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Integrated overview of results from a farmlet experiment which compared the effects of pasture inputs and grazing management on profitability and sustainability

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Abstract. The Cicerone Project conducted a grazed farmlet experiment on the Northern Tablelands of New South Wales, Australia, from July 2000 to December 2006, to address questions raised by local graziers concerning how they might improve the profitability and sustainability of their grazing enterprises. This unreplicated experiment examined three management systems at a whole-farmlet scale. The control farmlet (farmlet B) represented typical management for the region, with flexible rotational grazing and moderate inputs. A second farmlet (farmlet A) also used flexible rotational grazing but had a higher level of pasture renovation and soil fertility, while the third farmlet (farmlet C) had the same moderate inputs as farmlet B but employed intensive rotational grazing. The present paper provides an integrated overview of the results collated from component papers and discusses the inferences that can be drawn from what was a complex, agroecosystem experiment. The measurements recorded both early and late in the experiment were tabulated for each of the farmlets and compared with each other as relative proportions, allowing visual presentation on a common, indexed scale. Because of equivalent starting conditions, there was little difference between farmlets early in the experimental period (2000–01) across a wide array of measured parameters, including herbage mass, potential pasture growth rate, liveweight, wool production per head, stocking rate, gross margin and equity. Although the experiment experienced drier-than-average conditions, marked differences emerged among farmlets over time, due to the effects of treatments. During the latter half of the experimental period (2003–06), farmlet A showed numerous positive and a few negative consequences of the higher rate of pasture renovation and increased soil fertility compared with the other two farmlets. While intensive rotational grazing resulted in superior control of gastrointestinal nematodes and slightly finer wool, this system had few effects on pastures and no positive effects on sheep liveweights, wool production or stocking rate. Whereas farmlet A showed higher gross margins, it had a negative and lower short-term cash position than did farmlets B and C, due largely to the artificially high rate of pasture renovation undertaken on this farmlet during the experiment. Although farmlet B had the highest cash position at the end of the experiment, this came at a cost of the declining quality of its pastures. Modelling of the farmlet systems allowed the results to be considered over the longer timeframes needed to assess sustainability. Thus, returns on investment were compared over realistic amortisation periods and produced outcomes based on long-term climatic expectations which were compared with those that arose under the drier-than-average conditions experienced during the experimental period. The main factors responsible for lifting the productivity of farmlet A were the sowing of temperate species and increased soil fertility, which enhanced the amount of legume and increased pasture quality and potential pasture growth. The factor that affected farmlet C most was the low proportion of the farmlet grazed at any one time, with high stock density imposed during grazing, which decreased feed intake quality. The paper concludes that more profitable and sustainable outcomes are most likely to arise from grazing enterprises that are proactively managed towards optimal outcomes by maintaining sufficient desirable perennial grasses with adequate legume content, enhancing soil fertility and employing flexible rotational grazing.

Additional keywords: farming systems, modelling, multi-disciplinary, optimisation, parasitology, pasture legumes, pasture quality, risk.

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Introduction

The present paper aims to integrate the findings from a series of related papers which were part of a multi-disciplinary study of different grazed farmlets, conducted on the Northern Tablelands of New South Wales (NSW), Australia, from July 2000 to December 2006. The experiment was set up to answer questions chosen by local livestock producers about ways of enhancing the feed supply, either through pasture renovation and soil fertility or through intensive grazing management.

Managing a grazing enterprise is challenging under any circumstances and especially so when climatic conditions are highly variable, as they are in this region (Behrendt *et al*. 2013*c*; Sutherland *et al*. 2013). According to Williams (1994), in striving for long-term sustainability, graziers need to learn to use a systems approach, which simultaneously balances financial, land, ecosystem and day-to-day stock management decisions. Lodge *et al*. (1998) described some of the paddock management factors that are readily observed by farmers as follows: the proportions of desirable perennial grasses and legumes, the amounts of green leaf and surface litter and the level of ground cover. To this list could be added observable attributes of livestock such as condition, liveweight, pregnancy and general animal health. However, when one considers additional influences on a farm system, such as soil fertility, pasture composition, grazing management and the stochastic (random) behaviour of prices and climate, it is clear that making optimal decisions presents an intractable challenge for most managers.

In the present paper, we have summarised the relative contributions of soil, pasture, animal, economic and environmental parameters over time in a similar fashion to the measurements of sustainability reported by both Scott *et al.* (2000) and Lodge *et al.* (2003). This approach to quantifying sustainability has been found to be useful not only for scientists but also for graziers whose visual assessments of pastures have been found to be highly correlated with research assessments (Lodge 2002).

The main conclusion from the recent national Sustainable Grazing Systems experiment, conducted across southern Australia, was that the productivity and sustainability of pasture-based systems can be enhanced by higher levels of soil fertility, the amelioration of low soil pH, the sowing of deep-rooted perennial grasses and the use of grazing methods that permit substantial rest periods between grazings (Andrew *et al.* 2003). On the Northern Tablelands of NSW, there has been a considerable body of research into the growth of both sown and native pastures and their responses to nutrients (Wolfe and Lazenby 1973; Lazenby and Lovett 1975; Cook *et al*. 1976, 1978; Robinson and Lazenby 1976; Whalley *et al*. 1976). In spite of this published evidence that substantial responses can be gained from the sowing of pastures and the amelioration of nutrient deficiencies, many graziers in this region today question the long-term economic benefits of these technologies, given the perceived high costs of improving pastures (Vere and Campbell 2004), while many have expressed interest in intensive grazing management as a potential alternative management solution (Scott *et al*. 2013*c*).

Comprehensive multi-disciplinary studies of grazing management are rare in Australia. One of the earliest and most complete studies was a replicated experiment conducted by Moore *et al*. (1946) which compared continuous and rotational grazing over either 4- or 8-week intervals. These authors found that, apart from retaining a somewhat higher level of lucerne in the pasture, rotational grazing was not a reliable way to increase livestock production. However, as noted by Hacker (1993), there has also been relatively little research into *intensive* rotational grazing (IRG) systems in Australia. Also, most of the studies undertaken have compared such systems with *continuous* grazing (Earl and Jones 1996; Waller *et al*. 2001; Dowling *et al*. 2005; Sanjari *et al*. 2008). Livestock-producer members of the Cicerone Project felt that, at least for the Northern Tablelands region of NSW, which is part of Australia's temperate high-rainfall zone, the use of *continuous* grazing as the control treatment is inappropriate, as few graziers practise 'continuous stocking' as implemented in these earlier experiments.

While there are recorded cases of farm managers and proponents of intensive grazing management claiming benefits of such systems, including increased soil phosphorus, stocking rates and profits (McCosker 2000; Cawood 2004), there are also publications where some of the claims have been refuted (Waugh 1997; Dowling *et al*. 2005; Hall *et al*. 2011). The earliest of these papers, written by a grazier from central NSW, reported unsatisfactory cattle growth when he implemented 'time control grazing' on his property. After this experience, he resorted to a less intensive form of rotational grazing, with a rest period of ~30 days (Waugh 1997). In a recent report of grazing systems on rangelands across inland Queensland, Hall *et al*. (2011) found that stocking rate was a much more important driver of performance than was grazing system. However, shortly after the release of these findings, the methodology used in the project was reportedly criticised by proponents of time-control grazing and holistic resource management (Cawood 2011).

The debate about rotational grazing remains unresolved, partly because research has not adequately addressed the human variables that affect management systems (Briske *et al.* 2011). However, those planning the Cicerone farmlet experiment did consider the decision-making approaches of livestock producers in designing the farmlet treatments (Scott *et al*. 2013*c*). During the planning phase, Cicerone producer members and collaborators agreed that the research conducted into IRG systems in the high-rainfall zone of Australia had not been conducted in a sufficiently comprehensive fashion to satisfactorily answer the questions that members had. While Norton (1998), in his extensive review of the literature, hypothesised that intensive grazing management might result in increased production of pasture, which could lead to increased stocking rates, the Cicerone Project decided that such suggestions needed to be tested under realistic experimental conditions. Thus, livestock producers requested that both pasture renovation with higher soil fertility and IRG be compared with a more typical management system within a whole-farmlet experiment. This would permit the multiple facets of such systems to be measured at a credible scale (Scott *et al*. 2013*c*).

The Cicerone farmlet experiment can be seen as an agroecological experiment with interactions among the many component parts of grazed farming systems interacting in complex ways with the climate and management. Eberhardt and Thomas (1991) pointed out that the design of adequate ecosystem experiments often means that conventional experimental-design criteria need to be challenged; they also highlighted the need for more care to be taken in drawing inference about cause and effect from such experiments due to the many complex interactions within agricultural ecosystems. Details of the selection of experimental treatments and hypotheses employed in this experiment have been described in detail by Scott *et al*. (2013*c*). In brief, the hypothesis of the Cicerone farmlet experiment was that, compared with the typical farmlet (farmlet B), higher pasture inputs combined with higher soil fertility (farmlet A) and/or intensive grazing management (farmlet C) will result in a more profitable and sustainable enterprise.

Materials and methods

The general methods adapted for use in the Cicerone farmlet experiment have been described by Scott *et al*. (2013*c*), whereas other more specific methods are contained in related component papers in this Special Issue. The approach taken here has been to summarise the results and calculate indices for all measured parameters so that readers can assess for themselves the validity of the interpretations of evidence drawn by the authors of the present paper.

This method of comparing treatments across a range of criteria is based on an approach developed for an earlier grazed experiment that aimed to quantify sustainability (Scott *et al*. 2000). Thus, a wide array of data summarising the many objective measurements from each of the farmlets were extracted from the Cicerone database (Scott *et al*. 2013*c*), from both early and late in the experimental period, to allow direct comparisons to be made between each of the farmlets according to multiple criteria. Where appropriate, the values presented over the later period have been averaged over two or more years, so as to reduce the effects of year-to-year variation in some of the data and thereby provide more robust measurements of the observed differences.

In each of the tables presented, to facilitate comparisons between farmlets, the proportion of the maximum or minimum value, depending on whether a high or low result is considered desirable, have been added to normalise all of the data to a scale of 0–1. The proportions were calculated as described by Scott *et al*. (2000). In brief, if the desired value of a particular factor is *high* (e.g. wool cut), then its average value for a particular farmlet was divided by the *maximum* of the values over the three farmlets for that parameter, to give a proportion of the maximum value attained for each farmlet. Alternatively, if the desired value of a parameter is *low* (e.g. number of drenches), then the *minimum* value over the three farmlets was divided by the value for each farmlet, to give a proportion of that minimum value for each farmlet. For example, in a case with a *high* desired value, such as soil nitrogen, row 1 of Table 1 shows values in 2001 for farmlets A–C of 17.4, 5.2 and 13.4, respectively. Dividing each of these numbers by the maximum of the three (17.4) gave proportions of 1.00, 0.30 and 0.77, respectively. In cases where one or more observation was negative (e.g. cash position), the data for all three farmlets were first adjusted to be equal to or above zero by adding the absolute value of the most negative observation, before calculating the proportion. The overall average index values for each farmlet are simple averages of all calculated indices without any attempt to weight different parameters as, in our view, any weightings would be too subjective.

As all of the comparisons made in the present paper are among average measurements from each of the three unreplicated farmlets, no statistical analyses have been reported here. The case for drawing causal inference among these three farming-system treatments has been discussed in detail by Murison and Scott (2013). Wherever feasible, the component papers of this Special Issue have reported on the various statistical analyses conducted and the significance of the differences found among treatments for the particular measured parameters.

Results

The average values of raw data derived over a wide array of parameters for each farmlet and the proportions, or indices, from early (2000–01) and late (2003–06) in the experiment are presented in Tables 1 and 2, respectively. The overall average index across all measured parameters early in the experiment was 0.91, 0.86 and 0.86 for farmlets A, B and C, respectively (Table 1), which suggests that all three farmlets were quite similar at that time. By late in the experiment, the differences between farmlet A and the other two farmlets had increased, such that the average index across all parameters was 0.91, 0.76 and 0.76 for A, B and C, respectively (Table 2).

The relative proportions for each measured parameter are also shown graphically in Figs 1 and 2, from both early and late in the experiment. In general, the relative indices shown in Fig. 1 (from 2000–2001) display considerable similarity among the three farmlets except for several parameters that changed quickly following the imposition of differential treatments on the farmlets from July 2000 (e.g. soil-fertility measurements and the lower cash position of farmlets A and C due to investments in pastures, fertiliser and fencing and water infrastructure).

Table 1. Average data from farmlets A–C early in the trial (2000–2001) for a wide array of soil, pasture, ground-cover, livestock-production, animal-health, farmlet-productivity and financial measurements and proportions of the highest data value of each measurement, normalised on a 0–1 scale

H, high; L, low; NDVI, normalised difference vegetation index

Factor	Units	Aim	Year(s)	Average data			Proportion of maximum value (for aim of H)/minimum value (for aim of L)			Source of data
				A	B	C	A	B	C	
Soil layer										
Soil N	mg N/kg soil	H	2001	17.4	5.2	13.4	1.00	0.30	0.77	(Guppy *et al*. 2013)
Soil P	mg P/kg soil	H	2001	29.5	14.5	21.0	1.00	0.49	0.71	(Guppy *et al*. 2013)
Soil S	mg S/kg soil	H	2001	14.5	6.5	8.0	1.00	0.45	0.55	(Guppy *et al*. 2013)
Pasture layer										
Sown perennial grasses	%	H	2000	51.7	30.5	43.9	1.00	0.59	0.85	(Shakhane *et al*. 2013*b*)
Legume	%	H	2000	1.4	3.7	3.1	0.38	1.00	0.86	(Shakhane *et al*. 2013*b*)
Warm-season grasses	%	L	2000	14.9	25.6	21.3	1.00	0.58	0.70	(Shakhane *et al*. 2013*b*)
Total herbage mass	kg DM/ha	H	2000–2001	3402	2791	3350	1.00	0.82	0.98	(Shakhane *et al*. 2013*a*)
Greenness (satellite NDVI)		H	2000	321	341	341	0.94	1.00	1.00	(Donald *et al*. 2013)
Livestock production										
Greasy fleece weight/head (ewes)	kg/head	H	2001	3.2	3.2	3.1	1.00	0.99	0.96	(Cottle *et al*. 2013)
Fibre diameter (ewes)	Microns	L	2001	19.4	19.1	19.2	0.99	1.00	0.99	(Cottle *et al*. 2013)
Staple length (ewes)	mm	H	2001	60.7	59.5	60.6	1.00	0.98	1.00	(Cottle *et al*. 2013)
Liveweight/head (ewes)	kg/head	H	2000–2001	43.1	43.6	43.3	0.99	1.00	0.99	(Hinch *et al*. 2013*a*)
Fat score/head (ewes)	Score (1–5)	H	2000–2001	2.6	2.7	2.7	0.97	0.99	1.00	(Hinch *et al*. 2013*b*)
Liveweight/head (weaners)	kg/head	H	2000 drop	20.0	18.8	18.5	1.00	0.94	0.93	(Hinch *et al*. 2013*a*)
Parasites (faecal egg count)	Number/g	L	2000–2001	164.3	203.2	224.7	1.00	0.81	0.73	(Walkden-Brown *et al*. 2013)
Number of drenches/mob.year	Number/year	L	2000	1.7	1.7	1.7	1.00	1.00	1.00	(Walkden-Brown *et al*. 2013)
Farmlet productivity										
Liveweight/ha (weaners)	kg/ha	H	2000 drop	75.0	69.5	61.8	1.00	0.93	0.82	(Hinch *et al*. 2013*a*)
Greasy fleece weight/ha	kg/ha.year	H	2001	12.6	11.3	10.8	1.00	0.90	0.86	(Cottle *et al*. 2013)
Stocking rate (annual average)	dse/ha	H	2000–2001	7.5	6.7	8.2	0.92	0.82	1.00	(Hinch *et al*. 2013*a*)
Financial										
Fodder cost/farm	$/year	L	2000	$4135	$2894	$3791	0.70	1.00	0.76	(Scott *et al*. 2013*b*)
Wool value/ewe	$/head	H	2000–2001	$31.59	$32.66	$32.75	0.96	1.00	1.00	(Cottle *et al*. 2013)
Wool income/ha	$/head	H	2000–2001	$182	$178	$177	1.00	0.98	0.97	(Cottle *et al*. 2013)
Gross margin/ha (full-size farm)	$/ha	H	2000–2001	$215	$230	$181	0.93	1.00	0.79	(Scott *et al*. 2013*b*)
Cash position (full-size farm)	$/farm	H	2000–2001	–$76 393	$118 908	$2486	0.00	1.00	0.40	(Scott *et al*. 2013*b*)
Equity	%	H	2000–2001	92%	100%	100%	0.92	1.00	1.00	(Scott *et al*. 2013*b*)
Labour per dse	h/year.dse.ha	L	2000–2001	35	32	43	0.91	1.00	0.74	(Scott *et al*. 2013*c*)
Average index							0.91	0.86	0.86	

Table 2. Average data from farmlets A–C late in the trial (2003–2006) for a wide array of soil, pasture, ground-cover, livestock-production, animal-health, farmlet-productivity and financial measurements and proportions of the highest data value of each measurement, normalised on a 0–1 scale

H, high; L, low; NDVI, normalised difference vegetation index

Factor	Unit	Aim	Year(s)	Average data A	Average data B	Average data C	Proportion of maximum value (for aim of H)/minimum value (for aim of L) A	B	C	Source of data
					Soil layer					
Soil-N	mg N/kg soil	H	2003–2006	24.9	14.1	10.4	1.00	0.57	0.42	(Guppy *et al.* 2013)
Soil-P	mg P/kg soil	H	2003–2006	58.1	24.1	30.1	1.00	0.41	0.52	(Guppy *et al.* 2013)
Soil-S	mg S/kg soil	H	2003–2006	12.2	6.4	6.8	1.00	0.52	0.56	(Guppy *et al.* 2013)
					Pasture layer					
Sown perennial grasses	%	H	2005–2006	47.3	17.4	26.7	1.00	0.37	0.57	(Shakhane *et al.* 2013*b*)
Legume	%	H	2005–2006	5.3	1.3	1.6	1.00	0.24	0.30	(Shakhane *et al.* 2013*b*)
Warm-season grasses	%	L	2005–2006	15.7	29.6	29.9	1.00	0.53	0.52	(Shakhane *et al.* 2013*b*)
Green dry matter	kg DM/ha	H	2005–2006	942	905	989	0.95	0.91	1.00	(Shakhane *et al.* 2013*a*)
Digestibility of green	%	H	2005–2006	66	55	58	1.00	0.84	0.87	(Shakhane *et al.* 2013*a*)
Dead dry matter	kg DM/ha	L	2005–2006	1048	2131	2055	1.00	0.49	0.51	(Shakhane *et al.* 2013*a*)
Legume dry matter	kg DM/ha	H	2005–2006	51	5	6	1.00	0.10	0.12	(Shakhane *et al.* 2013*a*)
Greenness (satellite NDVI)		H		554	481	496	1.00	0.87	0.90	(Donald *et al.* 2013)
					Sustainability					
Ground cover	%	H	2005–2006	88	96	98	0.90	0.98	1.00	(Shakhane *et al.* 2013*a*)
					Livestock production					
Greasy fleece weight/head (ewes)	kg/head	H	2003–2005	3.6	3.5	3.1	1.00	0.97	0.86	(Cottle *et al.* 2013)
Fibre diameter (ewes)	Microns	L	2003–2005	18.7	18.5	18.2	0.97	0.98	1.00	(Cottle *et al.* 2013)
Staple length (ewes)	mm	H	2003–2005	88.8	86.1	80.9	1.00	0.97	0.91	(Cottle *et al.* 2013)
Staple strength (ewes)	N/ktex	H	2003–2005	42.0	40.2	43.9	0.96	0.92	1.00	(Cottle *et al.* 2013)
Liveweight/head (ewes)	kg/head	H	2004–2005	46.3	44.6	42.6	1.00	0.96	0.92	(Hinch *et al.* 2013*a*)
Fat score/head (ewes)	Score (1–5)	H	2004–2005	2.7	2.5	2.5	1.00	0.90	0.91	(Hinch *et al.* 2013*b*)
Pregnancy scan	Proportion	H	2005	0.98	0.81	0.82	1.00	0.83	0.84	(Hinch *et al.* 2013*b*)
Lambs marked/ewe joined	%	H	2004	85	90	84	0.94	1.00	0.93	(Hinch *et al.* 2013*b*)
Lamb mortality (scan to weaning)	%	L	2005	31	17	19	0.55	1.00	0.89	(Hinch *et al.* 2013*b*)
Liveweight/head (weaners)	kg/head	H	2004 drop	18.0	20.0	19.6	0.90	1.00	0.98	(Hinch *et al.* 2013*a*)
Liveweight gain/head (cattle)	kg/head.day	H	2004–2005	0.97	0.95	0.89	1.00	0.98	0.92	(Hinch *et al.* 2013*a*)
Parasites (faecal egg count)	Number/g	L	2002–2006	594.4	790.2	367.9	0.62	0.47	1.00	(Walkden-Brown *et al.* 2013)
Number of drenches/mob.year	Number/year	L	2005–2006	2.7	3.0	1.9	0.70	0.62	1.00	(Walkden-Brown *et al.* 2013)
					Farmlet productivity					
Liveweight/ha (weaners)	kg/ha	H	2004 drop	89.7	64.0	54.7	1.00	0.71	0.61	(Hinch *et al.* 2013*a*)
Greasy fleece weight/ha	kg/ha.year	H	2004–2005	23.4	17.1	13.5	1.00	0.73	0.57	(Cottle *et al.* 2013)
Liveweight gain/ha (cattle)	kg/ha.year	H	2004–2005	84.5	71.4	78.7	1.00	0.85	0.93	(Hinch *et al.* 2013*a*)
Stocking rate (annual average)	dse/ha	H	2004–2005	11.9	8.2	7.6	1.00	0.69	0.63	(Hinch *et al.* 2013*a*)
Silage produced	t digestible DM/ha	H	2005	20.2	0.0	0.0	1.00	0.00	0.00	(Shakhane *et al.* 2013*a*)

(*Continued next page*)

Table 2. (*Continued*)

Factor	Unit	Aim	Year(s)	Average data A	Average data B	Average data C	Proportion of maximum value (for aim of H)/minimum value (for aim of L) A	B	C	Source of data
Financial										
Fodder cost/farmlet	$/year	L	2005	$13761	$8247	$7448	0.54	0.90	1.00	(Scott *et al.* 2013*b*)
Wool value/ewe	$/head	H	2003–2005	$39.80	$41.05	$38.06	0.97	1.00	0.93	(Cottle *et al.* 2013)
Wool income/ha	$/ha	H	2003–2005	$303	$215	$180	1.00	0.71	0.59	(Cottle *et al.* 2013)
Gross margin/ha (full-size farm)	$/ha	H	2003–2005	$303	$241	$214	1.00	0.79	0.71	(Scott *et al.* 2013*b*)
Cash position (full-size farm)	$/farm	H	2003–2005	–$152 316	$461 125	$241 595	0.00	1.00	0.64	(Scott *et al.* 2013*b*)
Equity	%	H	2003–2005	92%	100%	100%	0.92	1.00	1.00	(Scott *et al.* 2013*b*)
Labour per dse	h/year.dse.ha	L	2005	18	20	22	1.00	0.90	0.82	(Scott *et al.* 2013*c*)
Average index							0.91	0.76	0.76	

Figure 2 shows that the differences that developed over time between the three farmlets were more marked, especially between farmlet A and the other two farmlets.

As it is not feasible in a single paper to satisfactorily discuss all of the component issues in depth, the reader is referred to those related papers noted in Tables 1 and 2 for more detailed background and discussion of particular factors measured in the farmlet experiment. The most significant relationships among the relative measures of the various parameters on each farmlet are discussed below.

Discussion and conclusions

An interpretative discussion of some of the results is given below, followed by a broader, more integrative discussion of the relevance of the experiment and its findings and, finally, a statement of the conclusions reached.

Interpretation of the results

Soil nutrient concentrations

Soil nutrient concentrations diverged quickly (Table 1) and became more different over time in response to treatment (Table 2). Soil phosphorus and, at times, soil sulfur, were significantly correlated with positive changes in botanical composition (Guppy *et al*. 2013; Shakhane *et al*. 2013*b*), including sown perennial grasses and legumes, pasture quality (Shakhane *et al*. 2013*a*), liveweight and stocking rate (Hinch *et al*. 2013*a*). These results are consistent with other Northern Tableland results which have shown the importance of improving livestock production through higher rates of nutrient cycling and retention of those nutrients by livestock in the grazing ecosystem without leakage below the pasture root zone (Chen *et al*. 2002). However, it is noteworthy that there may not have been sufficient time for the nutrient flows within the farmlet experiment to have stabilised, as called for by van Keulen *et al*. (2000).

Botanical composition

The maintenance of sown perennial grasses, the moderate increase in legume content and decrease in warm-season grasses were closely associated with the pasture renovation and increased soil fertility on farmlet A (Shakhane *et al*. 2013*b*). The proportion of sown perennial grasses was maintained somewhat better by IRG (farmlet C) than under typical management (farmlet B), which had a substantial decline in this group as well as a large increase in warm-season grasses.

Kemp (2000, p. 145) described how grazing management tactics that encourage the more desirable species to persist need to be used. He stated that controlling the 'ability of animals to select what they eat' is an essential part of grazing management, as continuous grazing, especially of large areas, leads to patches developing in pastures. As found by Shakhane *et al*. (2013*b*), the combination of extended grazing periods and moderate inputs resulted in a greater level of patch grazing on farmlet B.

The importance of legumes in grazed pastures in Australia is well known. Even though there was, in general, a low legume content (mostly white clover) on all of the farmlets, this was associated with the drier-than-average seasons experienced

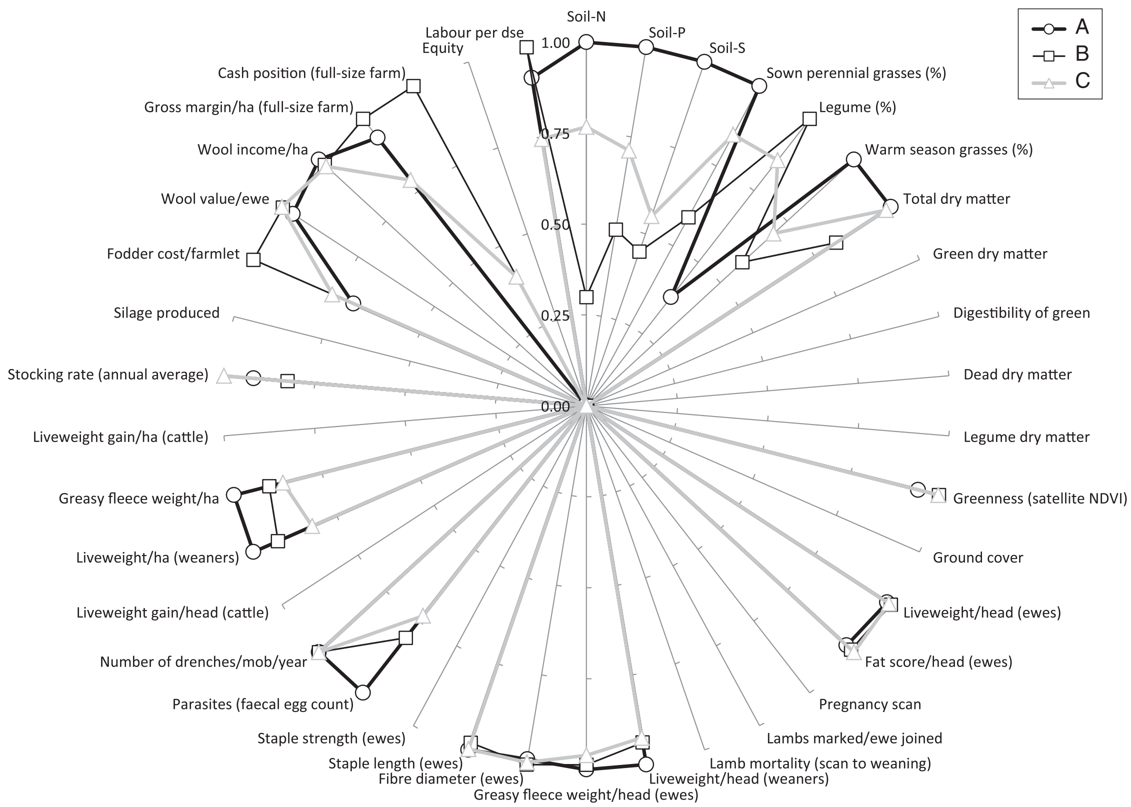

Fig. 1. Diagram showing relativity among farmlets A–C early in the trial (from 2000 to 2001) for a wide array of soil, pasture, ground-cover, livestock-production, animal-health, farmlet-productivity and financial measurements, normalised to a 0–1 scale (proportions extracted from Table 1).

(Behrendt *et al*. 2013*c*). Nevertheless, farmlet A had a significantly higher legume content than did either of the other farmlets due to the dual effects of higher soil fertility and longer graze and shorter rest periods than on farmlet C (Shakhane *et al*. 2013*a*). Singh *et al*. (1999) noted that higher soil phosphorus concentrations tend to be associated with a higher legume content in pastures, even during dry periods. The persistence of the perennial legume, white clover, on the Northern Tablelands of NSW, was studied in a long-term experiment over more than 30 years by Hutchinson *et al*. (1995). When the vegetative presence of the legume was reduced to low levels, they found that it was difficult to get substantial recruitment from seed pools, resulting in low levels of legume, especially following periods of drought (Hutchinson *et al*. 1995). As reported by McCaskill and Blair (1988), in dry seasons, legume growth tends to be consumed rather than accumulated, resulting in increased animal liveweights. Even though the levels of legume measured on the Cicerone farmlet experiment were generally low, they still had significant effects on livestock production (Hinch *et al*. 2013*a*) and wool growth (Cottle *et al*. 2013).

Herbage mass and quality

In general, farmlets B and C had much higher levels of dead and total herbage than did farmlet A, whereas all three farmlets tended to have similar levels of green herbage. Although farmlet C reported similar levels of green herbage, its availability to the grazing animal was less due to the intensive nature of its grazing management which meant that a much smaller proportion of the farmlet was accessible to the livestock at any one time. With its greater level of temperate species (Shakhane *et al*. 2013*b*) and higher soil fertility, farmlet A had significantly higher digestibility levels, resulting in a higher level of green digestible herbage over much of the experiment (Shakhane *et al*. 2013*a*). Digestible herbage is known to be increased substantially by higher concentrations of soil phosphorus and sulfur, resulting in increased animal production (Saul *et al*. 1999).

Potential pasture growth

Measured pasture growth was similar among farmlets (Shakhane *et al*. 2013*a*), due to the generally dry conditions. However, the level of greenness, detected by measuring the normalised difference vegetation index (NDVI) via Landsat satellite images, which is a surrogate measure of potential pasture growth, was significantly higher for farmlet A than for the two other farmlets (Donald *et al*. 2013). Pasture growth rate is known to be the principal factor supporting changes in stocking rate, which diverged over time among the farmlets (Hinch *et al*. 2013*a*).

Liveweight

The substantial differences in animal performance among ewes, hoggets, wethers and cattle were linked to the amount of

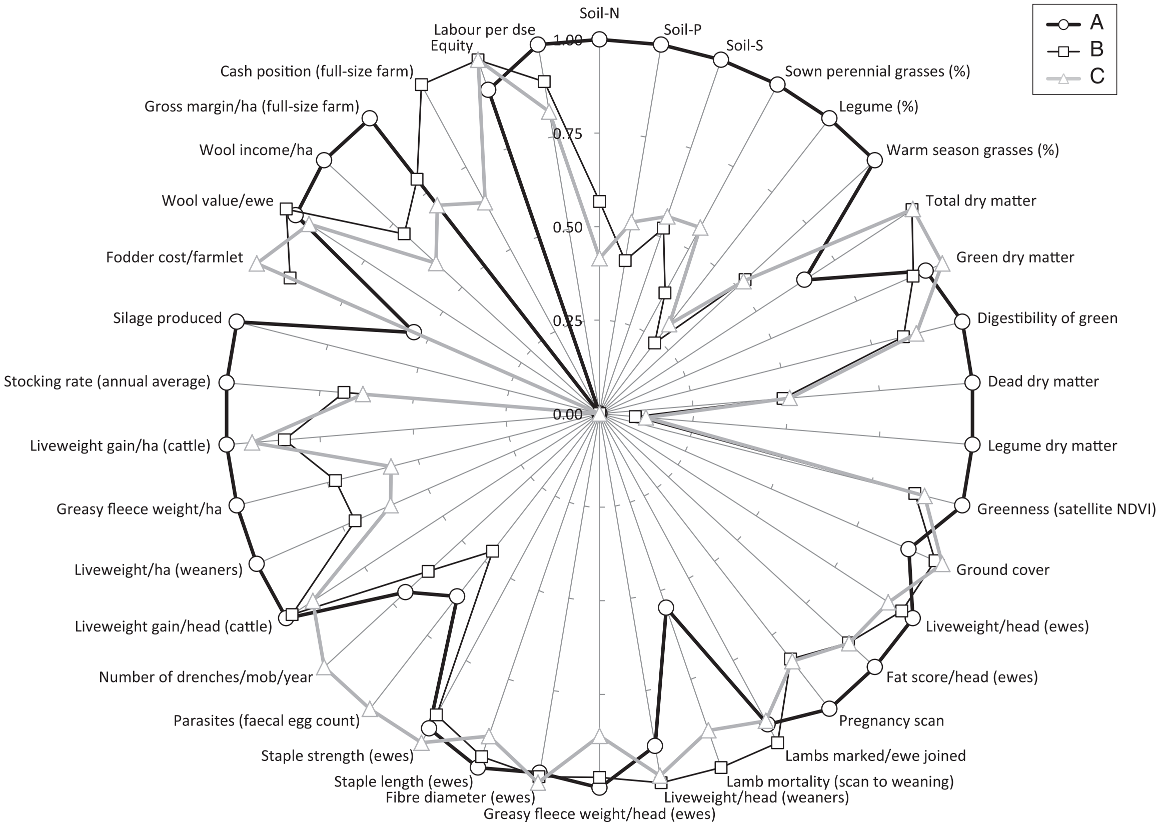

Fig. 2. Diagram showing relativity among farmlets A–C late in the trial (from 2003 to 2006) for a wide array of soil, pasture, ground-cover, livestock-production, animal-health, farmlet-productivity and financial measurements, normalised to a 0–1 scale (proportions extracted from Table 2).

green digestible herbage and the degree of dietary choice offered under the different grazing management regimes (Hinch *et al.* 2013*a*). Under the IRG regime, high stocking densities meant that animals competed intensely for the green digestible herbage available, as shown by the rapid disappearance rate of the green component of pastures on that farmlet (Shakhane *et al*. 2013*c*). The differences among animal liveweights on farmlets were greatest when the period of grazing rest on farmlet C was longest. Liveweights were also affected by the amount of legume herbage, stocking rate and the amount of supplement fed (Hinch *et al*. 2013*a*).

Fat scores and reproduction

As with animal liveweights, the fat scores of breeding ewes tended to be higher on the two farmlets that offered longer graze periods (farmlets A and B) (Hinch *et al*. 2013*b*). The greater amount of green digestible herbage and the flexible grazing regime also led to higher levels of pregnancy in scanned ewes of farmlets A and B (Hinch *et al*. 2013*b*).

Wool production and quality

The differences among farmlets in wool production per head and wool quality, while often significant, were not large. However, due to the combination of a higher production per head and stocking rate, the amount and value of wool production per hectare were substantially greater on farmlet A than on the other farmlets (Cottle *et al*. 2013).

Parasites

Overall, gastrointestinal nematodosis (GIN), as indicated by faecal worm egg count, was significantly reduced on farmlet C compared with the other two farmlets (Colvin *et al*. 2008; Walkden-Brown *et al*. 2013). The greatest impact was seen on *Haemonchus contortus*, with a lesser impact on the other major nematode species (*Trichostrongylus* spp. and *Teladorsagia circumcincta*). As a consequence, sheep on farmlet C received fewer anthelmintic treatments. Comparisons of GIN-free sheep (treated with long-acting anthelmintics) and sheep with natural infections showed that there was no impact of GIN on production traits on farmlet C, whereas bodyweight, fat score, fleece weight and pregnancy rate were all higher in worm-free sheep on farmlets A and B. There was strong evidence that the control of GIN on farmlet C was mediated through the intensive grazing management which interrupted the free-living stages of the nematode life-cycle (Colvin *et al*. 2012). Short grazing periods (2–4 days) prevented autoinfection and sufficient rest periods prevented large scale re-infection by allowing a significant decline of infective larval populations on pasture. In spite of the better control of GIN on farmlet C, sheep on this farmlet recorded lighter liveweights and fleece weights per head than those on the other farmlets, especially early in the experiment when the grazing rest periods were longest.

Economic outcomes

The economic analyses used different strategies to answer a sequence of related questions.

Scott *et al*. (2013*b*) used a representative-farm approach to provide realistic ‘full-scale’ financial results by adjusting the results from the farmlet scale to that of a commercial-scale farm representative of the study area. This allowed the analysis to be extended from simple enterprise gross margins to the more useful cash-flow analysis for a ‘Farm’ as a whole. A comparison of the two approaches showed the importance of understanding the meaning of the financial measures used. In terms of gross margins, the full-scale Farm A performed considerably better than Farm B or Farm C. Farm A also produced more wool and beef per hectare than did Farm B or Farm C. But in terms of cash flow, Farm B was far superior to Farm A because the latter was not able to cover its high level of fixed costs, due to its high investments in pastures and soil fertility within the duration of the experiment, and thus experienced negative cash balances for most of the period 2000–2005. Farm C was inferior to Farm B in business returns due to several factors such as the grazing rest period being too long, with high stocking densities resulting in lower liveweights for both sheep and cattle and lower wool cut per head for sheep. The below-average rainfall conditions experienced during 2000–2006 meant that direct economic analysis of the experimental results did not include the potentially higher returns from average or above-average rainfall years that may have allowed Farm A to pay its debt. This suggested that some modelling was needed to evaluate the three farm systems under a wider range of conditions.

The modelling that complemented the experimental results of the Cicerone experiment has been discussed in other papers in this Special issue (Behrendt *et al*. 2013*a*, 2013*b*, 2013*c*; Scott *et al*. 2013*a*, 2013*b*). Economic analysis required some modelling to complement experimental results for three reasons. First, the experiment was not long enough to capture some of the important economic measures related to sustainability, such as return on investment and long-term net worth. Second, the duration of the experiment also meant that there was not enough time for the pasture renovation investment to be paid back and, therefore, did not provide a fair comparison of return on investment among treatments. Third, the run of poor years experienced over most of the experimental period biased the economic performance of all three systems towards lower yields than would be expected on average. Modelling allowed longer time periods as well as a broader range of weather patterns to be introduced into the economic analysis, therefore helping reduce the impact of these three limitations.

Scott *et al*. (2013*a*) introduced climatic variability into the analysis by using a stochastic discounted cash-flow model based on the Cicerone farmlet data. The analysis evaluated Farms A and B at a commercial scale over 20 years, so that the return on investment could be evaluated. In this case, over a period of 20 years, Farm A was found to be more profitable but also more ‘risky’ (variable), especially at the highest stocking rate explored (15 dse/ha). This indicated there was a need to understand the trade-offs between risks and returns and led to further economic analyses.

Behrendt *et al*. (2013*b*) studied the risk–return trade-off in the context of pasture persistence and fertiliser application under climatic uncertainty, through a model calibrated using the results from the Cicerone farmlet experiment. The study found that it was economically efficient to reduce both fertiliser inputs and stocking rates with increasing fertiliser costs, which also reduced the variability of returns (or the riskiness of the system). Although this strategy maintained similar levels of total available pasture and per-head livestock performance, it led to a reduction in the persistence of desirable species within the sward, which could affect future returns. These results revealed the importance of embedding risk in the decision process, so that decisions can be adjusted as climatic variability unfolds.

Behrendt *et al*. (2013*a*) built on the previous analysis by embedding risk into the decision process to allow optimisation methods to distinguish between strategic decisions involving long timeframes and tactical decisions that can be adjusted over the short-term. They argued that, in evaluating the benefits of adopting alternative technologies, the way in which risk interacts with management must be considered. Their study examined the conflicting goals of maximising profit while achieving persistence of desirable species within a grazing system by deriving optimal decision rules for the seasonal management of a paddock in the presence of climatic uncertainty. Results showed the conditions under which a pasture should be renovated, given a grazing rest, or have its stocking rate reduced, on the basis of available pasture and its composition at the start of each season. Typically, the stocking-rate decision rule was driven by quantities of available pasture in spring, whereas during summer, autumn and winter, the decision was influenced by both the pasture mass and the proportion of desirable species in the sward. The lowest stocking rates tended to occur during winter and summer, with the highest occurring during spring. As such, a seasonal savings and consumption pattern was derived that was optimal for the given economic conditions. The re-sowing of pastures was identified to be optimal only under severely degraded states of the pasture resource, and was most prominent in autumn and winter. These findings provide a general framework for evaluating the performance of grazing systems under climatic uncertainty while taking pasture persistence into account.

Climate constraints

Details of the rainfall and temperature experienced over the experimental period and their relationship to the long-term climatic record have been provided by Behrendt *et al*. (2013*c*). In brief, the experiment experienced drier-than-average soil-moisture conditions and suffered from more frequent and more severe frosts than average. As explained in that paper, the results from the farmlet experiment need to be interpreted with that knowledge; this is the reason that the outcomes from the modelling were important to understanding the findings in the context of longer timeframes.

Integrative discussion

As large grazing experiments experience considerable variation over space and with changing climatic conditions over time, one cannot expect such experiments to have great precision (Spedding and Brockington 1976). Our experience accords with Tanaka *et al*. (2008) who stated that research on farming systems which attempts to integrate multi-disciplinary strands can be extremely difficult to fund, carry out, statistically analyse and publish. The integration of the multiple findings from this research has been a challenge for all project participants, including the livestock producers who led this Project. Also, during the conduct of this farmlet experiment, there were unavoidable compromises that had to be made to achieve a balance between practical relevance and scientific rigour.

While many farming system studies have been useful, some have failed to adequately mimic the practices of commercially relevant farming systems (Thomson *et al*. 1995). In contrast, the Cicerone farmlet experiment was strongly influenced by and found to be highly relevant to producer members (Edwards *et al*. 2013).

Results indicated that the relative performance of the three farmlets diverged considerably over the duration of the experiment and over a wide array of criteria. The strategy of pasture renovation with higher soil fertility employed on farmlet A resulted in a substantial improvement in overall performance compared with farmlets B and C, which were similar overall. This is consistent with the findings of Waller *et al*. (2001) who found that greater increases in animal production came about by upgrading pastures than through grazing management.

The integrated results of the Cicerone farmlet experiment were also, to a large extent, consistent with the results of the national Sustainable Grazing Systems (SGS) experiment. Thus, as reported by Sanford *et al*. (2003), there was a large effect of soil phosphorus, botanical composition, legume content and stocking rate. Whereas the SGS experiment used modelling to suggest that rotational grazing was unlikely to markedly increase pasture production, the Cicerone farmlet experiment confirmed this experimentally. Compared with flexible rotational grazing, IRG did not lift pasture growth substantially over the duration of the experiment and resulted in generally lower per-head and per-hectare animal production. In another SGS study, Chapman *et al*. (2003, p. 794) concluded that 'neither grazing method explored will optimise system performance under all conditions' because rigid grazing rules have an impact on both pastures and animals. Overall, these authors concluded that graziers need to strive for both high per-head animal performance as well as high perennial-grass persistence, so as to capture the growth and environmental benefits attributed to that pasture component. They suggested that farms might employ more tactical grazing strategies that combine set stocking and rotational systems on different parts of their farms at different times, so as to ensure high per-head performance.

The Cicerone experiment compared different grazing management systems to those studied by Chapman *et al*. (2003). Whereas Chapman *et al*. (2003) compared low and high rates of fertiliser application (6.4 and 25 kg P/ha.year, respectively), the Cicerone farmlet experiment was managed to achieve either moderate or high levels of soil fertility, based on soil tests. For comparison, the annual rates of fertiliser applied to farmlets B and C were ~4.9 and 4.3 kg P/ha, respectively, whereas farmlet A received ~13.1 kg P/ha.year (Guppy *et al*. 2013). It is noteworthy that the higher level of phosphorus application employed on farmlet A was not 'high' compared with that in many other studies of pasture fertilisers in Australia.

In a study of different grazing strategies in northern Queensland, O'Reagain *et al*. (2011) found that, under variable climatic conditions, the best financial and sustainable outcomes over the long term were achieved through a variable stocking strategy that allowed the adjustment of stocking rate early in each dry season. Such a system is similar to the flexible grazing management employed on farmlets A and B in the present experiment. However, in view of the high costs incurred in the initial years on farmlet A and the pasture degradation that developed over time on farmlet B, it is clear that decisions need to be made that retain desirable pasture species in the pasture in such a way that the life of a pasture is extended towards a region of optimal condition and management (Behrendt *et al*. 2013*a*).

In a replicated grazing study of native pastures on the North West Slopes of NSW, Lodge *et al*. (2003) found that, compared with continuous grazing, rotational grazing or the addition of legume and fertiliser resulted in substantial improvements to the production and sustainability of those pastures. Research conducted on a site adjacent to the Cicerone farmlet experiment found that a combination of a persistent legume (white clover) and a strongly perennial temperate grass (phalaris) had considerable sustainability benefits. Thus, McLeod *et al*. (2006) found that such a pasture had a deeper rooting depth which enabled more soil-water extraction, which was associated with greater sustainability characteristics (Scott *et al*. 2000) than either a phalaris-dominant pasture or a degraded pasture. Also, on the Central Tablelands of NSW, sown perennial grass pastures were found to contribute to sustainability, provided that they last long enough to provide positive economic returns (Dowling *et al*. 2006).

We acknowledge that, due to a lack of resources (Scott *et al*. 2013*c*), insufficient measurements relating to sustainability, such as the indirect effects of the state of pastures on groundwater, soil acidification and erosion over the long term, were undertaken within the farmlet experiment. As noted by Jones *et al*. (1995) and Saul and Chapman (2002), there remains a need to evaluate the environmental effects of grazed systems over the long term as it can take many years for pasture composition and soil fertility to reach steady-states.

When seeking answers to broad agroecological questions such as agricultural sustainability, Edwards *et al*. (1993) pointed out the need for multi-disciplinary approaches which not only include farmers but also take a 'whole-farm level' approach. Modelling of livestock farming systems has also been suggested as useful in striving for more sustainable systems (Gibon *et al*. 1999), so long as it is conducted in an inter-disciplinary fashion. The Cicerone farmlet experiment adopted both multi-disciplinary and modelling approaches.

Grazed experiments that have comprehensively measured most components of a farming system are rare. Saul *et al*. (2011) found that upgraded pastures were associated with an increased stocking rate, higher ewe liveweights, condition scores, lambing and weaning percentages, wool cut per head and fibre diameter but with no increase in supplementary feeding. They also estimated that the break-even point for financial returns on investments in upgraded pastures occurred after 7 years. In addition, they estimated an internal rate of return on pasture improvement of 27%, assuming the upgraded pastures were managed to persist for 12 years. In the case of pasture renovation on the Cicerone farmlet experiment, Behrendt *et al*. (2006) estimated that the risk-efficient rate of pasture replacement was 4% per annum.

Over the duration of the experiment, the level of green herbage declined well below critical thresholds on several occasions, as shown by pasture assessments (Shakhane *et al*. 2013*a*) and the trends in liveweights and supplement fed (Hinch *et al*. 2013*a*). The ability of sheep to select a high-quality diet decreases as the level of green herbage on offer declines below the critical threshold of 550 kg green DM/ha (Hamilton *et al*. 1973). Levels of green herbage were affected by rainfall and season, pasture species, soil fertility, stocking rate and grazing management. Thus, the low levels of green herbage on farmlet A (Shakhane *et al*. 2013*a*) were exacerbated by the stocking rate being too high at times, as evidenced by the high levels of supplement required in the later years of the experiment. Had a greater level of green herbage been retained, it is likely that pasture growth and persistence would have been enhanced with less supplement required (Shakhane *et al*. 2013*a*).

Both farmlets B and C recorded higher levels of dead herbage than did farmlet A (Shakhane *et al*. 2013*a*). On farmlet B, the low levels of green herbage in winter were related to the rise of warm-season grasses and low levels of legume. Farmlet C also experienced similar low levels of green herbage and digestibility to those on farmlet B but, because only a small proportion of the farmlet was available to the grazing animals at any one time, the high stock density resulted in intense competition for, and rapid depletion of green herbage during each brief grazing event (Shakhane *et al*. 2013*c*). Chapman *et al*. (2003) argued that the rigid application of grazing management regimes can result in pastures of lower quality. In rotationally grazed systems, there are compromises and trade-offs that occur between pasture and animal production such as the lower legume levels and lower levels of per-head and per-hectare production (Saul and Chapman 2002).

Hall *et al*. (2011) compared three grazing systems, from continuous grazing through to intensive grazing, under extensive commercial conditions in Queensland and found that diet quality tended to be lower in the more intensive grazing systems. Others too have found that longer grazing rest periods can result in lower-quality herbage because of a higher proportion of stem to digestible leaf (Waller *et al*. 2001).

Critique of the three farmlet management systems

The control farmlet (B), which was managed according to guidelines considered typical by the region's livestock producers, was found to have the highest cash position at the end of the experiment. This was achieved largely by accumulating income through employing a modest stocking rate and constraining expenditure. In doing so, it achieved high per-head weight gains and performed best in terms of lambs marked per ewe joined and in lamb mortality. However, in other respects, it was found wanting, especially in its pastures, which became degraded over time, with low levels of legume, declining levels of sown perennial grasses, increasing levels of warm-season grasses and evidence of patch grazing and increased broadleaf weeds in all paddocks except one that was renovated in 2004 (Shakhane *et al*. 2013*b*). Thus, in spite of its superior financial position, we contend that this farmlet represents the least sustainable management option.

In contrast, farmlet A, which benefited substantially from renovated pastures and higher soil fertility, suffered financially from the high rate of pasture renovation (29% of the farmlet in the first year). This was largely an artefact of Project management that determined that the farmlets had to be developed quickly so that differences among farmlets would emerge over a short timeframe. Farmlet A also suffered financially due to the cost of sowing two paddocks of so-called 'high performance' pastures based on Italian ryegrass, which producer members wanted investigated. In both cases, the Italian ryegrass pastures failed to persist longer than 18 months and needed to be re-sown to perennial pastures.

As noted by Carter and Day (1970), there needs to be a sufficient financial incentive if producers are to consider a more productive strategy, such as increased stocking rates, with its inherent risks and need for greater managerial skill. The modelling (Behrendt *et al*. 2006) and economic-risk (Scott *et al*. 2013*a*) studies conducted confirmed that optimal solutions demand that pastures be managed to persist over long periods, so as to justify investment in such technologies. Thus, assuming a rate of pasture renovation at the most risk-efficient level of 4% per annum (Behrendt *et al*. 2006) and a stocking rate of either 11.9 or 15 dse/ha, farmlet A was shown to have the potential for a substantially higher cumulative net present value over a 20-year horizon than the value from an analysis based on the artificially high rate of pasture renovation during the present experiment (Scott *et al*. 2013*a*); the risk level for the 11.9 dse/ha scenario was substantially lower than for the 15 dse/ha scenario. As pointed out by Scott *et al*. (2013*a*), given some better seasons, this farmlet had much more potential for 'upside risk', or more favourable economic outcomes, than did either of the other farmlets.

In terms of meeting some criteria that are associated with 'sustainability' (Scott *et al*. 2000), farmlet A achieved higher concentrations of soil nutrients, higher botanical composition proportions of temperate perennial grasses and legumes and higher per-hectare livestock production than the other farmlets, while also achieving high levels of animal production on a per-head basis. However, it must be acknowledged that these increases came at a considerable cost and that insufficient environmental factors were able to be measured. Thus, although farmlet A reached a substantially higher average index (0.91) over all measured parameters by the latter half of the experiment than did farmlets B and C (0.76 and 0.76, respectively), it is difficult, due to insufficient information, to conclude that any one system would in fact be more profitable or sustainable over the long term.

Regarding the higher numbers of gastrointestinal nematodes on both farmlets A and B than on farmlet C (Walkden-Brown *et al*. 2013), it is clear that the two farmlets that employed flexible rotational grazing were constrained substantially by needing to graze multiple mobs across no more than eight paddocks per farmlet. No doubt, better control could have been achieved if more paddocks had been allowed and if more deliberate use had been made of cattle to graze paddocks before sheep, as recommended by Niezen *et al*. (1996). The question therefore arises: how many paddocks would be optimal for such flexible rotational grazing systems? Through modelling, Morley (1968) predicted that, from the point of view of pasture growth alone, the optimum number of paddocks for a rotational system would probably be less than 10. In view of the experience of the present farmlet experiment, with its desire of taking into account a wider array of factors, including multiple mobs and control of internal parasites, we suggest that it is likely that the optimum number of paddocks would be well above 10 per farm.

While the IRG regime of farmlet C clearly resulted in superior control of gastrointestinal nematodes, this management regime did not result in increased pasture production, higher soil phosphorus concentration, higher stocking rates or higher profit. While the differences among farmlets in the amount of green herbage were not significant, the digestibility of both green and dead herbage was significantly lower on farmlet C (and B) than on farmlet A. Nevertheless, farmlet C had a slightly finer wool fibre diameter, slightly stronger staple strength for ewes, needed less supplementary feeding and had slightly higher ground cover. Due to the nature of intensive grazing systems, a much smaller proportion of paddocks on farmlet C was grazed at any one time; this higher stock density during grazing is likely to be the main reason for the lower animal performance on farmlet C as the animals had to compete intensely for the available green herbage. It is also likely that part of the reason for the lower animal performance on farmlet C was the low amounts of legume on this farmlet, which was associated with low soil nitrogen concentrations which would, in turn, have constrained pasture growth in winter.

It is interesting to speculate how the performance of farmlet C might have been enhanced. One suggestion from a Cicerone member, late in the experimental period, was that a 'higher input' version of farmlet C (similar to the inputs on farmlet A) should be studied (Edwards *et al*. 2013). Unfortunately, no funding was available to create this fourth farmlet to allow such a comparison. As with the other farmlets, it would also have been interesting to observe and measure the consequences of some better seasons on farmlet C, although we contend that the moderate soil fertility, the low proportion of legumes and the moderate proportion of temperate species on this farmlet would have limited the potential for high pasture growth rates.

Implications for optimal management of grazing enterprises

In spite of the limited duration of the experiment of 6.5 years and the constraints imposed by the drier-than-average conditions, the consideration of the multiple lines of accumulated evidence, together with modelling and optimisation procedures, has yielded several important outcomes from this body of work. Whereas modelling analyses suggested that farmlet A had the greater *potential* for profit over the long term, given a more representative climatic experience, one needs to reflect on how that might be achieved with lower levels of risk. If, for the creation of optimal net worth outcomes, pastures need to be maintained to persist over some 25 years (equivalent to a 4% per annum replacement rate) this would mean that managers would need to pay much greater attention to the maintenance of soil fertility and the strategic resting of pastures before they reach a critical degraded state (Behrendt *et al*. 2013*a*).

The challenge for graziers is to 'simultaneously balance many 'balls' in the air' (Williams 1994). On the basis of the interacting factors described in the present paper, we suggest that it is important to distinguish between the short-term, tactical 'balls' and the longer-term strategic 'balls'. Some tactical decisions include moving stock between paddocks, supplementary feeding and drenching. In contrast, strategic decisions can be crucial for delivering optimal results over the long term. Such decisions include maintaining soil fertility and an adequate proportion of legumes through nutrition and grazing management to help manipulate pasture composition, the gradual renovation of pastures to enhance the proportion of desirable species, integrated parasite management, allowing increases in stocking rate only when the potential for pasture growth has been enhanced, the creation of more protection for lambing ewes, and the provision of sufficient paddocks to facilitate rotation when necessary.

Decisions regarding changes to stocking rate would be aided greatly by being able to regularly monitor all paddocks through remote sensing, so as to estimate potential pasture growth rate (Donald *et al*. 2013), which is a fundamental parameter governing stocking rates. Regular and timely estimates of paddock- and farm-scale green herbage mass, which can also be derived from satellite images (Edirisinghe *et al*. 2011), would also greatly assist graziers to ensure that critical quantities of green herbage are always available to their stock as a means of optimising pasture utilisation while avoiding over-grazing that can threaten pasture persistence and limit the need for supplementary feeding.

In addition, regular monitoring of liveweights and condition scores would enable the detection of changes in livestock performance and allow adjustments of stocking rates or paddock moves to be made in a more timely way. Options for reducing worm burdens in sheep within flexible rotational grazing systems include preparation of 'clean' pastures for young, susceptible stock (Bailey *et al*. 2009), mixed grazing with cattle or sheep of lesser susceptibility (wethers), and lightly grazing pasture with cattle before grazing with sheep.

Ultimately, improved tools need to be developed to assist graziers to work their way through these decision dilemmas. There is a need for more robust and timely delivery of optimal solutions which take into account the different rates of change of the various factors that can be controlled by management so that long-term profits can be realised without damage to the natural resources that support grazing enterprises.

The present paper has highlighted the complexity of managing grazing enterprises and the problems of making any simple, prescriptive recommendations. Grazed farms are challenging agroecosystems that require a wide range of measurements, skills and observations that need to be continually reviewed to achieve desired outcomes. In addition, conditions and circumstances vary from paddock to paddock, from farm to farm, while skill levels and goals vary from one livestock producer to another. Issues that might appear to be simple, such as maintaining a desirable pasture composition, are affected not only by the species and their relative growth rates across different seasons but also by soil type, soil fertility, slope, aspect, rainfall and temperature, grazing rest, livestock species, livestock class, ground cover and the manager's attitude to risk.

The particular version of IRG tested here (on farmlet C) provided substantial benefits in terms of animal health but the level of animal production supported by this system was overly constrained by the limited dietary choice offered grazing animals and the low amounts of legume, which restricted the protein supply for livestock. The typically managed farmlet (B), which had the best cash position over the relatively short duration of the experiment, was found to have developed several negative attributes that suggested that it may not be a profitable or sustainable alternative management system over the long term. In answer to the hypothesis put earlier in the paper, we conclude that more profitable and sustainable outcomes are most likely to arise from grazing enterprises that are proactively managed towards optimal outcomes, which include the maintenance of sufficient desirable perennial grasses, combined with adequate legume content and are supported by the maintenance of soil fertility while employing flexible rotational grazing.

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