Simulation Models and Sustainability of Grazing Systems

OSCAR J. CACHO
Department of Agricultural and Resource Economics
University of New England,
Armidale, NSW 2351, Australia.

This paper discusses the potential contribution of dynamic simulation models to the measurement of sustainability from the standpoint of an individual producer. By running 100-year simulations and allowing the interaction between animals and plants to determine the actual stocking rate for a given management strategy, insight is gained into the carrying capacity of different systems. Questions of stability and long-term profitability are addressed by using phase diagrams. Advantages of the approach and further research needs are discussed.

INTRODUCTION

Sustainability is an elusive goal, more of a moving target than a fixed objective. A cursory review of the literature reveals that most of what has been written deals with sustainability on a global scale. Gale and Cordray (1994) attempt to make some sense of sustainability by focusing on the fundamental issues of definition and consensus. They discuss the many meanings of the term and ask what should be sustained and why, how to measure sustainability and what are the political implications. Ruttan (1994) deals with the questions of substitutability between resources, intergenerational transfers and discount rates. Dalsgaard et al. (1995) present a tentative list of ecological attributes for quantification and ranking of farming systems in terms of sustainability, including diversity, cycling, stability and capacity. Cai and Smit (1994) discuss the different spatial scales in which sustainability must be measured ('from the field to the globe') and argue that a different set of analytical questions must be answered depending on the scale being measured. They contend that achievement of sustainable agriculture must eventually involve an integration of all the spatial scales. De Wit et al. (1995) discuss general criteria for sustainable livestock production, they point out to the time dimension and importance of dynamic processes. These authors emphasise the multi-objective nature of the problem, which makes it difficult to state that one system is 'more sustainable' than another as the score may differ according to the criterion being measured.

This paper is concerned with sustainability at the level of the individual production system and not on a global scale. A producer may wish to manage his/her operation in a way that will continue to yield returns into the indefinite future and benefit future generations. The objective of this paper is to discuss ways of measuring the 'sustanability value' of a given set of management strategies from both economic and biological standpoints. The definition of sustainability used by Pandey and Hardaker (1995): *'an improvement in the productive performance of a system without depleting the natural resource base upon which future performance depends'* can therefore be adopted here .

Two aspects which cannot be ignored when studying sustainability in agriculture are (i) any measure must include economic as well as biological criteria and (ii) the dynamic nature of the production system and the environment (both physical and economic) must be accounted for. The dynamic aspect is particularly important in a grazing system, where plant and animal populations interact with each other and are influenced by the environment. The growth, or otherwise, of the 'natural capital' represented by soils and pastures can only be managed indirectly, by controlling stocking rates and grazing strategies. Animals produce income and, in the process, use up natural capital. The return on this capital, and its long term viability, depend not only on the way the system is managed but also on changing economic conditions. It follows that any attempt at measuring the sustainability of grazing systems must have a sound bioeconomic basis.

This paper starts with a brief description of the model used, followed by details of the computer experiments and the management policies tested, the simulation results are then presented and, finally, the implications of the proposed technique and future research needs are discussed.

THE MODEL

A detailed dynamic simulation model of a grazing system was used for this study. The model operates at three levels of aggregation and is implemented using object oriented techniques (see Cacho and Bywater, 1991). At the lowest level (individual animal and plant), account is taken of the effect of animal physiological status on diet selection (leaf, stem and dead matter consumed) level of feed intake and energy partition. At the next level of aggregation (mobs and grazing blocks) animals and paddocks are grouped into management units, at this level the interaction between pastures and animals is determined by grazing rules (rotational or continuous grazing) which can be adjusted throughout the year to match feed supply and demand. At the highest level (whole farm), groups of mobs and grazing blocks are integrated with other management events, such as shearing, lamb drafting, flock replacement etc. The execution of the model is controlled by a management calendar; as the simulation proceeds through time events are encountered, on days specified in advance by the user, and procedures appropriate to the type of event are executed. Detailed descriptions of the model are presented in Finlayson et al. (1995) and Cacho et al. (1995).

MANAGEMENT POLICIES

For the purposes of this paper, a management policy is defined as a set of decision variables represented by a given management calendar. Four deterministic computer experiments were executed on a hypothetical farm carrying a self-replacing sheep flock. Each experiment was run for 100 years, with a recurring (annual) management calendar and a recurring pattern of seasonal pasture growth parameters. Pasture growth parameters were based on a series of 20-year trials in the Canterbury Plains of New Zealand (Rickard and Radcliffe, 1976) and were adjusted fortnightly.

All experiments were subject to the same management policy except for the *target stocking rate* and the amount of hay fed during winter (Table 1). The target stocking rate (TSR) is defined as the number of stock units (SU) per hectare which the stock replacement strategy attempts to maintain (an ewe with a lamb represents one stock unit). The TSR does not necessarily match the actual stocking rate, as animal mortality occurs when not enough grass is available to maintain a given population density.

Table 1. Management policies tested

Policy	Property	TSR	Winter Hay
1	irrigated	28	yes
2	dryland	18	yes
3	dryland	15	yes
4	dryland	15	no

Fortnightly results were obtained on the condition of animals and pastures (i.e. herbage consumed, body weight, green dry matter per hectare), financial transactions (i.e. animal sales and purchases) and management events (i.e. number of sheep shorn, dipped, vaccinated). Gross margins were produced for each simulated year, assuming a constant set of (deterministic) prices and costs, and phase diagrams were produced to subjectively analyse the dynamics of each management policy.

RESULTS AND DISCUSSION

Table 2 shows a summary of the results obtained for each of the management policies tested. The average stocking rates (SR) obtained were lower than the target stocking rates in all cases, reflecting the fact that animal mortality occurred. As expected, the largest average stocking rate (20.77 SU/ha) was obtained in the irrigated property (table 2). An interesting result was that policy 2 resulted in a lower stocking rate (12.93 SU/ha) than policy 4 (13.8 SU/ha), it was originally expected that feeding no hay in winter (policy 4) would result in the lowest stocking rate, the reason why this did not occur will become clear below, when herd dynamics are discussed.

Table 2. Actual stocking rate (SU/ha), meat and wool production and gross margins obtained in each 100-year simulation, The figures are means, standard deviations are shown in brackets.

	Management Policy			
	1	2	3	4
SU/ha	20.77	12.93	14.90	13.80
	(1.24)	(4.67)	(0.42)	(0.79)
Meat (kg.ha)	24.25	10.21	10.72	13.21
	(9.18)	(12.23)	(8.52)	(14.64)
Wool (kg/ha)	52.33	32.05	34.40	33.59
	(8.22)	(10.92)	(4.21)	(4.15)
GM ($/ha)	228.29	80.26	53.93	76.27
	(52.77)	(56.83)	(37.76)	(38.96)

The advantages of irrigation are clear, as indicated by meat and wool production, as well as gross margins which were considerably higher in the irrigated property than in the dryland property (table 2), reasons for these results are obvious and require no further explanation. Dryland results, however, require further analysis, as different policies show advantages according to different criteria. Among the dryland policies, policy 3 resulted in the highest stocking rate (14.9 SU/ha) but the lowest gross margin (53.93 $/ha), while policy 2 yielded the opposite result, with policy 4 being intermediate in terms of both actual stocking rate and gross margins. If we take average stocking rates to reflect the carrying capacity of the system, these results suggest that gross margins are negatively related to carrying capacity. Another result that deserves comment is the higher meat produced with policy 4 (13.21 kg/ha) as compared to the other two policies (10.21 and 10.72 kg/ha), this occurred because no hay was cut in spring to give to the ewes the following winter, thus leaving more grass available to fatten lambs. Since no costs were incurred for cutting and baling hay, policy 4 produced a higher gross margin than policy 3. The results discussed so far give a fairly limited understanding of what actually happen as a result of each policy, we now turn to a dynamic view of the results for further insights.

Herd Dynamics

Interesting patterns arise when the actual stocking rate is plotted against time (figure 1). These patterns are caused by the effects of overgrazing and animal mortality. After periods of high mortality grazing pressure diminishes and pastures recover, thus allowing an increase in animal numbers and a consequent increase in grazing pressure, which eventually may lead to another period of high mortality and so on.

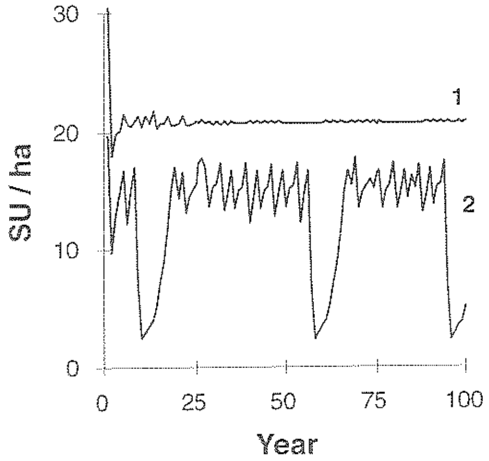

Figure 1. Time trajectory of population density in the simulated farm obtained with management policies 1 (irrigated) and 2 (dryland).

In the irrigated property (figure 1, policy 1), high mortality occurred in year one, with SR dropping from 28 to 18 SU/ha, the flock recovered partially up to year 5, when an irregular cycle emerged with SR ranging between 21 and 20 SU/ha. After year 25 the population reached a virtually stable equilibrium, settling at approximately 20 SU/ha, with alternating periods of very small fluctuations followed by periods of no changes in the size of the flock.

The dryland property (figure 1, policy 2) exhibited a more dramatic pattern of population density fluctuations and did not settle on a stable point. In year one the population decreased from 18 to 10 SU/ha, it then recovered partially up to year 5, when it reached 16.7 SU/ha, just to drop to 12.3 in year 6 and recover once more up to 16.7 SU/ha in year 8. A rapid collapse of the population occurred in years 9 and 10, reaching a low SR of 2.4 SU/ha and then slowly recovering over a period of 9 years. The pattern just described was repeated (although not exactly) with the population collapsing in years 58 and 96.

To avoid clutter and emphasise the effect of hay feeding, policies 3 and 4 were plotted separately, in figure 2, notice the narrower vertical scale in this figure. When the target stocking rate in dryland was decreased to 15 SU/ha (figure 2, policy 3) the population settled into a stable equilibrium after year 25. We thus can conclude that the carrying capacity of this property, under the given management policy, is 15 SU/ha. It is interesting to note that the stable equilibrium reached in scenario 3 is partially dependent on the provision of hay during winter, as evidenced by the irregular pattern that arises when hay is withdrawn (figure 2, policy 4).

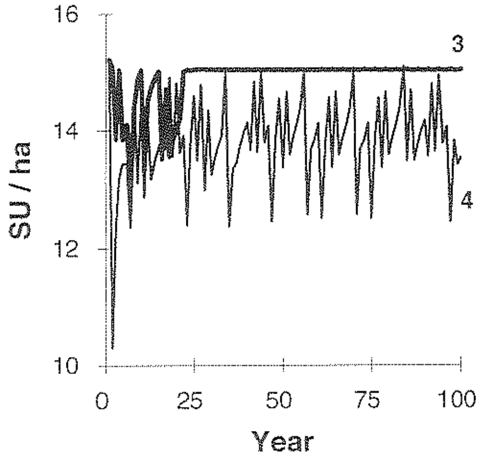

Figure 2. Time trajectory of population density in the simulated farm obtained with management policies 3 and 4.

The reason for the lower average stocking density obtained in policy 2 as compared to policy 4 now becomes clear (compare figure 1, line 2 with figure 2, line 4). Although the population in policy 2 spent the majority of the time cycling between 13 and 17 SU/ha, the three large drops in the population, brought about by overgrazing, produced a lower average value than that obtained in policy 4, where the population fluctuated between 12 and 15 SU/ha with no major collapses occurring.

Phase Diagrams

Additional insights are obtained when the results presented in the previous section are plotted as phase diagrams and a measure of profitability (gross margins) is included. Only the dryland results are discussed in this section, as the results from the irrigated property are fairly uninteresting once an equilibrium is reached.

Figure 3 presents two sets of phase diagrams for policies 2, 3 and 4. The diagrams on the left present a plot of the population density in the current year (t) against that in the following year (t+1), these diagrams provide a different view of the population fluctuations presented in figures 1 and 2. The diagrams on the right show the time path of gross margin (GM) and stocking rate, they provide a (subjective) simultaneous assessment of the stability of the herd and the overall profitability of the business in the long run.

In terms of population fluctuations, policies 2 and 3 have an attractor at approximately 15 SU/ha, while the attractor for policy 4 occurs at approximately 14 SU/ha (compare figures 3 A, C and E). The orbits around the attractor change with the management policy applied; the most striking difference between policies 2 and 3 is the size of the orbits around the attractor. Note that the population collapses previously discussed appear as wide orbits in figure 3A.

In terms of gross margins, the attractors for policies 2, 3 and 4 occur at approximately 80, 45 and 50 $/ha respectively. These results clearly show that there is a tradeoff between stability and profitability. On the one hand, policy 2 produces higher profits but is more unstable and suffers sudden population collapses, accompanied by negative gross margins, which could be catastrophic for a firm with high debt. Policy 3, on the other hand, produces lower profits but is quite stable and therefore less exposed to the possibility of bankruptcy.

The patterns observed in figure 3 suggest that it would be desirable to find management policies associated with an attractor as high as possible on the GM axis coupled with orbits which do not deviate towards low GM values. In other words, we want policies which produce high, stable profits, or high profits with orbits biased towards higher profits. In terms of stocking rate, it is not clear whether we should strive for higher population densities per hectare or higher productivity per animal at low stocking rates.

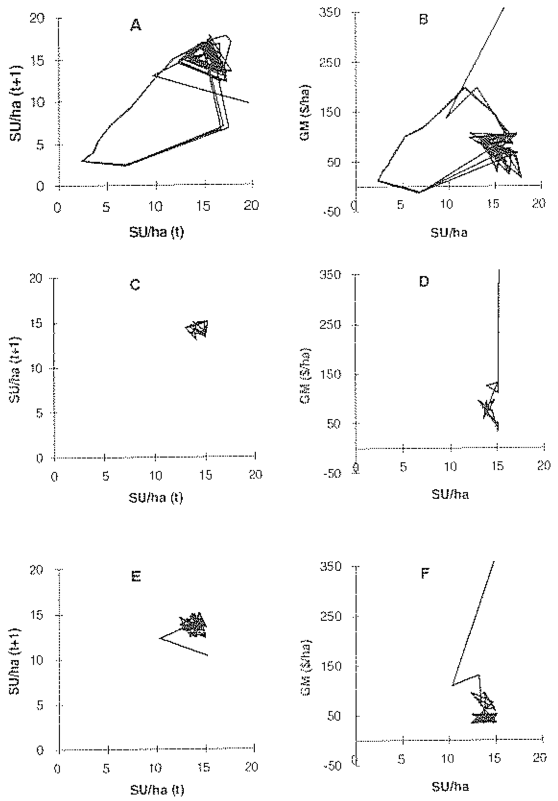

Figure 3. Phase diagrams for management policies 2 (A, B), 3 (C, D) and 4 (E, F).

It should be emphasised that the results discussed here were obtained by running the model in deterministic mode. The seasonal pasture growth *potential* was the same every year (i.e. the same 'average' environmental conditions occurred each year), the *actual* amount of pasture produced however, changed between years, as it was ultimately determined by the annual grazing pattern and the size of the herd (SR). Thus in addition to the profitability and stability considerations discussed here, resistance to random changes in weather and prices should be considered when evaluating a given policy. This and other issues are discussed in the concluding section below.

RESEARCH NEEDS AND FURTHER THOUGHTS

In future studies the deterministic model can be used, as shown here, to identify a set of 'desirable' attractors. Management policies associated with desirable attractors in the deterministic model, should then be run in stochastic mode to identify those strategies which can withstand external (environmental and economic) shocks.

The question of how to define a desirable attractor then arises from this discussion. Although a detailed answer is out of the scope of this paper, we can say that the definition of a desirable attractor must include the objectives and risk attitude of the producer as well as the constraints placed by society and special interest groups concerned with sustainability. Also the level of debt and available credit will influence the number of desirable, and feasible, policies available to a given firm. Obviously, a policy which is sustainable from an individual producer's standpoint is not necessarily sustainable from a global standpoint. However, in order to obtain global sustainability it is necessary to first identify sets of locally sustainable strategies. We can then select those (or develop new) strategies which are also globally sustainable.

Soil loss is a problem which was not addressed here, but which requires attention. According to Pimentel et al. (1995) soil erosion rates may exceed 100 tons/ha/yr in severely overgrazed pastures, with more than half of the world's pasturelands being overgrazed and subject to erosive degradation this problem cannot be ignored. As it stands, the model used for this study implicitly assumes that the growth potential of a pasture is not affected by age or soil degradation. The actual amount of soil lost under given environmental conditions depends mostly on slope and pasture cover, these dimensions should be added to the model before it can seriously contribute to the measurement of sustainable management policies.

Another factor that may lead to stability of a grazing system is the mix of species available in a pasture and the proportion of annual versus perennial species (Cransberg and McFarlane, 1994). Techniques used to evaluate the permanence of ecological communities (eg Law and Morton, 1993) may provide some insights into ways to approach the study of stable and productive mixes of pasture species.

Although there is no doubt that dynamic models have the most to contribute in the study of sustainability, the potential role of static optimisation techniques should not be underestimated. A static model could be used to identify the sets policies which lead to 'desirable' long term goals (attractors), while a dynamic model would be used to determine the attractor(s) associated with a given set of policies. Iterative feedback between static and dynamic models could then be used to solve complex multicriteria decision making problems.

Finally, given the large number of variables and interactions in a grazing system, and the complexity of the phase diagrams which arise, we need sophisticated search techniques to identify the policies which lead to desirable attractors. We require tools capable of locating 'interesting' areas in an extremely complex, multidimensional landscape, genetic algorithms (Beasley et al., 1993) and other related techniques may contribute in this regard. First, however, we need to understand how to define the attributes of desirable attractors, we can achieve this understanding by learning from our modelling efforts.

REFERENCES

Beasley, D., D.R. Bull and R.R. Martin, An overview of genetic algorithms: Part I, fundamentals. *University Computing*, 15, 58-69, 1993.

Cacho, O.J. and A.C. Bywater, Managing complexity: An object oriented approach to the simulation of grazing systems. *Proceedings of the 9th biennial conference on Modelling and Simulation*, Gold Coast, Queensland, 214-219, 1991.

Cacho, O.J., J.D. Finlayson and A.C. Bywater, A simulation model of grazing sheep: II. whole farm model. *Agricultural Systems*, 48, 27-50, 1995.

Cai, Y.L. and B. Smith, Sustainability in agriculture - a general review. *Agriculture, Ecosystems and Environment*, 49, 299-307, 1994.

Cransberg, L. and D.J. McFarlane, Can perennial pastures provide the basis for a sustainable farming system in Southern Australia? *New Zealand Journal of Agricultural Research*, 37, 287-294, 1994.

Dalsgaard, J.P.T., C. Lightfoot and V. Christensen, Towards quantification of ecological sustainability in farming systems analysis. *Ecological Engineering*, 4, 181-189, 1995.

Gale, R.P. and S.M. Cordray, Making sense of sustainability - 9 answers to what should be sustained. *Rural Sociology*, 59, 311-332, 1994.

de Wit, J. , J.K. Oldenbroek, H. van Keulen and D. Zwart, Criteria for sustainable livestock production: a proposal for implementation. *Agriculture, Ecosystems and Environment*, 53, 219-229, 1995.

Finlayson, J.D., O.J. Cacho and A.C. Bywater, A simulation model of grazing sheep: I. Animal growth and intake. *Agricultural Systems*, 48, 1-25, 1995.

Law, R. and R.D. Morton, Alternative permanent states of ecological communities. *Ecology*, 74, 1347-1361, 1993.

Pandey, S. and J.B. Hardaker, The role of modelling in the quest for sustainable farming systems. *Agricultural Systems*, 47, 439-450, 1995.

Pimentel, D., C Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri and R. Blair, Environmental and economic costs of soil erosion and conservation benefits. *Science*, 267, 1117-1123, 1995.

Rickard, D.S. and J.E. Radcliffe, Seasonal distribution of pasture production in New Zealand. XII Winchmore, Canterbury Plains, dryland and irrigated pastures. *New Zealand Journal of Experimental Agriculture*, 4, 329-335, 1976.

Ruttan, V.W., Constraints in the design of sustainable systems of agricultural production. *Ecological Economics*, 10, 209-219,1994.