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Optimising pasture and grazing management decisions on the Cicerone Project farmlets over variable time horizons

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Abstract. This study addresses the problem of balancing the trade-offs between the need for animal production, profit, and the goal of achieving persistence of desirable species within grazing systems. The bioeconomic framework applied in this study takes into account the impact of climate risk and the management of pastures and grazing rules on the botanical composition of the pasture resource, a factor that impacts on livestock production and economic returns over time. The framework establishes the links between inputs, the state of the pasture resource and outputs, to identify optimal pasture development strategies. The analysis is based on the application of a dynamic pasture resource development simulation model within a seasonal stochastic dynamic programming framework. This enables the derivation of optimum decisions within complex grazing enterprises, over both short-term tactical (such as grazing rest) and long-term strategic (such as pasture renovation) time frames and under climatic uncertainty. The simulation model is parameterised using data and systems from the Cicerone Project farmlet experiment. Results indicate that the strategic decision of pasture renovation should only be considered when pastures are in a severely degraded state, whereas the tactical use of grazing rest or low stocking rates should be considered as the most profitable means of maintaining adequate proportions of desirable species within a pasture sward. The optimal stocking rates identified reflected a pattern which may best be described as a seasonal saving and consumption cycle. The optimal tactical and strategic decisions at different pasture states, based on biomass and species composition, varies both between seasons and in response to the imposed soil fertility regime. Implications of these findings at the whole-farm level are discussed in the context of the Cicerone Project farmlets.

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Introduction

The Cicerone Project's farmlet experiment was set up to investigate the sustainability and profitability of three farm management systems in the New England 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 (defined as 'typical' district practice) represented a moderate input system with the same flexible grazing system as Farmlet A; and Farmlet C represented an intensive rotational grazing system with more than four times as many paddocks as the other farmlets but with the same moderate inputs as the typical practice farmlet (B). Empirical results from the experiment showed that botanical composition in all of the farmlets changed in response to the level of system inputs as well as grazing management (Scott *et al*. 2013; Shakhane *et al*. 2013). Over the period of the experiment, the most notable trends in botanical composition were declines in the proportion of sown perennial grasses (such as *Phalaris aquatica* and *Festuca elatior*) with a corresponding increase in the proportion of warm-season grasses (such as *Bothriochloa macra*, *Sporobolus elongatus*, *Paspalum dilatatum* and *Themeda australis*) (Shakhane *et al*. 2013). There is difficulty in prescribing pasture resource management strategies directly from these results due to the influence of management interacting with the effects of climate (Behrendt *et al*. 2013*b*; Scott *et al*. 2013).

The decisions for enhancing and maintaining the productivity of pasture resources on a farm, through the use of alternative technologies, occur at different stages over the planning horizon. The sowing of more productive 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. As pointed out by Scott and Cacho (2000), fertiliser decisions have been commonly treated by many graziers as a 'discretionary' expense, resulting in lower net worth over the long-term compared with maintaining soil fertility as an essential, or 'non-discretionary', strategy. Grazing management, which incorporates decisions about both stocking rate and the time livestock spend grazing a paddock (and the corresponding rest periods), operates at a tactical level over different periods, depending on the type of grazing management system. In a 'set stocking system', the relevant decision period may be a year, but this decreases to weeks or months in flexible grazing systems and to days in intensive rotational grazing systems.

In evaluating the benefits of adopting alternative technologies we must consider the role of risk and its interaction with management. Climatic uncertainty, fluctuating prices and other random processes mean that technologies that are more profitable in the short-term may also be more risky. Short-term decisions regarding the production of pasture and livestock interact in complex ways with longer-term decisions on pasture renewal and botanical composition. This type of decision problem can be better understood through a state-based dynamic approach that takes a long-term view of profit and pasture persistence as explained below.

The decision problem

This paper addresses the problem of balancing the trade-offs between the need for production and profit on the one hand, and the goal of achieving persistence of desirable species within the grazed pasture on the other. The three decision variables considered here are: (i) investing capital to replace a degraded pasture, (ii) adjusting the seasonal stocking rate and (iii) maintaining soil fertility. The objective is to maximise the present value of long-term profit under conditions of uncertainty, and this is subject to biophysical constraints represented by the growth of pastures and animals.

This is a complex problem that graziers have to deal with constantly in spite of imperfect knowledge of the state of their farm's resources and future climate risk. The researcher too needs to appreciate that this problem involves multiple and conflicting objectives of pasture resource production, persistence, livestock productivity and profit. This occurs in a dynamic and risky environment where investments in sowing pastures and grazing management decisions are made under uncertain climatic conditions. A feature of the state-based method used here is that decisions at any point in time are expressed as rules that depend on the state of the pasture resource at that time. This means that decisions are made based on the state of the pasture resource as it progresses through time and there is no attempt to predict the future, but probabilities of future events are embedded in the decision process (Hardaker *et al*. 1991). This is defined as a typical sequential decision problem (Fig. 1), where both tactical and strategic decisions are made at intervening states of the system as uncertainty unfolds (Trebeck and Hardaker 1972).

The state of the system is represented by the combination of three variables: herbage mass, botanical composition and fertility of the soil. In a multi-paddock grazing system, a mosaic of pasture states and soil fertility conditions would exist. The strategic decisions available to the producer at this stage include the re-sowing of a pasture with more desirable species. The

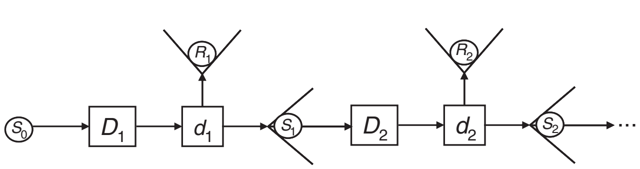

Fig. 1. Sequential decision making in pasture resource management.

tactical decisions include the application of fertiliser and grazing management.

In Fig. 1, the initial state of the system (S_0) is observed and the strategic decision (D_1), whether to sow a new pasture, is made. This is followed by the tactical decisions (d_1) regarding grazing management and fertiliser application. The tactical options available in d_1 depend on the strategic decision made in D_1; if a new pasture was sown, fertiliser application should occur and stock should be excluded from the paddock, but these restrictions do not apply if a new pasture was not sown. The decisions made combine with the S_0 and climate outcomes to produce livestock products with their economic return (R_1) and a new pasture state (S_1); the arcs around these two variables indicate the uncertainty that surrounds the outcomes. The S_1 becomes the S_0 for the new season and influences the decisions made (D_2 and d_2), which in turn result in a new return (R_2) and state (S_2). This process continues through time for the desired planning horizon and the economic returns are accumulated to calculate their present value. If the probabilities that different outcomes will occur are known, the decision model can be implemented and solved.

Within each stage of the sequence, the optimal decision will be based on the current state of the pasture resource and the expected returns from all future stages, which are influenced by the stochastic climate. As such, all possible future stages of the sequential stochastic decision problem must be solved in order to solve the first stage decision (Trebeck and Hardaker 1972) in a backward induction process. The problem is defined and solved as a stochastic dynamic programming model (Kennedy 1986). The presence of embedded risk means that the development plan will be adjusted over time depending on uncertain events and the resulting states that influence economic returns (Hardaker *et al*. 2004).

This paper utilises the data from the Cicerone Project farmlet experiment, together with other experimental and bioeconomic modelling studies, to identify the optimal pasture investment and grazing management decisions that achieve the most profitable and sustainable outcomes. This 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 modelling approach also allows significantly more combinations of stocking rate, grazing rest and climate scenarios to be analysed than could be achieved through a biophysical experimental study.

Methodology: bioeconomic framework

In the bioeconomic framework developed for this study, data from the Cicerone farmlet study was used as input to calibrate two simulation models, AusFarm (CSIRO 2007) and the Dynamic Pasture Resource Development (DPRD) simulation model (Behrendt 2008), which provided the information required to solve the decision problem (Fig. 2). The framework is briefly described in the following sections; more details can be found in Behrendt (2008).

The stochastic dynamic programming (SDP) model used to identify optimal tactical and strategic decisions requires a transition probability matrix to be defined (Kennedy 1986), which contains the probabilities that a system starting in any state will move to another state. The transition between different

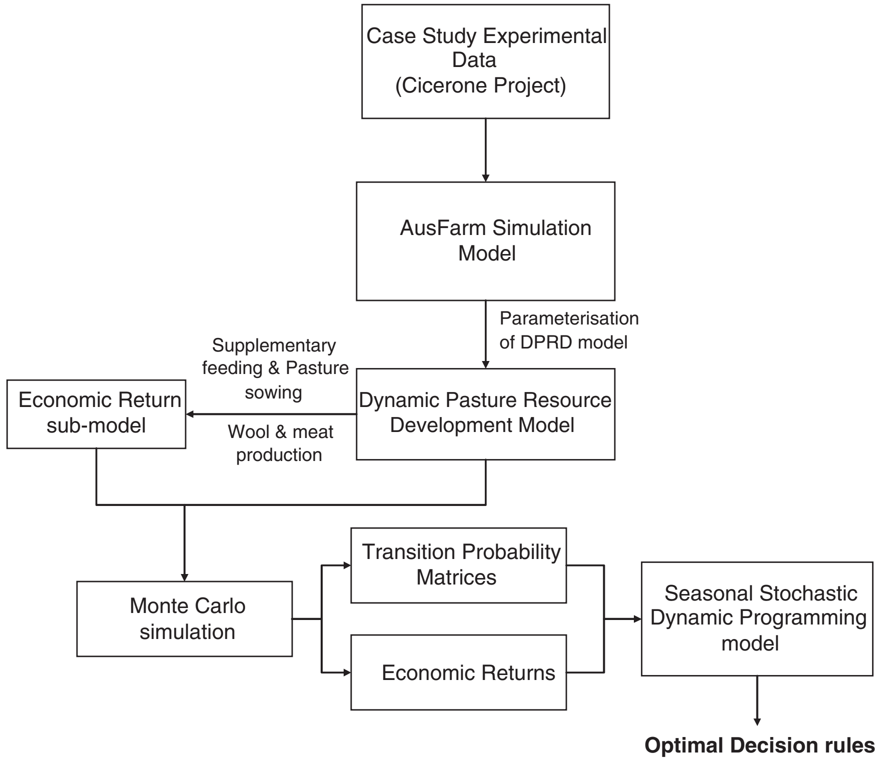

Fig. 2. Bioeconomic modelling framework.

states of the pasture resource (in terms of biomass and botanical composition) depends not only on its initial state and the tactical or strategic decisions taken, but also on the effects of an uncertain climate, which has a large influence on pasture growth and hence feed availability (Robinson and Lazenby 1976; Dowling *et al.* 2005). Solving this problem required the development of a DPRD simulation model to produce transition probability matrices for a seasonal SDP model (Behrendt 2008).

The link between the DPRD and the SDP models allowed the solution to be based on randomised simulations of 30 years of climate data from 1976 to 2006 rather than the 6.5 years spanned by the Cicerone experiment. The DPRD model simulates changes in botanical composition and pasture utilisation by a variable number of grazing livestock.

The seasonal SDP model maximises the expected net present value of returns from a sheep production system over the long run, and thereby maximises the sustainable economic yield from the combined pasture and soil resource (Behrendt 2008).

Pasture resource simulation

The DPRD model operates at the single paddock level and contains five submodels accounting for soil fertility, pasture growth and selective grazing, botanical composition, sheep meat and wool production, and economic performance. The method models changes in pasture biomass within seasons and botanical composition between seasons (Behrendt 2008).

Within a single production year, four seasons were chosen as the time intervals that adequately represent the tactical and strategic decision points within a grazing system. Within each season, pasture growth and consumption by grazing livestock were modelled at a daily time step. Between seasons, the relative areas occupied by 'desirable' species (using *Phalaris aquatica*, *Trifolium repens* and *Austrodanthonia* spp.) and 'undesirable' species (using *Bothriochloa macra* and *Vulpia* spp.) within the whole sward, are modelled using exploited population growth modelling (Clark 1990). Modelling this spatial measure of sward composition, similar to basal measurement common in agronomic experiments (Whalley and Hardy 2000), allows botanical composition and potential growth to respond to utilisation by grazing livestock. Simulations were used to provide data on the expected production outcomes, economic performance and variability associated with the technologies relevant to the development and management of the Cicerone farmlets.

The DPRD model pasture growth submodel was parameterised using experimental simulation output from a farm-scale, mechanistic grazing systems model AusFarm (CSIRO 2007), which itself was calibrated using data from the Cicerone farmlet experiment. Complex biophysical models such as Ausfarm, that simulate biological systems in great detail at a daily time step, are not well suited to economic optimisation models, because of the time required to solve each simulation run (Cacho 1998). Hence there is a need to achieve a balance between complexity of the biophysical model and adequacy of information for improved decision making. Achieving this compromise was the primary reason for developing the DPRD.

The AusFarm parameters were calibrated to field experimental data from the Cicerone experiment. A time series comparison between simulated data from AusFarm and observed data from paddock A3 is illustrated in Fig. 3. The predicted AusFarm data represent the partial paddock area-weighted mean amount of DM available per ha. The observed data represent the visually estimated amounts of pasture DM available that were recorded for the Cicerone paddock A3 from 1 March 2003 until 12 December 2006 (Shakhane *et al*. 2013).

Livestock movement records were available for the period 1 February 2001 to 14 April 2006 (Scott *et al*. 2013). The plotting of observed data from the Cicerone paddock against paired AusFarm simulated data reveals the simulation data to be acceptable for their application in this analysis (the slope of the line between observed and predicted data is ~1.0 with $P < 0.001$).

The potential for the statistical validation of the DPRD model against AusFarm output is limited due to the complexity of the modelled system and the dynamic interactions which are not accounted for in AusFarm. An accepted method of testing, evaluating and gaining confidence in a model is by demonstrating its application through experimental simulation, and testing it in the context within which it has been designed to apply (Johnson 2011). The results from this process are presented in another paper in this special edition (Behrendt *et al*. 2013*a*).

Decision variables

The full decision problem described above proved to be impossible to solve with the available computing resources within an acceptable time frame, because of the large number of possible combinations of states and decisions. A manageable version of the model was obtained by maintaining soil fertility constant at one of three possible values [10, 20 and 35 ppm Colwell P (Colwell 1963)] through appropriate fertiliser application. This resulted in a reduction in the number of possible states, which were then based only on botanical composition and pasture mass. The tactical decision of stocking rate and the strategic decision of pasture renewal were taken at the start of each season and are the main focus of this study.

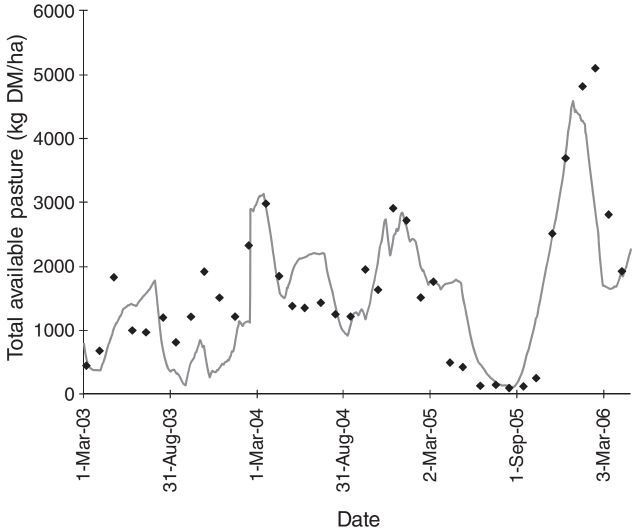

Fig. 3. Continuous AusFarm simulated data and experimental data from the Cicerone Project database indicating change in pasture mass over time for paddock A3. Predicted AusFarm (–) and Cicerone Project observed (◆) pasture mass data (available from March 2003 to December 2006).

The stocking rate decision (*sr*) provided the opportunity for a range of grazing pressures or tactical grazing rests to influence production, economic returns and future botanical composition. Ten possible season-long *sr* values were modelled: 0, 2, 4, 8, 10, 15, 20, 30, 40, and 50 dry sheep equivalent (DSE) per ha, where a DSE is a standard unit of livestock feed requirements (Davies 2005) and equivalent to a standard reference weight of 50 kg in the DPRD model (Freer *et al*. 2007; Behrendt 2008).

The pasture renewal decision represents a capital investment that consists of re-sowing the model paddock. The decision to replace a degraded pasture provides an opportunity for future herbage production to be enhanced by more productive pasture species. A stocking rate of 0 DSE/ha accompanies the decision to replace a pasture in the season of establishment, but stocking rates for the second and subsequent seasons are part of the optimisation process.

The possible pasture states considered in the model consisted of 10 levels of pasture biomass (between 100 and 5000 kg DM/ha for both desirable and undesirable species) and 10 different levels of botanical composition (between 5 and 95% of the basal area occupied by desirables in the sward). This resulted in 1000 possible states (10 undesirable biomass states × 10 desirable biomass states × 10 botanical composition states). This means that a transition matrix has 1 million elements (1000 columns × 1000 rows) and there are 44 transition matrices (4 seasons × 11 possible decisions) for each soil-fertility level. To produce these matrices required 44 000 runs of the DPRD model, and each run involved 200 Monte Carlo iterations using random numbers. The results from each simulation were used to populate one row of a matrix. Three sets of matrices were produced, one for each soil fertility level. Once the transition probability matrices were available and saved to disk, the problem was solved using the seasonal SDP model (Behrendt 2008).

Other assumptions

The three different soil fertility regimes were defined as follows:

(1) High input system: high initial level of soil P (35 ppm Colwell P) and high application rates of single superphosphate fertiliser (150 kg/ha.year) to maintain the required level of soil P. This level of soil P is less than the target level of Farmlet A, although it still represents high soil fertility levels when compared with regional practice where Edwards and Duncan (2002) found that ~93% of a sample of 73 farms on the Northern Tablelands were low in soil P.

(2) Moderate input system: moderate initial level of soil P (20 ppm Colwell P) and moderate application rates of single superphosphate fertiliser (100 kg/ha.year). This level of soil P is the same as the target level of the medium input systems of Farmlets B and C of the Cicerone Project.

(3) Low input system: low initial level of soil P (10 ppm Colwell P) and low application rates of single superphosphate fertiliser (42 kg/ha.year).

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 in the DPRD model.

Sheep production system

The DPRD livestock model includes selective grazing and livestock performance and is based on a simplified flock structure. The value of wool and meat produced is defined according to a base Merino wether enterprise (wool focussed), which is embedded in the model. The simulation outputs are adjusted to reflect the relative differences in the value of outputs for the self-replacing Merino enterprise (wool : meat) that operated within the Cicerone Project. This method provides a convenient way of representing different sheep production systems and their emphasis on different outputs (wool and meat). Industry gross margins for two typical New South Wales sheep production systems (Davies and Scott 2007) were used to estimate the value adjustment factors for wool and meat (Behrendt 2008).

Table 1 shows the calculation of wool and meat value adjustment factors for the self-replacing Merino production system used for solving the SDP model. The derived adjustment factors were multiplied by the price of wool and meat in the economic submodel, which subsequently influenced the optimal decision rules.

Results

The optimal solution is in the form of a state-based decision rule. For each soil fertility regime and each season there were 1000 possible states. There is an optimal solution that describes the optimal seasonal stocking rate and pasture renovation decision for each state and therefore the output dataset is quite large. The mean optimal decision rules are summarised graphically in Fig. 4 using contour plots for each season and soil fertility regime combination. These contour plots simplify the presentation of this large dataset and allow the identification of all optimal decisions by finding corresponding pasture state coordinates. The state of the pasture at the start of the season is expressed as total pasture DM available (comprising both desirable and undesirable species) on the vertical axis, and the proportion of desirables in the sward on the horizontal axis. The optimal stocking rate decision is shown for all possible combinations of pasture mass and proportion of desirable species. For simplicity, stocking rate decisions were aggregated into six groups. The light blue regions are states of pasture where a tactical grazing rest (0 DSE/ha) was the optimal decision for the season. The other shaded regions represent mean seasonal stocking rates of 2, 8, 15, 25, and 40 DSE/ha. The grey regions indicate the states where it was optimal to renovate the pasture.

Table 1. Wool and meat value adjustment factors for different sheep production systems derived from industry gross margins
Gross margin data sourced from Davies and Scott (2007)

Production and economic measures	Merino wethers (19 micron wool) Wool	Self-replacing Merino flock (19 micron wool and 6-month-old wether weaners) Wool : Meat
$Wool_q$ (kg)/DSE	4.50	2.52
$Meat_q$ (kg cwt)/DSE	3.95	5.89
$Wool_p$ ($/kg)	5.71	5.48
$Meat_p$ ($/kg)	1.92	2.18
$WoolV_E$ ($)/DSE	25.69	13.82
$MeatV_E$ ($)/DSE	7.59	12.82
Value adjustment factors		
$VA_{WOOL\ E}$	1.00	0.54
$VA_{MEAT\ E}$	1.00	1.69

The optimal stocking rate decision varied with season and the state of the pasture (Fig. 4). In spring the decision was largely based on the pasture mass available. The highest seasonal stocking rates across all proportions of desirables were maintained in spring, whereas the lowest stocking rates were maintained in winter and summer. In summer, the desirable species have comparatively lower growth than the undesirable species (dominated by *Bothriochloa macra*), and the results for this season suggest that the risk of selective overgrazing of the desirable component of the sward outweighs the short-term economic benefit of high stocking rates.

During winter, when there were less than 40% desirables in the sward, there was a band of lower optimal stocking rate decisions (less than 5 DSE/ha) and tactical grazing rests (sr = 0 DSE/ha) across all quantities of available pasture mass (Fig. 4, subplots *b*, *f*, and *j*). This band also occurred for summer and autumn but at higher optimal stocking rates than for winter (Fig. 4, subplots *e*, *i*, *h* and *l*).

Interestingly, for winter, autumn and summer, and under moderate-high soil fertility, tactical grazing rests were optimal whenever available pasture DM was less than 500 kg DM/ha across all states of botanical composition. This suggests that the optimal decision at such low levels of pasture biomass, (which may have resulted due to concurrent high stocking rates in the preceding season combined with severe drought conditions) was predominantly driven by the trade-off between current and future production and profit rather than by botanical composition.

Fig. 4 also illustrates the impact of soil fertility levels on the optimal tactical decision given the range in initial pasture states. Within any particular season, increasing soil fertility resulted in more pasture states with high optimal stocking rates. This was most noticeable for the spring season.

In some situations, during winter, autumn and summer, tactical grazing rests were used instead of re-sowing. This pattern was particularly evident at low proportions of desirable species combined with high soil fertility. With low soil fertility and lower stocking rates, pasture re-sowing became the dominant optimal decision during autumn and winter. The results suggest that, when soil fertility is high, tactical grazing rests are more profitable than re-sowing the pasture. Results also indicate, as supported by experimental evidence, that pastures under a high fertility regime can maintain higher stocking rates and have a capacity to recover from low levels of desirable species in the sward given adequate grazing rest (Cook *et al*. 1978; Garden and Bolger 2001).

The decision to renovate a pasture varied with season, level of inputs and the state of the pasture resource at the start of the season. Table 2 shows the levels of herbage mass below which

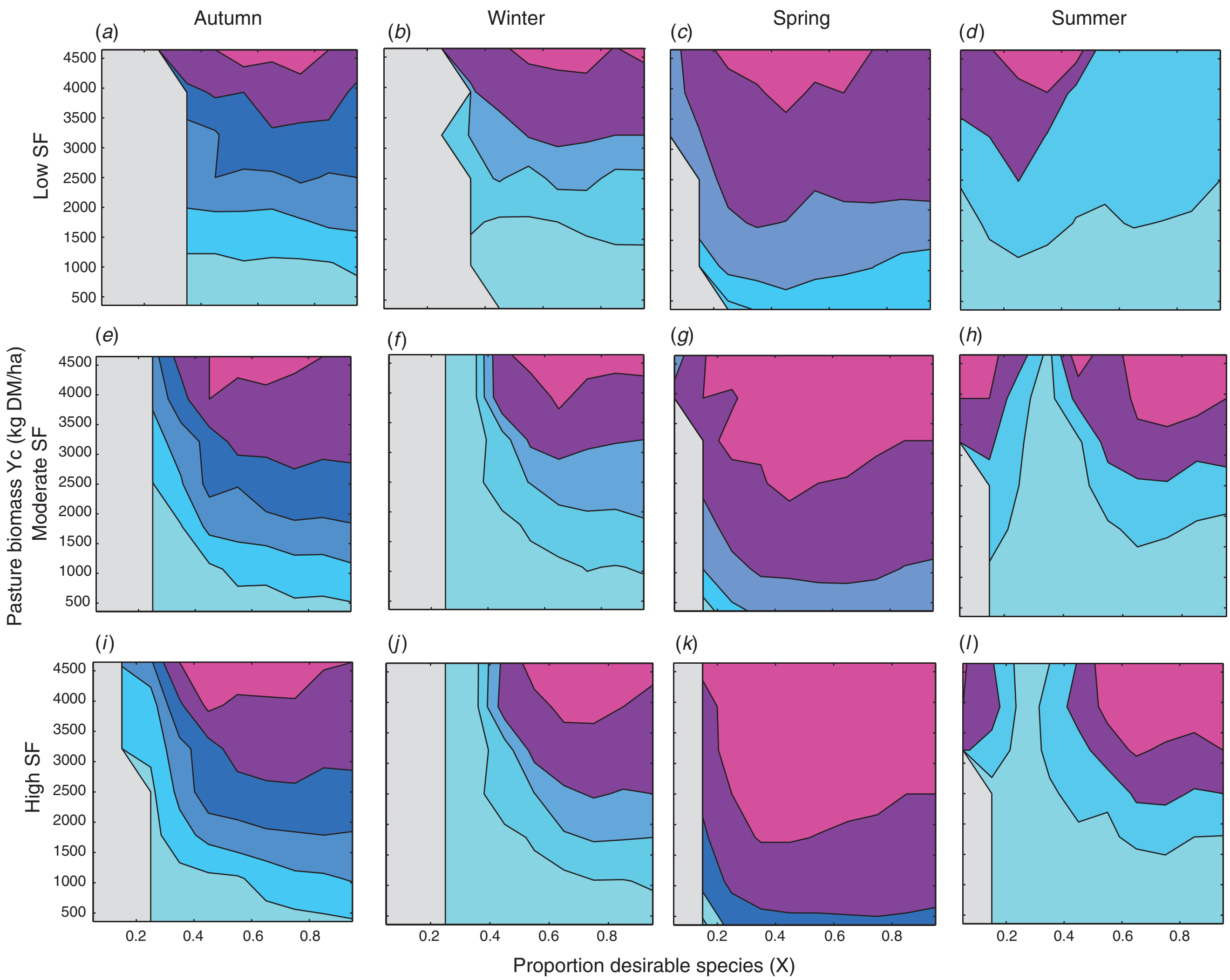

Fig. 4. Stocking rate and re-sow contour plots showing the relationship between the state of the pasture resource (in terms of season, pasture mass and proportion of desirables at the beginning of the season) on the mean optimal decision, being either the season-long stocking rate decision or re-sow decision, for a paddock with different fertiliser input regimes under a wool : meat production system. The mean optimal decision contours represent pasture re-sowing (■), grazing rest (■), mean stocking rate decision of 2 (■), 8 (■), 15 (■), 25 (■) and 40 dry sheep equivalent/ha (■).

pasture renovation became the optimal decision, depending on the proportion of desirable species within the sward. Empty cells in the table indicate that the optimal decision for the particular situation was to not re-sow, even at low herbage mass. Table 2 shows the pasture renovation decision boundaries in more detail than that shown in Fig. 4, as the data here has not been aggregated.

The conditions for optimal re-sowing were most prominent in the autumn and winter seasons (Fig. 4 and Table 2) at lower levels of soil fertility. If the state of the pasture resource was poor enough, in terms of biomass and species composition, re-sowing pastures in those seasons became the most profitable decision.

Some general patterns emerge from the data in Table 2. First, as the proportion of desirables in the sward increased, the herbage mass at which re-sowing was triggered declined. This was consistent across all levels of soil fertility and supports the finding from the previous section, where tactical grazing management, using either complete grazing rests or reduced stocking rates, was the optimal option to rejuvenate degraded pastures.

Second, although the results indicate that re-sowing should largely occur during autumn and winter, this activity was also considered during summer and spring under severely degraded pasture states (generally at 5% desirables or less) and under moderate to high soil fertility regimes.

Third, with regard to different levels of fertiliser inputs, there was a tendency for a higher soil fertility regime to result in less pasture states at which re-sowing was optimal. This supports the role of higher soil fertility in increasing the capacity of the pasture to rejuvenate botanical composition either by tactical grazing rests or low stocking rates.

Table 2. Levels of herbage mass (kg DM/ha) at the beginning of a season below which pasture renovation becomes the optimal decision for each season, soil fertility regime, and proportion of desirable species within swards

Empty cells in the table indicate that the optimal decision for the particular situation was to not re-sow, even at low herbage mass

Soil fertility regime	Proportion desirables in the sward (x) 5%	15%	25%	35%
	Autumn			
Low	5000	4625	4062	–
Moderate	5000	5000	–	–
High	5000	3050	–	–
	Winter			
Low	5000	4625	3925	1660
Moderate	5000	5000	–	–
High	5000	5000	–	–
	Spring			
Low	2420	1502	–	–
Moderate	4785	–	–	–
High	4837	–	–	–
	Summer			
Low	–	–	–	–
Moderate	2420	–	–	–
High	3330	–	–	–

Discussion

The results illustrate how a bioeconomic approach can be used to identify optimal tactical and strategic decisions in the development and management of a dynamic pasture resource under stochastic climatic conditions. The combinations of management decisions used can be viewed as technology packages. The technologies investigated included soil fertility as a strategic decision, the strategic sowing of introduced pasture species and the tactical use of grazing management to utilise the pasture resource and manipulate botanical composition.

Optimal stocking rate

The optimal decisions reported in Fig. 4 and Table 2 balance the economic returns from the present utilisation of the pasture with the future benefits of maintaining a desirable botanical composition. The capacity for the bioeconomic framework to seasonally adjust stocking rates, unconstrained by flock structure, allowed the identification of the optimal seasonal harvesting of DM. The implicit assumption is that a rotational grazing system is applied within the whole-farm system, which is consistent with the management of the farmlets in the Cicerone experiment.

The optimal stocking rates were highest during spring, followed by autumn, winter and summer in descending order. In conjunction with tactical grazing rests, which predominate during winter and summer, this suggests that the optimal harvest pattern is a seasonal saving and consumption cycle. This cycle is related to the uncertainty of future pasture growth and the consequences, both economic and biophysical, of selectively grazing the desirable component during periods of high variability in pasture growth. In this analysis it was optimal to reduce stocking rates during periods of low growth of desirable species, during both summer and winter, in order to ensure the proportion of desirables in the sward was maintained or increased. This allowed a higher proportion of desirables to be attained for the following seasons of autumn and spring when the probability of higher growth of desirables was higher, with corresponding greater availability of highly digestible DM.

The use of complete grazing rest of a pasture as part of optimal tactical grazing management occurs in response to both herbage mass and the proportion of desirables. The use of tactical grazing rests was optimal under a wider range of pasture states (low proportion of desirables and low pasture mass) when soil fertility was high than when it was low. Also, as the proportion of desirables declined, the pasture mass boundary for inducing grazing rest or very low stocking rates, increased.

Even though spring maintained the highest intrinsic rates of desirable population growth and the highest livestock harvest impact coefficient on desirable species, complete grazing rest during spring was only found to be optimal under severely degraded pasture states and low soil fertility (as shown in the light blue sections of subplots *c* and *g* in Fig. 4). This is consistent with the findings of Boschma and Scott (2000), who found that severe grazing during moderate drought conditions in spring led to higher mortality of desirable perennial grasses than under severe drought conditions or severe grazing in summer and autumn. Optimisation results suggest that the expected benefit from high utilisation during spring outweighs the potential costs of pasture resource degradation, provided that sufficient grazing rest is provided to the pasture in the preceding winter and following summer.

The use of tactical grazing rests has been broadly researched and promoted as a means of maintaining a higher proportion of desirable species (Kemp *et al*. 2000; Michalk *et al*. 2003). In this study, guidelines were derived for triggering seasonal grazing rests based on the state of the pasture (Fig. 4). An alternative strategy to complete grazing rest was the application of lower stocking rates (2 DSE/ha), which occurred frequently at pasture states with low levels of herbage mass and desirables. This especially occurred in winter when there were less than 30% desirables in the sward and summer across all proportions of desirables with a concurrent pasture mass of ~1500 kg DM/ha or less. The optimal grazing rests and reduced grazing pressure tactics reflect the pasture saving and consumption cycle previously described.

Optimal re-sowing of pastures

With the option of tactical grazing management to enhance botanical composition, it was nearly always more profitable to apply a grazing rest or a period with reduced stocking rate than to re-sow a degraded pasture. Although the sowing of pastures has played a major role in the development of grasslands in the high rainfall, temperate pasture zone (Crofts 1997), the re-sowing of pastures appears to be the optimal decision only in severely degraded pastures with increasing prominence under low soil fertility regimes.

The analysis suggests that, if a low input system is in place, repeated sowing of introduced species is the optimal method of maintaining higher quality pastures for meat production. This process would be analogous to producers who do not invest in soil fertility and so their best opportunity to provide a high quality feed source is through the continual re-sowing of introduced species. This was not found to be the most profitable system overall, but does indicate the most profitable method of producing sheep meat under low soil fertility regimes.

The SDP analysis also indicated that degraded pastures would only be re-sown when less than 15% desirables existed in the sward. This varied with season, the amount of DM present, and the soil fertility regime. For example, as shown in Table 2, sometimes it was optimal to renovate pastures when pasture mass was high (>3000 kg DM/ha), but the proportion of desirables was low (5%). This represents a pasture with small patches of desirables that no longer contribute significantly to the feed base for grazing livestock. At this state of the pasture resource, the profitability of re-sowing was higher than the benefit of maintaining that degraded pasture.

To incorporate the strategic decision of re-sowing pastures into the SDP model, the stocking rate was held at 0 DSE/ha in the season of sowing. The dynamic optimisation process then derived the optimal stocking rate for the sown pasture in the following season. The results from this analysis suggest that, once established, early grazing of newly sown pastures is optimal. In this specific study, some resulting degradation of the newly sown sward would be acceptable as long as the pasture maintains a sufficient level of desirables and its capacity to respond to grazing rest further along the planning horizon. This suggests that the opportunity cost of delayed grazing on newly sown pasture is one of the dominant factors suppressing the profitability of sowing introduced species. For example, as long as an autumn sown pasture maintained over 1000 kg DM/ha by the start of winter, it was optimal to graze that pasture, albeit at low stocking rates. The apparent reason for this is that the proportion of desirables in the sward may be exploited and it is acceptable for them to decline towards the optimal target levels of botanical composition (Behrendt 2008). This is in contrast to industry recommended best practice management of newly sown pastures (Keys 1996) and highlights the importance of tactical management for long-term persistence (Scott *et al*. 2000*a*) against that of management for maximising the proportion of sown species within a pasture sward. In this analysis, the undesirable species modelled in this study made a valuable contribution to the feed base, and the use of tactical grazing rests or reduced stocking rates to continually maintain a higher proportion of desirables had a high opportunity cost. As such the profitability of the newly sown pasture was maximised by utilising the pasture resource to an optimal level of desirables, rather than a maximum level of desirables.

Autumn and winter were the seasons in which re-sowing of pastures occurred the most, which corresponds to predicted optimum times of sowing pastures in the New England Tablelands (Dowling and Smith 1976). However, the re-sowing of pastures in summer and spring was also considered optimal under severely degraded pasture states (5–15% desirables and less than 3000–4500 kg DM/ha pasture mass). On agronomic principles (Keys 1996; Scott 1997) this is not acceptable and represents a limitation of the model, as it is assumed the generally strategic decision of re-sowing is available at all seasonal decision stages. The outcomes of this analysis also raise questions into the sensitivity of the intrinsic rate of growth in the basal area of desirable species used. This is a logical area for further research and development of the model.

Implications at the whole-farm level

The time frame for decision making regarding pasture development has been suggested to be 10–15 years for profit maximisation and 20–30 years for the sustainability and persistence of the pasture system (Scott and Lovett 1997; Lodge *et al*. 1998). A key feature of the optimal decisions derived using the bioeconomic framework developed for this study is that they are optimal regardless of the time frame being considered, as they represent an infinite planning horizon within a stochastic climate. In addition, each optimal decision guides the current state of the pasture towards the long-term optimal and sustainable state (Behrendt 2008). This sustainable state corresponds, in principle, to that of the maximum economic sustainable yield of a resource (Clark 1990), whereby the pasture is viewed as an exploitable renewable resource. The sustainable state is based on the objective of profit maximisation, but is constrained by the impact of livestock harvesting on the desirable population, the concurrent impacts on the productivity of the grazing system, and the capital cost of resource renewal.

The seasonal contour plots provide a visual guide to the optimal decisions as functions of the state of the pasture resource at the beginning of each season. With further refinement such a tool could be used to help guide a producer on the optimal management of a paddock, based on its state at the start of a season. However, key results may depend on the functional species groups modelled, and this will need to be explored in future research. For example, it has been suggested that more sustainable pastures in this region are associated not only with deep-rooted, fertiliser-responsive perennial grasses but also with maintaining a persistent component of perennial legumes, which supply nitrogen to support grass and animal growth through nutrient cycling (Scott *et al*. 2000*b*).

The whole-farm implications of these results are that it is optimal to pursue a sustainable economic yield strategy designed to mimic the optimal seasonal harvest pattern. Depending on the mosaic of pasture states within the farming system, there may need to be increased emphasis on maintaining a greater proportion of tradeable livestock, which is already a common strategy adopted within the region. There is also the option of transferring the feed between seasons using silage or hay, but the economics of doing this were not considered in this study.

In the application of this method to a whole-farm system, an additional layer of complexity arises wherever multiple livestock production systems exist, such as is typically found in the region. Different livestock production systems, with particular emphasis on meat or wool, maintain different optimal targets for pasture mass and botanical composition (Behrendt 2008).

A logical extension to this model is the integration of the SDP methodology into a multi-paddock grazing system. This would provide the ability to optimise the management of a mosaic of pasture types and compositions, which may also exist within different parts of a landscape. It would also provide the opportunity to consider different flock structures and determine the optimal proportions of tradeable or disposable stock within a grazing system. The addition of fertilisation as a decision variable is also a necessary extension to this model, as currently the question of which level of fertilisation is optimal, in conjunction with grazing management and pasture renovation decisions, is only indirectly answered through the comparison of the results between the three analysed fertility regimes.

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