

# TESTING MANAGEMENT-ORIENTED HYPOTHESES WITH SIMULATION MODELS<sup>1, 2</sup>

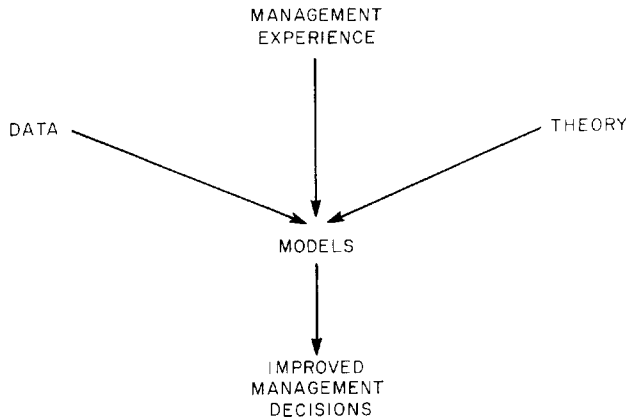
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*Abstract.* We need to manage and to use our renewable resources more wisely and yet more intensively in the future. To do this we need to incorporate more of our experience, our data, and our theory into the decision-making process. We can use simulation models in this synthesis effort to advantage. We can perform management experiments with ecosystem level models, generate meaningful output from those experiments, and condense and interpret this output in a manner useful to the management agency personnel. The result will be better resource management decisions based on scientifically and technically defensible information which will have greater internal consistency and which will produce better results under many conditions.

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It is a basic tenet that renewable resource managers work with stressed ecosystems. Herein, stress is defined as a major change in ecosystem structure and function caused by technological man in contrast to those changes caused by nature.

renewable resource managers must be concerned with complexes of ecosystems. Resource managers are extracting useful products from these ecosystems. They must modify and manipulate them to do this. And they must do this at an ever increasing rate to provide products for



Another tenet is that the ecosystem is the basic unit in resource management (Van Dyne 1969). Foresters, wildlife biologists, fisheries specialists, range scientists, watershed managers and other

the needs of mankind. In new or evolving resource management the managers must gather and combine all the experience, data and theory that they can in new ways to solve problems (see above).

Another evolving tenet is that models can and will be useful tools in the overall ecosystem management process. The process illustrated above is not one-directional, as will be discussed below.

The objective of this paper is to il-

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illustrate some of the roles that models can play in the overall management process. I will illustrate these roles with a few examples from our recent work and from the scientific literature on grazingland systems.

#### GRAZINGLAND SIMULATION MODELS

Man is trying to maximize both primary and secondary productivity simultaneously in grazinglands. In most other areas of resource management this is not as great a concern. Earliest major publications on grazingland simulation models have appeared in the scientific and technical literature only within the last 10 years (fig. 1). We are only beginning

What are the claims that these model builders and model users are making about models contributing to better renewable resource management? Complex ecosystems must be simplified for purposes of management, and models serve a role in conceptual simplification. Models provide a paradigm or a structure into which to embed our theories, data, and experience. For example, they provide a conceptual framework of logical interrelationships. Models are integrating mechanisms because they allow us to take data from field, laboratory, and armchair and couple it in a unique way.

Users ask, what predictions or projections can you make from the models? Many of the scientists who develop mod-

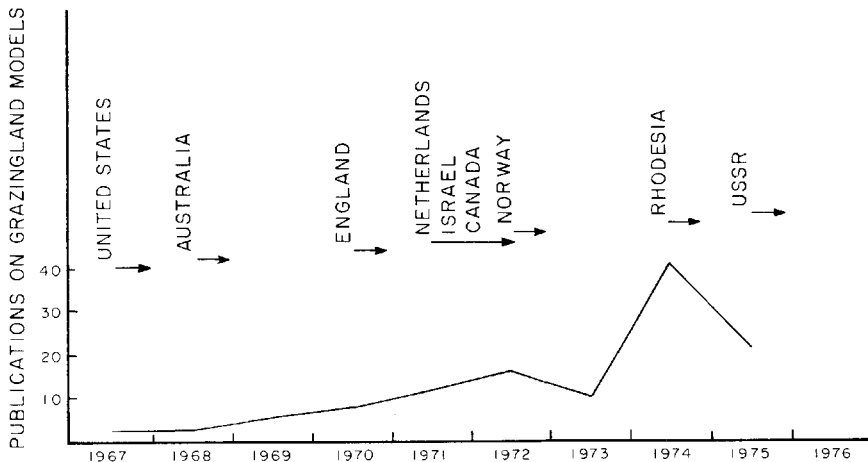


FIGURE 1. Publications on grazingland models from 1967 through 1975 based on a quick review of scientific literature. The time of beginning of contributions from different nations is shown.

to learn from these models—to learn what we know, what we don't know, what we can do with them, and possibly many of the things we should not attempt to do with them.

In a cursory review of the scientific literature I have identified more than 100 simulation models of grazinglands or their component parts published between 1967 and 1975 (Van Dyne and Abramsky 1975, Van Dyne *et al* 1977). This count does not include the simplified analytical predator-prey type models which have some utility in principle but seldom are parameterized for grazingland situations.

els want the model for research guidance, and their mechanistic models are excellent tools for cause-and-effect reasoning. All of the users say that models are not a utopia. Models do not replace all other approaches to dealing with complex problems. Models are simply a supplement to other approaches we will need for more intensive decision-making in resource management. Present models are most useful in providing order-of-magnitude or directional, qualitative responses rather than providing hard-and-fast dictates or specifying absolute requirements for renewable resource decision-making purposes.

### HYPOTHESES REGARDING ECOSYSTEM RESPONSES TO STRESS

Generally the resource manager's experience is obtained in independent studies or situations. Managers, however, may want to test hypotheses over a time frame, in a location, or with combinations of management treatments different from those situations in which they gained their original knowledge and experience.

#### *The Nature of Contemporary Management Questions*

Managers are concerned primarily with questions such as: What is the response of the total ecological system to intensity, season, and type of grazing? What is the response to different herbicides, fertilizers, predation, fire, air pollution, rainfall enhancement, ionizing radiation, or mechanical manipulation? Answers to these questions increasingly require information on the ecosystem as a whole. The questions are not of the type: "What would a management treatment do to cattle production or what would it do to blue grama grass production?"—these are questions of single-species focus. Current questions are concerned with the overall system response and the interconnections of system components.

#### *The Nature of Contemporary Management-Oriented Hypotheses*

In intensive management, as compared to extensive management, the questions are concerned with the sort of responses resulting from combinations of treatments, e.g., grazing, herbicides, and fire. But we are just beginning to formally structure our knowledge into hypotheses about ecosystem response to separate management stresses. For the short-grass prairie, we recently developed such a set of 50 formal hypotheses (Van Dyne *et al* 1977). These hypotheses have been derived from field experience (one type of field data) and from general theory about ecosystems. Conventionally, we test these hypotheses in field experiments. It might be possible, but it would take a great deal of time, money, and scientific expertise that may not be available in a given situation. For example, the Bureau of Land Management, the federal agency that manages the largest block of

grazinglands in the United States, has (under court order) the next 10 years in which to write 212 environmental impact statements on their grazingland management procedures. The Bureau probably does not have the time, money, nor scientific expertise to do all of this adequately if they use conventional approaches. This is because the requirements are to look at the response of the total ecological system rather than a single component. And, more importantly, they must predict such ecosystem response to *many* management stresses operating under *many* variations in climatic conditions starting in *many* initial conditions. The combination is a truly staggering number of situations to evaluate! Later I discuss how a large number of such situations may be evaluated in experiments conducted with simulation models.

Several types of hypotheses may be generated about grazingland systems and their components. Some are based on field data and observations and some are based on laboratory experimental results. Field data and observations may be concerned with levels, or dynamics, of the systems' *state variables* (e.g., biomasses of plants and animals), or the flows of matter or energy due to *rate processes* (e.g., photosynthesis and food intake rates). We may also generate hypotheses utilizing our general theory about ecosystems or their component parts. These concepts are illustrated at the top of pg. 193. These approaches result in two sets of hypotheses: one about ecosystems and their responses and one about physical and physiological processes in ecosystems. The two sets should be consistent. The process of simulation modelling is one way of testing this consistency.

We have taken hypotheses stated in words by experienced resource managers and converted them into simple graphs (fig. 2). The managers stated that grazing a pasture so intensively as to leave only a small amount of herbage results in poor animal gains/head (fig. 2d). Leaving more herbage improves gain/head up to a plateau. Animal gains/unit area may be highest at an intermediate level of herbage left after grazing. By increasing or decreasing the amount of

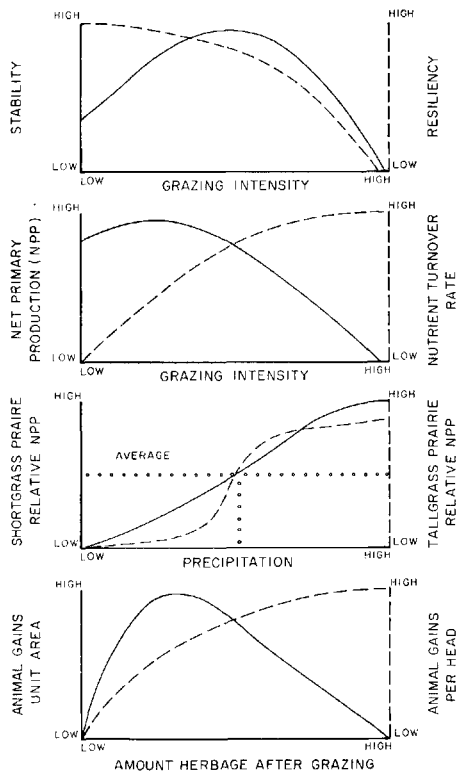
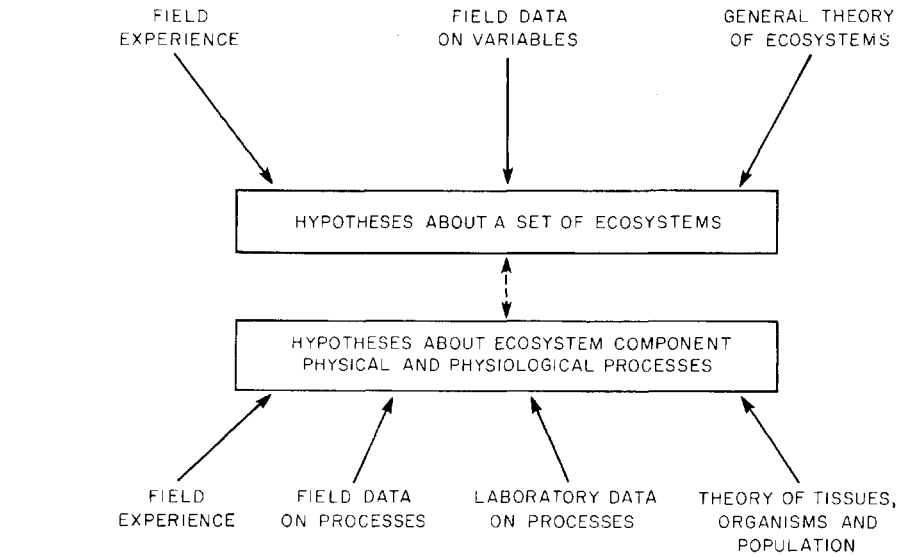


FIGURE 2. Example hypotheses about the response of grazingland systems in general to grazing intensity, precipitation, and utilization level. Curves shown by dashed lines refer to the axis labelled on the right side of each graph. (Referred to in text as a, b, c, and d from top to bottom.)

herbage remaining around the optimum point, animal production is decreased. The next step is to secure more information and graph this information for ease of interpretation. This hypothesis is about a grazingland response to one kind of stress—grazing as it affects the herbage or the animal.

An hypothesis which states that net primary production of a grassland is a sigmoid function of amount of precipitation (fig. 2c). Deviation from average precipitation has a more rapid impact on production in a semiarid grassland (e.g., shortgrass prairie) than in a subhumid grassland (e.g., tallgrass or true prairie). Average production is attained in both systems under average precipitation.

These examples show how we can generate hypotheses from verbal statements based on a combination of theory, data, and the accumulated experience of managers. We can formulate the hypotheses graphically to give, at least, the directional responses. We can also, in many cases, put numbers on the axes of these graphs.

*A Macrohypothesis of Interconnected Microhypotheses*

Let us consider the lower set of hypotheses noted above as *microhypotheses*. These microhypotheses are concerned with the mechanisms by which matter and energy move through an ecosystem

over time. If we couple these micro-hypotheses together we have a *macro-hypothesis*, i.e., a model of the system. When we can express the microhypotheses in mathematical functions, and when we couple these expressions, the result is a simulation model. Such models are often large and complex, requiring the

usage of large, fast digital computers. Versions of such models are described in detail by Van Dyne *et al* (1977) and Innis (1978).

We can divide the model (i.e., macro-hypothesis) into loosely coupled sub-models. We can divide the submodels into more tightly connected microhypothesis

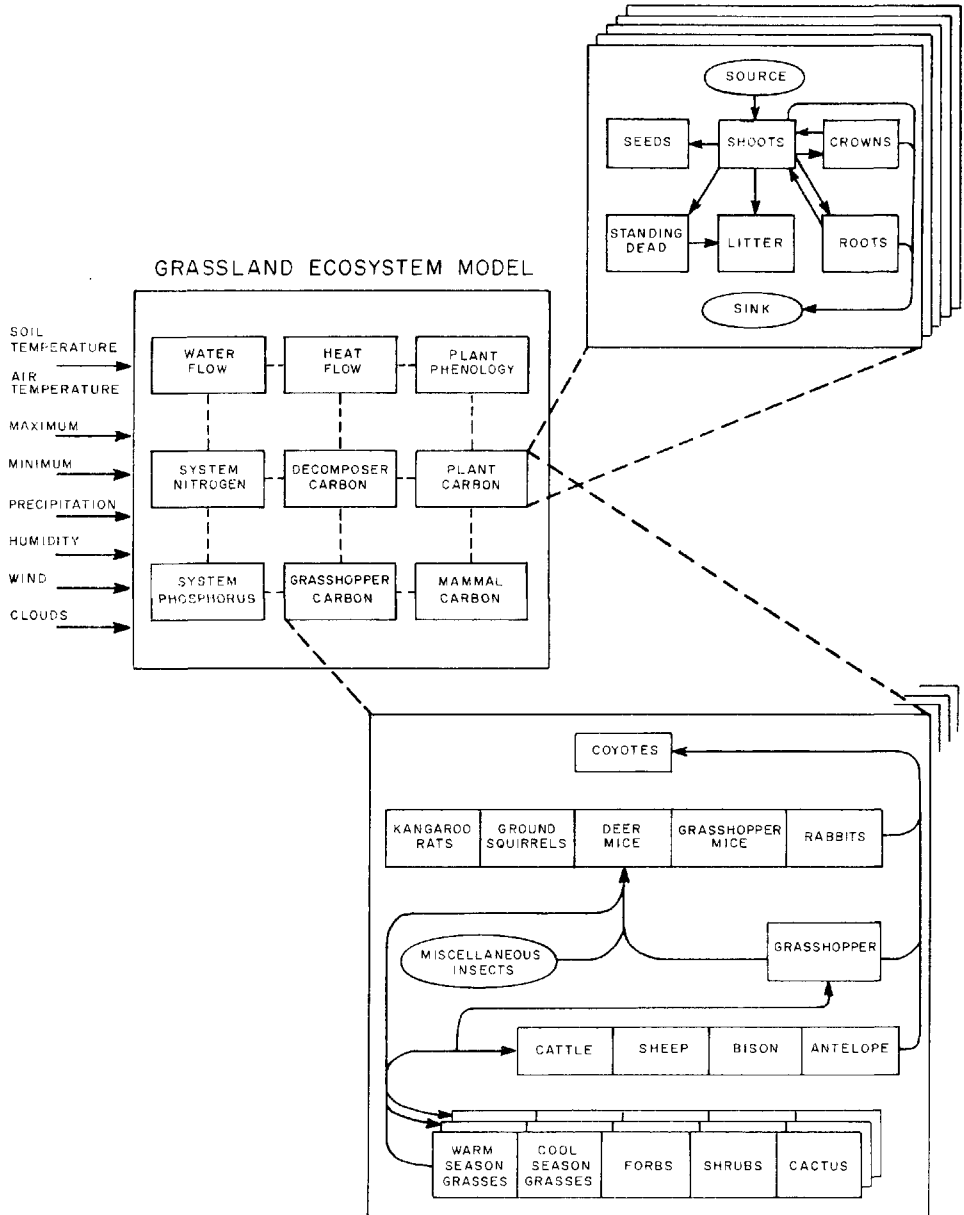


FIGURE 3. A simplified grazingland ecosystem model diagram (left) with expansions of submodels (right). Driving variables are *external*.

eses showing flows of matter and energy through the component parts (fig. 3).

This is a *system model* (i.e., an ecosystem-level model) that we designed to simulate the intraseasonal dynamics of grasslands. The model is a difference equation model, forced by seven driving variables which are primarily climatic but which also include soil temperature at the 2 m depth for heat flow considerations. It has water, heat, carbon, nitrogen, and phosphorus flows, and consists of nine submodels which are coupled together through transfers of information.

Each of the submodels can be dissected. The plant-carbon submodel (fig. 3, upper right) is made up of a series of compartments such as seeds, live shoots, standing dead, and litter. Each of the plant compartments may be repeated for different species or groups such as warm-season grasses, cool-season grasses, forbs, shrubs, and cactus.

The mammal submodel and the grasshopper submodel show that different trophic levels may be represented (fig. 3, lower right): a secondary consumer level (i.e., coyotes) and primary consumers (i.e., some small herbivores, large herbivores, and insects of two different types). The herbivores all feed on the shoots, standing dead, and seed portions of the five different categories of plants. The mammalian herbivores represented are cattle, sheep, bison, pronghorn antelope, kangaroo rat, ground squirrel, deer mice, grasshopper mice, and rabbits.

Each arrow in the model diagram represents a rate process. There are about 300 of these rate processes in the overall model; it requires about 900 parameters to characterize the rate process functions. In addition, the model will give us about 50 management-oriented output variables which are calculated from the state variables at a given time.

The results obtained using the model as a macrohypothesis depend upon the many innerconnected microhypotheses. The model microhypotheses then become critical. For example, how can we hypothesize the cows' dietary selection process? How does a cow select from among the 15 different plant components to get her diet? How do plants

take in carbon from a source and incorporate it into shoots? In other words, how do we model the processes of grazing, photosynthesis, ingestion, decomposition and many others?

There is no unique way to model these hypotheses. Modelling is an art and we use various art forms. Some microhypotheses are modelled at a high level of resolution, i.e., these are very mechanistic and operate over short periods of time. Some are more empirical and may operate over long periods of time. In some microhypotheses we use several driving and state variables to predict the change or the rate function. The form in which variables are combined in flow calculations varies widely among microhypotheses. Description of these approaches is beyond the scope of this paper. In fact, such description yet remains to be done in a single ecologically oriented textbook.

#### MODELS AND HYPOTHESIS TESTING

The system model can be used to test hypotheses such as those noted above and in figure 2. If the results of model runs are consistent with our hypotheses about real-life systems, then the model is a useful, powerful tool. It is useful because we can place some faith in its output. It is powerful because we can use it to generate predictions about many system variables simultaneously and we can make these predictions under many different combinations of management alternatives and climatic situations. Therefore, we should examine in more detail the possible model outputs and how we can use models in hypothesis-testing experiments.

#### *Kinds of Model Outputs*

Simulation models give perhaps two separate kinds of outputs, values over time for the variables or for the flows. As model output we can get time series graphs for model variables, selected values for variables over given time intervals (e.g., the maximum, minimum, or average value), values of flows plotted against time, intergrated values of flows for selected time intervals, plots of flows against variables, plots of variables against variables (e.g., trajectory diagrams) and plots of flows against flows.

### Examination of Model Output

For best value in prediction and extrapolation, a model should be built with cause-and-effect relationships. We should be able to sense some of those cause-and-effect relationships by looking at the output of a model such as in figure 4. This is an example of output from a 6-year simulation of a shortgrass prairie (Van Dyne *et al* 1977).

graph is kilograms cattle weight per animal showing their change during the year when they are stocked in the pasture. Because cattle were only in the system part of the year their values are zero before and after the grazing season. During the growing season they show gains and losses in weight.

These are only examples of the variables in the model. The time response

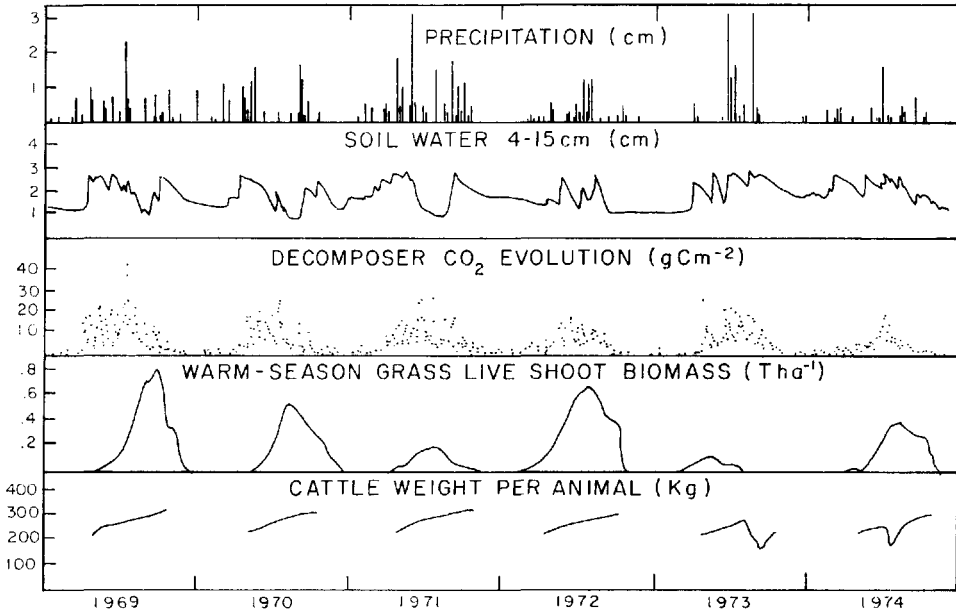


FIGURE 4. Values of selected driving variable, state variable, and rate process values from a 6-year simulation run for a shortgrass prairie grazingland system.

The top graph gives values for one of the driving variables over time, i.e., rainfall impulses in centimeters for each day it occurred. The second graph is an example of one of the state variables, i.e., water in one of the soil layers (4 to 15 cm). The centimeters of water in that depth of soil are plotted showing the way they vary over the simulation years. The third graph is an example of a daily rate process value. The rate here is the  $\text{CO}_2$  output in grams of carbon per square meter per day. The fourth graph is an example of the state variable warm-season grass live shoot biomass. The values are given in metric tons dry weight per hectare showing the buildup and dropoff of warm-season grasses in different seasons and years. The bottom

graph is kilograms cattle weight per animal showing their change during the year when they are stocked in the pasture. Because cattle were only in the system part of the year their values are zero before and after the grazing season. During the growing season they show gains and losses in weight.

These are only examples of the variables in the model. The time response of each of these variables is not always understandable from examination of the other variables plotted. For example, the big drop in cattle weights in 1973 is related to changes in vegetation phenology and to increases in grasshoppers, and these variables are not plotted in figure 4 but are available in model output.

We can get from a single model run a large number of plots like those shown in figure 4. In fact, in this grassland ecosystem model (Van Dyne *et al* 1977) we produce some 1300 plots, in one run, from which to tell what is happening in the system. The model should produce a simulation of real life—when it rains, soil water would build up; when it does not rain, soil water should decrease; when there is soil water available and the

temperature is right, then grass should grow, decomposers decompose, and the cattle gain weight.

One run of a model provides much information about the dynamics of the system, but it is only for a given set of conditions. For a given run, we take one set of driving variable records, one set of initial conditions, and one set of parameter values (if we are running the model deterministically). This gives us one result. To test hypotheses about system response to management we have to vary something in different runs. For example, we could vary the grazing intensity. To do this we use the same initial conditions, driving variable records, and parameter set, but we change the stocking rate. Now we look at the response of the system to different grazing intensities.

A model is a *synthesis of microhypotheses*, i.e., a synthesis of information about

structure and function of the system. In a single run of the model we can get several hundred output graphs for variables and process rates. We can easily generate a large number of runs of the model (being stopped only by time, patience, money, or wisdom). We need to design efficient experiments to conduct on these models. We soon become swamped with model run output so we have to devise ways of reducing the output.

#### *Analyses of Syntheses*

The model is a synthesis and the output of the model is a synthesis of information. We need to devise methods of analysis and presentation to combine and reduce the output from several model runs. For example, a model can be run for several levels of a design variable (e.g., grazing intensity). We can integrate values of rates over the year's time

#### SYSTEM RESPONSE TO GRAZING INTENSITY

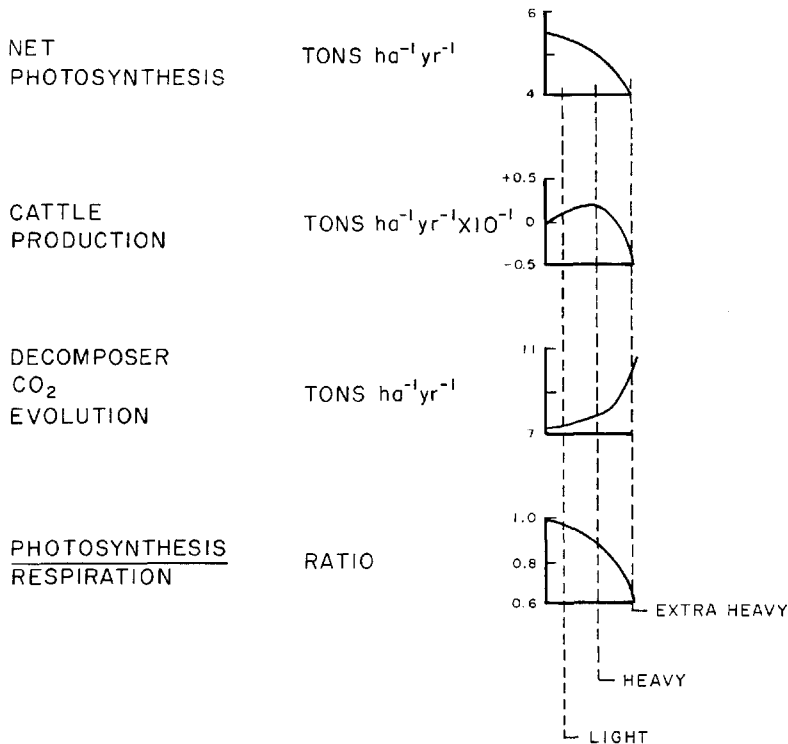


FIGURE 5. Plots of integrated values of selected rate processes from model runs made under different grazing intensities with cattle.



for net photosynthesis, cattle production, decomposer CO<sub>2</sub> evolution, and photosynthesis respiration ratio, and plot them against grazing intensity (fig. 5). In this case our design variable is a continuous variable. Then we can analyze the results by fitting a quadratic function for the relationship between cattle production and grazing intensity. Utilizing this quadratic function we can calculate the stocking rate which results in the maximum production rate. (Incidentally, the stocking rate for maximum cattle production derived from model experiments run in a few minutes is within 10% of the value derived from field experiments started in 1942 and running for 35 years (Van Dyne *et al* 1977)).

stocked at equivalent rates, differences in response of the system will be due primarily to their differences in grazing habits, metabolic efficiencies, and treading and trampling (see table 1).

Two components of the system's water balance are shown in table 1, the evaporation and the transpiration rate. We can see the four herbivores stocked at equivalent rates did not have different impacts on the water cycle in the system. We see some slight but observable differences in net primary production under grazing with the different herbivores. These model runs suggest better secondary production can be obtained from cattle or bison than from sheep or pronghorn antelope.

TABLE 1  
*Some results of model runs made with different large herbivore species stocked at the same relative grazing intensity.*

Integrated Flow	Units	Herbivore Species			
		Cattle	Bison	Sheep	Pronghorn
Net Primary Production	(g dw m <sup>-2</sup> yr <sup>-1</sup> )x10 <sup>1</sup>	51	49	52	52
Large Herbivore Production	(g C m <sup>-2</sup> yr <sup>-1</sup> )x10 <sup>3</sup>	77	66	45	23
Forage Consumption	(g dw m <sup>-2</sup> yr <sup>-1</sup> )x10 <sup>0</sup>	15	14	13	11
Photosynthesis: Respiration	x10 <sup>-2</sup>	76	73	76	73
Evaporation	cm cm <sup>-2</sup> yr <sup>-1</sup>			12	
Transpiration	cm cm <sup>-2</sup> yr <sup>-1</sup>			13	
Decomposer CO <sub>2</sub> Evolution	(g C m <sup>-2</sup> yr <sup>-1</sup> )x10 <sup>1</sup>			30	
Gross Primary Production	d <sup>-1</sup> x10 <sup>-4</sup>	53	51	52	51
Primary Producer Biomass					
Gross Primary Production	x10 <sup>-3</sup>			25	
Solar Energy Input					

The model output shown in figure 5 illustrates the situation in which the design variable in the model experiment is a continuous variable. The resource manager, however, may be interested in system responses to design variables which are not continuous in a given scale (e.g., the effect of different species of herbivore in the grazing situation). Thus, in our model's pastures, we can switch from cattle to bison to sheep to pronghorn antelope. We can design an experiment where we can stock them at equivalent rates based on equivalent metabolic body size. Since they are

#### MODEL DEVELOPMENT AND USAGE IN A MANAGEMENT CONTEXT

The previous sections described, in general, the procedures for developing and experimenting with simulation models. In this section I suggest a variety of steps needed to implement this approach in a resource management context in order to ensure that the model focuses on a certain problem or class of problems.

##### *Components and Steps*

To develop and use models as an aid for resource management decision-making requires that information be assembled in

advance and organized in a manner for easy usage in model development. Examples of steps and components are illustrated in figure 6.

A resource management situation dictates the boundary conditions for a model, i.e., the time and space domain of the model. The management situation also constrains the objectives of the model. It is unlikely that a single model can be developed which will be highly useful in addressing all problems of resource management decision-making. But with a given area, such as grazing-land management for arid and semiarid

areas, it is possible to predict in advance some of the information which will be required for modelling. For example, initial condition values (for starting a model run) for state variables and time series of state variables (for evaluating reasonableness of model output) can be derived from field-collected records or from information derived from resource managers.

The driving variable, initial condition, submodel, and evaluation information files are *objects* that can be prepared in advance for usage in the various steps or *processes* of modelling. Given all these

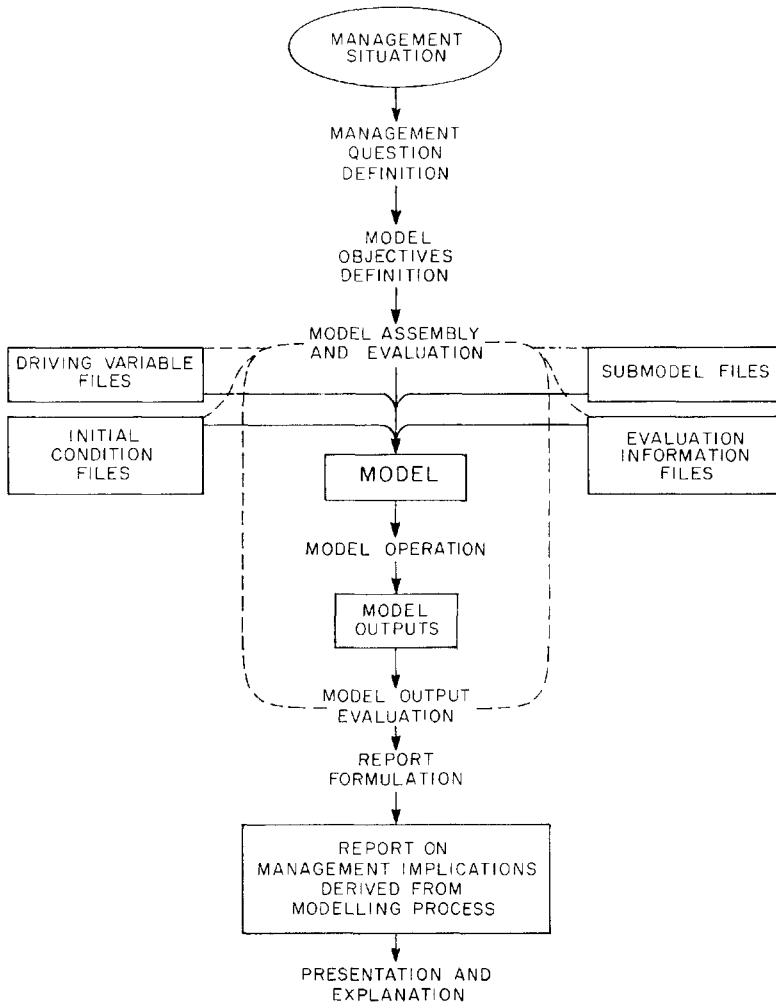


FIGURE 6. Processes and components of modelling to assist resource management decision-making. Items in boxes represent objects; other items represent processes.

objects you can assemble and run a model, generate output, and interrogate that output (fig. 6). It is likely that the first set of output will lack reality in some areas, thus requiring you to restructure your model, information file, or initial condition file. After going through the model development-redevelopment loop several times, one should obtain model output that is interpretable. This version of the model should be experimented with to give the information needed to enable an agency to assist in resource management decision-making.

Even if the above steps are carried out successfully and if a report is presented and explained to the management agency, there still is a difficulty. Too often the entire cycle in figure 6 is completed essentially without much involvement of the resource management agency. Hypotheses about management response are generated out of the model and reports

are made and presented, but they are not absorbed and used by the agency. Personnel from the agency should enter directly into the overall activity. A clientele must be developed during model development. Those of us in research and development activities need to improve our skills and techniques for working with the agency. Furthermore, only in working closely with the agency is it possible to ensure that the information it needs gets considered in the development or structuring of a given model. Unfortunately, however, there are few examples of agencies requesting and getting assistance from model developers in joint projects. Such projects need to be carried out over a considerable period of time and funding limitations or priorities, or both, have prevented this.

*Frameworks for Including Man in the System*

Most of the grazingland models ap-

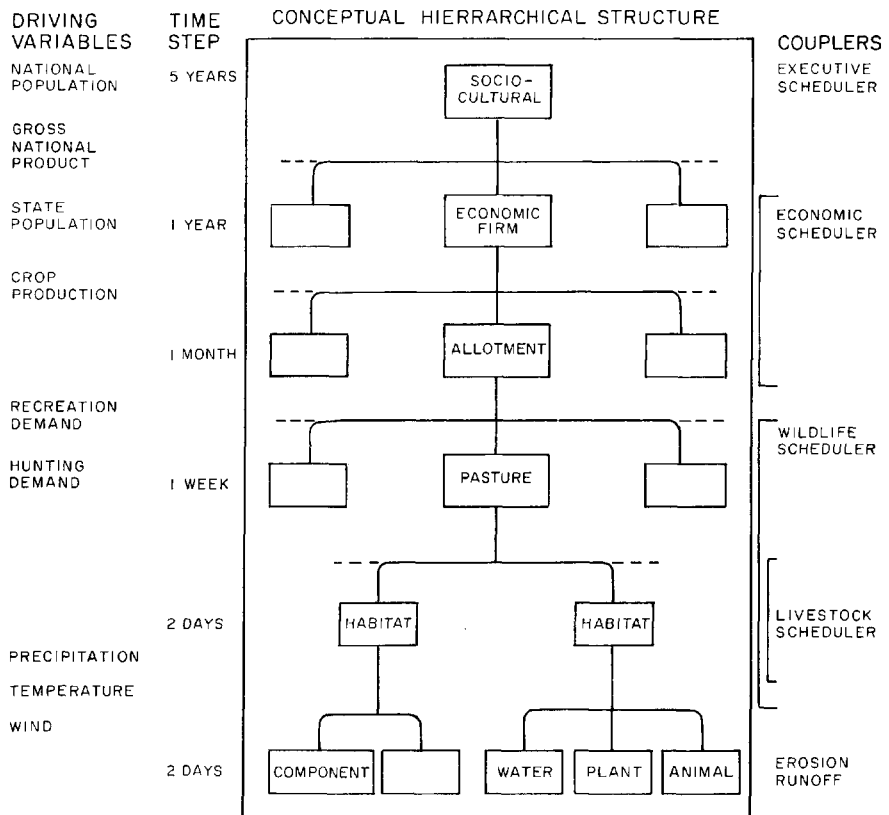


FIGURE 7. A conceptual hierarchical structure for resource management modelling with ecosystem, economic, and socio-cultural considerations.

pearing in the scientific and technical literature consider but do not include man. In essence, man's management enters the model in decision-making and affects processes in the system. Seldom is man a state variable in ecological models.

Direct inclusion of man in a model requires a different structure of model and modelling effort than is the case for ecological modelling. An initial idea of what such a model structure might be like is given in figure 7. Characteristics of this class of models are that they are multi-layered and they have highly varying mechanisms and empiricisms in their various flow structures. They also have spatial connotations and highly variable time frames.

Models are only approximations of what occurs in the field. One way of approximating spatial diversity is to break space into component parts and then assume each component part (e.g., each habitat) is uniform within. The state of one habitat, however, can influence another habitat, such as the amount of forage available in different habitats influencing the movement of animals.

A hierarchical structure is evident in the framework outlined in figure 7. Within any given habitat there are various components such as have been discussed in the models described earlier in this paper (i.e., water, plants, animals, etc.). Various habitats are combined together, perhaps to comprise a pasture in the grazingland situation. Various pastures may be combined to comprise a grazing allotment, as in a Forest Service or Bureau of Land Management situation. Grazing allotments may be combined to comprise a complex of economic firms in terms of individual land owners, their livestock enterprise, other agricultural enterprises, and nonagricultural interrelated enterprises. Those economic firms then bring in money and people, and at the next level we have social and cultural structures.

The situation outlined in figure 7 is the real-life problem that perhaps a grazingland resource manager faces when starting to write an environmental impact statement. But as far as I know,

no such general conceptual structure has been developed by the agencies faced with environmental impact analyses of grazingland management. For example, the Bureau of Land Management thus far in starting the development of some 212 environmental impact statements has no defined strategy clear to those of us outside the Bureau. In developing their first environmental impact statement on the Challis, Idaho Planning Unit, I estimate they have expended 15 professional person years of effort. Many people feel this first statement is inadequate (CAST 1976), and review of their impact statement reveals they must include considerations at social-cultural, economic firm, allotment, and pasture levels. And a great deal of detail must be included for individual species or groups of plants and animals and for water runoff. They are dealing with large-scale systems which start with individual ecosystems, but then get coupled in a hierarchy similar to that in figure 7.

There are few, if any, examples of operational models of this type in the ecological or resource management literature. Some consequences of this type of conceptualization follow. At the ecological level, many of the components operate on a 1-hour or 1-day event scheme. In contrast, in the same structure the social-cultural components may have a 5-year time step. Notice the concept of driving variables in figure 7. At the ecological level the driving variables are precipitation, temperature, and wind; but at the socio-cultural level driving variables may be national population, gross national product, state populations, or crop production in the state.

The conceptual structure in figure 7 is presented to suggest that, in theory, eventually we can couple together ecosystem models with the economic and social models. We need that kind of information and model structure to produce output to assist in developing an integrated, fully useful environmental impact statement. And the environmental impact statement is only part of the overall management planning process!

#### *Some Model and Modelling Benefits and Costs*

What would be the benefits of utilizing

a systems approach in resource management decision-making?

One major benefit is derived through having a sound conceptual framework for cause-and-effect reasoning. This can be approached, but not completed, if you simply have a large, complex, and well-thought-out chart of relationships among all the variables. Cause-and-effect relationships should be based on scientifically and technically defensible information rather than just guesswork. The relationships need to be coupled so that they provide internally consistent answers. It may be necessary still to write a 500 page environmental impact statement, but the observations on page 25 of such a report should be consistent with the observations on page 225 and with those on page 425. The process that is used now in developing such statements does not result in internally consistent answers.

The modelling approach allows us to examine many of our management impacts in a quantitative way rather than only in a qualitative way. We need to examine many more alternative strategies than is done at present. Generally the environmental impact statement for renewable resource management develops only a few manipulation strategies and one do-nothing strategy. To be realistic, we need to evaluate many more alternative strategies and look at more responses under many more conditions. To promote more uniform and better management from area to area, we need to have some mechanism for providing greater technical transferability. Models also are useful here.

After learning of several of the benefits of models and the modelling process in renewable resource management decision-making, one may inquire what are the costs. Resource management modelling still is at an early learning stage so some of the present costs are still in education not just in application. Large-scale models, such as the one illustrated in figure 3, may require 20 professional person years of effort for development in the present learning phase (Innis 1978). In the application phase the time cost should be greatly reduced.

Another problem in assessing costs is concerned with the degree of mechanism

or empiricism in the model. For example, consider a system of first-order, constant-coefficient, linear differential equations. This kind of model was common in much of the ecological literature and was primarily an outgrowth of those groups who first modelled with analog computers. Such equation systems may require one or two orders of magnitude less work to construct than do mechanistic models with cause-and-effect relationships, but the latter type of models are more useful to the management users and scientist developers because more of their parameters have real-life meaning and because the models can be adapted to more situations and conditions.

Yet another problem in estimating costs of models concerns the scope of the model. If one includes abiotic, biotic, economic, and sociologic components in the same structure, the cost increases as compared to limiting the model to just an ecosystem (i.e., abiotic and biotic components). Another aspect of scope is spatial consideration. Here, there is an increase in cost, in both development and operation, of a model which couples together different spatial units. In the latter case, however, one deals with a *family of coupled submodels*, each submodel representing one spatial unit. Since one is dealing with repeating units, the development cost does not increase proportionally to the number of units, although the operational cost will increase proportionally to the number of units.

Given the above considerations, it is impossible to estimate the costs of a model in general. Specifics need to be provided. There is sufficient experience, however, to estimate cost reductions in the repeated implementation of a given general model to different, but similar, situations. Consider examples of (1) adapting a generalized ecosystem model to new locations of the same ecosystem type, and (2) adapting a generalized ecosystem model to new locations of a different but related ecosystem type. Suppose that the original model is structured for grassland ecosystems and is parameterized for, and tuned to, a shortgrass prairie. Then case (1) above refers to adapting the model to other shortgrass

prairies with somewhat different plant and animal components and soil conditions. Successive adaptations might cost about 60, 50, 45, and 40% of the original model cost. For case (2) the adaptations might be to shrub-grassland types wherein new plant and animal components would need to be included in the model. Successive adaptations might cost 90, 60, 50, and 45% of the original model cost. Personnel time would decrease more rapidly than would computer time in successive adaptations to new situations.

Another overall cost to be considered in the systems approach is that of in-house training. In some resource management agencies not many of the managers are familiar with, nor perhaps even sympathetic to, systems analysis and operations research methods. It is important that the managers become familiar with the advantages and limitations of these methodologies. The managers must be able to consider modelling methods in proper perspective relative to the other tools and techniques available as aids in the management decision-making process.

How much resource allocation does modelling justify? The answer to this question is not easy. Consider the benefits and costs of using simulation models to synthesize and analyze system information and to provide outputs to assist in the decision-making process. Consider the magnitude and kind of problem facing the agencies in developing management plans and environmental im-

pact statements (such as for the Challis planning unit mentioned above). Given the state of the art of modelling and models and given the agency situation, I think about 20% of total expenditure placed into modelling activities can be justified on environmental impact statement development for problems similar to the grazingland management case.

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