Management of California Oak Woodlands: Uncertainties and Modeling[1]

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Abstract: *A mathematical policy model of oak woodlands is presented. The model illustrates the policy uncertainties that exist in the management of oak woodlands. These uncertainties include: (1) selection of a policy criterion function, (2) woodland dynamics, (3) initial and final state of the woodland stock. The paper provides a review of each of the uncertainty issues. The final section of the paper describes a modeling approach that can be developed to assist policy makers in evaluating alternative oak woodland policy actions.*

The management of natural resources is the topic of numerous academic journals, and hundreds of books and popular articles. Natural resource management has different meanings to different groups of people. Natural resources can be viewed as environmental assets which provide value to society in any number of ways. This value can be gained from using the natural resource as an input into the productive process, as a sources of raw materials, as a provider of life-sustaining services, and as a provider of esthetic and recreational amenities. The management of a natural resource is further complicated by various uncertainties. Uncertainty exists in determining the exact composition or stock (size) of the natural resource, in understanding the ecological dynamics of the natural resource, and with respect to whether the resource can be managed to achieve some socially preferred state.

It is then not surprising that, when one suggests that we need to better manage our natural resources, controversy erupts concerning how the natural resource should managed and for whose benefit. One segment of society may wish to have natural resources managed to improve their short-run and/or long-run productivity (e.g., range management for livestock) while another group may wish to have the natural resource managed to sustain or improve its amenity qualities (e.g. wildlife habitat).

Ideally, the highest value of the natural resource to society could be attained by maximizing the discounted net social value of the resource. This can be a difficult natural resource management problem since it requires information on the prices and costs of differing natural resource uses. Some of these have market values and cost (e.g. firewood), and other uses may have observable costs, but not have observable market prices (e.g. open space). These uses must have values measured through non-market evaluation techniques. Nevertheless, management of a natural resource requires that choices be made between competing resources uses and over time and space. These choices will not only affect differing groups in society but also potentially affect the ecological dynamics of the natural resource system. Effects on natural resource systems are typically valued in terms of their ultimate impact on human society although this is not universally accepted.

Commoner (1972) presents a principle of minimum interference, which suggests that there should be minimal to no management of natural resource systems by society. However, the obvious is that society does attempt to manage natural resource assets and that the outcome of that management is judged by whether it is consistent with collectively desired outcomes.

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A California natural resource that is subject to such complex debate over its allocative uses is the oak woodlands. There are about 10 million acres of oak woodlands (also known as hardwood rangelands) in California. Oak woodlands provide a number of valuable economic uses. These include cattle grazing, water resource development, wildlife habitat, open space, hardwood lumber and firewood, and land for urban development. There is a long history of concern about the public and private management of California's oak woodlands. These concerns include conflicts over changing land use, rights and responsibilities of ownership, and the extent and character of urban forces reshaping the oak woodlands, and the long-run sustainability of these woodlands.

Local, state, and federal agencies are under increasing pressure to deal with a wide diversity of private and public interests in a comprehensive and economically sound manner. To achieve this goal, improved oak woodland management guidelines are needed for land use planning and for ecologically and economically sustainable management practices in water production, grazing, wildlife, hardwood lumber, and housing. The California Department of Forestry and Fire Protection has summarized the policy issues and objectives for state action (California Dept. of Forestry 1988).

The broad objectives of this paper are to provide an overview of the problems associated with managing California's oak woodlands as a natural resource management problem and the development of a comprehensive oak woodlands control model that could assist policy-makers in achieving collectively desired outcomes. The modeling approach takes a systems view of the oak woodland's management problem. The model is intended to be an evaluative, not prescriptive, tool.

Oak Woodlands Management: The Uncertainty Problems

The following control problem is a mathematical representation of the oak woodlands management problem. It is presented to facilitate discussion of the uncertainty that exists in establishing oak woodland management policies.

$$\text{Maximize or Minimize } \int_{t_0}^{t_1} I\big(S(t), U(t), t\big), \text{ subject to:}$$

$\dot{S}(t)=f(S(t),U(t),t)$, the oak woodland ecosystem dynamics,

$(t_0) = S_0$, initial state of the oak woodlands,

$S(t) = Gt(S(t))$, the final state or terminal value of the oak woodlands,

ht(S(t), U(t), t) (0, oak woodland constraints.

S(t) is the state of the oak woodlands at any given period of time between t_0 (current time period) and t_1 (future time period). The state describes those attributes that compose a specific oak woodland. For example, acres of land suitable for cattle range, volume of wood available for firewood and other hardwood uses, acres available for housing development, acres suitable for amenity purposes, acres suitable for wildlife habitat, and water development potential could characterize a specific oak woodland state. U(t) represents the control variables which affect the state of the oak woodlands from one period of time to the next. These controls could include the amount of cattle grazing in some specified time period, amount of oak harvested for firewood, amount of land utilized for wildlife habitat or housing. X(t) are the random disturbances that can affect the oak woodland state and include natural phenomena such as drought, fire, wind, and plant diseases and insect infestations.

The oak woodland management problem can now be stated as follows. Maximize or minimize I, some real valued policy criterion function, which has as its arguments S(t), the state of the oak woodlands in any time t; U(t) the uses of oak woodlands in any time t; and t time. This maximum or minimum is subject to $\dot{S}(t)$, the oak woodland ecosystem dynamics known as equations of motion; S(0), the initial state or value of the oak woodlands; $G_t(S(t))$, the final state or terminal value of the ending state; and h(S(t), U(t), t), specific ecological and policy constraints on the controls and states of the oak woodlands.

This oak woodland management problem is dynamic and stochastic and can be characterized as a closed loop control problem. This implies that resource allocation policies are conditional upon learning more about the ecological and economic dynamics and the impact that resource uses of and policies for have on the dynamics.

This model illustrates that managing oak woodlands is subject to varying degrees of uncertainty in the decision-making process. Uncertainty arises from (1) specification and selection of a policy criterion function and its parameters, (2) oak woodlands dynamics including the evolution of oak woodland ecology over time and the impacts that management decisions and random disturbance have on that evolution, and (3) the initial stock and final oak woodland stock or value. The next four sections discuss these uncertainties from the perspective of an investigator who is interested in developing a model to assist public policy-makers in evaluating different oak woodland management policies.

Policy Criterion Functions

Policy criterion functions provide the basis for evaluating the desirability of management policies and actions which lead to specific outcomes. These outcomes can be viewed as the state of the oak woodland ecosystem in some given time period. Public-policy decision makers must choose between alternative management strategies (policies) and actions that influence different sectors of the society in various ways and have different welfare connotations to these segments of society.

The uncertainty that must be addressed is the choice of a specific policy preference function and the estimation of its parameters. A number of researchers have attempted to address this issue including Theil (1968), Prescott (1972) , and Fromm (1969). Rausser and Freebairn (1974) discuss the issues associated with the selection of preference functions and estimate a preference function for United States beef import quotas.

Policy preference functions can be viewed as the objective function of the public agency which has the management responsibility for the natural resource. This means that the public policy entity must combine its legal mandates with its perceptions of society’s wishes into a societal welfare function, which becomes its objective function. An attempt is then made to maximize this function given various constraints. Rarely, if ever, is the public agency certain as to what the societal welfare function looks like or whether, upon selecting a specific societal welfare function, it is the one which will maximize societal welfare.

There are two basic approaches to the development of a policy preference function. The first approach is to develop an explicit objective function. The formalization of an explicit objective function and its optimization allows for the endogenous (internal to the system) determination of the control parameters and thus the time-dependent resource states. The controls and resultant states are then reviewed by the policy-maker for management feasibility. If the optimization set of controls and states is not considered practical by the policy-maker then another objective function is selected and the process begins over again. This process would continue until a workable set of policies is determined.

The policy-maker would determine which is the more practical from a policy perspective.

An example of this type of policy preference function is the maximization of a social welfare function. The function is composed of the benefits and costs that accrue to differing uses of the natural resource over time and space. A number of studies have used the optimization of an explicit objective function to evaluate natural resource issues. Noel and McLaughlin (1983) use this approach to address the problem of groundwater overdraft problem in the San Joaquin Valley.

The second approach to the development of a policy preference function is an implicit approach. Such an approach assumes that the public policy decision-maker has implicitly optimized a societal welfare function and has chosen a set of management options that targets specific state outcomes. These targets become the ideal levels the public-policy decision maker has for the natural resource system. A deviation from them is considered a loss or cost to societal welfare.

The optimization criterion is to keep the evolution of the natural resource system as close to the target levels of controls (e.g., timber harvesting levels) and states (e.g., cubic feet of unharvested forest) as possible. An example of this type of policy criterion function is the quadratic tracking function (Athans 1972). The optimization of this function results in a minimization of the deviation of the targeted levels of states and controls. The deviation costs are measured by the relative weights placed on achieving a specific state versus achieving a specific control. The policy maker thus has the option of placing a greater weight on achieving a specific targeted state than control or vice versa. The optimization of the tracking function then is a minimization problem, which finds the minimum cost path of targeted state and control deviations. Dixon and Howitt (1979) use this type of policy preference function to evaluate an intertemporal forest harvesting problem.

The choice of what type of policy preference function to use is a subject of theoretical and empirical debate. Rausser and Freebairn (1974) list six points, which should be considered in the selection process. They conclude that the explicit function approach is preferred to the implicit approach since the arbitrariness of the former is less than that of the latter. Their view is not universally accepted (Naylor 1970).

Whatever approach is taken, a policy preference function must be estimated. This is a three-step process involving: (1) selection of the relevant variables as arguments, (2) determination of the appropriate mathematical structure, and (3) obtaining an estimate of a set of values for the parameters of the function.

Uncertainty in Dynamics of Oak Woodland Systems

Management of oak woodlands is subject to ecological uncertainties. The areas of uncertainty that are important to both the modeler and decision-makers are structural uncertainty and functional uncertainty. Structural uncertainty is caused by a lack of knowledge concerning the exact mathematical form that represents the ecosystem dynamics and a lack of data to estimate the form even if it were known. Functional uncertainty is concerned with changes in structure arising from sampling and measurement error. Structural and functional uncertainties create a stochastic set of natural resource system parameters, which essentially means that decision-making is done with incomplete information. This implies that selection of a policy is conditional upon current information concerning the structural and functional aspects of the ecosystem. However, new data assist in updating knowledge, creating a sequential policy-making process. Thus, the oak woodlands management problem has a dual nature. The policies chosen to manage the system affect both the value of the objective function and quality of future information on the structural parameters of the ecosystem. This is an active learning problem, which recognizes the stochastic nature of the ecosystem and represents a closed loop control problem, which seldom has an analytical solution (Aoki 1967).

Given the structural and functional uncertainty problems associated with natural resource management, the modeling of complex ecological systems has received a considerable amount of attention from biologists, ecologists, engineers, and economists. The modeling efforts have been concentrated in two areas: those models whose purpose it is to provide an understanding of complex biological systems and those models which are directed to biological system control. Central to both is the difficulty in inferring the true model from the phenomena being modeled. An example of the research being done in this area is provided by Mees (1990).

The second source of uncertainty in the mathematical modeling of natural resource systems is that of random disturbances, which can change the ecosystem parameters over time and space. These random disturbances include lightning-caused fire, floods, drought, erosion, disease, and insects. The impact of these disturbance processes on ecosystem management is discussed in detail by Averill and others (1994). The authors argue that these random disturbances can have both positive and negative effects on an ecosystem. It is not a question then of whether these disturbances can be ignored, but of finding a way to characterize these disturbances in physical and economic terms. Several tools are available to assist in this process including global positioning systems (GPS), geographic information systems (GIS) and geo-statistical technologies.

Certainty equivalence is an approximation approach to the stochastic (uncertainty) problems created by both the structure and function issues and random disturbance issue discussed above. The certainty equivalence approach uses expectation of the stochastic parameters of the biological system functions. A number of restrictive assumptions underlie this approach (Chow 1975). However, it is likely that researchers and decision-makers will continue to approximate the complex, dynamic biological systems with linearized versions of models that use certainty equivalency to handle structural and functional uncertainty problems. Standiford and Howitt (1992) use certainty equivalency in their bioeconomic model of California's hardwood rangelands. They derive production functions for forage, hunting, cattle, and oak firewood. A near optimal control was used to solve for state and control variables to give optimal time paths for oak density and cattle stocking.

The Initial State of the Oak Woodland System

This section discusses the biological, socio-political and economic criteria needed to adequately describe the initial state of the oak woodland ecosystem in California. This modeling phase should be the most straightforward to design and measure, but it is greatly complicated not only by the large amount of information needed on the parameters of the ecosystem but the more difficult problem of quantifying the relationships between the parameters. For example, one might be able to measure with reasonable accuracy the number of acres of various oak woodland types delineated by composition and structure. However, describing the habitat potential of each structural-composition type for various wildlife species is far more difficult.

Another important issue to address in defining the initial state is the scope or scale of the ecosystem. As the scale of the model increases to statewide, for example, information must necessarily be more generalized, which increases the uncertainty and thereby reduces the model's evaluative power. The result is either no feasible solution or a general one that is useless.

On the other end of the spectrum, the project area could be scoped down to as small as a watershed scale where more detailed information could be (and has been to varying degrees) collected, reducing uncertainties but providing solutions that disregard important landscape level concerns.

Figure 1 briefly summarizes that state of knowledge necessary to develop a oak woodlands policy model. By no means is the summary exhaustive nor is it sufficiently detailed to show the distinction between studies related to state or control issues. It is basically designed to illustrate, in one glance, where past efforts have focused and where the major gaps in knowledge exist.

Figure 1—Description of the current state of oak woodland research. Literature cited in this figure is not cited in the references section of the paper. For complete citations, please contact the authors at California Polytechnic State University, San Luis Obispo, California.

Silvics and Silviculture

Composition & Structure	Productivity	Regeneration
Allen, et al., 1991 Bolsinger, 1988 Byrne, et al., 1991 Davis, 1995 Holzman & Allen-Diaz, 1991 Mayer, et al., 1985 Pillsbury, et al., 1983, 84, 85, 91 Riggs, 1990	Bartolome & McClaren, 1985 Jameson, 1967 Jensen, 1987 George & Jacobsen, 1987	Muick & Bartolome, 1987 McCreary, et al., 1991 Swiecki & Bernhardt, 1993 Plumb, unpublished

Ecological Processes

Fire	Water	Nutrient Cycling	Pathogens & Insects	Wildlife Interactions
Rothermal, 1983 Zavon, 1982	Epifanio, et al., 1991 Gordon, et al., 1989 Duncan & Woodmansee, 1975 Murphy, 1970 Smith, 1977	Dahlgren & Singer, 1994 Firestone, 1995 Covington, 1981	IMPACT, 1987	Block, et al., 1990 Wilson, et al., 1991 Barrett, 1979 Verner, 1980 Bertram & Ashcraft, 1983

Land Use & Effects

General	Range/Grazing	Homesites	Habitat	Urban-interface
Doak, 1989 Greenwood, et al., 1993 Huntsinger, 1990, 91, 92 Pillsbury & Oxford, 1987 Tietje & Berlund, 1995 Doak & Stewart, 1986 Heady & Pitt, 1979 Clawson & George, 1985 Fortman &Huntsinger, 1985	Hall, et al., 1992 Holland, 1973, 80 Kay, 1987 Pacific Mer. Res., 1994 Bartolome, et al., 1980 Hooper & Heady, 1970 Rosiere & Torell, 1985 Frost & Edinger, 1991 Duncan, 1967	Whittington & Tietje, 1993	Tietje, et al., 1991 Airola, 1988 Graves, 1977 Ohmann & Mayer, 1987	Scott, 1995 Stewart, 1991

Resource Demands & Values

Grazing	Game	Row Crops	Fuelwood/Products	Ecological/Conserve
Wright & Preister, 1986 Alden & Mayer, 1984 Bowie & Watson, 1986 McClaren & Bartolome, 1987 Reed, 1974	Loomis & Fitzhugh, 1987, 89		Standiford, 1989 Standiford, et al.,1996	

Socio-political

Tree Ords./Prop. Rights	BMPs	Education/Extension
Bernhardt & Swiecki, 1991 BOF, 1982 Cox, et al., 1982	BOF, 1986 Gaertner, 1995 Passof, et al., 1985 Standiford & Tinnin,1996 Gingrich, 1971	IHRMP, 1990-95 Wright & Priester, 1987

This summary of past research indicates a reasonably good understanding of many of the management components for the oak woodland ecosystem, especially with regard to land use effects of different practices on the ecosystem and vice versa. It also appears that research has been done on the current structure, composition and ecological processes of the oak woodland ecosystem to begin such policy modeling. Nevertheless, to adequately define a desired future condition (final state), it is essential that more research be done on the natural range of variation in structure, composition, and ecological functions.

Figure 2 is illustrates the concept of a natural range of variation in structure and fire occurrence. Like all North American ecosystems, the oak woodland resource developed under the influence of humans for millennia. In order to assure that a sustainable policy is designed, it is essential that the final state fall within the natural ranges of variations before the impact of humans. Once defined these natural ranges of variation are defined, one is ready to specify the final state in the policy model.

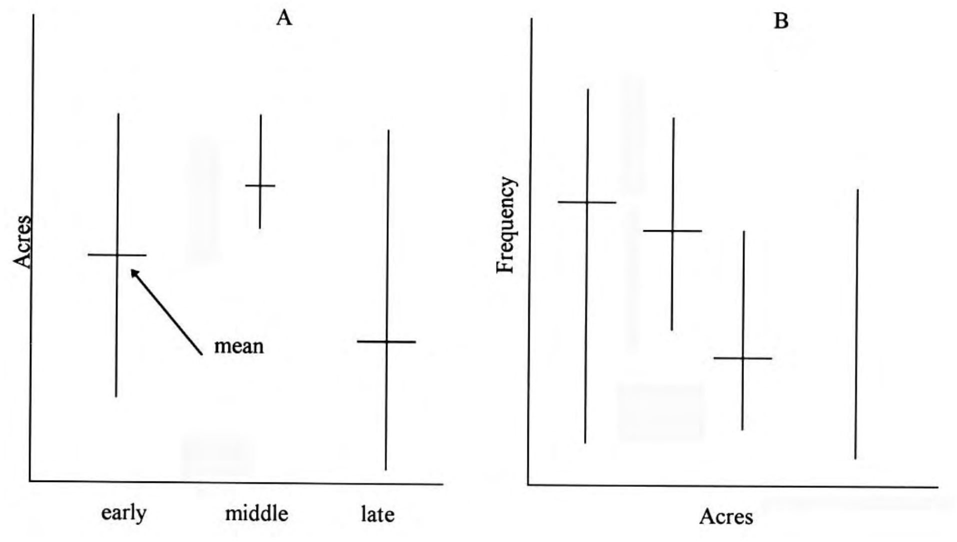


Figure 2—Natural ranges of variation in structure (A) and fire occurrence (B). Height of lines represents the distribution range.

The Final State of the Oak Woodland System

The management of oak woodlands requires that the public agencies who have management responsibility to evaluate societal interests in the form of a policy preference function, gain or have knowledge concerning the ecosystem dynamics, and determine the initial and desired final states of the oak woodlands.

The California Department of Forestry has as one of its goals the achievement of such a sustainable state (Calif. Dept. of Forestry 1988) This raises a question of controllability. Controllability is the ability of a policy instrument to modify the initial oak woodland ecosystem over a specific time horizon to achieve the final state. Aoki (1973) shows that the controllability condition is a necessary and sufficient condition for achievement of specific policy goals within a specific time period.

The real issue from a management perspective is whether this potential final state can be defined so as to be achievable. That is, is there a set of policies that will allow the initial oak woodland ecosystem state to converge to a sustainable state? The answer to these questions lies in the stability and controllability of the system in question. A completely controllable system is stabilizable regardless of its asymptotic stability properties (Aoki 1974). From an ecosystem management perspective, it is more important to know the controllability properties of the system than its asymptotic stability properties.

It is unlikely that complete controllability and, hence, stability in the oak woodland can be achieved or that it is even desirable. The same random disturbances previously mentioned, even if predictable, are not totally controllable. The very desirability of controlling such disturbances is brought into question by Averill and others (1994) who note, "Efforts to suppress (manage) disturbances, such as lightning fires, floods, drought, diseases and insects, which have been perceived to be in conflict with economic interests, have resulted in reduced biodiversity and ecosystem health. The more we attempt to maintain an ecosystem in a static condition, the less likely we are to achieve what we intended. We must be willing to bear both the economic and biologic consequences of such management."

The more preferred policy prescription from both a controllability and desirability perspective is to allow for a range of final states. Such a range would allow for a flexibility in establishing management polices and would add reality to modeling. The modeling problem would then be to find a minimum set of policies that addresses the critical question of timeliness of policy outcomes and curb the excessive expectations of policy or management actions.

The Modeling Process

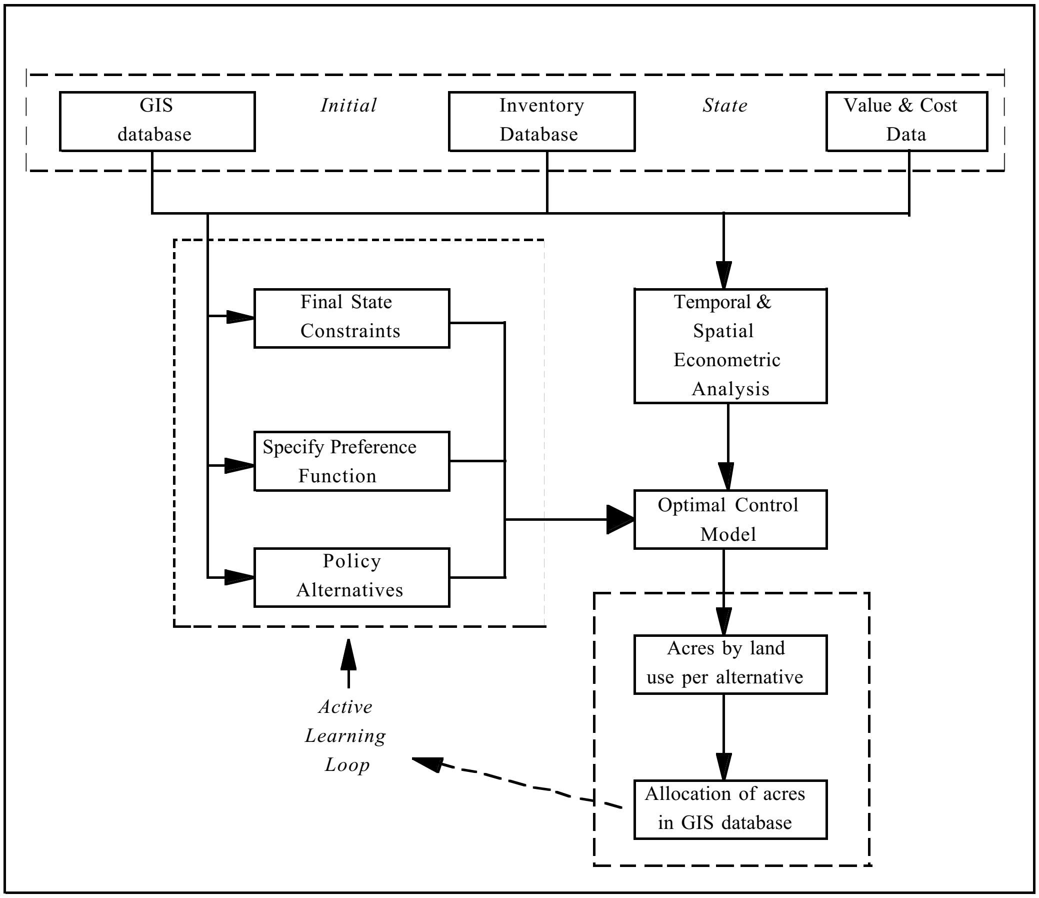
Thus far we have discussed various key issues that influence efforts to model policy governing the management of the oak woodland ecosystems. Now it is time to summarize these issues in a comprehensive modeling system that is useable as a policy analysis tool. *Figure 3* illustrates the process of modeling various policy alternatives relying upon a similar process developed by Covington and others (1988), which they called a "Terrestrial Ecosystem Analysis and Modeling System" (TEAMS). *Figure 3* illustrates the necessary component of an interactive oak woodland's policy evaluation model. Each of the problem variables in oak woodland management is connected and allows the decision-maker the opportunity to observe the bio-economic responses that may occur under differing policy scenarios. The model stresses the importance of the interactive learning process in evaluating differing oak woodland policies.

This type of model is useful for running any number of policy scenarios under changing economic and biological system conditions. GIS and inventory data bases are used to establish an initial state. Economic benefit-and-cost data for differing uses of the oak woodlands are used along with input from public policy officials to estimate a policy preference function. The GIS and inventory data are also used to estimate the biological system equations of motion. A final state can be specified or determined endogenously to the model, and differing policy constraints can be specified. These parameters are then combined in an optimal control model. The policy preference function is optimized given the various biological and policy constraints and the resulting land use allocations are observed.

The model can be used to evaluate tradeoffs. For example, very restrictive and directive management policies could be put into the model as constraints. This could shorten the time to achieve the final state, but such a course may not maximize the policy preference function. Alternatively, one could pursue a course that increases the value of the policy preference function, but extends the time to achieving the final state, even to a point where the final state is never achieved.

Another important use of this type of modeling framework is assessing the value of information. Earlier, the problem of uncertainties, especially in the biological system equation estimation, was discussed. As additional information about the different parameters making up the management problem becomes available, the model's parameters can be re-estimated. This allows for a re-

Figure 3—Oakwood Land Policy Modeling System.



examination of existing policies or new policies given additional information. Additionally, under certain circumstances, the value of new information can be estimated from the model. This type of modeling could provide the justification for obtaining new information or refining existing information.

This interactive learning process of estimating and refining the important parameters of the oak woodland management problem, trying alternative management policies, and observing the model's response enables the policy-maker to undertake final policies that are reasonable and defensible.

Conclusions

The oak woodlands of California are a valuable resource, but one that is in jeopardy from competing land uses. Policies must be designed that promote actions leading to the highest net benefit to society of the oak woodland resource while retaining the structure, composition, and ecological functions to ensure their sustainability. There are several approaches to designing these policies. One is incrementalizing existing policy, also known as "tweaking," or just "muddling through." This approach probably best describes the development of California's de facto oak woodland policy. Policy-making in this manner may minimize controversy, but has a much lower chance of achieving a desired future condition of the oak woodland ecosystem.

Another approach would be to clearly specify a desired future condition and undertake a rational analysis of the forces that are shaping the oak woodland resource. Assuming that the necessary information were available, policies could be identified that would constrain land uses and practices so as to achieve the desired future condition. There are potentially numerous policy paths to this desired future state, some socially and economically aggressively direct, others more gentle and circuitous. Whatever the course, at least society and policy-makers would be more certain that proposed policies would achieve a sustainable state.

The authors submit that this later approach is superior as a means of setting policy. We have attempted to clarify how one might design a model to aid policy-makers in pursuing this policy approach. The research problem becomes one of identifying the arguments, and relationships and obtaining the data to minimize the uncertainties that influence construction of such a model.

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