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Simulating the impact of fertiliser strategies and prices on the economics of developing and managing the Cicerone Project farmlets under climatic uncertainty

Karl Behrendt[A,E], *James M. Scott*[B], *Oscar Cacho*[C] *and Randall Jones*[D]

[A]EH Graham Centre for Agricultural Innovation (NSW Department of Primary Industries and Charles Sturt University), Charles Sturt University, School of Agricultural and Wine Science, Wagga Wagga, NSW 2678, Australia.
[B]University of New England, School of Environmental and Rural Science, Armidale, NSW 2351, Australia.
[C]University of New England, School of Economics, Armidale, NSW 2351, Australia.
[D]NSW Department of Industry and Innovation, Forest Road, Orange, NSW 2800, Australia.
[E]Corresponding author. Email: kbehrendt@csu.edu.au

Abstract. The application of fertilisers to pastures in the high rainfall regions of southern Australia has contributed to large increases in carrying capacity following the widespread adoption of the practice since the late 1940s. Recently, large shifts in the worldwide demand for fertiliser inputs have lead to large rises in the cost of fertiliser inputs. These increasing costs have significant potential ramifications on the future management of soil fertility and its interaction with the persistence and profitability of sown pastures, especially during periods of climatic uncertainty.

A dynamic pasture resource development simulation model was used to investigate the implications of fertiliser rates and costs on the efficient management of soil fertility under climatic uncertainty. The framework also allowed the investigation of how the management of soil fertility interacts with the utilisation of pasture resources through different stocking rates. In the application of this method to the Cicerone Project farmlets case study, fertiliser input costs were found to influence the optimal combination of fertiliser inputs and stocking rate. Analyses of the dynamic interaction between fertiliser application and cost, stocking rate and the persistence of desirable species enabled the identification of the most risk-efficient strategies. The implications for grazing industries in the high rainfall regions of southern Australia are discussed.

Additional keywords: climatic uncertainty, dynamic pasture resource model, fertiliser input costs, pasture persistence, risk-efficient frontier.

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Introduction

Australia maintains approximately 60% of its surface area as native or sown grasslands supporting the majority of the nation's livestock industries (Kemp and Michalk 1994). Of these grasslands, 6% have been improved through the sowing of introduced species combined with fertiliser application. These modified pastures carry 41% of Australia's domestic livestock (Hutchinson 1992). The sowing of so-called 'improved' pasture species with fertilisation had the greatest influence on returns to livestock production during the post-war decades of the 1950s and 1960s; these practices were considered to be most feasible economically in the high rainfall regions (Menz 1984; Vere and Muir 1986). Over these decades, net farm incomes were estimated to have doubled as a result of this development as the application of phosphate-based fertiliser increased pasture production by up to 10-fold and livestock production by at least 3-fold in the high rainfall temperate pasture zone of Australia (Crofts 1997).

Since 1974, when a government subsidy for the purchase of superphosphate was removed, the area of pasture receiving fertiliser applications has been substantially lower than those areas where introduced species have been sown (Crofts 1997). This divergence, which resulted in a reduction in soil fertility on sown areas, has been suggested as one of the key reasons for the decline in productivity of legumes in pastures (Vere 1998). In turn, this has influenced livestock production and the productivity and persistence of sown and fertility-responsive grass species (Kemp and King 2001).

More recently, continued increases in the worldwide consumption of fertilisers has lead to large rises in the cost of fertiliser inputs used at the farm level (IFA 2008). The increasing cost of fertiliser inputs would be expected to further reduce the consumption of phosphate fertilisers in Australia, as producers have tended to treat expenditure on fertiliser inputs as discretionary (Scott and Cacho 2000), although it has been accepted that fertiliser is an economical input over the long term (Freebairn 1992).

The Cicerone Project farmlet experiment

The Cicerone Project's farmlet experiment was set up to investigate the sustainability and profitability of three farm management systems in the Northern Tablelands region of New South Wales (Scott *et al*. 2013). The experiment was conducted on three farmlets, each of 53 ha, over the period July 2000 to December 2006. Farmlet A represented a high input, flexible grazing system; Farmlet B represented a moderate input system with flexible grazing (described as typical district practice); and Farmlet C represented an intensive rotational grazing system with the same moderate inputs as the typical practice farmlet (B) but with more than four times the number of paddocks. Empirical results from the experiment showed that botanical composition in all of the farmlets changed in response to the level of system inputs and, to a lesser extent, to grazing management (Shakhane *et al*. 2013).

Increases in the productivity of grazing enterprises from the application of fertiliser have occurred due both to increases in the growth rate of pastures, including newly established, as well as naturalised and native pastures, and improvements in the quality of the feed on offer for ruminant production (Sale and Blair 1997; Saul *et al*. 1999). The improved quality of feed on offer is a result of changes in both botanical composition and improvements in the DM digestibility and crude protein content of the grasses and legumes found within the sward, as well as the pastures' response to utilisation (Saul *et al*. 1999). The maintenance of soil fertility has also been shown to be necessary for the persistence and productivity of introduced and desirable species and to slow the ingress of less desirable species (Cook *et al*. 1978*a*; Garden and Bolger 2001).

Decisions for developing and managing pastures, through the use of alternative technologies, occur at different stages over the planning horizon. The sowing of introduced species is a strategic decision, whereas, in most grazing systems, the application of fertiliser tends to operate at a more tactical level between production years. Grazing management, which includes both the choice of stocking rate and time livestock spend on a paddock (and the corresponding rest periods from grazing), operates at a tactical level over periods ranging from a year in 'set stocking' systems to weeks or months in tactical grazing systems through to days in intensive rotational grazing systems.

The natural phenomenon of climate variability exposes producers to production risk (Antle 1983). In the high rainfall temperate pasture zone, variable climatic conditions have been identified as one of the main sources of risk faced by sheep production businesses (Counsell and Vizard 1997). In evaluating the benefits of the technologies represented by different strategic and tactical decisions, consideration must be given to interactions between the technologies and to the exogenous risk experienced by the grazing enterprise. The expression of these interactions is in the form of biomass production in the short term and botanical composition of the pasture over the longer term. This means that there are important inter-temporal trade-offs between the productivity of a grazing system and the persistence of desirable species comprising the pastures.

Another paper in this edition identified the optimal pasture investment and grazing management decisions that achieve the most profitable and sustainable outcomes at three soil fertility regimes (Behrendt *et al*. 2013). This paper adds to that study by analysing fertiliser strategies in more detail and extending the analysis to include the effect of fertiliser prices on the economic value of developing and managing the Cicerone Project farmlets under climatic uncertainty. The modelling approach used here enables some of the key outcomes of the Cicerone Project farmlets to be investigated over a much longer time frame than was possible within the experiment. The use of computer experiments also allows significantly more combinations of fertiliser applications, stocking rate, and climate scenarios to be explored and analysed than could be achieved through a biophysical experimental study.

The bio-economic framework used here takes into account climate risk and the dynamic relationships between soil fertility and pasture composition. This allows the estimation of benefits and costs associated with the application of fertiliser to be enhanced beyond what could be achieved by analysis of the empirical results of the Cicerone experiment alone. In the following section, the conceptual framework is briefly described, whereas a more detailed description has been given by Behrendt (2008) and in the Supplementary Material found on the Journal website.

Methods

This study is based on the Dynamic Pasture Resource Development (DPRD) model (Behrendt 2008), which is capable of simulating a dynamic pasture resource under stochastic climatic conditions. The method involves simulating changes in botanical composition in response to pasture growth and its utilisation by grazing livestock. This is done within a Monte Carlo simulation approach that allows risks associated with climate variability to be introduced into the analysis. The DPRD simulation model operates at the paddock level on a daily time step and contains 5 submodels accounting for:

- soil fertility [soil phosphorus (P), fertility gain through fertiliser application, fertility lost through consumption and fixation],
- pasture supply (pasture mass, growth, quality and consumption),
- botanical composition (intrinsic rate of population growth, impact of harvesting by livestock, and pasture renovation),
- pasture consumption and subsequent sheep meat and wool production (selective grazing of sward between species groups, pasture and supplementary feed consumption, wool growth and quality, net balance of liveweight gain or loss), and
- economic performance (seasonal value of production based on 1997–2007 mean meat and wool prices, seasonal costs of production including supplementary feeding and pasture sowing and fertiliser costs).

Figure 1 illustrates a conceptual outline of the DPRD model at the paddock level.

The production year is separated into four seasons that are linked to tactical and strategic decision points within a grazing system. The parameters that determine plant growth and botanical composition are allowed to change at seasonal time steps within the model. Within each season, pasture growth and

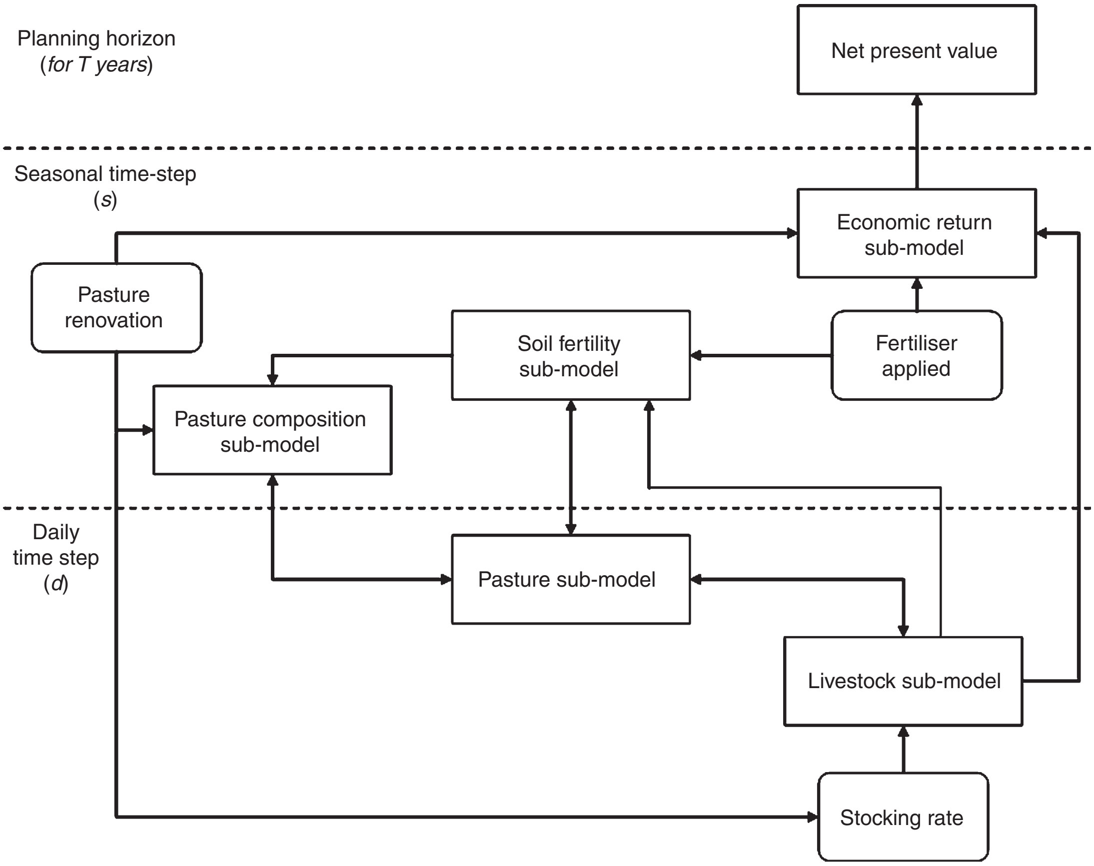

Fig. 1. A diagrammatic outline of the Dynamic Pasture Resource Development simulation model at the paddock level. Pasture renovation, fertiliser applied and stocking rate are decision variables.

consumption by grazing livestock operate on a daily time step. The relative areas occupied by desirable and undesirable species groups within the whole sward are modelled using exploited population growth modelling (Clark 1990). Computer experiments for different combinations of stocking rate and fertiliser application were undertaken over a 10-year planning horizon.

The 10-year Monte Carlo simulations of the DPRD model were used to derive a risk-efficient frontier (Cacho *et al*. 1999). The method consists of testing different combinations of technologies and management strategies and ranking them based on expected returns and risk to identify optimal sets of risk-efficient strategies. In contrast to the previous paper (Behrendt *et al*. 2013), in this case the risk is non-embedded, as the simulations describe the risky consequences of decisions applied in advance, before any risky states occur.

Botanical composition of the pasture resource

In the DPRD model, the space occupied by plant species is assumed to respond to climate, management and inputs. The approach used is analogous to in-field measures of the basal area of pasture species and is also similar to the methods of basal area adjustments applied in some rangeland models (Stafford Smith *et al*. 1995). Separation of pasture yield and basal area of species groups in modelling is justified as the latter variable provides a more meaningful and stable indicator of ecological or botanical composition change than pasture yield (Cook *et al*. 1978*b*).

The total area of pasture comprises two components, 'desirable' species and 'undesirable' species based primarily on nutritive value and acceptability to animals (McIvor 2001). Botanical composition is constrained to the relationship $X_D + X_U = 1.0$, where X_D is the proportion of desirable species and X_U is the proportion of undesirable species within the pasture sward. The population of X_D in the sward is modelled by differential equations describing population growth and harvesting. The pasture is treated as an exploitable renewable resource as described by Clark (1990). Within the model, botanical composition changes are influenced by soil fertility, which affects both the maximum area and rate of growth in area occupied by the X_D population within the sward (Cook *et al*. 1978*a*; Dowling *et al*. 1996; Hill *et al*. 2005). The modified partial paddock approach used within the DPRD model allows the X_D components within the sward to increase their basal area over time when soil nutrient status and grazing rest is adequate, even when no re-sowing occurs. This assumption is supported by field evidence, where degraded sown pastures increase their basal areas under conditions of high soil fertility and in response to grazing rests, with a consequent increase in the proportion of the sward that is occupied by X_D native or introduced species (Cook *et al*. 1978*a*; Garden *et al*. 2000).

Soil fertility and pasture growth

The soil fertility submodel is similar to the fertility scalars used in other biophysical models of grazing systems (Moore *et al*. 1997), but with the index limiting pasture growth at a daily time step as described in Cacho (1998). The soil fertility effect for a season is based on the soil P levels [expressed as mg/kg Colwell P (Colwell 1963)] carried over from the previous season and any increases in soil P from the application of fertiliser. The relative yield restriction for pasture growth is estimated using the Mitscherlich equation (Thornley and France 2007). Changes to the level of soil P between seasons are a function of the amount of fertiliser applied and the maintenance fertiliser requirements of the grazing system. This assumes that pasture growth responds to fertiliser applied in the current season, and the residual P pool for the following season is reduced due to maintenance P requirements over the season. Maintenance fertiliser requirement is estimated from the relationships described in Helyar and Price (1999) as a function of P losses from the paddock through livestock product exports (sheep meat and wool) and removal of soil P to sheep camps, the accumulation of non-exchangeable inorganic and organic P reserves, and P gains from non-fertiliser inputs (such as that sourced from rainfall). The soil fertility submodel also accounts for the phosphate-buffering capacity of the soil and the minimum amount of slow release P from non-expendable pools available for plant growth. Pasture growth in the DPRD model is based on the sigmoidal pasture growth curve of Cacho (1993).

Livestock production

To represent the production of wool and meat, the livestock submodel responds to changes in the available pasture mass and changes in botanical composition, which inherently affect the quality of feed on offer. A mechanistic approach is applied in the DPRD livestock submodel, with much of it based on the equations used in the GrazPlan suite of models (Donnelly *et al*. 1997; Freer *et al*. 2007). This ensures there are adequate feedback mechanisms between the selective grazing by livestock and changes in botanical composition.

In this submodel, grazing sheep are capable of selectively grazing between the desirable and undesirable partial paddocks and among the digestibility pools of DM available to them within each partial paddock. With the two functional groups maintaining different proportions of DM in each digestibility pool, the livestock's capacity for selective grazing will enable production to respond to changes in botanical composition, as well as to determine the impact of grazing livestock on botanical composition. This representation of selective grazing is based on the assumption that grazing sheep will aim to maximise their intake based on the DM digestibility of plants, and has been validated by research into the influence of pasture degradation on diet selection and livestock production at a site adjacent to the Cicerone farmlet experiment (Chen *et al*. 2002). Supplementary feeding is also available in the model as a means of substituting for the consumption of pasture DM.

In this analysis, supplementary feeding was used to ensure that the animals did not fall below a condition score of 2, which represents the minimum for wethers to be capable of survival and production, with a reduced likelihood of producing tender wool (Morley 1994), or when total pasture DM was less than 100 kg DM/ha, to prevent disappearance of the pasture sward from the DPRD model simulation. The supplementary feeding decision rules were set at such low levels to allow economic optimisation to run largely unconstrained while ensuring negative pasture mass values did not occur. The lower limit of 100 kg DM/ha was not a sustainability constraint but a numerical constraint to avoid errors in the model solution.

The DPRD model was calibrated based on a complex mechanistic grazing systems model, AusFarm (CSIRO 2007), which is a scriptable version of the GrazPlan suite of decision support tools (Donnelly *et al*. 1997). The AusFarm program in turn was calibrated to data from the Cicerone Project's farming systems experiment as detailed in Behrendt *et al*. (2013). The initial state of pasture and soil resources reported at the start of the Cicerone Project experiment formed the starting conditions for the analysis.

Experimental design

Experiments using the DPRD model were performed to investigate the effects of stocking rate and fertiliser input on wool and sheep meat production, profitability and risk. These experiments addressed several of the same issues studied in the Cicerone Project farmlet experiment, but have the capacity to consider much longer time frames and allow significantly more combinations of stocking rate, grazing rest and climate scenarios than was possible within the Cicerone experiment. Each simulation experiment ran over a period of 10 years which corresponds to the perceived maximum persistence of sown perennial pastures by 80% of producers in the high rainfall temperate pasture zone of south-eastern Australia (Reeve *et al*. 2000). Ten stocking rate levels [3–30 dry sheep equivalents (DSE)/ha set stocked] were tested against four levels of fertiliser application (0, 42, 125 and 250 kg/ha.annum of single superphosphate, SS). This represents a 10 by 4 factorial experiment, a total of 40 treatment combinations, with 300 iterations per treatment (representing 300 randomised annual combinations of a 30-year climate dataset over 1976–2006 for Armidale, NSW). In preliminary testing of the DPRD model, this number of iterations was required to enable convergence of model outcomes with increasing numbers of iterations, with convergence measured using the sum of squared deviations between subsequent outcome populations (Behrendt 2008). Three fertiliser prices were tested ($254, $550 and $850/t SS) to assess the effect of this input cost on optimal pasture resource management.

The initial values used in the simulation experiments represent the mean values extracted from the Cicerone Project database for all paddocks measured around the start of autumn 2001. The starting soil fertility level was assumed to be moderate with 22 mg/kg Colwell P, the botanical composition was 44% X_D and 56% X_U species in the sward, and the pasture mass was 2300 kg DM/ha. The assumed starting point for the simulations was 1 April (start of autumn season).

Results

The summarised biophysical results derived from the simulation experiments are shown in Table 1.

Table 1. Biophysical results of the simulation experiments (mean of 300 iterations with one standard deviation in parentheses)
SS is single superphosphate

Stocking rate (DSE/ha)	Fertiliser applied (kg SS/ha.year) 0	42	125	250
Proportion of area occupied by desirable species at the end of the simulation				
3	0.19 (0.05)	0.49 (0.06)	0.86 (0.04)	0.89 (0.04)
6	0.08 (0.03)	0.28 (0.07)	0.77 (0.06)	0.85 (0.06)
9	0.05 (0.00)	0.13 (0.06)	0.70 (0.08)	0.80 (0.08)
12	0.05 (0.00)	0.06 (0.02)	0.58 (0.10)	0.76 (0.09)
15	0.05 (0.00)	0.05 (0.00)	0.47 (0.11)	0.72 (0.11)
18	0.05 (0.00)	0.05 (0.00)	0.35 (0.12)	0.67 (0.13)
21	0.05 (0.00)	0.05 (0.00)	0.23 (0.12)	0.65 (0.13)
24	0.05 (0.00)	0.05 (0.00)	0.12 (0.08)	0.61 (0.14)
27	0.05 (0.00)	0.05 (0.00)	0.07 (0.04)	0.56 (0.16)
30	0.05 (0.00)	0.05 (0.00)	0.05 (0.01)	0.50 (0.18)
Soil fertility at the end of the simulation (mg/kg Colwell P)				
3	3.0 (0.0)	8.3 (1.1)	34.6 (1.8)	81.5 (1.9)
6	3.0 (0.0)	5.5 (1.0)	28.5 (1.9)	74.7 (2.2)
9	3.0 (0.0)	4.1 (0.8)	23.3 (2.2)	68.5 (2.5)
12	3.0 (0.0)	3.4 (0.5)	19.0 (2.3)	63.1 (2.9)
15	3.0 (0.0)	3.1 (0.2)	15.7 (2.3)	58.1 (3.2)
18	3.0 (0.0)	3.0 (0.0)	12.9 (2.3)	54.3 (3.6)
21	3.0 (0.0)	3.0 (0.0)	10.9 (2.3)	50.2 (3.7)
24	3.0 (0.0)	3.0 (0.0)	10.5 (2.5)	46.7 (4.1)
27	3.0 (0.0)	3.0 (0.0)	9.1 (2.0)	43.7 (4.0)
30	3.0 (0.0)	3.0 (0.0)	8.2 (1.8)	41.5 (4.6)
Wool production (kg clean wool/head.year)				
3	3.4 (1.1)	4.4 (0.6)	5.0 (0.5)	5.1 (0.5)
6	3.0 (1.1)	3.7 (0.8)	4.7 (0.5)	4.9 (0.5)
9	2.8 (0.9)	3.2 (0.9)	4.4 (0.6)	4.6 (0.6)
12	2.7 (0.8)	2.9 (0.9)	4.0 (0.6)	4.4 (0.6)
15	2.6 (0.6)	2.7 (0.7)	3.7 (0.6)	4.2 (0.6)
18	2.6 (0.5)	2.7 (0.6)	3.4 (0.5)	3.9 (0.6)
21	2.6 (0.4)	2.6 (0.5)	3.2 (0.5)	3.7 (0.5)
24	2.7 (0.4)	2.6 (0.4)	2.9 (0.5)	3.5 (0.5)
27	2.7 (0.3)	2.7 (0.4)	2.7 (0.5)	3.4 (0.5)
30	2.7 (0.3)	2.7 (0.3)	2.6 (0.4)	3.2 (0.4)
Wool fibre diameter (microns)				
3	18.5 (2.2)	20.2 (1.5)	21.2 (1.2)	21.4 (1.2)
6	18.0 (1.9)	19.2 (1.8)	20.7 (1.4)	21.0 (1.4)
9	17.9 (1.7)	18.3 (1.9)	20.2 (1.5)	20.7 (1.5)
12	18.0 (1.4)	17.9 (1.7)	19.7 (1.6)	20.3 (1.6)
15	18.0 (1.2)	17.8 (1.5)	19.2 (1.6)	19.9 (1.7)
18	18.0 (1.1)	17.8 (1.3)	18.7 (1.6)	19.5 (1.7)
21	18.0 (1.0)	17.9 (1.2)	18.2 (1.5)	19.2 (1.7)
24	18.1 (1.0)	18.0 (1.1)	17.8 (1.4)	18.9 (1.7)
27	18.1 (0.9)	18.0 (1.0)	17.6 (1.3)	18.7 (1.6)
30	18.2 (0.9)	18.1 (1.0)	17.5 (1.2)	18.4 (1.5)
Liveweight change (kg liveweight/head.year)				
3	5.4 (13.5)	16.5 (5.6)	22.0 (4.2)	23.1 (4.2)
6	–0.5 (13.8)	10.2 (8.2)	19.1 (4.9)	20.7 (4.8)
9	–4.0 (12.9)	3.7 (10.7)	15.7 (5.5)	18.1 (5.4)
12	–6.2 (11.8)	–1.5 (11.5)	12.2 (6.1)	15.5 (5.9)
15	–7.9 (10.4)	–4.9 (10.8)	8.6 (6.3)	12.8 (6.2)
18	–8.8 (9.3)	–7.1 (9.8)	5.0 (6.5)	9.8 (6.4)
21	–9.7 (7.9)	–8.4 (8.8)	1.5 (6.7)	7.4 (6.4)
24	–10.0 (7.0)	–9.4 (7.6)	–2.6 (7.3)	5.0 (6.4)
27	–10.3 (5.9)	–10.2 (6.5)	–5.5 (7.1)	2.7 (6.3)
30	–10.7 (5.1)	–10.4 (5.7)	–7.9 (6.7)	0.1 (6.0)

Table 1. (*continued*)

Stocking rate (DSE/ha)	Fertiliser applied (kg SS/ha.year) 0	42	125	250
Supplementary feeding (kg DM/ha.year)				
3	18 (36)	0 (0)	0 (0)	0 (0)
6	113 (161)	4 (12)	0 (1)	0 (0)
9	298 (338)	42 (87)	1 (3)	1 (2)
12	581 (563)	194 (297)	8 (20)	4 (11)
15	906 (778)	461 (578)	21 (48)	15 (35)
18	1305 (1025)	827 (860)	43 (89)	33 (72)
21	1750 (1247)	1258 (1154)	95 (174)	54 (109)
24	2242 (1494)	1748 (1418)	245 (352)	84 (157)
27	2755 (1712)	2229 (1648)	445 (568)	136 (235)
30	3328 (1898)	2804 (1918)	778 (857)	232 (340)

Fertiliser strategies and soil fertility

Soil fertility at the end of the simulation period ranged from 3.0 to 81.6 mg/kg Colwell P. The levels of soil P increased with increasing rates of fertiliser application and decreasing stocking rates. With an initial soil P level of 22 mg/kg Colwell P, maintenance states of soil fertility were achieved at stocking rates of 9–12 DSE/ha and superphosphate applications of 125 kg/ha.year, which correspond to the findings of Guppy *et al*. (2013). This relationship is demonstrated in Fig. 2*a*, which shows how the mean soil P levels change over the simulated period in response to different rates of fertiliser application. It indicates that at a stocking rate of 12 DSE/ha, the application of 125 kg SS/ha.year largely is approximately equivalent to a maintenance rate. In contrast, the application of 250 kg SS/ha.year continues to build up soil P levels whereas application rates of 0 or 42 kg SS/ha.year degrade soil P levels. The latter ultimately affects pasture productivity and composition, and the levels of profitable production attainable from grazing livestock.

Pasture resource

The proportion of X_D remaining and the level of soil P after 10 years of grazing were affected by both the stocking rate and levels of fertiliser application. The proportion of X_D ranged from 90 to 5% (Table 1). The highest levels of X_D were maintained under low stocking rate and high soil fertility conditions. With increasing stocking rates and decreasing soil fertility, the persistence of X_D declined to the lower limits within the 10-year simulation period (Fig. 2*b*).

Under the lowest soil fertility conditions, the highest level the proportion of X_D reached was 19%. At higher soil fertility levels, the persistence of X_D increased, with higher stocking rates capable of being maintained. With low rates of fertiliser application (42 kg SS/ha.year) stocking rates of ~3 DSE/ha allowed the pasture to persist in its initial state until the end of the 10-year simulated period. With stocking rates of 15 and 30 DSE/ha, moderate and high levels of fertiliser application respectively were required to maintain the pasture in its initial state.

There was also a tendency for the final proportion of X_D in the sward, after 10 years of set stocked conditions, to be more variable with increasing stocking rates and fertiliser applications (Table 1). Under low fertiliser applications and moderate to high stocking rates, the proportion of X_D at the end of 10 years consistently trended towards the lower limit and the expected outcomes were not as variable.

Notably, Fig. 2*c* also indicates that total available pasture in the paddock declines under low levels of fertiliser application (0 and 42 kg SS/ha.year) at a stocking rate of 12 DSE/ha, whereas under moderate and high fertiliser application rates (125 and 250 kg SS/ha.year), similar quantities of total available pasture are maintained over the simulated period. This indicates that the observed livestock production benefits from high fertiliser applications arise from differences in pasture composition and its subsequent effect on pasture quality (due to the higher proportion of X_D in the sward).

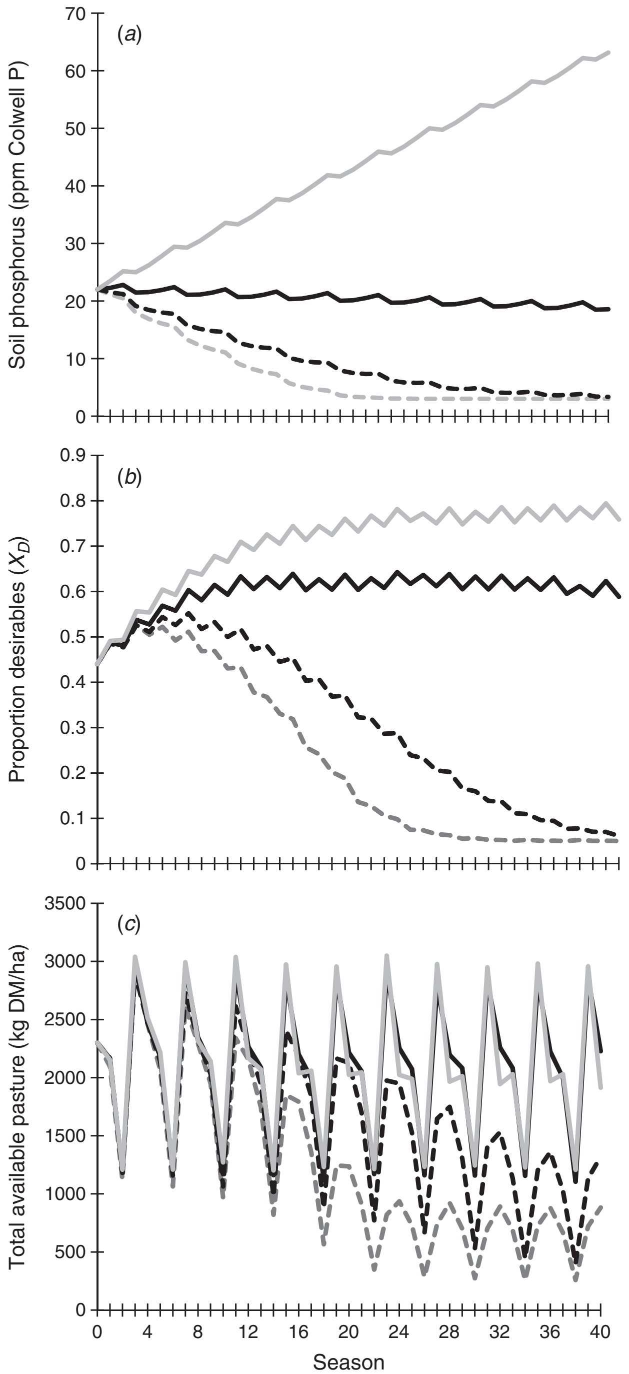

Fig. 2. Mean (*a*) soil fertility levels, (*b*) proportion of desirable species in the pasture sward, and (*c*) available pasture DM; for 300 iterations over the simulated period of 40 seasons under different fertiliser strategies [—— 250 kg single superphosphate (SS)/ha.year; —— 125 kg SS/ha.year; - - - - 42 kg SS/ha.year; - - - - 0 kg SS/ha.year] at a stocking rate of 12 dry sheep equivalent/ha.

A pattern was found between the mean annual pasture mass and proportion of X_D at the end of the 10-year simulation (Fig. 3). This indicated that when a mean pasture mass of less than 1500 kg DM/ha was maintained and received low levels of fertiliser application, the proportion of X_D in the sward degraded to 5% within the 10-year simulation. However, with increased mean annual pasture mass the proportion of X_D in the sward, after 10 years, increased. These results suggest that a mean pasture mass of at least 2000 kg DM/ha is required to maintain the proportion of X_D at over 50%. However, as soil fertility improves, the mean pasture mass required to maintain higher proportions of X_D declines. This response occurs due to the ability of the X_D functional group to more rapidly increase their basal coverage under favourable seasonal conditions with high levels of soil fertility.

Wool production and liveweight change

Livestock production was sensitive to stocking rate and fertiliser application. Wool production ranged from 2.6 to 5.1 kg clean wool/head with corresponding fibre diameters of 17.5–21.4 microns (Table 1). Wool cut increased with decreasing stocking rates and increasing levels of fertiliser application.

Over the 10-year simulation, total mean annual wool production increased with increasing stocking rates, albeit at a declining rate of increase with increasing stocking rates (Table 1). Wool production was also lower under lower levels of fertiliser application.

Liveweight gain was strongly influenced by level of fertiliser application and stocking rate. The expected liveweight gain or meat production over a year increased with increasing levels of

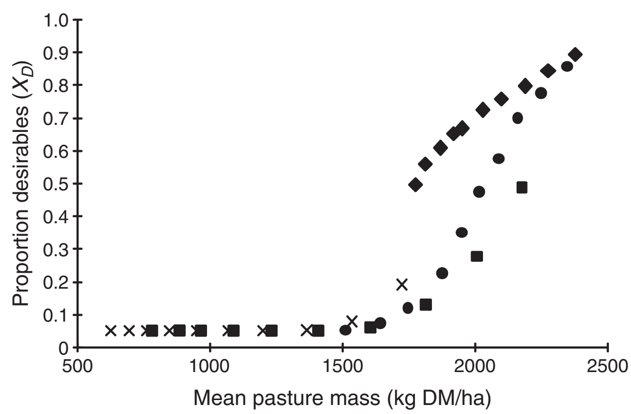

Fig. 3. Relationship between mean pasture mass and persistence of desirable species measured as the proportion of desirables, X_D, in the sward after 10 years of grazing under different rates of fertiliser application [×, 0 kg single superphosphate (SS)/ha.year; ■, 42 kg SS/ha.year; ●, 125 kg SS/ha.year; ◆, 250 kg SS/ha.year].

fertiliser application. The mean total annual gain per head varied from a loss of 10.7 kg to a gain of 23.1 kg over the four seasons. Maximum liveweight gain per ha occurred when stocking rates were 3, 6, 12 and 15 DSE/ha under zero, low, moderate and high fertiliser rates, respectively (Table 1). These stocking rates correspond to gains per head of 5.4, 10.2, 12.2 and 12.8 kg to produce a total of 16.2, 62.5, 146.0 and 192.5 kg liveweight/ha, respectively.

Supplementary feeding tended to increase exponentially with increasing stocking rates, but its rate of increase is reduced with increasing levels of fertiliser application (Table 1). The highest rates of supplementary feeding were not profitable (Table 2) and occurred when high stocking rates were run in conjunction with no or low levels of fertiliser applications. This explains the reason for the convergence of wool and meat production at the higher stocking rates, as the animals are largely maintaining survival condition scores from the consumption of supplements.

Economic returns and risk

The economic returns, presented as the average annual gross margin ($/ha.year) and expected present value of the 10-year simulation ($/ha), were sensitive to the level of fertiliser application, its input cost and the imposed stocking rate (Table 2). The variability of annual average gross margin returns, indicated by the standard deviation, increased with increasing stocking rates for all levels of fertiliser application. However, at each stocking rate level, there was also a general trend for standard deviations to decrease with increased fertiliser input.

The patterns for annual gross margin were similar to those for meat production per ha. However, as stocking rates increased, wool production (and its fibre diameter) had an increasing influence on gross margin. Annual gross margins tended to increase with increasing levels of fertiliser application across all stocking rates, regardless of the fertiliser input cost. At stocking rates of less than 9 DSE/ha, moderate and low fertiliser rates achieved higher annual gross margin returns than the high fertiliser rate. This was due to reduced exports of P via products, increasing amounts of the P being applied contributing to the residual P pool, and P levels having less effect on productivity once Colwell P levels reached over 35 mg/kg.

If the risks associated with expected returns are ignored, the maximum gross margins at a fertiliser cost of $254/t occurred with high fertiliser applications and a stocking rate of 27 DSE/ha, which is significantly higher than the targeted and achieved stocking rate in the Cicerone Project. The stocking rates that maximised average annual gross margins were 6, 9 and 18 DSE/ha under zero, low and moderate fertiliser levels, independently of fertiliser cost. The only exception was under high fertiliser application rates, where the stocking rate that maximised gross margin reduced from 27 to 24 DSE/ha at fertiliser costs of $550 and $850/t, respectively. These 'optimum' stocking rates take into account the inter-temporal costs and benefits of changing soil fertility through its effect on pasture growth and composition;

Table 2. Economic results of the stochastic simulation experiments (mean of 300 iterations with one standard deviation in parentheses)
SS is single superphosphate with bolded data indicating strategies that are risk-efficient combinations

Stocking rate (DSE/ha)	Input cost of single superphosphate ($/t bulk)									
	$254				$550			$880		
	Fertiliser applied (kg SS/ha/year)				Fertiliser applied (kg SS/ha.year)			Fertiliser applied (kg SS/ha.year)		
	0	42	125	250	42	125	250	42	125	250
	Mean gross margin ($/ha.year)									
3	49 (37)	67 (17)	64 (14)	36 (14)	55 (17)	28 (14)	–38 (14)	42 (16)	–10 (14)	–113 (14)
6	64 (103)	131 (42)	161 (31)	141 (31)	118 (43)	125 (31)	66 (31)	106 (43)	87 (31)	–10 (32)
9	40 (179)	160 (86)	237 (48)	229 (50)	147 (90)	200 (48)	156 (49)	133 (90)	166 (48)	77 (51)
12	–14 (258)	134 (174)	292 (67)	302 (70)	122 (176)	256 (65)	225 (69)	111 (175)	219 (66)	150 (70)
15	–78 (320)	72 (269)	325 (88)	357 (91)	54 (276)	289 (87)	278 (92)	40 (274)	253 (87)	211 (88)
18	–153 (380)	–16 (352)	341 (109)	390 (114)	–31 (354)	303 (109)	322 (111)	–42 (355)	268 (110)	241 (114)
21	–241 (424)	–108 (422)	338 (143)	418 (136)	–122 (419)	294 (145)	350 (137)	–135 (416)	256 (145)	270 (140)
24	–328 (473)	–210 (472)	285 (205)	435 (158)	–218 (470)	260 (194)	358 (164)	–233 (471)	220 (197)	290 (161)
27	–417 (505)	–309 (511)	227 (267)	438 (185)	–323 (519)	186 (262)	357 (189)	–332 (521)	154 (266)	283 (188)
30	–522 (531)	–413 (559)	128 (346)	411 (217)	–427 (545)	93 (340)	339 (218)	–440 (551)	49 (339)	260 (218)
	Expected present value ($/ha)									
3	408 (40)	**527 (29)**	492 (39)	273 (41)	**433 (29)**	208 (39)	–297 (40)	**332 (30)**	–85 (37)	–881 (42)
6	591 (104)	**1044 (53)**	1243 (86)	1079 (100)	**943 (56)**	957 (93)	503 (90)	**850 (54)**	662 (89)	–84 (94)
9	478 (145)	**1306 (101)**	**1831 (131)**	1762 (148)	**1214 (95)**	**1546 (134)**	1190 (160)	**1108 (104)**	**1277 (136)**	581 (152)
12	134 (158)	1189 (153)	**2262 (189)**	2323 (212)	1096 (152)	**1982 (195)**	1725 (215)	1013 (148)	**1702 (164)**	1146 (232)
15	–309 (182)	800 (174)	**2529 (233)**	**2747 (286)**	670 (180)	**2260 (224)**	2140 (295)	565 (183)	**1976 (236)**	1622 (280)
18	–839 (203)	205 (215)	2676 (293)	**3010 (374)**	91 (217)	**2386 (322)**	**2478 (362)**	6 (222)	**2111 (272)**	1847 (384)
21	–1483 (219)	–441 (241)	2679 (356)	**3225 (462)**	–547 (265)	2337 (390)	**2709 (405)**	–657 (245)	2042 (382)	2080 (458)
24	–2122 (249)	–1188 (292)	2328 (537)	**3359 (538)**	–1248 (286)	2113 (469)	**2762 (527)**	–1364 (298)	1808 (452)	**2236 (514)**
27	–2793 (301)	–1920 (339)	1929 (559)	**3389 (602)**	–2022 (323)	1602 (594)	2757 (644)	–2096 (337)	1361 (561)	2182 (646)
30	–3597 (363)	–2695 (364)	1236 (625)	3186 (813)	–2814 (393)	966 (611)	2635 (773)	–2914 (377)	617 (592)	2019 (825)

however, they do not take into account the risks associated with different fertiliser and stocking strategies. This means that the profit maximising strategies identified apply only to risk-neutral producers.

Optimal management strategies

To identify the optimal sets of management strategies independently of risk attitude, the simulated results were used to calculate the expected present value of annual gross margins over the 10-year planning horizon. Expected present values were then used to identify optimal sets of management strategies using a risk-efficient frontier (Cacho *et al*. 1999) for each level of fertiliser input cost (Fig. 4). Each point in the charts of Fig. 4 represents the result of a management strategy (fertiliser and stocking rate combination) in terms of its expected present value (profit) and its standard deviation (risk). Although the standard deviation of present value is a simplified representation of risk, it provides a convenient measure of variability of profits.

Risk-efficient management strategies represent the combinations at which economic return is maximised at a given level of risk. Risk-efficient strategies form a frontier along which expected returns and risk increase with increasing levels of fertiliser application and increasing stocking rates for all levels of fertiliser input cost.

Points that do not lie on the frontier represent inefficient management strategies. The strategy of applying no fertiliser in this analysis was found to be inefficient across all levels of fertiliser cost when compared with strategies where fertiliser was applied.

Table 3 provides an indication of the characteristics of risk-efficient management strategies for different levels of risk aversion in decision makers. The identified risk-efficient management strategies have been evenly grouped into low, moderate and high risk aversion sets, with the low risk aversion strategies found on the frontiers furthest to the right (i.e. risk-neutral sets of strategies that maximise returns regardless of the level of risk). In contrast, high risk aversion strategies are found furthest to the left of the frontier where profits are maximised but subject to low risk exposure. In other words, moving from high to low risk aversion is equivalent to moving from left to right in Fig. 4*d*, and this corresponds to higher coefficient of variation in expected profits (see last row of Table 3).

Results indicate that it is economically efficient to reduce fertiliser inputs with increasing fertiliser cost (Table 3), which results in a decline in the levels of soil P at the end of the 10-year

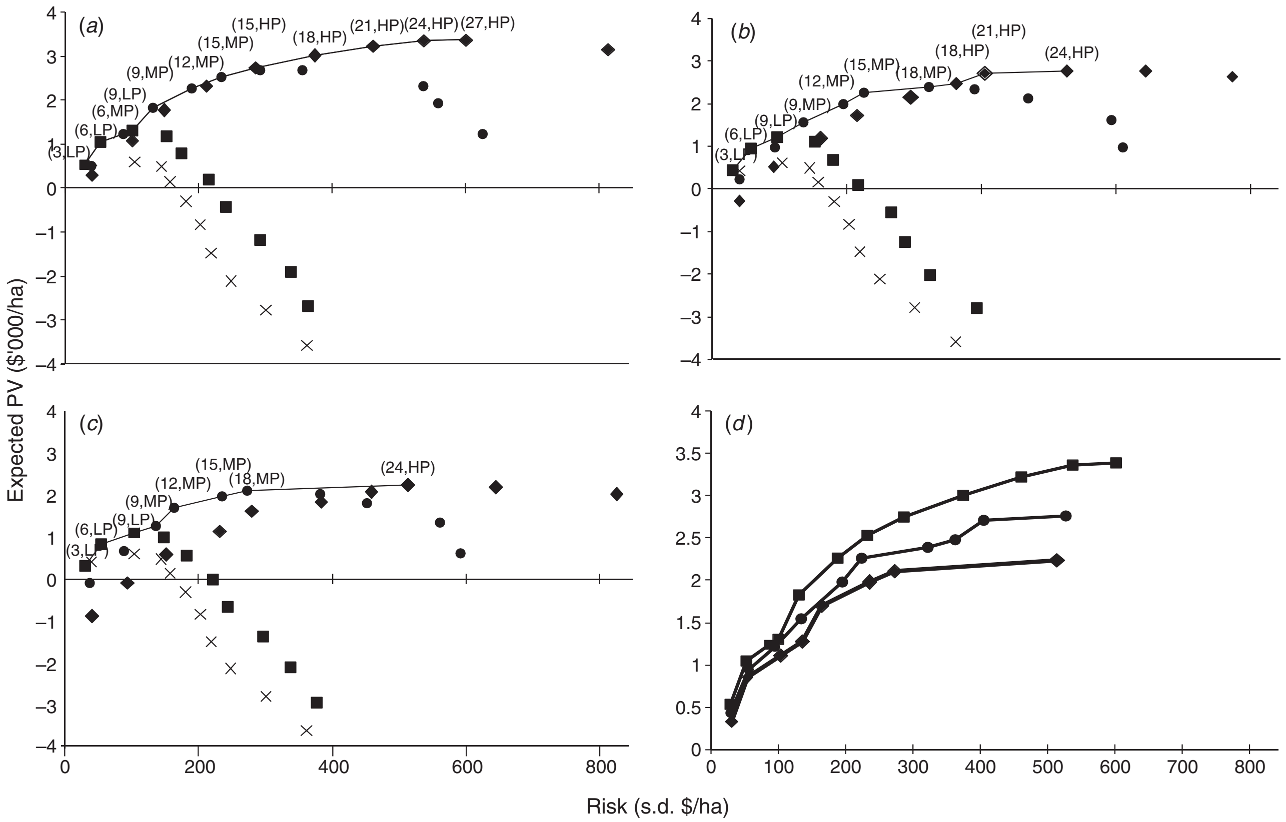

Fig. 4. Risk-efficient frontiers (solid line) for different combinations of stocking rate, fertiliser rate and price with (*a*) single superphosphate (SS) price $254/t, (*b*) SS price $550/t, (*c*) SS price $850/t, and (*d*) risk-efficient frontiers for different SS prices combined (■, $254/t; ●, $550/t; ◆, $850/t). Efficient sets in graphs (*a*), (*b*) and (*c*) are identified by stocking rate and fertiliser level in parentheses (SR.LP = 42, MP = 125, and HP = 250 kg SS/ha.year). Markers in graphs (*a*), (*b*) and (*c*) indicate different fertiliser strategies (×, 0 kg SS/ha.year; ■, 42 kg SS/ha.year; ●, 125 kg SS/ha.year; ◆, 250 kg SS/ha.year).

Table 3. Mean characteristics of risk-efficient sets of fertiliser and stocking rate strategies at different levels of fertiliser input costs and risk aversion

Descriptor	Fertiliser cost								
	$254			$550			$850		
	Risk aversion			Risk aversion			Risk aversion		
	High	Moderate	Low	High	Moderate	Low	High	Moderate	Low
Fertiliser applied (kg SS/ha.year)	63	156	250	42	125	250	42	97	167
Stocking rate (DSE/ha)	6	12.8	22.5	6	13.5	21	4.5	10	19
Proportion desirables	0.42	0.62	0.62	0.29	0.52	0.57	0.39	0.47	0.54
Soil phosphorus (mg/kg Colwell P)	12	29	49	6	18	50	7	15	25
Total available pasture (kg DM/ha)	2062	2072	1886	2004	2052	1906	2092	2026	1948
Meat production (kg LW /head.year)	12.3	12.3	6.2	10.1	10.4	7.6	13.3	10.6	6.4
Wool growth (kg clean/head.year)	4.00	4.07	3.64	3.78	3.89	3.75	4.05	3.89	3.58
Wool fibre diameter (microns)	19.6	19.8	19.1	19.2	19.5	19.2	19.7	19.4	19.0
Supplementary feeding (kg DM/ha.year)	12	11	77	17	19	57	2	18	50
Gross margin ($/ha.year)	130	303	420	107	262	343	74	173	271
Expected present value ($)	1030	2342	3246	863	2043	2650	591	1362	2108
Standard deviation of present value ($)	67	210	494	60	219	432	42	135	341
Coefficient of variation of expected present value (%)	6.5	9.0	15.2	7.0	10.7	16.3	7.1	9.9	16.2

simulated period. With increasing fertiliser input costs, risk-efficient sets of strategies also tended to reduce stocking rates, which also reduced risk (measured as the standard deviation of returns) within each level of risk aversion. However, increasing fertiliser price was associated not only with declining returns but also with increasing coefficient of variation of mean returns. The risk-efficient strategies also tended to maintain a reduced proportion of X_D in the pasture sward with increasing fertiliser input costs, but while maintaining similar levels of total available pasture. Table 3 also indicates that per head livestock performance (wool and meat production) is maintained across the risk-efficient sets, although, as would be expected, mean gross margins and expected present values for the risk-efficient strategies decline with increasing fertiliser input costs.

Discussion

The results of the simulation experiments indicate strong relationships between stocking rate and the rates of fertiliser applied on the persistence of X_D, and the production from those pastures. Stocking rate affects the level of pasture harvested and the degree of susceptibility of X_D not to persist under adverse seasonal conditions, such as drought. The persistence of X_D also interacts with soil fertility, which is a function of the level of fertiliser applied. These interactions and relationships are supported by experimental work conducted by others such as Cook *et al*. (1978*a*, 1978*b*) and Hill *et al*. (2004) who showed the importance of fertiliser application in maintaining the production of pastures and the persistence of sown species, while concurrently reducing the encroachment by X_U.

The results of the simulations suggest a maintenance fertiliser rate in the model of 1.2–0.93 kg of P/DSE.year. This corresponds to identified maintenance rates for sheep grazing systems in the high rainfall temperate pasture zone from long-term grazing trials (Cayley and Saul 2001) and the predicted maintenance rate of P application for the Cicerone farmlets of 1.1 kg P/DSE.year (Guppy *et al*. 2013).

When the model's relative performance of the various treatments is compared with long-term experimental trial work in the case study region (Hutchinson 1992), and the reported outcomes from the Cicerone farmlet trial, the results appear credible. For example, Shakhane *et al*. (2013) reported a significant correlation between soil P and desirable pasture functional groups such as sown perennial grasses and legumes on the farmlet trial. Guppy *et al*. (2013) also found a significant positive correlation between soil P and legume herbage, green digestible herbage and stocking rate. However, the use of seasonal pasture growth functions is a particular limitation when identifying, in absolute terms, optimal seasonal stocking rates, as they do not take into account adjustments to stocking rates and grazing management on a day-to-day or week-to-week basis.

The relationship between mean pasture mass and the persistence of X_D, illustrated in Fig. 3, suggests that for them to persist at proportions greater than 50%, moderate to high rates of fertiliser are required as a co-requisite to maintaining the pasture mass over 1900–2000 kg DM/ha on average over a year. Given the expected seasonal variation found in pasture mass, this would correspond to the minimum amount of pasture mass (1100–1200 kg DM/ha) required for the persistence of X_D as suggested by field experimentation (Dowling *et al*. 1996; Scott *et al*. 1997).

In this analysis, if risk of returns is ignored, high fertility systems maintained the highest gross margins under all levels of fertiliser input cost. The simulation results indicated that fertiliser strategies that increased P levels were also required to run higher stocking rates to ensure they remained a risk-efficient strategy. Low input systems were also found to be risk-efficient strategies. However, if consideration is given to the fixed costs of a grazing business, (which is ignored in gross margin analysis), which typically are in the vicinity of $80–$150/ha for wool producers in the Tablelands of NSW (Barrett *et al*. 2003), the lowest risk-efficient combinations of stocking rate and fertiliser input strategies (stocking rates of 3 and 6 DSE/ha and 42 kg SS/ha.year) would not be profitable. This also applies to the strategy of applying no fertiliser, which would result in degraded soil fertility and pastures, and an unprofitable grazing business as it remained a stochastically inefficient strategy when compared with strategies involving the application of fertiliser under all fertiliser input costs tested. These results support the findings of Scott and Cacho (2000) who concluded that maintaining soil fertility through applications of fertiliser should be a non-discretionary (or essential) strategy, especially when inter-temporal interactions with residual value of fertiliser and effects on pasture composition are taken into account.

Much of the literature regarding the choice between risky alternatives in agricultural production is oriented towards 'expected utility theory' (Hardaker *et al*. 2004). This assumes that producers will aim to maximise their personal satisfaction or 'expected utility' based on their personal utility function, which depends on their level of risk aversion. Antle (1983) suggests that, because risk affects the economic efficiency of all producers, regardless of their level of risk aversion, dynamic risk-neutral models are more useful than static risk-averse models for understanding the role of production risk in decision making.

In this analysis, the trade-offs between the profitability of the different combinations of strategies and their riskiness were examined through the use of a risk-efficient frontier. Once risk-efficient sets of decisions are identified, producers can select optimal strategies based on the profit they wish to generate and the risk they are willing to accept. In this analysis, risk-indifferent producers (those who aim to maximise average returns regardless of risk) would choose to operate with high stocking rates (~20 DSE/ha) and high fertiliser rates (167–250 kg SS/ha.year), even with increasing costs of fertiliser (Table 3). In contrast, a highly risk averse producer would select a combination of low stocking rates (4.5–6 DSE/ha) with low fertiliser rates (42 kg SS/ha.year).

The experimental simulations presented in this paper are a demonstration of the capacity of simulation models to generate detailed analyses which may assist decision makers to better understand the system they are managing. However, there are several limitations of this model and analysis that could be enhanced to further improve the information available for decision making.

In this application, the DPRD model may be enhanced further by increasing its complexity with the incorporation of pasture growth functions on a shorter time step (e.g. weekly or monthly); modification of soil fertility functions to more accurately reflect the interactions between both the levels of supplementary feeding and soil fertility, and pasture biomass and soil loss; and the development of a multi-paddock model with the capacity to handle more complex flock structures. In addition, it would be expected that changes in the value of outputs (meat and wool) with a more complex flock structure, would influence the optimal strategies identified for different levels of risk aversion in the decision maker. Another limitation of the use of such simulation techniques is that the risk to which the decision maker is exposed is not embedded in the decision making process (Hardaker *et al*. 1991). The tactical nature of stocking rate decisions has been addressed in Behrendt *et al*. (2013). In this study, the cumulative future consequences of fertiliser and stocking rate decisions, and their dynamic interactions within grazing systems has been taken into account, while the more tactical nature of fertiliser applications still remains an area of future research. This research will include fertiliser application as a decision variable and soil fertility as a state variable in the decision optimisation process.

To solve this dynamic and stochastic pasture resource management problem and identify optimal decisions in response to the state of the pasture resource and fertiliser input costs, the risks associated with decisions need to be embedded in the sequential decision making process, as described in Behrendt *et al*. (2013). This requires the use of more advanced numerical search procedures, such as genetic or evolutionary algorithms, grid-search techniques or stochastic dynamic programming.

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