Ecosystem Management via Interacting Models of Political and Ecological Processes

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Outline

1. Summarize an Ecosystem Management System (EMS) that accounts for the interaction of political and ecological processes.

2. Summarize an ecosystem model that focuses on cheetah population dynamics.

3. Describe a simplified model of the President of Kenya interacting with rural residents.

4. Summarize my approach to EMS model parameter estimation.

5. Conclude.

EMS Overview

EMS Components:

1. A probabilistic, spatio-temporal *model* of interacting political and ecological processes.

2. A software system for statistically fitting and evaluating this model against political and ecological data.

3. Relevant political and ecological data with links to on-going data collection efforts.

4. Analysis software (source and executable form) that fits the model to this data.

5. Software for writing user-customized reports.

6. documentation for this software.

7. Output from this fitted model in a report form that is understandable by stakeholders at many different education levels.

8. Literature pertaining to the ecosystem being managed.

9. All of the above placed on a free, publicly-available website.

Overview of Example Model

- Kenya, Tanzania, and Uganda control a large portion of cheetah rangeland.

- The major social groups (hereafter, *groups*) within each country that influence cheetah viability are:

    1. rural residents

    2. pastoralists

3. ranchers
4. the EPA
5. the President
6. the legislature

- The model component of the EMS consists of models of these groups interacting with each other and a model of the ecosystem.

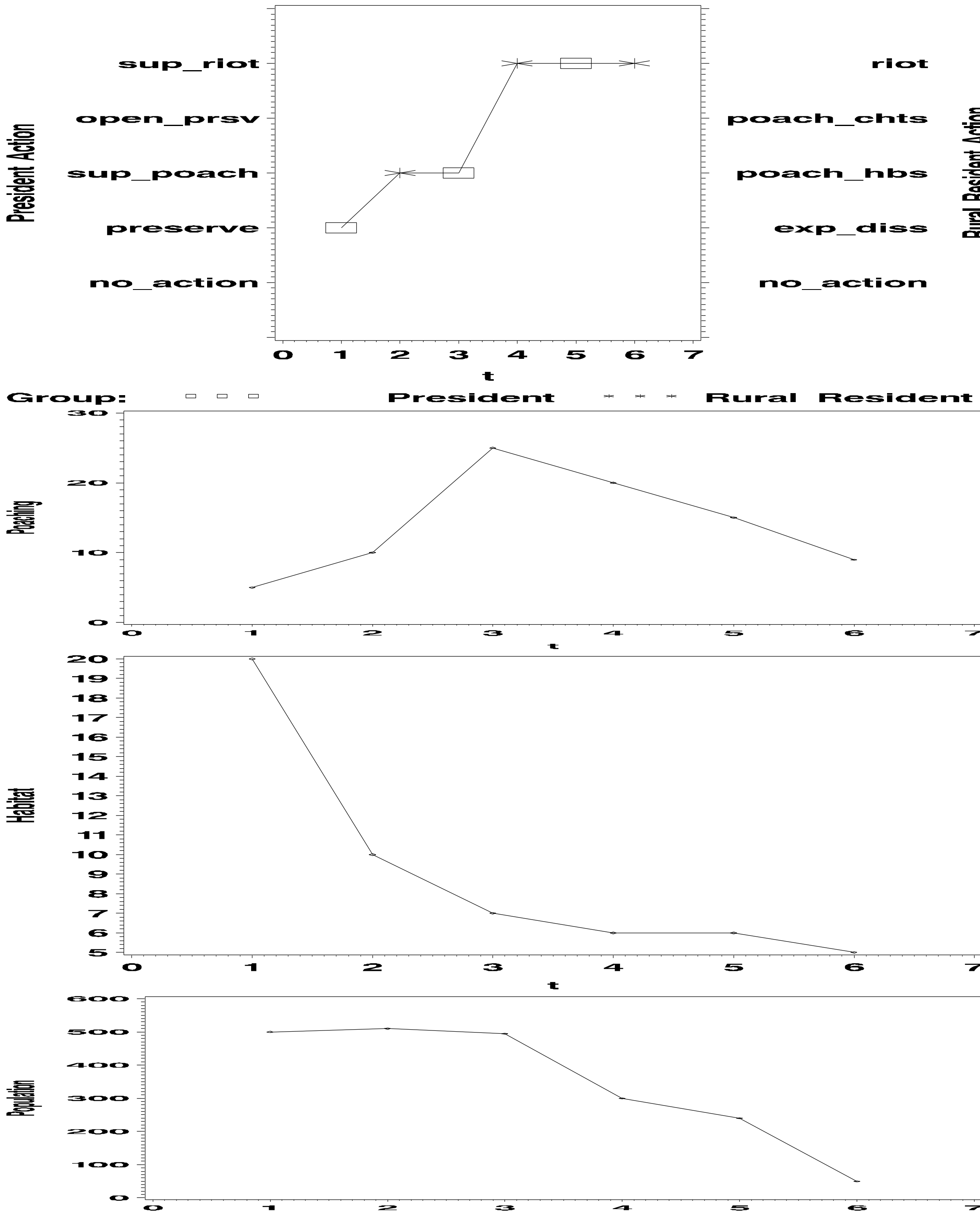

Figure 1: History of political actions and the ecosystem's reactions.

- A group's output action decision maximizes that group's expected utility.
- Actions of each group influence the decision making of other groups and possibly the probability distributions of ecosystem variables. Over time, a sequence of decisions and changes in the ecosystem produce feedback effects on group decision making.
- A history of political actions "emerges" from the interactions of decisions made by groups that are each attempting to reach their individual goals.

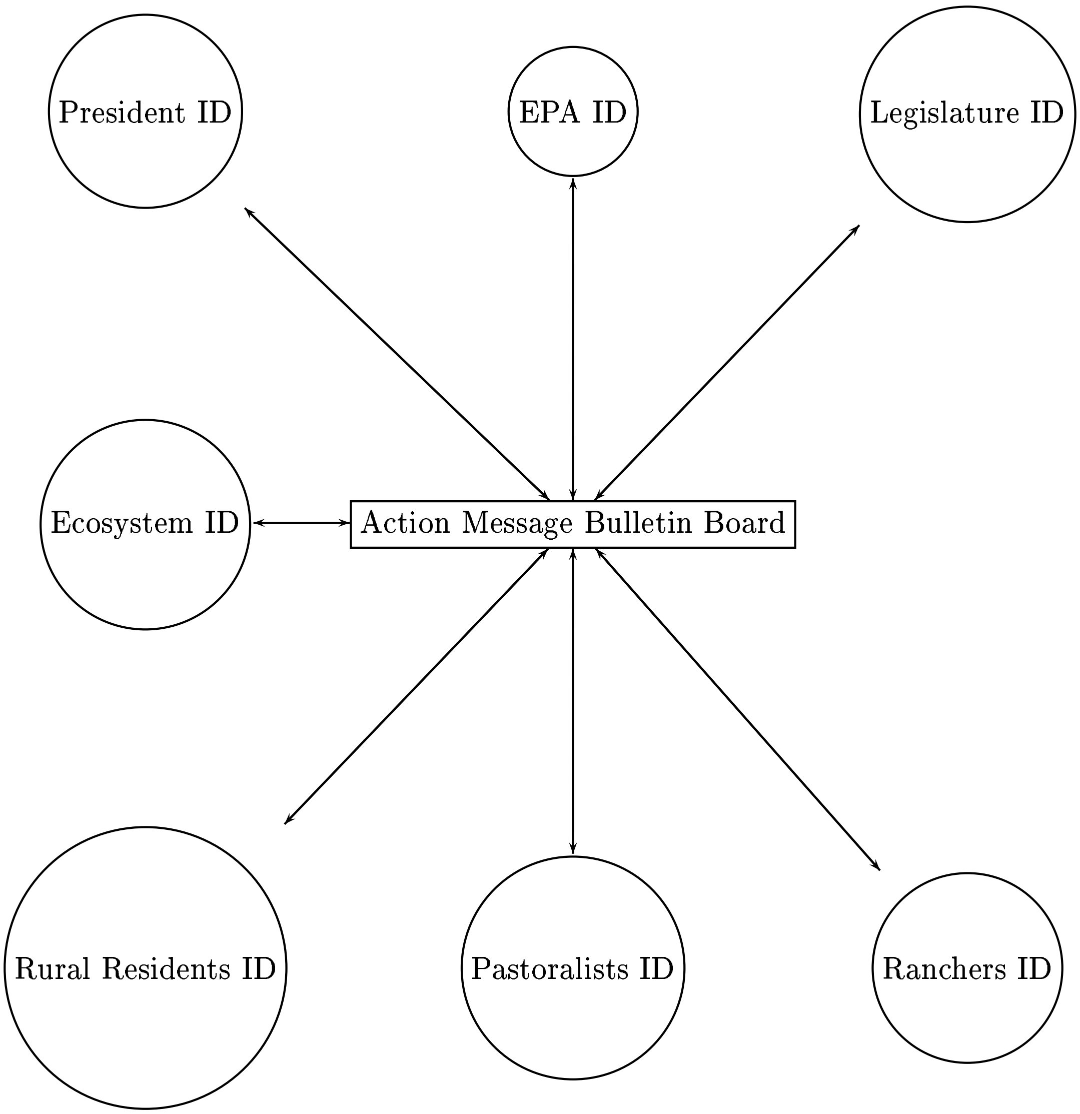

Figure 2: Schematic of the Interacting IDs Model of Interacting Political and Ecological Processes.

Ecosystem management by these countries is simulated by having

- This distributed, local goal reaching behavior model of political process is sometimes labeled "new Institutionalism" and is a paradigm based in political economics.
- The EMS model is defined stochastically and graphically with as a collection of interacting Influence Diagrams (IDs).
- An ID is a graphical representation of a multivariate probability distribution. The representation is in the form of a mathematical construction called a *graph*.
- Random variables indexed by root vertices are assigned unconditional distributions, all other random variables are assigned conditional distributions for each possible event of the variables indexed by that variable's parent or parents.
- The ID model architecture graphically portrays dependencies, random components, and possible system control points. By conditioning on control variables, the effect of different interventions can be explored.
- ID notation:

  node: any random or nonrandom variable in the model

  circle: chance (random) node

  double circle: deterministic node

  square: decision node

  diamond: utility or value node

- A subset of an ID's nodes that are interconnected is called a *sub-ID*.
- Within-group decision making:
  1. A Situation sub-ID represents the group's perception of the current situation.
  2. A Scenario sub-ID represents the group's perception of the future situation *and the status of their goals* under the implementation of a particular option.

3. Goals include economic well-being and the *perceived* effect of decision options on audiences that are important to the group.
4. An option is selected that maximizes overall goal satisfaction.

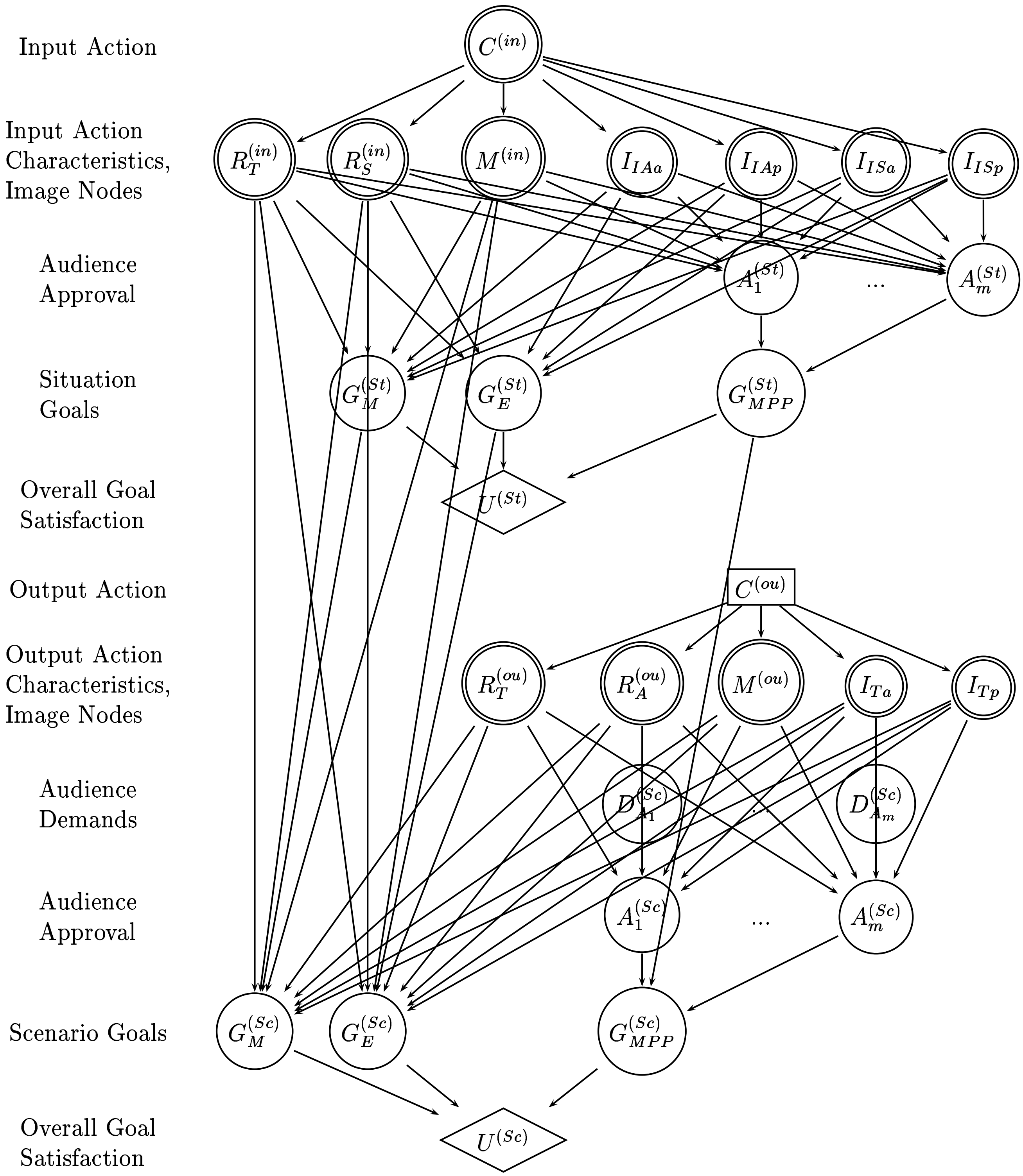

Figure 3: Group ID Architecture.

Example Spatio-Temporal Ecosystem ID: Cheetah Population Dynamics

Main sections:

1. Decision nodes for representing (a) management options, (b) subregions of Kenya, and (c) a time point at which ID output distributions are to be computed.
2. A model of cheetah population size implemented as a system of stochastic differential equations (SDEs) and represented in the ID as a set of chance and deterministic nodes.

Probabilistic Representation of Geographic Characteristics:

- Roughly homogeneous subregions of the study region large enough to sustain the species are identified.
- Strict homogeneity is not required because chance nodes represent within-subregion heterogeneity.
- The major climatic/ecological regions of Kenya represented in the ID: Marsabit, Eastern, Samburu, Tsavo surroundings, Masailand, Laikipia, Nakuru, Western, Central, Turkana, and Coastal.
- The subregion climate chance node has values:
  very_arid, *arid*, *semi-arid*, and *non-arid*.
- The subregion land-use chance node has values:
  nomadic-camel, *nomadic-cattle*, *ranching*, and
  farming.

Probabilistic Representation of Cheetah

Carrying Capacity:

B_t is the subregion's herbivore biomass.

k_0 is the *herbivore* carrying capacity at time t_0.

The SDE birth-death model for B_t with random carrying capacity is

$$dB(t) = B(t)(k_0 - B(t))dt + B(t)\sigma dW_t^{(B)}$$

where $dW_t^{(B)}$ is a zero mean, unit variance white noise process.

A subregion's cheetah carrying capacity is a function of herbivore biomass:

$$K_t \equiv \text{nearest integer}(\beta_{K_t}^{(0)} + \beta_{K_t}^{(1)} B_t).$$

Cheetah Population Dynamics Model:

- $f \in (0,\ 1)$**:** instantaneous birth rate,

  $r \in (0,\ 1)$**:** instantaneous mortality rate (death rate),

  $c \in (0,\ 1)$**:** proportion of the N animals that meet over a short period of time. This implies that cN is the number of meetings over a short period of time.

  P**:** the probability that any one meeting does not result in a litter.

  k**:** carrying capacity of the environment in terms of maximum number of animals that can be supported.

- Uncertainties surrounding cheetah population size:

  1. heterogeneity of land use, vegetation, and climate within an area,
  2. the partial effect that herbivore density has on carrying capacity,
  3. the partial effect that poaching and pest hunting has on an area's death rate
  4. shocks to the system such as droughts.

- Birth and death rate SDEs:

  $\underline{W}_t \equiv (W_t^{(f)}, W_t^{(r)}, W_t^{(N)})'$ be a vector of three independent Wiener processes.

  $a_f(X_t) \equiv -(\alpha_f + \beta_f^2 X_t)(1 - X_t^2)$ (drift),

  $b_f(X_t) \equiv \beta_f(1 - X_t^2)$ (diffusion),

  and

  $f_t = U(X_t) \equiv (1 + X_t)/2.$

  The distribution of f_t and r_t at t are the solutions to the SDEs:

$$df_t = (1/2)a_f(U^{-1}(f_t))dt + (1/2)b_f(U^{-1}(f_t))dW_t^{(f)}$$

$$dr_t = (1/2)a_r(U^{-1}(r_t))dt + (1/2)b_r(U^{-1}(r_t))dW_t^{(r)}.$$

- The tendency of more females to have litters within protected areas is represented by having the parameter α_f be conditional on the area's status.

- To represent the effect of poaching and pest hunting on r_t, α_r is conditional on the degree of poaching and pest hunting.

- The variability of the sample paths of f_t and r_t are controlled by the parameters β_f and β_r, respectively.

- The within-subregion cheetah count (N_t) SDE is:

$$\begin{aligned} dN_t &= \left[f_t(1 - P^{cN_t})N_t - r_t N_t - (f_t - r_t)\frac{N_t^2}{k} \right] dt \\ &\quad + \beta_N dW_t^{(N)}. \end{aligned}$$

  where P, c, N_0, and β_N are fixed parameters, and k is a random parameter.

- Conditional on k, the random vector $(f_t,\ r_t,\ N_t)'$ is the solution to this system of nonlinear SDEs.

- The cheetah population is said to be *viable*
  if $E[N_{t_f}] > 0$ at a distant, future time, t_f.

Fraction-of-Area-Detected Node

- To make the model observable, the final output node, D_t is defined to be the fraction of a region's area on which cheetah have been detected.

- $d = N_t/a_r$

  $\xi =$ the minimum cheetah density that results in a cheetah detection report.

  $\rho =$ cheetah density above which cheetah are certain to be reported.

- Then,

$$D_t = \begin{cases} 0, & d < \xi \\ (d-\xi)/(\rho-\xi), & d \in (\xi,\, \rho) \\ 1, & d > \rho. \end{cases}$$

- It is possible for N_t to be positive but D_t to be zero.

Example: President and Rural Resident Interactions

- The goals that a president is trying to reach are:

  1. Stay in Office
  2. Maintain Order

- The audiences that are important to a president are:

  1. Military
  2. Campaign Donors

- The actions that the President can post are:

  1. *no action*
  2. *create preserve*
  3. *increase antipoaching enforcement*
  4. *open a preserve to development*

5. *suppress a riot*

- The goals that a rural resident is trying to reach are:

  1. Feed Family
  2. Protect Livestock
  3. Avoid Prosecution for Poaching

- The audience that is important to a rural resident is:

  1. Family Members

- The actions that a rural resident can take are:

  1. *no action*
  2. *express dissatisfaction*
  3. *poach cheetahs*
  4. *poach herbivores*
  5. *riot*

EMS Model Parameter Estimation

- **Problem:** Huge environmental statistical models are difficult to estimate and validate because theory and/or data sets are not complete enough to allow the reliable use of frequentist or Bayesian statistical methods.

- **Proposal:** fix some of the parameters at values based on the substantive literature and then use the available data to estimate the balance of the parameters.

- **Consistency Analysis** (CA): first define a *hypothesis* distribution for the ID by fixing parameters to substantive theory-justified values (called the **hypothesis values**). Then, find parameter estimates for the *consistent* distribution so that this distribution deviates minimally from both the hypothesis and sample empirical distributions.

- **Needed Data Streams:**

  Ecosystem ID: Remotely-sensed land use, land type, wildlife preserve boundaries, cheetah population surveys, herbivore population surveys (about 40% acquired).

  Legislature ID: Acts and Bills of each Parliament (just beginning acquisition).

  Executive ID: Speeches (just beginning acquisition).

  IGOs: Reports from these organizations (to be acquired).

  Rural Resident and pastoralists: face-to-face interviews (major challenge).

Conclusions

- Qualitative theories of group ecosystem management decision making can be built with IDs.

- An ecosystem model based on the combination of qualitative and quantitative ecological theory can be represented as an ID.

- A model of how political processes interact with ecosystem processes can be built-up by having group IDs interact with an ecosystem ID.

- The effect of the actions of different groups on the ecosystem can be studied by running the interacting IDs forward in time. Extinction probabilities can be estimated under different governmental and nongovernmental environmental protection policies.

- CA allows this complex EMS model to be fitted to incomplete data sets.

ID Definitions

- A graph is a pair $G = (V, E)$ where V is a finite set of vertices and E is a subset of the $V \times V$ ordered pairs of distinct edges. For α, $\beta \in V$, if the edge (α, β) is in E but (β, α) is not in E, then the edge is *directed*; otherwise, the edge is *undirected.*

- If $\beta \to \alpha$ then β is a *parent* of α and α is a *child* of β. In a graph consisting of only directed edges, vertices having no parents are *roots*, and vertices having no children are *terminal.*

- A *path* of length n from α to β is a sequence $\alpha = \alpha_0, \alpha_1, ..., \alpha_{n-1}, \alpha_n = \beta$ of distinct vertices such that (α_{i-1}, α_i) is in E for $i = 1, ..., n$.

- A *cycle* of length n is a path wherein $\alpha_0 = \alpha_n$. The cycle is *directed* if it contains at least one directed edge. A graph whose edge set contains only directed edges is called a *directed graph.* A graph for which there are no directed cycles is called an *acyclic graph.*

- Kiiveri et al. (1984): the product of the unconditional and conditional distributions of a set of random variables indexed by the vertex set of a directed acyclic graph defines a joint probability distribution as long as this product is positive for all joint events.

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