall benefit as a result (Table 15).

The cropping enterprise contributed about 15% of the whole farm profit which was $91,000 or $303/cropped ha. Cropping related income was about $882/cropped ha ($10.34/kg grain) or 24% of the farm income. Costs associated with cropping were 32% of the total farm costs or $579/cropped ha ($6.78/kg grain) of which about 9% was due costs associated with the raised beds if formed twice as is recommended (David Watson, Agvise).

The rotation which was most profitable was not clearly defined as there was no difference in the overall production between the different removal times, as shown in Table 10.

4 Discussion

Farmers include lucerne in their mixed-farming enterprises for a range of reasons such as providing highly nutritious summer feed for livestock, augmentation of soil N reserves, a break in the cropping cycle for pests and diseases, as well as the rehabilitation of soils with poor soil structure (Lodge, 1991). However in the case of phase farming, for some climates and farming systems, it has been observed that some crops following lucerne can sometimes have reduced yields (Dalal et al., 2004). Therefore the overall value lucerne to mixed-farms at the whole-farm scale is complicated by a range of factors that relate to the rainfall year, price of commodities, management (*e.g.* time of removal prior to cropping, choice of cultivar, grazing management) and overall farming system. Various authors have attempted to assess the value of lucerne to mixed farming systems. Although few studies have adequately separated the effects from other rotational benefits such as disease control and improved N nutrition (Cresswell and Kirkegaard, 1995). Using a complex systems simulation approach this was possible.

4.1 Economics of lucerne in mixed farming systems studied

There was no clear economic benefit to the farm as a result of lucerne removal time (*e.g.* later versus earlier) or crop rotation. Losses in one aspect of the farming system were offset by other gains. However the area in transition was small compared to the total farm area. This study found, as have others, that the optimum time of lucerne removal for farm profit depends on the relative profitability of lucerne and the crops that replace it. The decision may vary depending on the prices received for livestock or crops, or costs of N fertiliser, as these fluctuate greatly from year to year (DEPI, 2014). Per hectare, the margins were higher from livestock than cropping and for the whole farm the gross margin was around $470/ha. Spring removal of lucerne followed by canola then wheat then barley is likely to be the most profitable rotation.

Using real data gathered over 39 years in south west Victoria, the average for gross income (adjusted for inflation) is $477 per hectare (DEPI, 2014) which is highly comparable with the data in Table 10. The dominant role of stocking rate in determining gross margins is consistent with other studies (Robertson et al., 2014; Warn et al., 2006). The average gross margin over the 39 year time period (adjusted for inflation) for prime lamb is $359 per hectare. Analysing the last ten years in isolation shows that average gross margin results have been $320 per hectare for prime lamb; this is roughly $200 lower than the current value and substantially lower than our results; but the use of lucerne permits high stocking rates. Around 15% of the farm income came from wool. Higher stocking rates would increase the income and profitability but also increase the variability of the gross margin (Warn et al., 2006).

Livestock had the highest costs per proportion of the total farm costs, but this is unsurprising as the farming system was livestock-focussed with 72% of the farm area used directly for pasture grazing. However the costs per unit area (*i.e.* grazing ha) or per kg of product, was around 10% of the price of the cropping

enterprise. For the livestock operation the supplementary feed made up less than 10% of the costs and therefore less vulnerable to the fluctuations of commodity prices. Ransom (2004) found heavy weight ewe lambs finished on lucerne have attracted a market premium from prime lamb producers, whereas ewes on annual pastures were sold at 18 months, due to a reduction in supplementary feeding.

In terms of income per ha, livestock and cropping were similar at about $900/ha. The gross margin per unit area was 70% higher for livestock, but per kilogram of product was more than three times higher for cropping and three times higher per unit of protein (assuming 12.5% protein/kg for crops, and 27.1% protein/kg for animals). For cropping one of the main costs, fertiliser, has been shown to vary greatly through time. While the costs of forming raised beds for cropping is substantial, it alleviates the effect of waterlogging and makes cropping possible. Riffkin and Evans (2003) concluded that the value of beds will only be realised in wet conditions where waterlogging is likely to cause yield losses, as there are substantial areas lost due to the loss of production area from the furrows. If the costs of production increase then the effects on cropping gross margins will be large; for example, as the price of N fertiliser increases then early removal of lucerne will be more valuable. The decision for early or late removal of lucerne at spring time therefore can be made bearing in mind the price of fertiliser, lamb prices and rainfall year.

4.2 Crop production

At Hamilton, early removal of lucerne resulted in greater crop yields and biomass production. This supports the work undertaken by Angus et al. (2000) in southern NSW where they found on average each additional month between lucerne removal and wheat sowing led to a yield increase of 8% compared to removal just before sowing. This occurred principally due to the effects of lucerne on the soil N and water. Over the long term, it was shown that the yield of the first crop after the lucerne ley was determined more by N at sowing than by stored soil moisture, even with a late removal of lucerne; earlier removal results in higher mineralisation of N from the lucerne residues. This is the main point of difference to other studies which have addressed lucerne transitions – here the effect was due to N as this is a high rainfall environment for cropping where soil water is often not limiting (if anything too much water can severely limit production).

The effects on N uptake due to different removal times were only evident in the first crop, indicating that either much of the N fixed by the lucerne stand becomes available in the first year. In southern NSW the supply of mineral nitrogen following two years of lucerne was 374 kg N/ha (Angus et al., 2000). Field trials with similar aims and objectives to those in this study were carried out nearby at Inverleigh in south-west Victoria (a drier environment; long term annual rainfall at nearby Bannockburn is 528 mm). Falkiner et al. (2013) concluded, as did our study, that if a crop is to be sown in late autumn its yield will be higher if lucerne is removed in spring of the year before, rather than autumn of the same year. However in their case the decrease in crop (canola and barley) yield with the autumn removal of lucerne was attributed the effect due to differences in stored soil moisture rather than N. At Inverleigh the relatively high grain protein in both the wheat and barley, regardless of time of lucerne removal, may indicate that soil nitrogen was not limiting at grain filling (Falkiner et al., 2013). By contrast the soils at Hamilton were rarely water limited during the cropping phase. The effects of soil moisture and N can be partly offset by the split applications of fertiliser, later sowing or choice of crop-cultivar, each of which can be tested using this modelling framework.

In various previous studies in low-rainfall, water-limited environments (Dalal et al., 2004; Latta and Lyons, 2006; McCallum et al., 2001) and possibly also at Inverleigh (Falkiner et al., 2013), the effect of reduced stored water particularly at sowing, can have a profound effect on growth of subsequent crops. In humid climates, however, biomass production and crop yield of subsequent crops were improved (Gregory et al., 2005; Kautz et al., 2010; Riedell et al., 2009). Without the use of raised beds waterlogging would have substantially reduced plant growth in the Hamilton environment. In this regard, the demonstrated capacity of lucerne to dewater the profile over summer is potentially advantageous in situations where seasonal waterlogging limits crop production.

The modelled yields of wheat, barley and canola were about 50% higher than average values for the region (DEPI, 2014) and about 25% higher than the experimental yields at Inverleigh (Falkiner et al., 2013). The average wheat yields ranged from 4-4.5 t/ha in the first phase and 5-5.5 t/ha in the second phase. The difference is partly due to the modelled system being based on best-practice rather than average management, and partly on the fact that the APSIM models do not account for a number of yield-reducing factors (frosts, lodging, and diseases). In practice, there is a very wide range of yields depending on the cultivar, use of raised beds and N fertiliser application (Acuna et al., 2011; Christy et al., 2013; McKenzie et al., 2003; Nash et al., 2013; Riffkin et al., 2012).

This study is the first we are aware of that addresses the effects of biological drilling on farm productivity and profit. Rasse and Smucker (1998) found that crops grown in rotation with lucerne have been reported to recolonise remnant lucerne root channels but whether or not this is beneficial is still unclear (McCallum et al., 2004). Using the AusFarm framework the phenomenon can be represented by modifying the efficiency with which water is extracted by roots even though the specific effects on soils and plants are uncertain. Results for Hamilton indicate that there was no notable benefit to crop production from increased water extraction efficiency as a result of biological drilling. The reason is that the crops at Hamilton were rarely in soil water stress and the effect of improved extraction of water would only be beneficial in cases where there was high transpiration demand and limited soil water. Therefore the results may be different for lower rainfall environments where crops suffer terminal drought. In particular from floral initiation through grain filling, the differences between plants grown in soils with significant biological drilling may become clear as plant roots may have greater access to soil moisture thereby enabling them to maintain green canopy will maintained for longer, and delaying senescence during grain filling. At Hamilton, this was not the case even in dry years (Figure 5) and so the increase in extraction efficiency (kl) was of little benefit.

Falkiner et al. (2013) found from their field experiment at Inverleigh that canola yields following an autumn lucerne removal were usually lower than after a spring removal. They suggested that this may be due to a root system unable to access moisture at depth however this goes against the idea that plant rooting is improved due to the biological drilling effect of lucerne. Lilley and Kirkegaard (2011) found that the yield impacts of preceding management often exceeded or overrode those of root modification by influencing the depth of profile wetting and duration of root descent. However as Cresswell and Kirkegaard (1995) and Kautz et al. (2013) point out, there are many soil processes which may influenced by plant roots from previous crops, and the modification of kl employed in this study only represented changes the combined effect of root length density (l) and soil diffusivity (k). Other factors may also be affected by lucerne roots - when macropores are sparsely distributed in the soil, they may not significantly contribute to the water retention curve, but will still have a large effect on the hydraulic conductivity near-saturation (Smettem and Ross, 1992). Clearly there is a lot still to be experimentally investigated to fully understand this phenomenon. Various aspects of lucerne root systems have been identified, however as yet it is not conclusively defined and therefore it is difficult to gather these observations into a unifying framework. We have provided an attempt to represent the phenomenon of biological drilling, which is simple and pragmatic. As the phenomenon is better defined these findings can be incorporated into the modelling framework.

Varying the order of crops in the rotation had little effect on the total simulated production from the 6 years of cropping (Table 10). Again, this may have been different in water limited environments where any differences in water use efficiency or rooting depth due to crop-type would have created differences in yield. There was a marginal benefit associated with the 3-year phase of the rotation with slightly higher (10% on average) yields in the second three year cycle compared with the first three year cycle. The reasons are associated were slightly higher water use due to a 80% higher soil water content at sowing and at anthesis. It is likely likely that this resulted from higher production during stem elongation into booting when the yield components are established. In the second cycle there were also higher amounts of N present in the second and third phases. In practice, farmers see advantages of different rotations where pulse crops are included or where stresses imposed by pests, diseases or weeds limit production can be managed by the 'break crop' effect.

At Invereigh, for either spring or autumn removal of lucerne, wheat performed better than barley and twice as well as canola (Falkiner et al., 2013). Despite its high costs of production (Table 16), canola was the best crop to grow after lucerne removal: it has a higher gross margin than wheat, but also it has a higher N demand that can exploit the N built up in the ley phase before it is taken up, leached from the root zone or denitrified in the wet soils. Also, considering the dewatering effects of lucerne and the longevity of the raised beds, canola might be best suited to the first crop as in practice it is generally more susceptible to excessive moisture than cereals (Gutierrez Boem et al., 1996).

Depressed yield in the second year after removal was due to water limited production as there was a less efficient conversion of the N to grain yield. At Inverleigh (Falkiner et al., 2013) it was found that crops with autumn removal, yielded 70% of the early removal and crops sown after spring removal of lucerne yielded the same as the crops grown in a continuous crop rotation. However, the crop yield penalty from autumn removal lasted for one year. Meinke et al. (1993) found that biopores lasted for at least 2 crops after the lucerne, which is related to the root density and soil diffusivity in a particular soil layer, and therefore the longevity of biopores effects and the direct effects of lucerne itself are likely to vary with climate and soil type. This was similar to our finding.

The greater availability of N in particular with early lucerne removal in the first year has potential to negatively impact on crop production in high rainfall areas where vigorous early biomass is produced that exhausts the N supply, thereby creating “haying off” (severe N stress during booting and grain filling; Herwaarden et al., 1998). The greater supply of N following lucerne may have a negative effect on barley causing a downgrade in price to feed grade quality. At Inverleigh, although grain protein concentration increased with the later removal, the content declined overall. The system at Hamilton is highly vulnerable to an imbalance of soil water and mineral N particularly in the vegetative stages of growth due to the high plant density (for wheat and barley 250 plants/m2), early sowing window (middle of April to middle May), and the high amounts of N (about 60 kg soil N and 50 kg fertiliser N) available at sowing. Therefore the issue of N supply throughout the growing season is as important as the overall N amount. Under these circumstances, there is not always a reduction in yield however there can be low yield quality with high levels of screenings and low grain protein. Rapid early development may result in overly thick canopies (producing excessive tillers/heads) that are inefficient in using sunlight, water and N and that increase the risk of disease and lodging, creating poor quality grain, particularly with barley. In cases where there is post-anthesis drought this may result in haying-off (Herwaarden et al., 1998) or premature ripening of cereal crops (Colwell, 1963). This was first identified by farmers in south-eastern Australia during the 1890s and became a problem during the 1950s when legume-based pastures included in rotation with cereals led to increased soil N content (Donald, 1960). Under these circumstances, delaying N application until early stem elongation might be more prudent as this period marks a considerable increase in plant demand for N and then a repeated application at the flag leaf stage and the unutilised soil water can be capitalised on.

4.3 Livestock

There were some clear benefits in terms of livestock production as a result of later removal of lucerne. Including a summer active perennial in a system may also offer further opportunities for growing out weaners, finishing lambs, flushing ewes to increase lambs born or maintaining the condition score of breeding ewes (Ransom, 2004). At Hamilton, from the simulations the benefit of including lucerne in the farming system was the provision of summer feed especially for finishing lambs as well as flushing ewes. Although with later removal of lucerne there were fewer lambs sold, they were heavier than the lambs sold when there was earlier removal, resulting in a greater total weight of lambs sold per hectare in the later removal management systems. This explains the higher stocking rate (when expressed on a DSE/ha basis) which also led to greater pasture utilisation. In the final year of the lucerne ley, the difference in pasture production between an early removal on 1 October and late removal on 1 March was a difference of 3.6 t/ha or over 700 kg/ha/month.

The lambing rate simulated was 1.30 lambs per ewe, which was higher than the regional average for cross-bred sheep (DEPI, 2014) and contributed to the high overall DSE per hectare. However the modelled DSE

per hectare was much lower than in the *EverGraze* experimental lucerne pasture systems at Hamilton where the stocking rates of 25-31 DSE/ha were achieved from 2006-2010 (Ward et al., 2013). Including lucerne in the feedbase allowed these high stocking rates through changes in the pattern of feed availability as well as an increased reproductive potential per hectare for systems raising twins (Warn et al., 2006). The farming systems simulated were between the regional average and those used in *EverGraze* with an average DSE per hectare in the range 17.6-18.4 and a pasture utilisation rate of 0.54-0.57. In order to achieve the same stocking rates as the EverGraze systems, the pasture utilisation would need to be an average of about 77%; to achieve this over the long term on-farm would require exceptional grazing management skills.

In the current simulation ewes were replaced and lambs sold on at a fixed date (1 December), with the number to be retained calculated according to a herbage allowance of green perennial. Retained lambs were sold when they ran out of perennial forage or else retained until 25 April. This sale policy is designed to make the best use of available feed, however the rule to set lamb numbers according to the available feed on offer at the start of December, did not utilise following summer lucerne production in all years. Retaining these lambs would have resulted in the higher stocking rates (*i.e.* DSE) comparable with the experiment conducted by Ward et al. (2013).

4.4 Pasture production

Annual pasture production averaged approximately 9-10 t/ha/yr for lucerne and 10 t/ha for the permanent pasture. Production was slightly lower although still comparable with that reported by Raeside et al. (2014) and Ward et al. (2013). Summer-active pastures also allowed for maintenance of sheep on pasture and lower supplementary feeding in summer and autumn following summer rain in some drought years. Apart from the feed value, at 10 t/ha the lucerne is fixing over 200 kg N/ha/yr. The difference between the early removal and late removal of this was roughly equivalent to 90 kg fixed N/ha. Lucerne can fix twice the N of sub clover and N is released over many more years to following crops — even though N supply to the crop immediately following lucerne can be relatively low, depending on the timing of lucerne removal before cropping. At Inverleigh decaying lucerne provided more than 150 kilograms per hectare of N to the crops in the first year, reducing fertiliser costs by $100/ha (Falkiner et al., 2013).

Lucerne is a plant which is well adapted to recover from hostile conditions such as heaving, freezing and drought. However, this means that lucerne can also be difficult and costly to remove when paddocks are being prepared for cropping. This combined with the high establishment costs are potential reasons for the poor adoption by the agricultural industry (Ransom et al., 2003b). However valuable, it is widely acknowledged that lucerne is difficult to remove from paddock prior to cropping (Davies et al., 2005; Ransom and Egan, 1998). Although late removal times might be preferable for livestock production, in practices it does not leave long enough plant-back period before sowing the crop - for canola the average sowing day was 93 (3 April) where as for wheat it was 122 (2 May). The use of fast or medium maturing spring wheat crops may be a solution to having to delay sowing due to this reason.

4.5 System efficiency

Comparing the earliest and latest removal of lucerne, the magnitude of the changes were greater for NUE (Table 16) than TE (Table 12), and the magnitude of differences in N use where different to those in N use efficiency. Later removal promoted greater N use efficiency however this came at the expense of total N use. It is not a simple case of “more N is better”, however, as its contribution to yield relates to the soil moisture and the timing of N available to the crop – effectiveness of the additional N rather than just the efficiency. In our modelling results there were differences in soil N availability at anthesis of the first crop after lucerne, however by harvest of the first crop there no differences in available soil N (Table 7). However the differences in residual soil water continued for two years (Table 4 and Table 5), indicating the system was possibly N limited as crops were not able to fully utilise the soil moisture.

Although there were differences in TE between treatments (Table 11) this is only beneficial in situations where water is a significant limitation to production – and therefore the efficiency of use is an important

consideration. TE was similar to the regional average (DEPI, 2014) as well as for other locations in NZ (Sim, 2014).

There were no differences in the water use efficiency due to crop biological drilling effects as the crops rarely went into terminal drought at Hamilton. In dry environments, harvest index is determined by the water transpired during grain filling and the prevailing TE during that period (Passioura, 1977). The substantial amounts of water left at anthesis, indicate that water is unlikely to be limiting. There was possibly some limitation during the vegetative phase as (Acuna et al., 2011) found a harvest index of 0.5 which was higher than the average harvest index of 0.37 in the simulations. Low harvest indices (0.38-0.42) and WUE for grain (9.5 – 18.0 kg/ha/mm) and biomass (24.9 – 43.3 kg/ha/mm) provide evidence for inefficient resource capture. The low crop harvest indices suggest a poor conversion of light, water and nutrients to grain indicating that potential yields are not being realised. Model outputs indicate that temperature limitations are the main causes of growth limitations which may subsequently effect grain filling and can trigger premature senescence (Riffkin and Evans, 2003).

5 Conclusions

Lucerne is a highly valued crop for mixed farmers in a range of climate zones, including the high rainfall temperate zone. However the biophysical and economic case for including lucerne leys remains complex and is best addressed using a whole of farming system analysis. Of the many reasons, the accumulation of N derived through fixation and the provision of summer feed are some of its most valuable aspects to production and profitability. The decision of when to remove lucerne prior to cropping depends aspects of the farming systems such as livestock stocking rate, climate, soil water holding capacity, soil N status and succeeding crop type. Spring removal of lucerne followed by canola is likely to be the most profitable rotation in environments such as at Hamilton. Spring removal allows a period for moisture accumulation and mineralisation of N in soil, which in years with reasonable crop prices is enough to offset the effects of a reduction in livestock feed. At Hamilton the soils have an abundance of water and N and therefore there were no negative effects on yield as a result of the competition from lucerne, and there were no positive effects due to the addition of N via symbiotic fixation. The reverse is also true and if farmers are able to improve pasture management and grazing skills, thereby increase pasture utilisation as well as increase stocking rates then livestock production is likely to continue to be more profitable per unit area than cropping. Therefore, this aspect combined with the benefits to livestock, provide a compelling case for the inclusion of lucerne in mixed farming systems.

The additional effects of lucerne on biological drilling, although not important in the system considered here, may be more valuable in low rainfall environments. The use different of crops and varieties with different rates of maturity, as well as flexible sowing dates can be used by managers to offset the negative effects of different removal dates.

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Appendix - Economic Parameters

Table 16. Parameter values used in the calculations of gross margins for lucerne based farming systems at Hamilton.

COSTS	
Livestock ($/dse)	
Animal health	1.46
Contract services	2.62
Freight/cartage	0.47
Shearing supplies	0.15
Repairs and maintenance	0.09
Casual labour	0.21
Other	0.41
Selling costs	2.24
Supplementary feed ($/t) [1]	151
Replacement animals ($/hd) [2]	115
Pasture/forage crops ($/ha) [3]	61
Cropping ($/ha)	
Production - canola	602
Production - wheat	523
Production - barley	459
Raised beds ($/ha) [4]	152
INCOME	
Livestock	
Mature animal sales ($/ewe) [5]	54
Weaner sales ($/kg CWT) [6]	3.69
Net greasy wool price ($/kg)	3.78
Crops ($/t farm gate)	
Canola	411
Wheat	201
Barley	187

[1] Supplementary feed is the same price as feed barley (which is approximated to be 85% the cost of barley)

[2] Replacement ewes are 1.5 years old

[3] Pasture costs relate to any costs associated with sowing, renovating or maintaining pasture (e.g. chemicals, contractors, fertiliser, seed etc)

[4] Raised beds are reformed at the start of each three year cycle

[5] Ewe sales are cast-for-age

[6] CWT is carcass weight which is 45% of the live weight

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

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FOR FURTHER INFORMATION

Agriculture Flagship
Dr Andrew Smith
t +61 8 8273 81061
e Andrew.Smith@csiro.au

Agriculture Flagship
Dr Andrew Moore
t +61 2 6246 5298
e Andrew.Moore@csiro.au