Ecosystem management via interacting models of political and ecological processes

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Abstract

Ecosystem management via interacting models of political and ecological processes.— The decision to implement environmental protection options is a political one. Political realities may cause a country to not heed the most persuasive scientific analysis of an ecosystem's future health. A predictive understanding of the political processes that result in ecosystem management decisions may help guide ecosystem management policymaking. To this end, this article develops a stochastic, temporal model of how political processes influence and are influenced by ecosystem processes. This model is realized in a system of interacting influence diagrams that model the decision making of a country's political bodies. These decisions interact with a model of the ecosystem enclosed by the country. As an example, a model for Cheetah (*Acinonyx jubatus*) management in Kenya is constructed and fitted to decision and ecological data.

Key words: Social systems, Ecological systems, Influence diagrams.

Resumen

Gestión de ecosistemas mediante modelos interactivos de procesos políticos y ecológicos.— La decisión de implementar opciones de protección medioambiental es de carácter político. Las realidades políticas de un país pueden permitir ignorar los análisis científicos más rotundos acerca de la futura salud de un ecosistema. Una comprensión predictiva de los procesos políticos que conducen a la toma de decisiones sobre la gestión de los ecosistemas puede contribuir a orientar las políticas relativas a dichas áreas. Con este objetivo, el presente artículo desarrolla un modelo estocástico temporal acerca de cómo los procesos políticos influyen y son influidos por los procesos de los ecosistemas. Dicho modelo se ha estructurado a partir de un sistema de diagramas de influencia interactivos que configuran la toma de decisiones de las instituciones políticas de un país. Dichas decisiones interactúan con un modelo del ecosistema presente en el país. Así, a modo de ejemplo, se elabora un modelo para la gestión del guepardo (*Acinonyx jubatus*) en Kenia, ajustándose a los datos ecológicos y de toma de decisiones.

Palabras clave: Sistemas sociales, Sistemas ecológicos, Diagramas de influencia.

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Introduction

Ultimately, the decision to implement ecosystem protection policies is a political one. Currently, the majority of ecosystem management research is concerned with ecological and/or physical processes. A management option that is suggested by examining the output of these models and/or data analyses may not be implemented unless the option addresses the goals of each involved social group (hereafter, *group*).

For example, Francis & Regier (1995) describe efforts to sustain the Great Lakes ecosystem. These authors identify the following major barriers to the sustainable management of this ecosystem:

1. Social science research and model building is restricted by research funding decisions to "safe" projects – typically the economic benefits of Great Lakes resource utilization. These authors see a strong need for social science research to understand the goals and restrictions that drive the many groups that advise, regulate, pollute, and advocate for the Great Lakes ecosystem.

2. Great Lakes physical and biological science is University department compartmentalized and hence ecosystem models that integrate limnological and terrestrial subsystems are under–developed.

3. Because of (2), science–based management policies are lacking in their reliability and hence are either ignored, corrupted or, at best have limited impact during the political process of negotiating treaties between Canada and the U.S. for the regulation of pollution, fishing, and recreation on the Great Lakes.

As a step towards meeting these needs, an Ecosystem Management System (EMS) is described herein that links political processes and goals to ecosystem processes and ecosystem health goals. This system is used to identify first the set of ecosystem management policies that have a realistic chance of being accepted by all involved groups, and then, within this set, those policies that are most beneficial to the ecosystem. Haas (2001) gives one way of defining the main components, workings, and delivery of an EMS. The central component of this EMS is a quantitative, stochastic, and causal model of the ecosystem being managed (hereafter, the *EMS model*). The other components are (2) links to data streams, (3) freely–available software for performing all ecosystem management computations and displays, and (4) a web–based archive and delivery system for items 1–3.

This article focuses on ecosystem management in developing countries. One of the first questions then, is what theoretical framework should be used to model political groups in developing countries? The "new institutionalists" (see Gibson 1999, pp. 9–14, 163, 169–171; Brewer & De Leon, 1983; Lindblom, 1980) draw on political economy theory to stress the following: (a) decision makers are pursuing their own personal goals, e.g. increasing their influence and protecting their job; and (b) decision makers work to modify institutions to help them achieve these goals. This view of the policy making process is particularly relevant for studying wildlife management in developing countries: as Gibson (1999, pp. 9–10) states "New institutionalists provide tools useful to the study of African wildlife policy by placing individuals, their preferences, and institutions at the center of analysis. They begin with the assumption that individuals are rational, self–interested actors who attempt to secure the outcome they most prefer. Yet, as these actors search for gains in a highly uncertain world, their strategic interactions may generate suboptimal outcomes for society as a whole. Thus, rational individuals can take actions that lead to irrational social outcomes." New institutionalism is not limited to explaining ecosystem management policymaking in developing countries. Healy & Ascher (1995) document the effect that individual actor goal seeking behavior had on how analytical ecosystem health models were used to manage national forests in the United States during the 1970s, ’80s, and ’90s.

Another paradigm for political decision making is the *descriptive* model (see Vertzberger, 1990). This approach emphasizes that humans can only reach decisions based on their internal, perceived models of other actors in the decision making situation. These internal models may in fact be inaccurate portrayals of the capabilities and intentions of these other actors.

The ecosystem model component of the EMS described in Haas (2001) can be extended to synthesize these two policy making paradigms. In Haas (2001), the ecosystem model is expressed as an *influence diagram* (ID) (see the online tutorial, Haas (2003b) for an introduction to IDs). To incorporate the interaction between groups and the ecosystem, a set of IDs are constructed, one for each group, and one for the ecosystem. Then, optimal decisions computed by each of these group IDs through time are allowed to interact with the solution history of the ecosystem ID. The model that emerges from the interactions of the group IDs and the ecosystem ID is called an *interacting influence diagrams* (IntIDs) model. In this model, each group makes decisions that they perceive will further their individual goals. Each of these groups however, has a perceived, possibly inaccurate internal model of the ecosystem and the other groups. The IntIDs model approach then, synthesizes insights from political economics (groups acting to maximize their own utility functions) and descriptive decision making theory (groups using —possibly— distorted internal models of other groups to reach decisions).

By choosing from a pre–determined repertoire of options, each group implements the option that maximizes a multiobjective (multiple goals) utility function. This is accomplished by having each group’s ID contain a decision option node representing the different actions that the group can take. Each group has an overall goal satisfaction node (hereafter, a *utility* node) that is influenced by the group’s goals. Each group implements an option that maximizes the expected value of its utility node. This is called *evaluating* the ID (see Nilsson & Lauritzen, 2000). A schematic of the architecture of an IntIDs model is given in figure 1.

As new types of actions are observed, the fixed repertoire of actions is periodically enlarged and the EMS model is re–fitted to the entire set of actions observations —see the Parameter Estimation with CA section, below.

Ecosystem management emerges as each group implements management actions that best satisfy its goals conditional on the actions of the other groups and the ecosystem's status. Conditional on these implemented management options, the marginal distributions of all ecosystem status variables are updated. By simulating these between–group and group–to–ecosystem interactions many years into the future, predictions of future ecosystem status can be computed.

Ecosystem status, state, or health (hereafter *status*) is a multidimensional concept and has been defined differently depending on those ecosystem characteristics of most interest to the analyst. This article focuses on the status of an endangered species within an ecosystem. One way to quantify this characteristic is with the number of animals of such a species in the ecosystem at a particular spatio–temporal point.

Kelly & Durant (2000) identify the cheetah in East Africa as an endangered species. The example given below of cheetah survivability in Kenya contains count variables for cheetah, and cheetah prey (herbivores having a biomass less than 35 kg). Future extensions of this model will have variables for individual cheetah prey herbivores such as Thomson's gazelle.

An output of the EMS model is the probability distribution on each of these counts by region and time point. These distributions are used to compute a typical measure of species survivability: the probability of extinction (POE) defined as the chance of a non–sustainable cheetah count at a specified spatial location and future point in time.

The uses and benefits of an EMS that combines both political and ecological processes are: (1) a (possibly empty) set of ecosystem management policies can be found that are both politically acceptable and effective at protecting the ecosystem; (2) the most likely sequence of future management activities can be identified so that more plausible predictions of future ecosystem status can be computed such as extinction probabilities; and (3) international audiences can predict which countries have any chance of reaching ecosystem status goals such as averting the extinction of an endangered species.

Because this modeling effort draws on several disciplines, the goals that are driving the model's development need to be clearly stated. They are (in order of priority):

1. Usability: develop a model that, because of its predictive and construct validity, contributes to the ecosystem management debate by delivering reliable insight into how groups reach ecosystem management decisions, what strategies are effective in influencing these decisions, and how ecosystems respond to management actions.

2. Clarity and accessibility: develop a model that can be exercised and understood by as wide a range of users as possible. Such users will minimally need to be literate and have either direct access to the EMS website or access to a printed copy of the EMS report. For the cheetah viability example below, all groups except rural residents and pastoralists meet these minimum requirements. A major challenge will be to bring the contents of the EMS report to groups that are illiterate and/or lack web access. One idea is to deliver the EMS report to any literate members of such groups, e.g. schoolteachers.

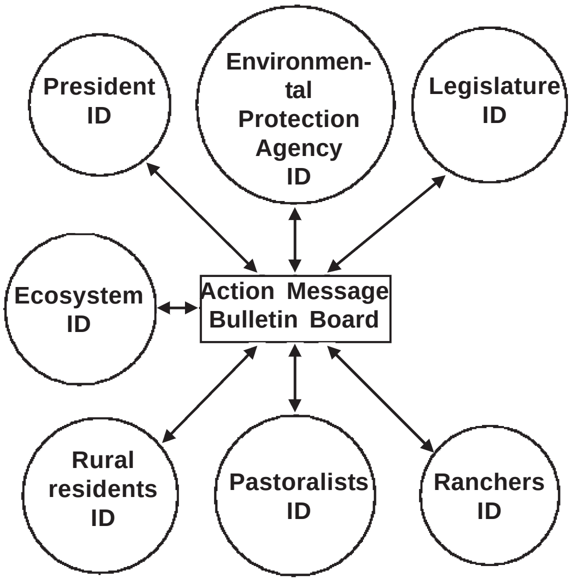

Fig. 1. Schematic of the IntIDs model of interacting political and ecological processes.

Fig. 1. Diagrama esquemático del modelo de IntIDs (diagramas de influencia interactivos) para los procesos interactivos de carácter ecológico y político.

There is a tension between predictive and construct validity in that the development of a model rich enough in structure to represent theories of group decision making and ecosystem dynamics can easily become overparameterized which in–turn can reduce its predictive performance. The approach taken here is to develop as simple a model as is faithful to theories of group decision making and ecosystem dynamics —followed by a fit of this model to data so as to maximize its predictive performance. Specifically, success in the model building effort presented herein will be measured along the following two dimensions: (1) the model's one–

step–ahead prediction error rate wherein at every step, the model is refitted with all available data up to that step; and (2) the degree to which the model's internal structure (variables and inter–variable relationships) agrees with theories of group behavior and ecology/population dynamics theories. The first dimension measures predictive validity and the second, construct validity.

One step ahead predictive validity is seen as essential to establishing the reliability of the EMS model. Such predictive validity is however, not without its challenges. For example, it is possible that once an EMS model becomes known to the groups it is modeling, these groups may alter their behavior in response to model predictions. This Heisenberg Principle effect would invalidate model predictions.

The influence of groups attempting to game EMS model predictions could be represented in the EMS model by adding another group called "the modelers." This group would post EMS model predictions to the bulletin board at every time step for all other groups to read. Once evidence on how model predictions are gamed is observed, such gaming behavior could be included in the group submodels of the EMS model and one step ahead prediction error rates computed as described in the Results section, below. Of course a second level of gaming is possible wherein groups attempt to manipulate an EMS model that includes groups attempting to game EMS model predictions. This second level of a Heisenberg Principle effect would be difficult to correct for and no solution is offered at this time.

This article proceeds as follows. The Materials and methods section gives the architecture of a group ID. The Results section applies this framework to the management of cheetah in Kenya and describes how the model can be statistically fitted to observations on political and ecosystem variables represented in the model. Conclusions are drawn in the Discussion section along with brief comparisons with related efforts.

Materials and methods

Group ID architecture

Overview

A group's ID is partitioned into subsets of connected nodes called the *Situation*, and *Scenario* subIDs (see figure 2 in Haas 2003a, Section 2). The Situation subID is the group's internal representation of the state of the decision situation and contains *Situation state* nodes. Conditional on what decision option is chosen, the Scenario subID is the group's internal representation of what the future situation (the Scenario) will be like after a proposed option is implemented. See Haas (1992, 2003a) for the cognitive theory that supports this decision making model architecture.

Actors, actions, and the time node

A decision option will hereafter be referred to as an *action*. Groups interact with each other and the ecosystem by executing actions. The decision making group, referred to as the DM_group receives an *input action* that is executed by an *actor* referred to as the *input–action–actor* group or InAc_group. The *subject* of this action is the *input–action–subject* group or InS_group (which may or may not be the DM_group). The DM_group implements an output action whose subject is the *target* group or T_group. Actions are either verbal (message) or physical events that include *all* inter– and intra–country interactions.

Each ID is a dynamic model and therefore has a deterministic root node Time. Time starts at t_0 and increments discretely through $t_1, ..., t_T$ in steps of δ_t.

Ecosystem status perceptions nodes

Quantities that represent ecosystem status can be input nodes to a group ID. These nodes influence a node that represents how sensitive the group is to the value of the corresponding ecosystem status node. The idea is that a group is affected by the ecosystem but is only conscious of it through filtered, perceptual functions of the underlying ecosystem status nodes. For example, a group ID is sensitive to the presence of a land animal such as the cheetah through the animal's density (number per hectare). This sensitivity is modeled by having the animal's density node influence a perceived animal prevalence node that takes on the values *none, few,* and *many*.

An ecosystem status node is stochastic due to it being a component of a stochastic ecosystem model. Sources of noise within this model include climate, unmodeled or mismodeled ecological functions, and inaccurate specification of model parameters.

Even if an ecosystem status node was deterministic, how values on this node would affect the representation of the ecosystem quantity in a group's perception of the ecosystem has its own set of uncertainties and noise sources. For example, consider the size of a minority population in a city. A demographic model allows for the stochasticity in birth rates, death rates, migration, and emigration. Now consider an elderly member of this city who's only source of information is TV news and newsletters from politically conservative groups. The perceived size of the minority population of the city by this elderly person may be only minimally affected by the probability distribution of this quantity computed from the demographic model. Further, this elderly person may reason about the size of this minority population in categorical terms (small, moderate, hordes). The credence this individual will give to these different values will be determined in–part by random encounters with members of this minority group (captured by the demographic model) and by some noisy function of images viewed on TV and statements made in newsletters ("...members of minority group X are over–running this city!").

Therefore, a separate node within each group ID is seen as necessary to capture both the more coarse resolution of perceptual models of continuously–valued quantities and the unique sources of stochasticity characteristic of perceptual processing.

Image nodes

A set of dimensions that defines the DM_group's image of another group is needed. Two such dimensions, Affect and Relative Power appear in many studies of political belief systems. Affect varies over the *enemy–neutral–ally–self* dimension (Murray & Cowden, 1999; Hudson, 1983, chs. 2–4). Relative Power varies over the *weaker–parity–stronger* dimension. The Affect dimension's *self* category is needed because the subject of an InAc_group's action may be the DM_group itself. This *self* category includes the DM_group's audiences (see below).

Economic, militaristic and institutional goals

This model is based on the cognitive–theoretic assumption that a group evaluates an input action directly on its perceived immediate and future impacts on economic, militaristic, and institutional goals. The two militaristic goals of Defend Country (inter–country), and Maintain Domestic Order (intra–country) are lumped into one Militaristic goal node.

Economic and militaristic goal status is computed with a two–step process: first an assessment is made of how the input or output action changes economic or military resource amounts; then, an assessment is made of how these new resource levels affect the associated economic or militaristic goal.

Here, only one institutional goal is modeled: Maintain Political Power. This goal is solely dependent on maintaining the contentment of several important *audiences*, discussed below.

A goal node is a binary–valued random variable with values *not–satisfied* and *satisfied*. A goal node is similar to a utility variable in political economics. The nodes that affect these utility judgements are the DM_group's InAc_group and InS_group image nodes, and the nodes representing the input action's immediate and future impact on the DM_group's resources.

Scenario goals are influenced by Situation goals —if an output action does not cause a resource or audience node change, the Scenario goal's distribution is the same as the corresponding Situation goal's distribution.

Audience effects

The influence of audiences on a decision maker is described by research that suggests perceptions of present and future reactions of important audiences have effects on decision making and bargaining, see Asch (1951), Festinger (1957), Milgram (1974), Rubin & Brown (1975), and Partell & Palmer (1999). An input action's impact on an audience is modeled as a function of the action's perceived effect on audience demands. For example, an important audience for (former) President Moi of Kenya was his ethnic group, the Kalenjin (Throup & Hornsby, 1998, p. 8). President Moi knew that only actions that brought benefits to that group would be favorably received by them.

The effects of perceived audience reactions to input actions is modeled by having input action characteristics influence Audience Demands Satisfaction Change nodes which in turn, influence Audience Contentment nodes. What demands an audience has and the effect of different input actions on the satisfaction of those demands are both represented by the conditional distributions of the Audience Demands Satisfaction Change nodes.

Say that the DM_group ID has *k* important audiences and consider the i^{th} such audience. Let the node $CA_i^{(St)}$ denote the perceived change in audience *i*'s demands satisfaction level due to an input action. $CA_i^{(St)}$ takes on the values *decreased*, *no change*, and *increased*. Let the node $A_i^{(St)}$ denote the perceived contentment level of audience *i*. $A_i^{(St)}$ takes on the values *discontented*, and *contented*. Likewise, in the Scenario subID, output action characteristics influence Audience Contentment nodes through the Audience Demands Satisfaction Change nodes. These nodes are also influenced by input action characteristics.

Situation contentment level influences Scenario contentment: if there is no change to an audience's contentment level due to the output action, Scenario contentment level inherits the Situation's contentment level.

The only goal node influenced by audience contentment nodes is the Maintain Political Power goal, $G_{MPP}^{(St)}$ —there is no goal of directly satisfying audiences because the decision maker has no concern for these audiences other than how they affect the decision maker's hold on political power.

Overall goal satisfaction

Goal prioritization is modeled by a single node representing the DM_group's overall sense of well–being. This node, denoted by $U^{(St)}$ (Situation) or $U^{(Sc)}$ (Scenario) is a deterministic function of the goal nodes wherein the coefficients in this function are interpreted as goal–importance weights and hence are assigned from knowledge of the group's goal priorities.

Group actions

To avoid creating a system that can only process a historical sequence of ecosystem management actions, a group output action classification system is needed that characterizes actions along dimensions that are not situation–specific. The idea is to map an exhaustive list of possible actions onto a set of dimensions that collectively completely describe an action. Several action taxonomies or classification systems have been developed in the political science literature (see Schrodt, 1995). These taxonomies however, lack a set of situation–independent dimensions for characterizing an action. The approach taken here is to base a set of action characteristics or *dimensions* on an existing action classification system. The Behavioral Correlates of War (BCOW) classification system is chosen for this extension for two reasons. First, BCOW is designed to support a variety of theoretical viewpoints (Leng, 1999) and hence can be used to code data that will be used to estimate a model of group decision making that synthesizes realist and cognitive processing paradigms of political decision making —and BCOW is at least as rich a classification system as other systems in the literature. Second, BCOW has coding slots for recording: (i) a detailed description of an action, (ii) inter– and intra–country groups, and (iii) a short history of group interactions. This last coding category allows causal relationships to be identified and tracked through time.

The BCOW coding scheme consists of a nearly exhaustive list of actions grouped into Military, Diplomatic, Economic, Unofficial (intra–country actor), and Verbal categories. The BCOW classification system exhaustively and uniquely characterizes a verbal action into either a comment on an action (Verbal: Action Comment), a statement that an action is intended (Verbal: Action Intent), or a request for an action (Verbal: Action Request).

Modifications have been made to the BCOW scheme for purposes of categorizing ecosystem management actions. These modifications are as follows. First, the Unofficial Actions category of the BCOW coding system is not needed since groups internal to a country are modeled as having nearly the same range of output actions as a country–level group. Hence, all BCOW Unofficial Actions have been absorbed into one of the other action categories. For example, Hostage Taking, BCOW code 14153 is coded as a Military dimension action. Second, all BCOW Verbal Actions have been inserted into the BCOW Diplomatic Action category. Third, because BCOW does not include many actions that are peculiar to ecosystem management, such actions have been added to the BCOW taxonomy at the end of each action category listing (see Appendix 1, tables A1–A3 at www.uwm.edu/~haas/ems-cheetah/bcow.pdf).

See Haas (2003a) for descriptions of nodes that determine realistic actor–input action combinations, and realistic target–output action combinations.

A proposed target and output action combination influences target image and action characteristic nodes. These nodes along with Situation goal nodes, influence Scenario goal nodes. Finally, Scenario goal nodes influence the Scenario Overall Goal Satisfaction node. Each target and output action combination is used to compute the expected value of the Overall Goal Satisfaction node. At time *t*, the output action that maximizes this expected value is designated by $c_{optimal}(t)$.

After determining $c_{optimal}(t)$, the DM_group posts to a bulletin board an *action–message* consisting of the time, the DM_group's name, the target's name, and the BCOW action code. At the next time value, all other groups read this message. Each group assigns the values on the action characteristics associated with the BCOW action code and assigns values to the InAc_group image and InS_group image nodes. Using these values, each group computes an optimal output action and posts it to the bulletin board. When all groups have posted an output action and the ecosystem ID has posted updated distributions on its status nodes, the time variable is incremented by the value of δ_t and the process is repeated (see fig. 2). Note that this protocol allows for feedback loops through time to emerge without need for additional model structure.

There are groups that directly affect the ecosystem and groups that only indirectly affect the ecosystem. Actions by *direct–affect* groups always have the ecosystem as one of the targets of an output action. When such an action message is read by the ecosystem ID, its effect on the ecosystem is computed. If the action does not affect the ecosystem, e.g. a riot by the rural residents of Kenya, then the ecosystem model computes no effect on the ecosystem due to this action.

Target, output action pair effectiveness

The militaristic or economic effectiveness of an output action is determined in–part by its target. To represent this interaction, Scenario nodes are needed to represent the DM_group's perception of the militaristic effectiveness of a target, output action pair given an input actor, input action pair. The nodes MilEf and EconEf take on the values *negative effect, no effect*, and *positive effect* and are influenced by Input Actor, Input Action, Target, and Output Action nodes. MilEf influences the Scenario Maintain Order goal, and EconEf influences Scenario Immediate Economic Resources Change.

Group ID hypothesis value assignment

In the Results section, below, Consistency Analysis (CA) is used to fit each ID's parameters to data. CA requires that each parameter in an ID be assigned an a–priori point value derived from expert opinion and/or subject matter theory. Let $\beta_H^{(j)}$ be such a value assigned to an ID's j^{th} parameter. Collect all of these *hypothesis parameter values* into the *hypothesis parameter vector*, β_H. See the Results section, below and Haas (2001, Appendix) for further discussion of CA.

Because of the complexity of each group's ID, it is difficult to directly assign hypothesis parameter values. For this reason, two optimization steps are performed to find hypothesis values that reflect the information contained in two types of hypothetical data sets. The first of these data sets is a collection of pairs of input and output node values on the group ID. Call this nontemporal data set an *action–reaction* data set. The second data set consists of a history of actions by all group IDs in the EMS

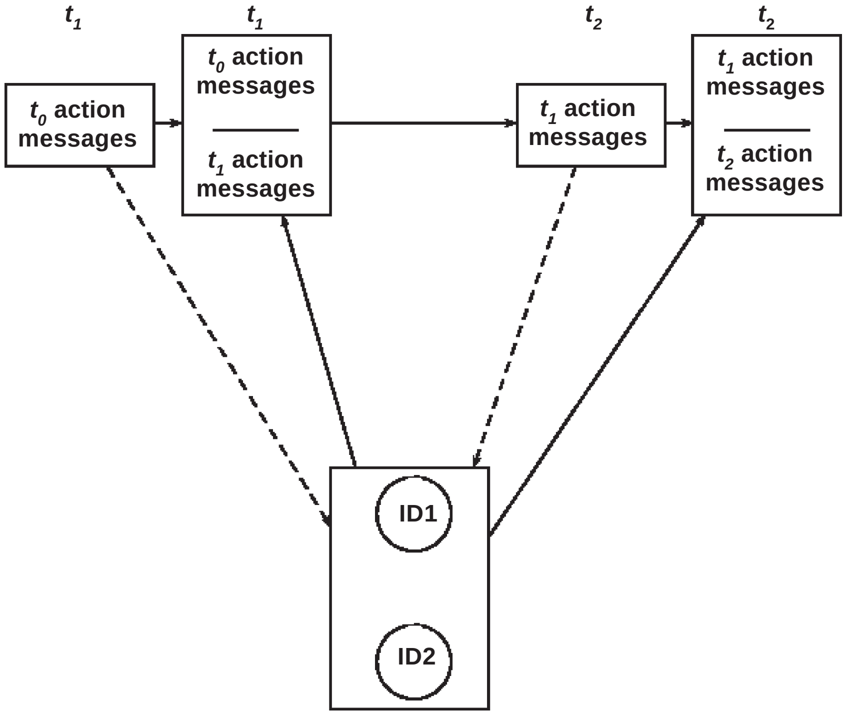

Fig. 2. Sequential updating scheme of an IntIDs model consisting of two IDs. Bulletin board states are indicated by the boxes in the top row. A dashed arrow indicates messages are read but not removed. A solid arrow indicates message addition.

Fig. 2. Esquema secuencial de actualización de un modelo de IntIDs (diagramas de influencia interactivos) que consta de dos IDs (diagramas de influencia). Los diferentes estados del tablón de anuncios se indican mediante los recuadros situados en la fila superior. Una flecha discontinua indica que los mensajes se han leído, pero no han sido eliminados. Una flecha continua indica la adición de mensajes.

model. Call this temporally–indexed data set an *actions history* data set. The action–reaction data set is used in an optimization procedure to find an initial β_H. The actions history data set is used by a second optimization procedure to refine these initial values. These two optimization steps are described in Haas (2003a, Section 2).

Results

Example: cheetah in Kenya

Background

Cheetah preservation is a prominent example of the difficulties surrounding the preservation of a large land mammal whose range extends over several countries. The main threats to cheetah preservation are loss of habitat, cub predation by other carnivores, and poaching (Gros, 1998; Kelly & Durant, 2000). Kelly & Durant (2000) note that juvenile survival is reduced by lion predation inside reserves because these reserves are not big enough for cheetah to find areas uninhabited by lions. Over crowding of reserves in Africa is widespread (see O'Connell–Rodwell et al., 2000) and cheetah do not compete well for space with other carnivores (Kelly & Durant, 2000). Gibson (1999, p. 122) finds that the three reasons for poaching are the need for meat, the need for cash from selling animal "trophies", and the need to protect livestock.

All input and output files for this example along with the EMS Java^{TM} based software is available at www.uwm.edu/~haas/ems-cheetah/.

ID descriptions

According to Gros (1998) and Gibson (1999, p. 164), the groups that directly affect the cheetah population are ranchers, rural residents, and pastoralists. Presidents, Environmental Protection Agencies (EPAs), legislatures, and courts indirectly affect the cheetah through their influence on these direct–affect groups. In this EMS model, group IDs are constructed to represent the president of Kenya, the Kenyan EPA, Kenyan rural residents, and Kenyan pastoralists. These group IDs interact with each other and an ID of the cheetah–supporting ecosystem contained within Kenya.

Hypothesis parameter values for each ID in the EMS model are available at the aforementioned cheetah EMS website under the Current EMS Report link. Abbreviations used below are: Pres. president; EPA. Environmental Protection Agency; RR. Rural residents; Pas. Pastoralists; and Eco. Ecosystem. The ecosystem is directly affected only by poaching activities and land clearing. Anti–poaching enforcement is directed against either the rural residents or pastoralists and may or may not be effective at reducing poaching activity. Likewise, the creation of a preserve or the opening of an existing preserve to settlement are actions directed against the rural residents and/or pastoralists.

In what follows, each group ID is described and hypothetical action–reaction data sets (tables 1–4) are given that are used to compute each group's initial β_H vector (Haa 2003a, Section 2). The heuristics listed in www.uwm.edu/~haas/ems-cheetah/heuristics.pdf are used to represent subject matter theory during the first step of this computation.

Gibson (1999, pp. 155–156) argues in his case studies of Kenya, Zambia, and Zimbabwe that the president in each of these countries has a different personal priority for protecting ecosystems. Further, presidents of politically unstable countries typically place a high priority on protecting their power and staying in office (Gibson 1999, p. 7). These insights have motivated the following president ID (see www.uwm.edu/~haas/ems-cheetah/kenpres.pdf).

The president has direct knowledge of rural resident and pastoralist actions. The president receives ecosystem status information exclusively from the EPA. The president's audiences are campaign donors and the military. The president's goals are to maintain political power and domestic order. The president's action repertoire is: *no changes, create a preserve, request increased antipoaching enforcement, open a preserve to settlement*, and *suppress a riot*.

EPA perceptions of the ecosystem's status are represented by the cheetah prevalence and herbivore prevalence nodes. These nodes are influenced by the values of cheetah density, herbivore density, and poaching rate in the ecosystem ID. The EPA's sole audience is the president. The EPA's goals are to protect the environment, and to increase the agency's staff and budget. The latter goal is motivated by an examination of the literature on bureaucracies. The main postulates of this literature are concisely stated by Ott (1981):

"Managers of public enterprises —e.g. municipal fire departments, public hospitals, the Department of the Interior— have incentive structures much different from their private counterparts. In a private firm the owners create incentives for managers to maximize the difference between revenues and private costs. Since the private manager has some contingent property rights in the revenue–minus–cost residual, he makes choices that tend to maximize the firm's and its owners'net worth.

Conversely, in the public sector there is no residual claimant: The public agency's budget must be exhausted by approved expenditures. If there is a surplus, it is remanded to the general fund and will usually result in a reduction of the agency's subsequent budgets. Since a surplus cannot benefit the agency, there can be no direct benefit to the agency of increasing a benefit–cost difference or of reducing the cost of achieving a given benefit level. Thus, broadly speaking, bureaucrats have strong incentives to increase costs, as these will, up to a point, increase the size of the bureau's budget. This budget augmentation can be accomplished in one or both of two ways: (1) by under–stating the marginal cost of the bureau's output; (2) by price discrimination.

If we assume that managers of public agencies are wealth maximizers to the same extent as managers of private firms, then their behavior —i.e., their budgeting decisions, their planning, and their production— can be understood in terms of the reward structure under which they function. The pecuniary compensation of civil service managers is determined, somewhat rigidly and quite uniformly, by the number and grade of people whom they supervise; thus there is a strong incentive for bureaucrats at each level in an agency to increase the number of employees in their sections. By so doing, their operating budgets and salaries will be enlarged.

The bureaucrat's decision problem is, therefore, to present the largest budget that his political executive —the mayor, the governor, or the cabinet secretary— would approve. This entails knowing the executive's demand for the agency's output as well as knowing the agency's own cost function. Knowledge of the latter is a qualification for management and comes from the seniority characteristic of civil servants who head agencies. Knowledge of the former is obtained as a result of the political process. A political candidate reveals his preferences both explicitly in his campaign platform and implicitly by embodying the preferences of those voter and special–interest groups who support him. Since department heads and cabinet secretaries are appointees of the elected politician, these political executives may, in turn, be presumed to reflect the preferences of the politician".

See also Niskanen (1971). For example, Healy & Ascher (1995) note that during the 1970's and 1980's the USDA Forest Service, using FORPLAN output, consistently proposed forest management plans that required large increases in Forest Service budget and staff (see also Gibson 1999, pp. 85, 115–116). Possible actions by the EPA are: *decrease antipoaching enforcement, maintain antipoaching enforcement*, and *increase antipoaching enforcement* (see www.uwm.edu/~haas/ems-cheetah/kenepa.pdf).

Table 1. Hypothetical action–reaction data for the Kenya president ID: *inac.* Input actor*;* $c^{(in)}$. Input action; $s^{(in)}$. Input subject*;* $c^{(ou)}$. Output action*; Target.* Output action subject; Pas. Pastoralist; RR. Rural residents; EPA. Environmental Protection Agency; Eco. Ecosystem; Self. DM_group

Tabla 1. Datos hipotéticos de acción–reacción con respecto a los diagramas de influencia del presidente de Kenia ID: inac. *Actor de la acción estímulo*; $c^{(in)}$*. Acción estímulo*; $s^{(in)}$*. Sujeto estímulo*; $c^{(ou)}$*. Acción resultado;* Target. *Sujeto que recibe el resultado (el objetivo); Pas. Ganaderos; RR. Residentes rurales; EPA. Agencia de Protección del Medio Ambiente; Eco. Ecosistema; Self. Grupo DM.*

	Input vector		Output vector	
inac	$c^{(in)}$	$s^{(in)}$	$c^{(ou)}$	*Target*
Pas	little poaching	Eco	do nothing	Pas
Pas	moderate poaching	Eco	request increased antipoaching enforcement	EPA
Pas	heavy poaching	Self	request increased antipoaching enforcement	EPA
RR	little poaching	Eco	do nothing	RR
RR	moderate poaching	Eco	request increased antipoaching enforcement	EPA
RR	heavy poaching	Self	open preserve	RR
RR	clear new land	Eco	do nothing	RR
RR	riot	Self	suppress riot	RR
EPA	negative ecoreport	Self	create preserve	Pas
EPA	positive ecoreport	Self	do nothing	EPA

The development of both the rural resident, and pastoralist IDs, below is derived from the study of these two groups by Gibson (1999, pp. 121–123, 143–147) and is an attempt to represent quantitatively the goals, audiences, and action repertoire of these two groups as described by that author.

Herbivore prevalence as influenced by the herbivore density node is the single ecosystem status node for the rural resident ID. A rural resident is pursuing the two goals supporting his/her family, and avoiding prosecution for poaching herbivores and/or cheetahs. Possible rural resident actions are: *little poaching, moderate poaching, heavy poaching, clear new land,* and *riot* (see www.uwm.edu/~haas/ems-cheetah/kenrr.pdf). The action *little poaching* includes the action of no poaching.

This version of the rural resident ID does not distinguish between poaching herbivores versus cheetahs. There is evidence that poaching activity tends to include both herbivores and carnivores (Gibson 1999, pp. 143–145). In the ecosystem ID, a poaching action modifies the herbivore count stochastic differential equation (SDE) and the cheetah death rate SDE (see below). A change in the area of protected regions affects the herbivore SDE and the cheetah birth rate SDE. Hence, a poaching action's affect on the ecosystem model is interpreted as the poaching of both herbivores and cheetahs. Future versions of this EMS model will have separate group actions for the frequency of poaching herbivores for meat, and the frequency of poaching cheetahs for either trophies or to protect livestock. Such differentiation will also allow the indirect effect on the ecosystem of herbivore poaching causing a reduction in cheetah carrying capacity.

Hunting big cats for trophies is market–driven and this world–wide market is not represented in either the rural resident or pastoralist IDs. The effect of this omission is that the model assumes a constant demand or constant market price for trophies. One way to model this demand–side effect on the motivation of rural residents and/or pastoralists to poach cheetahs is to develop a group ID of the buyers of such trophies. As a result of world–wide efforts to reduce the demand for trophies, this group would post lower market prices for trophies to the IntIDs bulletin board. These posted prices would, in–turn affect the perceived profit by rural residents and/or pastoralists from poaching cheetahs. This approach will be experimented with in future versions of this cheetah management EMS.

Cheetah prevalence as influenced by cheetah density is the single ecosystem status node in the pastoralist ID. Pastoralists have the three goals of supporting their family, protecting their livestock,

Table 2. Hypothetical action–reaction data for the Kenya EPA ID. (For abbreviations see table 1.)

Tabla 2. Datos hipotéticos de acción–reacción con respecto a los diagramas de influencia de la Agencia de Protección del Medioambiente de Kenia. (Para las abreviaturas ver tabla 1.)

Input vector			Output vector	
inac	$c^{(in)}$	$s^{(in)}$	$c^{(ou)}$	*Target*
Pas	heavy poaching	Eco	increase antipoach	Pas
RR	clear new land	Eco	negative ecoreport	Pres
Pres	request increased antipoaching enforcement	Self	increase antipoach	RR

Table 3. Hypothetical action–reaction data for the Kenya rural resident ID. (For abbreviations see table 1.)

Tabla 3. Datos hipotéticos de acción–reacción con respecto a los diagramas de influencia de los residentes rurales de Kenia. (Para las abreviaturas ver tabla 1.)

Input vector			Output vector	
inac	$c^{(in)}$	$s^{(in)}$	$c^{(ou)}$	*Target*
EPA	increase antipoach	Self	moderate poaching	Eco
Pres	open preserve	Self	clear new land	Eco
Pres	create preserve	Self	heavy poaching	Eco

and avoiding prosecution for poaching. Possible pastoralist actions are: *little poaching, moderate poaching*, and *heavy poaching* (see www.uwm.edu/~haas/ems-cheetah/kenpas.pdf). As with the rural residents, a poaching action does not differentiate between the taking of herbivores versus cheetahs.

The ecosystem ID is a modified version of the cheetah population dynamics ID of Haas (2001) and consists of four subIDs: management, habitat, direct effects on population dynamics, and population dynamics (see www.uwm.edu/~haas/ems-cheetah/ecosys.pdf). Management nodes represent time (t), region (q), and management options (m). Cheetah habitat is characterized by chance nodes for the region's climate (CL), unprotected land use (U), and the proportion of a region's area that is protected (R_t). A single direct effect chance node follows: within–region poaching pressure (P_t). The node U takes on the values *nomad_camel, nomad_cattle, ranching*, and *farming*.

Cheetah population dynamics is modeled with a system of SDEs consisting of the within–region nodes of birth rate (f_t), death rate (r_t), number of herbivores (H_t), cheetah carrying capacity (K_t), and cheetah count (N_t).

The SDE for H_t is

$$\frac{dH_t}{dt} = \alpha_1 H_t (1 - H_t/\alpha_0) + \sigma dW_t^{(H)} \qquad (1)$$

where H_0 is the initial count, α_0 (10,000) is the carrying capacity of the habitat (influenced by CL), α_1 is the difference between herbivore birth and death rates, σ (= 0.01) is the diffusion parameter, and W_t is a Wiener process. The initial value, H_0 is set to $0.6\alpha_0$. This model is a simplified version of the relationship given in Wells et al. (1998) wherein the probability of offspring upon the meeting of a male and female is assumed to be 1.0.

Poaching affects the value of α_1: *minor poaching, moderate poaching*, and *severe poaching* cause α_1 to take on the values 0.1, –0.1, and –0.3, respectively. If $E[H_t] < 2{,}000$, the rural resident ID's Herbivores node is set to *none*, if $2000 < E[H_t] < 10{,}000$, this node is set to *few*, and if $10{,}000 < E[H_t]$, this node is set to *many*.

As described in Haas (2001), the distribution of cheetah birth rate, f_t is the solution of the SDE

$$df_t = -.5(\alpha_f + \beta_f^2 f_t')(1 - f_t'^2)dt + .5\beta_f(1 - f_t'^2)dW_t^{(f)} \qquad (2)$$

Table 4. Hypothetical action–reaction data for the Kenya pastoralist ID. (For abbreviations see table 1.)

Tabla 4. Datos hipotéticos de acción–reacción con respecto a los diagramas de influencia de los ganaderos de Kenia. (Para las abreviaturas ver tabla 1.)

Input vector			Output vector	
inac	$c^{(in)}$	$s^{(in)}$	$c^{(ou)}$	*Target*
EPA	increase antipoach	Self	moderate poaching	Eco, EPA
Pres	create preserve	Self	heavy poaching	Pres, Eco
EPA	decrease antipoaching	Self	moderate poaching	Eco, EPA

where $f_t^{'} = 2f_t - 1$. This SDE was chosen because its solution is bounded between 0 and 1 making f_t a well–defined birth rate $f_t \in (0, 1)$. A similar development for cheetah death rate gives

$$dN_t = \left[f_t (1 - P^{cN_t}) N_t - r_t N_t - (f_t - r_t) \frac{N_t^2}{K_t} \right] dt + \beta_N dW_t^{(N)} \quad (3)$$

where $r_t^{'} = 2r_t - 1$. Note that the birth rate decreases as α_f becomes increasingly positive, and the death rate decreases as α_r becomes increasingly positive.

The tendency of more females to have litters within protected areas (see Gros, 1998) is represented by having the parameter α_f be conditional on the region's status. Similarly, to represent the effect of poaching and pest hunting on r_t, α_r is conditional on poaching pressure. The variability of the sample paths of f_t and r_t are controlled by the parameters β_f and β_r, respectively.

All other unmodeled effects (such as migration, emigration, or age–dependent parameter values) that could influence the within–region cheetah count differential (dN_t) are represented by the noise term in the cheetah count SDE:

$$dr_t = -.5(\alpha_r + \beta_r^2 r_t')(1 - r_t'^2)dt + .5\beta_r (1 - r_t'^2) dW_t^{(r)} \quad (4)$$

were P, c, N_0, and β_N are fixed parameters, and K_t is a deterministic function of the H_t temporal stochastic process.

Future versions of this cheetah count model will include terms to represent cheetah migration and emigration between adjacent regions including regions that are within the neighboring countries of Tanzania and Uganda.

As mentioned above, the effect of climate change on a region is represented by the ecosystem's climate node (*CL*) that influences herbivore carrying capacity.

Ecosystem status output nodes are herbivore and cheetah densities. Because the ecosystem ID is conditional on region, computed herbivore and cheetah densities are region–specific. Since the group IDs are not regionally–indexed, these region–specific ecosystem ID outputs need to be aggregated across regions. Here, this aggregation is accomplished by computing at each time step, a weighted average of the expected values of ecosystem output nodes with region area as the weighting variable. These weighted averages are written to the bulletin board.

Hypothesis parameter values for this ecosystem ID are taken from Haas (2001).

Example model output

As an example of EMS model output, figure 3 gives the event history over a three year period computed by the IntIDs EMS model using each ID's β_H values. Three months is the unit of time (expressed in units of *years*, i.e., groups read the bulletin board every 0.25 time units). The initializing action is RRs clearing new land. This action prompts a negative ecosystem status report by the EPA. Upon receipt of this report, the president calls for increased antipoaching enforcement (Time = 2000.5) and so forth.

The figure indicates a steady decline in both herbivore and cheetah density across Kenya. Say that preservation measures were enacted in 2001 and maintained through 2002. What changes in parameter values would be needed to reverse these declines? Through trial and error it has been found that the difference in herbivore birth and death rates would need to be maintained at 0.5, the cheetah birth rate parameter, α_f at –3.0, and the cheetah death rate parameter, α_r at 3.0.

Because a fixed time step is used, the EMS model may produce a frequency of actions from a group that may be higher than observed. For the case of an action being repeated —such as the president's call for increased antipoaching enforcement in the example, the repeated action should be interpreted as the group's continued preferred response which in reality may not be made public at time points following the first time that the action is posted on the bulletin board.

Parameter estimation with CA

CA overview

CA is used to fit the EMS model to data. Let U be an IntID's *r*–dimensional vector of chance nodes. Let $g_S(\beta)$ be a *goodness–of–fit* statistic that measures the agreement of this distribution (referred to here as the $U|\beta$ distribution) and the (possibly) incomplete sample, *S*. Let $g_H(\beta)$ be the agreement between this distribution identified by the values of β_H (referred to here as the *hypothesis distribution*) and the $U|\beta$ distribution. Let *gsmax* be the unconstrained maximum value of $g_S(\beta)$ over all β. Let *ghmax* be the unconstrained maximum value of $g_H(\beta)$ over all β. Up to errors in the approximation of $g_H(\beta)$, $ghmax = g_H(\beta_H)$. The CA parameter estimator maximizes

$$g_{CA}(\beta) \equiv (1 - c_H)\, g_s(\beta)/|gsmax| + c_H g_H(\beta)\ /|ghmax|$$

were $c_H \in (0, 1)$ is the analyst's priority of having the consistent distribution agree with the hypothesis distribution as opposed to agreeing with the empirical (data–based) distribution. Let $\equiv argmax_\beta \{g_{CA}(\beta)\}$ be the CA estimate of β. See Haas (2001, Appendix) for further details and a comparison with other parameter estimators, and Haas (2003a, Section 5) for mathematical definitions of all CA agreement functions.

CA example

The actions history–ecosystem status output (fig. 3) is used to illustrate CA. A smaller number of Monte Carlo realizations per ID causes the IntIDs model output to deviate slightly from the output of figure 3 and hence can be used as a data set that is different than the EMS model output under the IntID's hypothesis distributions.

The parameters estimated with CA are those defining the president's Overall Goal Satisfaction node, and the ecosystem ID's cheetah count node —resulting in 12 parameters to be estimated. For c_H set to 0.5, starting and ending values of each CA agreement function are in table 5. Values of *gsmax* and *ghmax* are 23.6962 and 1.2671, respectively. The CA optimization was limited to 200 function evaluations per step and hence did not achieve convergence on either step. This run required four hours on a 500 mhz PC. Table 5 indicates that significant improvements in model fit to a data set can be achieved after only a modest exploration of the parameter space.

One–step–ahead prediction error rates are given in Haas (2003a, Section 5). Also, a parameter sensitivity analysis of this model shows no highly unstable parameters (see Haas, 2003a, Section 4).

Discussion

A general purpose EMS has been developed that can help decision makers manage an ecosystem while taking into account political realities. Methods have also been developed for fitting the EMS model to a history of group actions and ecosystem observations.

This group actions and ecosystem observations data set can be augmented with actions directed towards similar environmental metrics. For example, management decisions concerning any large land carnivore such as lions can be included in the data set used to estimate the parameters of the example's cheetah management EMS model.

Modeling across multiple scales

Group behavior across a range of spatial scales is captured in the IntIDs EMS model structure by using a separate suite of group IDs for each country. Different temporal scales are modeled with selection of values for the time step between bulletin board updates in relation to the values chosen for the wildlife population dynamics model's diffusion rate parameters. Ecosystem behavior across a range of spatial scales is captured thru the use of an ecosystem model at the level of a homogeneous region – similar to an ecoregion.

A current shortcoming of the cheetah management model is that the population dynamics model's diffusion rate parameters are too fast. This was done to illustrate how the ecosystem model could interact with several group models.

Descriptions of related approaches

Post–normal science

In their development of *post–normal science*, Funtowicz & Ravetz (1993) argue that: (a) models as normally understood by scientists are not going to be successful in capturing the behavior of complex environmental systems, (b) diverse groups have

Table 5. CA agreement function values using artificial data: Am. Agreement measure; Pi. Percent improvement.

Table 5. Valores de la función de concordancia del análisis de consistencia utilizando datos artificiales: Am. Medida de concordancia; Pi. Porcentaje de mejora.

Am	$\beta = \beta_H$	$\beta = \beta_C$	Pi
$g_S^{Eco}(\beta)$	–1.9146	1.5273	179
$g_S^{Grp}(\beta)$	18.049	20.2800	12
$g_H^{Eco}(\beta)$	–1.2657	–.00035	100
$g_H^{Grp}(\beta)$	–.0014	–.00164	–17
$g_{CA}(\beta)$	–.3191	.4594	244

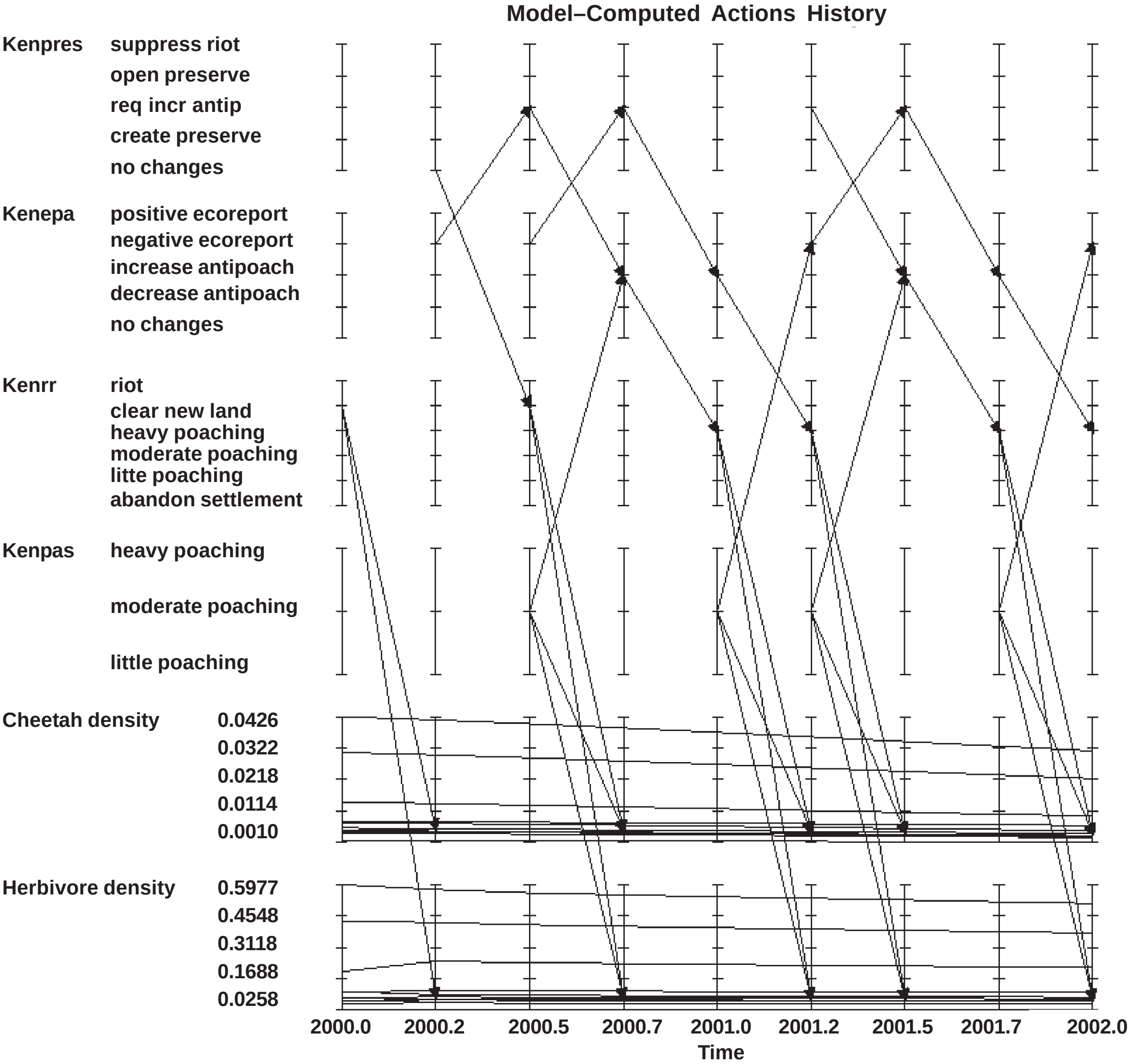

Fig. 3. Output action time series under β_H values. An arrow's tail locates a group's action and the arrow's head indicates the reaction of either a group or the ecosystem. Each line on an ecosystem variable plot is the mean for one of the eleven regions in Kenya.

Fig. 3. Serie temporal de los resultados de las acciones según los valores β_H. La cola de una flecha sitúa la acción de un grupo, mientras que su cabeza indica la reacción de un grupo o del ecosistema. Cada línea que figura en la representación gráfica variable del ecosistema corresponde al promedio de una de las once regiones de Kenia.

stakes in the outcomes of these systems and attach different values to such outcomes, (c) many of these groups are not members of established policymaking or scientific elites but nonetheless are demanding and receiving a significant role in the management of such complex environmental systems, so that (d) future management decisions should be made on "partial" scientific analysis and shared decision making that respects the values of groups that have been historically marginalized in policymaking debates.

The ID–based, combined political and ecological processes EMS model proposed here is similar to the post–normal science agenda in that it explicitly models the values and decision making processes of all groups affecting the environmental system. System complexity however, contrary to the post–normal science view, is not seen as hopeless to model but rather, stochastic models are proposed that, after being fitted to data, can have their out–of–sample or predictive validity demonstrated. Such demonstrations can lead to greater impact of the output of such models on the policymaking debate.

Multiagent models

Janssen (2002) describes a multi–agent simulation model of forest harvesting decisions of landowners in southern Indiana (U.S.A.), and in the Brazilian Amazon. This model employs finite–difference equations to represent farmers using a simple learning algorithm and a simple maximum expected utility decision making algorithm to reach harvesting decisions. For example, a decision to harvest trees is made if current economic conditions result in the utility of a harvesting proposal to be greater than that of not harvesting.

This approach to a model–based EMS is different from the approach described in this article in that: (a) a procedure has not been given for fitting the model to landowner behavior observations, (b) the group behavior model is relatively simple, and (c) there is no separate ecosystem model.

Differential and finite difference equation models

Costanza et al. (2001) has developed a simulation model of the dynamic characteristics of humans interacting with periodically harvested fish stocks. This model accounts for different spatial and temporal scales of social and ecological processes. For example, mis–perceived spatial scale of fish populations can lead to extinction because the regulatory region scale and the natural population scale are different. For the case of northern Atlantic fisheries, the U.S. claim to regulatory control for up to 200 miles offshore results in a large–area fishing quota being set —but population spawning grounds are small and separated areas. Implementation of such quotas then, can lead to local population depletion.

In this model, groups obey simple rules of behavior such as harvesting to maintain a maximum sustained yield, or unlimited fishing. Fish stocks are affected by: (a) harvesting and value–addition by humans before human consumption, (b) fishing regulation limits, (c) cheating (catches are over regulation limits), and (d) spatially heterogeneous area (three subregions).

This approach to a model–based EMS is different from the approach described in this article in that: (a) there are no stochastic terms, (b) a procedure has not been given for fitting the model to fisheries observations, (c) the group behavior model is relatively simple, and (d) there is no separate ecosystem model.

Carpenter et al. (1999) describes a model of multiple agents affecting a lake's nutrient loading. A stochastic finite difference equation model of a lake's phosphorous load along with a soils equation makes up the environmental model. Simple, deterministic, utility maximizing equations are used to represent the decision making of scientists, economists, regulators, and farmers. Two computations are made at each time step. First, each agent decides how much phosphorous to allow into the lake. This is done by modeling these agents as utility maximizers having only partial information access. Then, the soils and lake models are updated.

This approach to a model–based EMS is different from the approach described in this article in that: (a) no procedure has been given for fitting the model to observations on soils and lake status, (b) group behavior models assume high education levels and the ability to make fairly precise economic calculations, and (c) multiple spatial scales are not represented.

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