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Use of simulation models in research

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ABSTRACT

Simulation models are increasingly used in animal research both independently and in conjunction with experimental research. This paper describes the potential uses of models within research programmes and categorises research into three main types, component research, systems research and management research. The contribution of models to component research into lactation, growth, wool growth and feed intake is reviewed. It is suggested that the concepts and data concerning interactions within the pastoral livestock system are now sufficient for a comprehensive modelling analysis of this system to be undertaken. The potential use of production systems models in management research is illustrated through the analysis of farm management factors affecting production and returns from fine wool using a pastoral sheep farm simulation model.

Keywords: Models; animal research; lactation; growth; wool; food intake; grazing systems; pastoral livestock systems.

INTRODUCTION

All research involves models. In some cases this may be no more than an informal model, a concept which the researcher holds regarding the structure, operation or behaviour of the phenomenon under study. In the majority of cases it involves formal and usually static, linear models used to state and test hypotheses regarding the differences between one or more sets of treatments applied in an experiment, i.e. statistical models. In an increasing number of cases, non-linear, dynamic simulation models are being used in animal research.

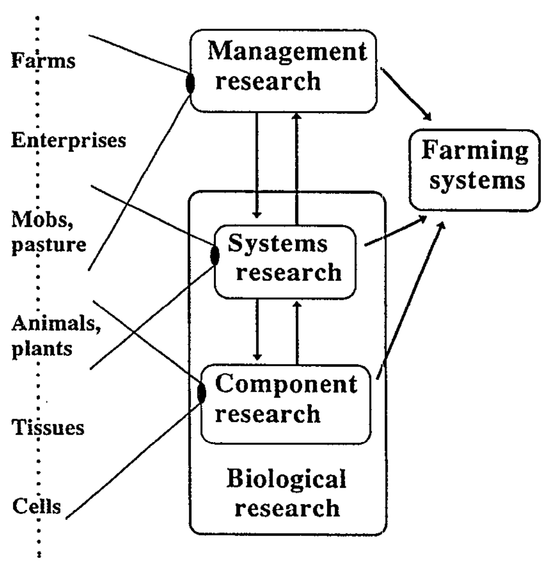
In many respects, the use of simulation models can be seen simply as an extension of the general use of models to conceptualise and state hypotheses regarding the natural world. However, simulation models provide a range of opportunities not normally associated with other types of models. Simulation models may take a variety of different forms from spreadsheet models to complex iterative models or sets of differential equations solved using continuous simulation languages. They may be specified at different levels of aggregation and be based on theoretical considerations or empirical observation. The type of model used in a research programme and the manner in which it is used will depend on the objectives and the stage or maturity of the research being undertaken.

This paper is concerned with the use of simulation models in animal research at all levels including research into basic biological function, systems research and management research.

USE OF MODELS IN RESEARCH

For the purposes of this paper, research is categorised into three main types targeting different levels in the hierarchy of systems as illustrated in figure 1. Ultimately, the purpose of biological research is to achieve better representation of biological function so that our ability to predict responses of, and therefore to manage, commercial systems is improved. Component research is concerned with understanding the mode of action or behaviour of components of production systems or their subsystems and includes tissue, cellular and subcellular research as well as research at the whole animal and plant level. Systems research is assumed here to mean research aimed at characterising and understanding interactions that occur between components at the production system level. This is as much a basic research objective as that associated with component research. The distinction between the two is to some extent arbitrary; apart from the hierarchical level at which the research is carried out, the main difference has been that systems research has naturally tended to use "systems approaches" and component research has traditionally used "reductionist approaches". In fact, systems approaches are applicable at all levels in the hierarchy.

FIGURE 1: Hierarchical Levels in Research Objectives



Management research is contrasted with biological research and is concerned with quantifying the effect of different system organisations and interventions on systems output so as to achieve "best" or "better" systems. Systems output includes both physical performance indices and financial returns and risk in different environments. It might be argued that this involves simply another step up the hierarchy but the objective in this case is not so much to understand why something happens as to utilise the best understanding and representation of the system available, whether in an experimental plot, a farmlet trial or a model, to examine the implications of different combinations of technology and management strategies. The easiest way to contrast the two is to take an extreme example of trials designed to quantify the impacts of major changes to the management of semi-natural grasslands in the UK (Sibbald & Maxwell, 1990). The intention of these trials was to quantify the effects of a different organisation of the system rather than to characterise the relationships causing the effect. As the differences in effect between management strategies diminishes, it becomes increasingly difficult to interpret the results of such trials without a quantitatively adequate understanding of the interactions determining behaviour. Thus there is an increasing need to undertake research to characterise these relationships and to represent them in ways in which their implications can be quantitatively assessed.

Potential Uses of Models in Biological Research

Over the last decade, there has been increasing use of models in animal research programmes, both independently and in conjunction with experimental work, and at all levels in the hierarchy. Models can be used for a number of different purposes in biological research, often depending on the stage of the research programme. Potential uses include:

a) Integration of existing data and concepts and evaluation for adequacy as quantitative explanations of behaviour.
b) Identification of required research/experiments.
c) Screening of potential experiments.
d) Hypothesis generation and testing.
e) Deduction of unmeasurable parameters.
f) Interpretation and evaluation of experimental results.
g) Identification of improved representation of biological functions.

The process of representing a system of interest in the form of a systems diagram and its translation into a set of mathematical equations in itself will often indicate areas where data are unavailable or inadequate to identify a particular relationship thought to be important in determining behaviour. Definition of a model involves two steps; the structure (variables and functional form) of equations must be defined, ie components and relationships necessary to accommodate the sources of variation defined as objectives must be identified; and then parameters must be quantified. The latter can only be done empirically in the sense that parameter values must be derived experimentally or deduced by reference to some data set. The former however may be done empirically, that is variables and equation forms may be determined on statistical grounds, as for example in step-wise regression, or it may be done on theoretical grounds based on an understanding of the function of biological entities. The applicability of empirically defined elements is constrained to conditions which are similar to those in which data used to develop the model were collected. Where structure has been defined on theoretical grounds to accommodate specified sources of variation however, the model should apply in all conditions where the same sources of variation are apparent.

Most models contain some mix of empirically defined and theoretical elements. Where a model is used as part of a biological research programme, those elements which are the target of the research will be theoretically defined, ie they must represent concepts regarding the mode of action or behaviour of the biological entities of interest.

Solution of a model and comparison with test data will indicate whether the concepts and data included in the model are adequate to explain the behaviour of the system under study. If not, aspects of the model which are poorly behaved can indicate where further research needs to be undertaken either to collect additional data or to redefine concepts, ie the model may be used to identify potential experiments. Alternative hypotheses concerning the mode of action of poorly described or behaved elements can be tested in the model to indicate whether these are adequate to accommodate observed responses; those which can be shown to be adequate become candidates for experimental evaluation.

Models can also assist in the design of experiments. Model identification is a formal process which tests whether and which parameters of a particular model structure (ie representation of a particular concept) can be quantified with a given data set. This allows the "best" model structure to be defined given available data. Alternatively, data required to quantify a given model structure can be defined. By adding or subtracting observations to a reference data set and by including estimates of the distribution of particular data items (error), the number and type of data (ie. experimental measurements) required to quantify parameters of the model can be identified.

In some cases, parameter values may be difficult, costly or even impossible to measure experimentally. A well constructed model can be used to examine the sensitivity of outputs and error to variations in such parameters. Parameters which have little effect on model output or error are usually unimportant in determining behaviour and their values are unlikely to be able to be deduced from measurable parameters. Where model output is very sensitive to the value of a particular parameter, the opposite applies; it can be assumed that the parameter is important in determining behaviour and that an estimate of its value, or one or both limits to its value, should be able to be deduced if it is not directly measurable (Baldwin *et al.*, 1990).

Models which represent underlying mechanisms determining behaviour can provide a means of evaluating and interpreting data collected in whole animal experimentation. A classic example is the interpretation of energy balance data and division into terms representing maintenance and production efficiency. Conventional regression analysis produces variable results in these circumstances because of the relationship between different components of energy balance. Baldwin *et al.* (1987) have shown how metabolic models provide a means of estimating maintenance and production costs so as to be able to evaluate energy balance data.

As noted above, the purpose of biological research is ultimately identification of improved representation of biological function. Examination of concepts regarding structure and function at low levels of aggregation should assist identification of critical determinants of behaviour at higher levels thus allowing reaggregation of factors required to achieve improved representation and performance in systems and management models (Bywater, 1984a; Black *et al.*, 1990).

MODELS IN COMPONENT RESEARCH PROGRAMMES

As noted above, there has been increasing use of simulation models in research at all levels in the systems hierarchy. At the component level, there have been a number of groups around the world using models in conjunction with experimental research. One of the longest running and most well known programmes of research into factors controlling digestion, metabolism and production of animals is that of Baldwin and his colleagues at the University of California, Davis. Other prominant programmes include the work of Thornley, France, Gill and others at the Grassland Research Institute (later Animal and Grassland Research Institute) at Hurley in the UK and that of Black and colleagues at the Prospect Laboratories in Australia. Use of models in component research in New Zealand has been somewhat limited in the past with most modelling being aimed at management objectives. More recently, models have been integrated with experimental work on some aspects of metabolism, nutrient intake and wool growth, as noted below.

Modelling work began at Davis in the late 1960's and provides numerous examples of the uses of models discussed above. The programme has involved a number of different models and modelling approaches targeted at a wide variety of topics including rumen function and digestion; metabolism in liver, adipose and mammary tissues; factors contributing to maintenance energy expenditures; and control of, and nutrient partition in lactation and growth. An earlier report of this programme was given at the 36th meeting of this Society (Baldwin, 1976)

Lactation

One of the earliest models developed at Davis was an attempt to evaluate available concepts and data on metabolism in dairy cows (Smith, 1970). Analysis with the model indicated a number of inadequacies in then current concepts with respect to the regulation of metabolism in a number of tissues and organs. This lead to development of modelling supported experimental programmes into metabolism and metabolic regulation in adipose (eg., Yang & Baldwin, 1973), liver (eg., Looney, 1985; Mesbah & Baldwin, 1983) and mammary tissue (eg., Forsberg *et al.*, 1985a, 1985b; Waghorn & Baldwin, 1984). A limitation of the original model was the large number of equations required to represent metabolite concentrations in blood, tissue and extra-cellular fluids. Use of Michaelis-Menten kinetics for representing net uptake and utilisation of single substrates or ratios of substrates by tissues was found to increase solution efficiency, stabilise model behaviour and allow estimation of rate constants directly from experimental data (Baldwin *et al.*, 1985). This has proved to be a significant step and has become the standard in tissue metabolic models. Changing either the capacity or affinity parameters of the Michaelis-Menten function provides a relatively simple means for accommodating changes in metabolic properties due to growth, hormonal changes in lactation, etc.

Following advances with the individual tissue models, reaggregation of separate elements into a second whole animal model in collaboration with the group at Hurley resulted in much improved performance characteristics (Baldwin *et al.*, 1987). This model has been used for evaluation of nutritional and hormonal factors associated with regulation of lactation and has given rise to a further major round of experimentation (eg, Hannigan *et al.*, 1992; Knapp *et al.*, 1992; Miller *et al.*, 1991). Updated versions of the mammary (Baldwin *et al.*, 1989) and liver (Freetly *et al.*, 1993) models have also been developed.

Development of the lactating cow model provides an example of progression through cycles of modelling and experimental work. It also illustrates the efficacy of modelling at different levels in the hierarchy to identify primary determinants of function at tissue and cellular levels followed by reaggregation to whole animal models. A more aggregated version of the dairy cow model is being developed for integration with the grazing system model of Cacho *et al.* (1994). It is based on the model of Baldwin *et al.* (1987) and includes concepts used by Neal & Thornley (1983) and France *et al.* (1987).

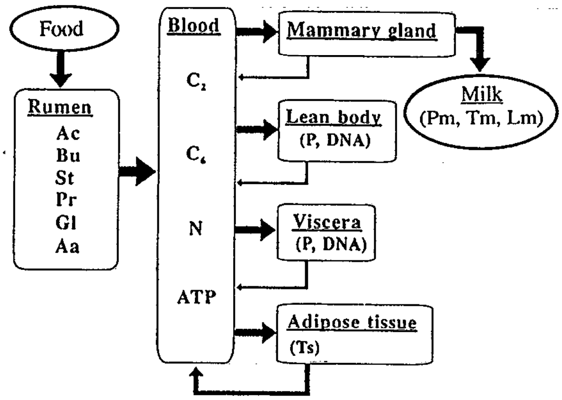
Neal & Thornley (1983) developed a model of the mammary gland which describes potential milk yield based on the concentration of lactation hormones, the number of secretory cells in the gland and the pattern of milk demand (either by machine or a suckling calf). This model was incorporated into the model of Baldwin *et al.* (1987) which accounts for the effects of nutrient availability on the amount and composition of milk produced. The model includes detailed representation of biochemical and physiological transactions; it accounts for 16 nutritional inputs to the rumen which are processed into 18 metabolic compartments and yield 6 metabolites. These metabolites provide materials and energy for transactions in lean body, viscera, adipose tissue and the mammary gland. The mathematical description of the model consists of 320 equations with over 1300 variables.

This model has proved to be an excellent research tool. However, simulation of an individual animal in such detail is impractical in the context of a management model. Where the objective is to study the effects of factors such as feeding strategies or stocking rates on the level and composition of milk produced by a dairy herd, the time required to solve such a detailed animal model in multi-year simulations of a whole herd, and the memory required to store the data representing the farm would be prohibitive.

France *et al.* (1987) developed a model of nutrient use and growth in steers which consists of six absorbed nutrients, transformed into three metabolic pools used for body growth in terms of protein, lipid and ash. The model requires 52 equations and is at a level of resolution which is closer to that needed for whole farm simulation. However, the model does not deal with lactation and fails to distinguish between body proper and viscera; the latter is considered to be important because the relative demands of these compartments are affected by pregnancy and lactation.

By aggregating some of the equations from Baldwin *et al.* (1987) and incorporating concepts from France *et al.* (1987), a model at the desired level of resolution has been specified. This model has enough detail to allow investigation of management factors affecting milk production and composition while avoiding explicit representation of detailed transactions not relevant to the intended application. In its current form, the model represents the processes of protein synthesis and degradation, gluconeogenesis, glycolysis, lipogenesis and lipolysis as affected by the concentrations of substrate available (see Figure 2). Rumen function is not explicitly treated yet; it is in the form of a lookup table containing the expected production of different metabolites depending on the type of pasture being grazed. The model has not yet been calibrated to New Zealand conditions.

FIGURE 2: Conceptual model of a dairy cow.



Boxes represent compartments within the animal. Absorbed nutrients: acetate (Ac), butyrate (Bu), stearate (St), propionate (Pr), glucose (Gl) and amino acids (Aa). Metabolites: lipids(C2), glucose (C6), nitrogen(N). Products: protein (P), DNA, triacylglycerol (Ts), milk protein (Pm), milk fat (Tm), lactose (Lm).

Animal Growth

A number of different approaches have been used to describe and/or predict animal growth. Models have been developed as part of experimental programmes aimed at understanding metabolic transactions such as that of France *et al.* cited above (France *et al.*, 1987), as a means of testing hypotheses concerning fundamental determinants of growth (eg Baldwin & Black, 1979), or simply to predict growth for extension or management use either alone (eg, Bell *et al.*, 1990; Fox & Black, 1977) or as part of larger systems models (eg, Graham *et al.*, 1976, Finlayson *et al.*, 1994).

Growth models differ in the way in which they treat two main sets of factors causing variation in growth and body composition; the first being physiological factors regulating growth and the second, nutritional factors. The former have been commonly described by a single equation such as the Gompertz equation (Gompertz, 1925), the allometric equation (Huxley, 1932) or a logistic equation. This approach has been used in fairly simple models designed for extension or management use (eg, Bell *et al.*, 1990) or where the principal objective has been an investigation into nutritional or metabolic factors influencing growth (eg, France *et al.*, 1987). A recent disussion of the use of the allometric equation for describing animal growth has been given by Pleasants *et al.* (1993). In some cases target growth levels are set independently to the model which then simulates the intake and metabolic transaction involved in growth (eg Marshall *et al.*, 1991).

Alternative specifications of physiological control of growth have been used by Oltjen *et al.* (1986) based on concepts evaluated by Baldwin & Black (1979). The latter model was developed in Australia to evaluate concepts that primary factors concerned in the regulation of tissue growth are cell number and size (as represented by mature DNA and DNA: protein ratio) and the specific activity of enzymes expressed as a function of tissue or organ weight (Baldwin & Black, 1979). The model contained explicit representation of nine tissue and organ systems each with three structural components and two enzyme groups. Rate constants and exponents were calculated from data on the first seven days of growth of rats and were then used to simulate growth to maturity of the same tissues and organs of five animal species including sheep and pigs. Concepts included in this model were used by Oltjen *et al.* (1986) to develop a model of lean body mass and fat in cattle with only two state variables representing whole body DNA and protein and a generalised nutritional term. Energy transactions in this model are described using the net energy system published by the National Research Council in the United States (NRC, 1976). The model has subsequently been combined with a more detailed representation of metabolism (Di Marco *et al.*, 1989) and also formed the basis for development of the lamb growth (St Pierre & Bywater, 1989) and mature sheep elements of the sheep farm management model described by Cacho *et al.* (1994).

Representation of metabolic factors associated with differences in growth and body composition also vary between models with some such as the model of France *et al.* (1987) explicitly representing transformation of major metabolites and others based on standard feed requirements sytems such as those of the National Research Council in the US and the Agricultural Research Council in the UK.

Wool Growth

Sheep differ between breeds and individuals in the characteristics and growth rate of their wool and in the response of these to changes in nutritional and physiological status. Some attempts have been made through modelling to unravel the complex events in the wool follicle determining fibre growth and morphology. Black & Nagorcka (1993) have reviewed quantitative aspects of wool production and suggest that growth and characteristics of wool fibres are determined by: The number and type of wool follicles; the number of cells in follicle bulbs; the rate of bulb cell turnover; the proportion of migrating bulb cells which enter the fibre; the commitment of cells entering the fibre; and the size of cortical cells. These factors were included in a model of sulphur amino acid incorporation into wool fibres designed to predict nutrient partition between wool growth and other tissues (Black & Reis, 1979). Alteration of these genetically determined factors allowed comparisons to be made between sheep with high or low genetic potential for wool production. It has been postulated that some of these genetic factors can be modelled by the patterns of spread and concentration of inducing chemicals or morphogens in the developing foetus. This is referred to as the reaction-diffusion model and has been applied to prediction of follicle initiation (Nagorcka & Mooney, 1985), follicle development (Mooney & Nagorcka, 1985) and differentiation of bulb cells to fibre cell types (Nagorcka & Mooney, 1982).

Scobie & Woods (1992) suggest that of the factors identified by Black & Reis (1979), the most important are the volume of the germinative region of the follicle (the number and size of cells) and the proportion of cells which enter the fibre. They propose a model of wool growth based on the bulb volume per unit of skin and the capacity at any given time for keratin formation, the first determining the volume of wool produced and the second the differentiation of cell types and the weight of wool produced. One of the problems in understanding the development and morphology of wool fibres is difficulties associated with measuring migration of cells from the bulb into different components of the fibre. Gandar *et al.* (1990) introduced the concept of the velocity field in wool follicles which models changes in length and mass of fibre by reference to the density of nuclei passing a particular point. Gandar & Hall (1994) suggest that this model is best used in interpreting experimental data to capture information on the distribution of growth from static observations of fibre sections and thus assist in the development of theories of fibre growth.

Feed Intake Regulation

Food intake regulation is known to involve a variety of different mechanisms which assume varying importance in different conditions. As indicated earlier, one of the main benefits of models is the ability to integrate concepts and data in order to evaluate whether they are adequate to accommodate observed behaviour in quantitative and dynamic terms. Intake regulation would appear to be a prime candidate for such evaluation although Poppi *et al.* (1990) have suggested that incorporation of all postulated mechanisms would result in an impossibly complex model. Nevertheless, they examined a number of possible expressions of both physical and metabolic regulation including a limit to ATP degradation which they suggest may be a surrogate for the build-up in concentration of a number of metabolites implicated in intake control. This mechanism provided estimates of changes in intake in a number of circumstances including protein supplementation and mixed diets of milk and forage which were sufficiently close to observed changes to indicate that further exploration of the concept would be worthwhile.

It has also been suggested that in some circumstances, intake may be controlled by a number of pathways in combination rather than one single pathway. Fisher *et al.* (1990) have proposed a simultaneous combination of simple expressions of physical and metabolic factors rather than the rate limiting approach of most other models. It is not clear how this might be achieved with more complex representations of the separate pathways, however. Models have been proposed emphasising different regulatory mechanisms including several representing rumen digestion and passage (eg, Illius & Gordon 1991), rate of energy use as a factor affecting meal size (Forbes, 1980), grazing behaviour and selection (Ungar & Noy-Meir, 1988) and the mechanics of eating rate and bite size in grazing ruminants of different body weight (Illius & Gordon, 1987). All of these models address short term regulation of intake; longer term control of intake through gradual changes in energy set points was examined by Monteiro (1972) and this was extended to include longer term changes in physical capacity due to changes in energy requirements by Bywater (1984b).

Detailed exploration of factors involved in metabolic regulation ought to be possible through examination of the types of mechanisms postulated by Poppi *et al.* (1990) in combination with rumen fermentation and animal metabolism models such as those developed at Davis cited earlier and by the group at Hurley (eg France *et al.*, 1987; Gill *et al.*, 1984). With respect to physical passage relationships, current models are not yet adequate to accommodate all feeds or sources of variation and additional factors need to be considered. A review of factors concerned with quantitative regulation of intake has recently been undertaken by Forbes (1993). In the grazing situation, further examination of factors affecting intake by different animal species of different pasture components should be possible as discussed below. This is required as a basis for aggregation to improve intake relationships in whole system models such as those of Cacho *et al.* (1994), Marshall *et al.* (1991) and White *et al.* (1983).

In many of the instances cited above, the use of models has added significantly to the progress made through experimental research. In some areas - and the study of intake regulation may be one - experimental research on its own has not resulted in a clear understanding of the mechanisms determining behavior and their interactions and relative importance under different conditions. Further progress may depend on a combination of experimental and modelling approaches and there has been an increased interest in the use of models in this context. Whether it will be successful remains to be seen.

Models in grazing system research

As noted earlier, as the difference in outcomes between technologies or management strategies in pastoral production systems diminishes, it becomes increasingly difficult to interpret the results of trials examining these factors without a quantitatively adequate understanding of the interactions within the system. For example, Bryant (1990) has demonstrated that large differences in grazing management at different times of year may result in very small differences in total milk output from pastoral dairy systems. It is our view that modelling provides the only feasible way of representing relationships in grazing systems so that interactions and their effects can be quantitatively assessed. Yet there have been few attempts to use models in this way. Most of the production systems models, and perhaps most production systems trials, have been directed primarily at management research objectives rather than systems research objectives, (ie at quantifying outputs rather than at understanding interactions). However, over the last decade, particularly in the UK and New Zealand, there have been some attempts to characterise interactions between animals and pastures in grazing systems through models and systems trials. There is perhaps now sufficient understanding of some of the major factors involved and sufficient data that quantitative explanations of trial results are possible through a combined modelling and experimental approach.

A principal concern in the interaction between the grazing animal and pasture is the effect of different animal species and grazing management strategies on tiller numbers and condition and the affects of these on photosynthesis, growth (leaf emergence and expansion) and senescence. These factors have been investigated by Bircham & Hodgson (1983), Grant *et al.* (1983, 1988), King *et al.* (1988), Korte *et al.* (1984) and Parsons *et al.* (1983) among others and have led to development of a model of grass growth under grazing (Johnson & Parsons, 1985). The model has been used to investigate effects of continuous vs rotational grazing and of the interval between grazings on pasture condition and instantaneous and average pasture growth rates (Parsons & Penning, 1988; Parsons *et al.*, 1988).

A consideration of particular importance in New Zealand pastures is the factors affecting clover content. We are not aware of any attempts to model these for explanatory purposes but data on persistence of a number of clover cultivars under rotational and continuous grazing of mixed swards are available (eg, Brock, 1988; Caradus *et al.*, 1991; Hay *et al.*, 1989) and a review of research on clover has recently been undertaken (Brock *et al.*, 1989). On the animal side, attempts to quantify grazing behaviour in terms of selection (Ungar & Noy-Meir, 1988) and effects of sward and animal factors on bite size and intake of grazing ruminants (Illius & Gordon, 1987) have been noted above.

We are not aware of any attempt to accommodate all the above factors in an explanatory model of the grazing system and it remains to be seen whether understanding of the factors affecting tiller dynamics, clover content, pasture growth and senescence and animal grazing behaviour is sufficient to adequately account for trial results such as those reported by Bryant (1990). In our experience, the dominance and variability of climatic parameters of temperature, moisture and light in determining photosynthesis can make isolation of other factors very much more difficult but we remain convinced that a well structured model is the only way in which such an evaluation is possible.

Models in management research

A number of simulation models have been developed to quantify outputs of alternative strategies or technologies of production in pastoral systems. This section will concentrate on models and modelling analyses conducted in New Zealand since this is an area where there has been considerable activity in this country. Models vary from a range of spreadsheet models (eg Keeling *et al.*, 1991; McMillan & McCall, 1991; Parker *et al.*, 1992) to larger simulation models such as STOCKPOL (Marshall *et al.*, 1991) and our own grazing system model LINCFARM (Finlayson *et al.*, 1994; Cacho *et al.*, 1994). While recognising that our understanding of the dynamics of grazing systems is not complete, such models attempt to capture the best available concepts and data so as to quantify the implications of different system organisations on output and financial returns and in some cases risk. In doing so they may provide insights more quickly or in ways that would be impractical through experimentation. While it has been argued that simulation models can not substitute for field experimentation (McCall, 1993), it can also be said that simulation models provide the capability to explore relationships that cannot be explored in any other way. Such a case is discussed in more detail below.

The discussion here is confined to the use of production systems models in management research rather than as direct advisory or management tools. There are a number of different ways in which production systems models may be used in management research, both in combination with experimental work and on there own. As with the use of models in component research, production systems models can be used to help guide experimental research or extension programmes. For example, the sensitivity of system performance to assumptions regarding components or relationships within the systems can indicate where potential gains are most likely to be made through research or extension efforts. McCall & Marshall (1991) investigated a number of animal and management factors affecting efficiency of beef production from pasture using a relatively simple model. Animal factors included changes in mature weight, conversion efficiency and maintenance requirements, all of which can potentially be altered either through genetic selection or by breed choice. Manipulation of mature weight was found to be the best way of improving efficiency.

Simple models can also be used to screen management or technology options for experimental evaluation. For example, there has been a resurgence of interest in the potential for once bred heifer systems in recent years. Keeling *et al.* (1991) have used a spreadsheet model to investigate the potential profitability of such systems in preparation for experimental evaluation. Nicol (pers com) has used a simple model to investigate different combinations of once bred heifer and hind systems in an attempt to exploit the complementary pasture requirement patterns of the two species.

The most common objective with management models is to investigate the effects of short or long term management options with respect to their effect on outputs (production, returns and risk) of the system. An example of the use of models to optimise short term management is given by McCall *et al.* (1986) who demonstrated the effects of grazing decision rules on animal intake and the potential errors associated with assumptions normally made in feed budgeting.

Some of the models cited above are designed to operate as single year simulations or are constrained to steady state conditions, meaning that opening and closing pasture covers and stock numbers must be equal. Other models are designed to allow multi year simulations. Where a comparison is made between different policies or strategies of production, use of single year, average or steady state conditions can result in misleading information regarding the output characteristics of the systems being compared. This is illustrated by the analysis of Cacho & Bywater (1994).

Perhaps the main advantage of production systems models is that they allow experimentation with a far greater range of variables over a much wider range of conditions than would be feasible in practice. An analysis of farm management factors affecting the production of fine wool (Bowman, 1989) provides a good example of the kind of experimentation possible with such models. Whilst the analysis concerns farming systems in Victoria, it was carried out at Lincoln and concerns an issue of relevance to New Zealand. More importantly, it is one of the most comprehensive evaluations of farm management practices using simulation to have been published.

The model used in this case was the sheep production model developed at Werribee in Victoria by White *et al.* (1983) and subsequently modified at Lincoln to improve the representation of factors affecting wool growth and fleece characteristics (Bowman *et al.*, 1993). Major functions in the model have been refined over several years based on data collected in the Hamilton region of Victoria. The analysis conducted with the model represented a 500 hectare farm in the locality and was run over a period of 23 years with climatic and price data from 1965 to 1988. This period included severe droughts in 1967/68 followed by good growing seasons in 1969/70. The experiment included two animal genotypes (medium fine and strong wool merino types) at three stocking rates, with three reproductive performance levels, three lambing times, three rates of supplementary feeding during two periods of supplementation in a full factorial design.

Output from the model includes various measures of wool production used to calculate wool price by two different methods (the reserve price schedule for the period and predicted hauteur as a measure of processing performance), number of lambs born, returns from animal and wool sales, production costs plus a number of intermediate measures (eg, pasture cover) and physical performance indices such as premating weights, weaning percentages, wool weights per hectare and others. Means and standard deviations of each measure were calculated from results of each year in the 23 year sequence. Selected performance statistics for the two breeds are shown in Table 1. Examples of physical performance measures and financial costs and returns for one combination of variable factors are shown in Tables 2 and 3.

TABLE 1: Selected Performance Statistics for Adult Peppin and South Australian Merino Ewes for the Period 1965/66 to 1987/88.

	Merino genotype			
	Peppin		South Australian	
	Mean[a]	Std.Dev.[b]	Mean[a]	Std.Dev.[b]
Clean fleece weight (kg)	3.02	0.11	3.48	0.14
Mean fibre diameter (um)	21.2	0.2	23.4	0.2
Staple length (mm)	90.2	1.2	102.6	1.6
Staple strength (N ktex^{-1})	39.8	4.1	40.5	4.1
Position of break (%)	65.1	6.7	62.7	13.6
Hauteur (mm)	64.9	2.0	72.9	2.1
Number shorn	3806	307	3329	268
Total wool weight (tonnes)	11.54	1.21	11.62	1.25
Wool price: method 1[c] ($ kg^{-1})	3 00	1.59	2.83	1.30
Wool price: method 2[d] (S kg^{-1})	3.20	1.68	2.84	1.31
Gross wool returns: method 1[c] (S)	34617	19482	32797	15765
Gross wool returns: method 2[d] ($)	36860	20586	32903	15742

[a] Mean for 1965/66 to 1987/88 financial years
[b] Standard deviation
[c] Price calculated using the reserve price schedule
[d] Price calculated using the predicted hauteur

TABLE 2: Example Financial Performance for One Combination of Variable Factors.

	Mean	Std. Dev.
RETURNS		
Wool	$46477	$22885
Lambs	$11610	$5417
Cull mature ewes	$6211	$4048
Cull maiden ewes	$7249	$3575
Interest	$1574	$804
Total gross returns	$73121	$33388
COSTS		
Enterprise	$20792	$12706
Supplementary feed	$3446	$5329
Labour and storage	$2170	$846
Total cash costs	$26408	$16037
Cash operating surplus	$46713	$19777
Operating income	$48010	$24270
Net cash income	$15813	$8981

(South Australian Merino flock: lambing in May, average reproduction rate, 7 breeding ewes ha^{-1}, medium level of supplementary feeding.)

Results from the analysis indicated that the management strategy which resulted in most improvement in performance and profitability was to delay lambing from the traditional time for the region, which is in autumn (May), to winter (June/July). This resulted in an improved feed supply in late pregnancy with better lamb survival and weaning rates. Fleece weight and staple length were reduced but so was fibre diameter (the main determinant of price) and there was an increase in staple strength. This led to an increase in wool price. Although there was lower production per animal, more animals were shorn and the result was an increase in total production and total returns. Other strategies produced conflicting physical results with less net effect on returns. Increases in stocking rate or reproductive performance decreased the quantity of digestible pasture at critical times of year and decreased fibre diameter but also decreased fleece weights, staple length and strength leading to little change in wool price. Although there was a decrease in production per animal, with more animals total production was increased and there was some increase in total returns. Effects of increasing the level and changing the time of supplementary feeding were to increase stock survival and weights, increase fleece weights, staple length and strength but also fibre diameter leading to little effect on price. The result was an increase in returns from both wool and stock sales but the increased cost of the feed resulted in little change to net revenue.

Objective measurement of wool is being introduced increasingly in both New Zealand and Australia. This will allow characteristics of wool samples to be identified which have not been distinguished in the past and opens the way for pricing on these factors. A comprehensive analysis of the farm management strategies likely to affect wool weights and fleece characteristics such as that described would not have been possible without the use of a simulation model. The resources required to undertake a live experiment of the scale accomplished within the simulation would be prohibitive and the time required to conduct such an experiment over a sufficient range of seasonal conditions would mean that the results would not have been available until several years after farmers would have had to respond to the change in market environment.

TABLE 3: Example Physical Performance for One Combination of Variable Factors.

	Mean	Std. Dev.
Flock stocking pressure - at mating (DSE ha^{-1})	10.11	0.82
- 6 weeks before lambing	11.10	0.75
- at the start of lambing	16.78	1.29
- at the end of lambing	18.58	1.40
- just after weaning	12.41	0.79
Stocking pressure of weaned lambs	12.87	0.82
Digestible pasture - at mating (kg DOM ha^{-1})	3947	616
- at the end of lambing	1637	310
- just after weaning	1424	528
Pregnant ewes with single lambs	2878	238
Pregnant ewes with twin lambs	132	18
Ratio of lambs born to ewes mated	0.919	0.006
Ratio of lambs weaned to ewes mated	0.793	0.014
Ratio of twins weaned to ewes mated	0.055	0.004
Total lamb losses (%)	13.0	1.4
Single lamb losses (%)	12.2	1.3
Twin lamb losses (%)	22.6	2.1
Ewe losses - total number	65	5
- relative losses % - dystokia	0.73	0.10
- relative losses % - preg. toxaemia	6.96	2.36
Supplementary feed - flock total (tonnes)	32.2	44.8
- single ewes	24.4	35.5
- twin ewes	1.1	1.5
- dry ewes	4.6	7.7
- adult ewe total	30.0	44 7
- maiden ewes	1.3	3.2
- lambs for sale	0.9	2.4
Lambs sold	1272	121
Average age of lambs when sold (weeks)	26.7	2.0
Average lamb sale price ($)	9.13	4.07
Maiden ewes sold	500	118
Average maiden ewe sale price ($)	14.50	6.61
Mature ewes sold	748	362
Average mature ewe sale price ($)	8.31	4.05
Pre-mating weight change (kg)	0.75	0.38
Average ewe weight at mating	57.6	1.7
Pre-lambing maternal weight change	-1.99	0.66
Maternal weight of lambing ewes	49.9	1.1
Average ewe weight at weaning	54.3	2.2
Lamb birth weight		
- singles (kg)	430	0 09
- twins	3.57	0.08
Lamb weaning weight		
- singles (kg)	22.0	2.2
- twins	19.0	2.3

(South Australian Merino flock: lambing in May, average reproduction rate, 7 breeding ewes ha^{-1}, medium level of supplementary feeding.)

The question remains as to how acceptable the results of such an analysis are likely to be to farmers and advisors. The model used in this analysis has been shown to provide good predictions in the region within which it was developed and this lends credibility to the conclusions from the study. Ultimately however, users of the information will make their own judgement on its worth. It is interesting to note the confidence with which experienced observers of the farming systems being studied can describe their expectations of performance after having studied output from a model. This provides a good indication of the value of the result.

CONCLUSION

As noted in the introduction, simulation models are being used increasingly in animal research both indendently based on published and unpublished data and perhaps more importantly, in conjunction with traditional experimental research. Models can make a major contribution to guiding experimental research in a variety of ways from initial identification of gaps in knowledge or data through to interpretation of experimental results and development of improved representation of biological functions. A number of instances in which models have been integrated into experimental research programmes and have significantly assisted progress have been described. In some cases, it seems likely that because of the complexity of interactions between components over time and in different conditions, modelling may be the only way in which progress will be made towards a clear understanding of the mechanics of the systems. It is suggested that regulation of food intake in ruminants and the interactions between different classes of stock, different pastures and different grazing management policies in pastoral livestock systems are two such cases.

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