Optimising Rotational Grazing In Sheep Management Systems

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Abstract Pastoral farmers choose the stocking rate for their farm and within year target levels of animal performance on the basis of expected seasonal pasture production. Shifting livestock from one paddock to another is a common mechanism used by farmers to allocate pasture to livestock and for conservation. Many variables, such as animal performance and pasture growth rate, influence the decision on when shifts between paddocks should be made. The costs of inappropriate grazing decisions can be high since they may lead to subsequent feed shortages and reduced animal performance. This paper describes the development of a discrete event, dynamic simulation model in Extend ™ to assist farmers to plan and control sheep grazing. Decisions to graze or close paddocks for conservation are based on herbage mass. The grazing time spent on each paddock is based on a linear interpolation of user-defined herbage allowances for each month. Animal intake is estimated from live weight, herbage quality and leaf mass. A Genetic algorithm block was developed in Extend™ and used to determine the optimal levels of key control and state variables contained in a grazing system. The optimal monthly sequencing of pasture allowance, nitrogen application, and lamb drafting weight and supplementation were determined for a farmlet simulation. The results represent targets that the farmer should strive to achieve during the year. From this information simple decision rules can be developed to indicate which control variables need to be modified by the farmer when the realised value of state variables (such as pasture cover) is significantly different from the optimal target value.

1. INTRODUCTION

Farms are complex systems, comprising biological, social and financial components that are subject to constraints of temporal uncertainty, particularly with respect to prices and weather. Decision analysis in relation to such a complex system requires consideration of the interactions among system components over time. In this context, computer simulation models have advantages because of their capacity to: handle many simultaneous and complex mathematical equations (manipulating many variables and interactions systematically), quickly evaluate alternative plans and incorporate current scientific knowledge into the processes involved.

Managing variable pasture supply with the assistance of a model can help farmers to set appropriate stocking rates and target levels of performance for different periods of the year. Tactical management options such as restricting feed intake, selling animals, using nitrogen fertiliser and feeding out supplements, can be compared quickly and systematically in order to develop plans which are likely to give the best outcome relative to the farmer's objectives [Parker, 1993]. However, the high variability of pasture production is an often disregarded feature of decision support models for pastoral livestock systems [Dake, 1994], and this restricts planning in relation to unknown future prices and pasture production [Dent and Blackie, 1979]. The addition of probabilities also allows the farmer to predict the value of different methods of management control.

This paper describes the development of a stochastic discrete event grazing model. The model is designed to provide decision support for tactical and operational planning of rotational grazing on sheep farms, and was constructed using the iconic simulation modelling package Extend™ [1995]. Such packages speed up model development for any level of complexity, require little time for training of computer literate users, and can reduce modelling costs by 80 - 95 percent [Murphy, 1995].

2. METHODS

2.1 Model Structure

Modelling rotational grazing obviously requires each paddock to be represented and their attribute data to be recorded and kept for use in subsequent calculations.

Two main approaches have been described in the literature as means to include discrete entities such as paddocks into grazing models. The first, adopted by Finlayson [1989], uses a continuous time model and records paddock and event data into dynamic arrays. The same approach was used by Sorensen *et al.* [1992] to represent animals and describe discrete events in animal production such as heat, conception, sex and involuntary culling. The second approach, applied by Woodward *et al.* [1995], and in several industrial and business applications [Murphy, 1995], is event driven modelling.

The approach adopted in this model is similar to that described by Woodward *et al.* [1995], except intake is calculated numerically. The advantages of this approach lie not only in making time event driven, but also in integrating intake and growth functions by time, so that the post-grazing mass can be predicted after accounting for the influence of sward surface height on intake and pasture growth rate. Unlike the actual farm system, where the mob or herd is allocated to paddocks, the grazing system was modelled by allocating paddocks to a mob. This allowed the number of paddocks, and paddock variables, to be redefined prior to and during simulation. Paddocks are represented by items which are submitted for processing (grazing, growth or harvesting).

The grazing model consists of 79 modules grouped into 8 hierarchical modules (Figure 1). These are labeled as the: *Executive block*, *Paddocks block*, *Decide Graze block*, *Graze block*, *Grow block*, *Reproduction block*, *Joint block* and *Control Panel block*. The Executive block controls the simulation of discrete events. The Paddocks block initialises the paddocks for the simulation and sets the initial attributes for each paddock: area, herbage mass, leaf, stem and dead fractions, mass and production potential. The Decide Graze block, sorts the paddocks by herbage mass and assigns the paddock with the greatest mass to be grazed and the remaining paddocks to the Grow block. The Graze block calculates the effects of defoliation on pasture quantity and composition, and estimates animal intake and performance, during grazing. Also, reproduction is simulated and gross margin and cash flow calculations are completed within this block. The Grow block simulates the growth and senescence of the pasture within paddocks during their rest (non-grazing) period. The Reproduction block is responsible for simulating reproduction in the flock at the start of the mating season and generates an array defining the parturition distribution, number of lambs and lamb sex. The Joint block combines paddocks from the Grow and Graze blocks, measures pasture cover, harvests pasture and applies nitrogen fertiliser. Pasture harvested is accumulated and the information is recorded to calculate the cost and quantity of supplements made and therefore the amount available on the farm for feeding to animals. The Control Panel block obtains inputs and save outputs to text files, stores information of multiple simulations and allows changes to be made to most decision variables used in the simulation. The optimisation algorithm is also placed in the Control Panel block.

Following the approach adopted by McCall [1984], Doyle *et al.* [1989] and Cacho *et al.* [1995], pasture mass is divided into three pools: leaf lamina, pseudostem and dead material. There are two advantages with this approach: first, it accounts for the loss of pasture mass because of senescence, which, in combination with animal intake enables the effect of transferring feed through time to be simulated; second, because leaf content is treated as an independent variable, it is possible to differentiate growth and intake responses of pasture with the same pasture mass but submitted to different previous management. For instance, a paddock may be grown up to, grazed down to, maintained at (through continuous grazing) or harvested to a particular pasture mass. Pasture growth and intake responses obviously differ for each of these scenarios.

In the Grazing block, the time spent grazing each paddock is determined from a pre-defined herbage allowance, leaf content of the pasture, the percentage of leaf in the diet consumed by the animal and the intake rate of the animal during the period concerned. The same data are used to calculate the post-grazing leaf, stem and dead material content and these are then set as attributes of the grazed paddock. Also, based on the composition of the diet (leaf %, stem % and dead %) and time of the year, the digestibility of the diet is calculated. Intake and digestibility are then used to estimate the metabolisable energy available to the animals and to calculate animal performance.

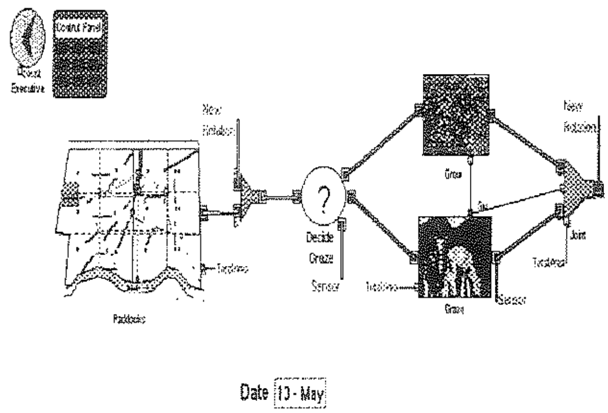

Figure 1: A diagrammatic representation of the grazing model [Barioni, 1997].

Supplementation is also handled by the Grazing block. When supplements are used, a substitution effect is estimated from rumen-fill and feed-drive effects. Ewe performance is simulated for an average animal, while lamb growth performance is calculated and recorded individually.

Global arrays are used when information is relevant to several blocks, particularly when they are grouped in different hierarchical blocks. This avoided an excessive number of connections which would make the model structure awkward. Five main arrays were created to store and transfer information among blocks: the *Control array*, *Pcover array*, *Sheep array*, *Parturition array* and *ProdAndEconomics* array.

The Control array transfers all the control variables from the Control Panel hierarchical block into the model. The Genetic Algorithm block, which belongs to the Control Panel hierarchical block, defines all the control variables in the model and therefore can change them during the optimisation process. When the optimisation module is disabled, user-defined parameters for the control variables (also inputted via the Genetic Algorithm block dialogue box) are executed.

The Parturition array, created by the Reproduction block, is large and stores information about: lambing date, sex, birth rank (twin or single), lamb live weight, body fat, protein and DNA content, whether the lamb is to be kept as a flock replacement, and milk production and the lactation adjustment factor for the dam. Twins are maintained together and therefore have the same value for all parameters in the array, including sex. The effect of this incorrect assumption in test simulations with large numbers of lambs was shown to be insignificant. The Sheep array stores information about the number of individuals, empty body weight, maximum empty body weight, body fat, protein and DNA content of each sheep category on the farm.

The function of the ProdAndEconomics array is to store and transfer information about production and economic variables including: accumulated wool production, wool price, accumulated weight of lamb carcass sold, the price for each lamb category sold, cull ewes sold and their price, accumulated nitrogen applied and its cost, accumulated supplement fed and its cost, total asset value of sheep (for deriving the cost of 'sheep' capital), and total revenue and expenses.

Finally, ArrayPCover transfers information about the pre- and post- grazing herbage mass of grazed paddocks and the average pasture cover of all paddocks in the simulation.

2.2 Optimisation Module

The performance of grazing systems is affected by several factors including state variables (e.g. pasture cover, proportion of leaf in the pasture and animal live weight) and control variables (e.g. herbage allowance per grazing, harvesting surplus pasture, supplementation and adjusting stocking rate). It is the combination of these factors which maximises system performance in either economic or biological terms. The multi-dimensional nature of the grazing decision problem makes it almost impossible to determine an optimum state - control variable sequence based exclusively on a series of sensitivity analysis. This is particularly true because a single control mechanism is generally not applied independently of others; rather a combination of control alternatives provides the best option for management. Decisions on the use of such control alternatives also have a temporal dimension because different outcomes to the same decision problem apply to different seasons of the year. This creates a combinatorial problem too big for a blind search to complete [Turban, 1992].

Several optimisation methods have been developed and applied to agricultural systems. Mathematical programming is already popular in agriculture [e.g. Boisvert and McCarl, 1990]. It has the advantage of relatively simple computation, but is quite restrictive in its formulation [Rothemberg, 1989]. On the other hand, the use of simulation models within an optimisation framework, because of their flexibility, is more likely to be useful for solving practical problems. However, optimisation of multi-dimensional problems in non-linear simulation models is not an easy task. Simulation models, according to Mayer *et al.* [1995], typically present three problems to optimisation methods: first, no derivative functions are available and where these are required, they have to be approximated numerically; second, most models include practical constraints that have to be accommodated by the use of penalty functions or a constrained optimisation method; third, the multi-dimensional response surfaces are rarely smooth or convex and can vary from "bumpy" to "almost chaotic" in relation to the inputs [Mayer *et al.* 1995]. Another problem arises because multiple optima are common [Mayer *et al.* 1995], indicating that alternate management policies, whether they are biological or economically driven, can result in similar consequences.

Goldberg [1989] and Mayer *et al.* [1995] pointed to the problem that gradient-type methods, often used for optimisation, track uphill to the closest local maximum and cannot usually escape from local optima which are unlikely to be the global optima in multi-dimensional problems. The identified local optima are therefore contingent upon the starting values used for the simulation.

More recent methods of optimisation, such as genetic algorithms and simulated annealing, are much more robust than gradient type methods and are not dependent on the parameter values assumed for the first iteration. While the majority of optimisation algorithms search the decision space by moving from point to point according to some transition rule, genetic algorithms maintain multiple solutions concurrently, climbing many peaks in parallel and are therefore less susceptible to the problems of local maxima and "noise" [Goldberg, 1989; Buckles and Petry, 1992]. This agrees with the results obtained by Mayer *et al.* [1995], who tested four methods of optimisation for a dairy model including 16 management variables (with 10^{13} possible combinations of management options). They concluded that simulated annealing and genetic algorithms were superior to the other methods tested for finding the optima.

The genetic algorithm was implemented as a block in Extend™ and used to maximise stocking rate [Barioni, 1997]. Control variables assigned to the optimisation were: herbage allowance in each month of the year, application of nitrogen (May and August), lamb drafting weight (Mar-Nov, Dec, Jan and Feb) and winter supplementation (May-Aug). Stocking rate and initial pasture cover could also be optimised by user-choice.

Herbage allowance was defined in relation to the potential intake of the animals in order to use a consistent parameter for the mob of sheep comprising different categories and live weight. For the optimisation exercises undertaken, only two annual nitrogen applications were allowed: one each in an autumn and spring month, when the maximum N response is expected. Rates of nitrogen application varied from 0 to 87.5 kg N/ha at intervals of 12.5 kg N/ha for each application. Supplements were available only from May to July (winter) at increments of 0.1 kg DM up to 0.7 kg DM/ewe/day. Initial pasture cover from 1200 to 2700 kg DM ha^{-1} was considered at intervals of 100 kg DM ha^{-1}.

3. SIMULATING OPTIMUM GRAZING – AN EXAMPLE

The optimisation was run for 12 months from 1 March for an theoretical 8 ha farmlet with 8 paddocks of equal size and pasture production potential. A mob of 140 ewes (17.5 ewes/ha), at an initial live weight of 55 kg, were grazed on a starting pasture cover of 1500 kg DM/ha. The maximum empty body weight of ewes was assumed to 63.7 kg. Inputted pasture growth rates were typical of those recorded at the Massey University Nº 4 Dairy Unit which has the same soils, pasture species and climate as the farmlet (Table 1). A lambing pattern was generated for 105 ewes and 35 two tooths using the reproduction sub-model. This produced a 130% lambing. The lambing pattern was stored and used as required during the optimisation. Barren ewes were sold at the beginning of lambing.

The optimum control sequence for herbage allowance, nitrogen application (May and August applications), winter supplementation and lamb drafting weight was identified using the genetic algorithm. Direct costs ($226.61/ha), wool ($5/kg/clean), nitrogen ($1.30/kg N applied) and hay ($0.23/kgDM consumed) were inputted for the gross margin calculation. Lamb schedules were those published by Stocker [1997]. The seasonal premiums assumed were based on the base lamb schedule prices shown in Figure 2. Carcasses were classified according to the carcass weight/GR grid specified by Kirton [1989].

Table 1: Daily net pasture growth rates (kg DM/ha/day) used in the simulations (Source: Dairy Nº4 dairy unit, Matthew *et al.*, 1996).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
24	23	21	23	29	22	17	27	40	50	47	36

[1] For each step of the simulation, pasture growth rate was interpolated linearly assuming the above growth rates on the 15th of each month.

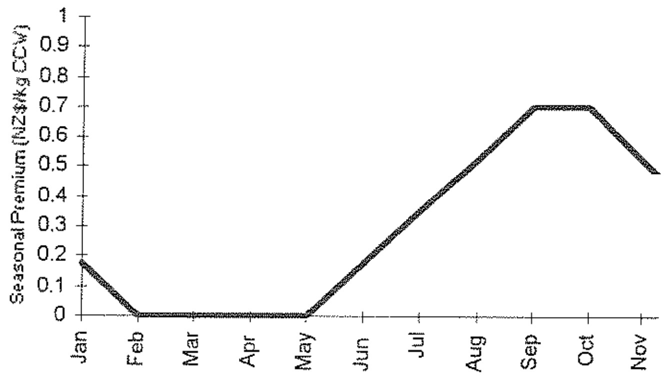

Figure 2: Seasonal premiums paid on lamb carcasses (c/kg).

The pasture allowances suggested by the optimisation for sheep (Table 2) are reasonably consistent with the recommendations of Rattray *et al.* [1987], except for the relatively high herbage allowances and residual covers in the winter. The higher allowances may reflect the stocking rate used in the experiment as well as the positive responses modelled for pasture growth to increasing leaf area index and of ewe milk production to body condition. These relationships require further study because in practice most farmers graze ewes much more tightly during the winter-early spring than the model suggests is optimal in order to control the level of pasture intake. Also, nitrogen was included quite generously in the optimisation relative to normal practice [Parker *et al.* 1994]. This reflects the high (1997) lamb prices compared to the cost of N-boosted pasture. One limitation of the model, however, is that lambs and ewes are grazed together throughout the year and distinct pasture management for these sheep classes as practiced on farms, was not able to be simulated. However, given the derived post-grazing residuals (Table 1) the performance of the lambs is unlikely to have been constrained by this factor except, perhaps in July and August.

Table 2: The optimum solution for the 8 ha farmlet simulation at stocking rate of 17.5 ewes/ha, 130% lambing rate and mating from11 March to 21 May (Gross Margin $NZ 587.47/ ha).

Month	Allowance per potential intake[1]	Nitrogen Applied (kg N/ha)	Supplement Used (kg DM)	Lambs drafting weight[2] (kg)	Allowance[3] (kg DM/ ssu /day)	Post-grazing (kg DM /ha)	Pasture Cover (kg DM/ha)
Mar	2.15	0	0	-	2.67	1042	1461
Apr	2.00	12.5	0	-	2.17	994	1433
May	1.10	0	0	-	1.56	1130	1579
Jun	2.75	0	0	-	3.11	1155	1470
Jul	2.30	0	0	-	2.27	887	1204
Aug	1.25	50	0	-	1.60	914	1291
Sep	2.00	0	0	-	2.78	1303	1753
Oct	2.00	0	0	35	3.53	1712	2127
Nov	3.50	0	0	35	5.00	1881	2259
Dec	3.00	0	0	37	3.46	1664	2167
Jan	1.55	0	0	33	2.28	1488	1986
Feb	2.75	0	0	-	3.41	1334	1708

[1] Calculated as the ratio between the total herbage mass offered daily and the potential intake calculated by the model (this is the control variable used in the optimisation). The units are kg DM/ kg potential intake/day.

[2] Threshold live weight for lamb drafting.

[3] Sheep stock units were calculated relative to a standard live weight of 55 kg.

4. CONCLUSION

The model developed in this study is able to guide major strategic and tactical management decisions, concerning the allocation of feed to a sheep flock. The use of an event driven model design and an optimisation algorithm are important factors in being able to achieve this outcome. The event driven approach allowed the simulation of individual paddocks on a farm, as well as the grazing period for each paddock. It permits different levels of herbage allowance to be tested and measured in terms of its effects on pre- and post- grazing herbage mass, rotation length, diet quality, animal performance and the enterprise gross margin. Optimisation provides feed management targets at both the operational and tactical levels which farmers should pursue.

Further improvements in farm system models to guide tactical and operational decisions should pay regard to control measures. Feedback controllers [Athans, 1972] or expert systems could be used to extend the capabilities of the model to guide control.

The Extend™ software had sufficient capacity to accommodate all of the processes necessary to model a grazing system plus incorporate the optimisation algorithm. However complex processes require customised blocks to be created and a reasonable amount of programming time and skills are required to achieve this. Also the package was not suitable for developing an adequate front-end for a decision support model that could be used by farmers or consultants. Software limitations include the impossibility of including multiple dialogues in one block and the inability to customise pull-down menus and windows. New versions of the package should address these limitations if the aim of the software is to provide a comprehensive development environment for decision support models. Another possibility for model developers is to create a user-friendly front-end with a spreadsheet or database package that would allow the transfer of information between model components via text files or some other connecting mechanism.

The development of the model also showed knowledge gaps still exist concerning major components of grazing systems. These gaps, such as the interaction between ewe body condition and milk production, need to be addressed in order to refine the ability of models to predict the behaviour and performance of grazing systems.

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