The Relationship Between Ecosystems and Human Systems:

Scale Challenges in Linking Property Rights Systems and Natural Resource Management

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Abstract

We hypothesize that sustainability requires human systems that are concordant at appropriate scales with the ecosystems to which they are related, given the limits of human information processing. Many current governance and management systems are at a scale which is either too large or too small for the ecosystems to which they are related, leading to unsustainable policies for these systems. Problems often occur when human systems developed and sustainable at one scale or for one ecosystem or for one part of an ecosystem are transferred without adequate modification to other scales and ecosystems or to the whole system. In this paper we develop an analytical framework for treating human systems, ecosystems, and their interactions simultaneously. We develop a simple simulation gaming model that illustrates some of these concepts. We are developing multiscale conceptual and mathematical models and empirical data bases, including a range of ecosystem and human system characteristics, aimed at testing our hypothesis and providing guidance for designing sustainable human systems within sustainable ecosystems.

Introduction

In the latter part of the 20th century, humans have been doing a particularly poor job of managing many natural resources in a way that is sustainable over the long term (Ludwig et. al. 1993, etc.). **Sustainability** is a concept that broadly refers to the persistence of the integrity and structure of a system over time. There is much discussion in the literature these days about how one "defines" sustainability, sustainable development, and related concepts (cf. Pezzey 1989; World Commission on Environment and Development 1987; Costanza 1991, Pearce and Atkinson 1993). Critics argue that the concept is useless because it cannot be "adequately defined." Most of this discussion is misdirected because it:

1. attempts to cast the problem as definitional, when in fact the real problems are ones of prediction, and
2. fails to take into account the range of time and space scales over which the concept must apply.

Defining sustainability is actually quite easy (Costanza and Patten 1995):

a sustainable system is a renewable system which survives for some specified (noninfinite) time.

Biologically, this means the resource avoids extinction, and lives to survive and reproduce; economically, it means avoiding major disruptions and collapses, hedging against instabilities and discontinuities. Sustainability, at its base, always concerns temporality, and, in particular, longevity. The problem with this definition is that, like "fitness" in evolutionary biology, determinations can only be made *after the fact.* An organism alive right now is fit to the extent that its progeny survive and contribute to the gene pool of future generations. The assessment of fitness today waits until tomorrow. The assessment of sustainability must also wait until after the fact.

What often pass as *definitions* of sustainability are therefore usually *predictions* of actions taken today that one reasons will lead to sustainability. For example, keeping harvest rates of a resource system below rates of natural renewal should, one could argue, lead to a sustainable extraction system—but that is a prediction, not a definition. It is, in fact, the foundation of MS Y-theory (maximum sustainable yield), for many years the basis for management of exploited wildlife and fisheries populations (Roedel 1975). As learned in these fields, a system can only be known to be sustainable after there has been time to observe if the prediction holds true. Usually there is so much uncertainty in estimating natural rates of renewal, and observing and regulating harvest rates, that a simple prediction such as this, as Ludwig et al. (1993) correctly observe, is always highly suspect, especially if it is erroneously thought of as a definition.

Despite the well-documented difficulties of designing sustainable resource systems (e.g. Hardin 1968), there are many documented examples, past and present, of natural resource systems which have proven effective and sustainable over time (Netting 1981, McKean 1992, Ostrom 1990, Berkes 1989, Bromley 1992). Recent efforts to devise simple regulatory policies have often threatened the sustainability not only of natural resource systems, but also of previously effective governance systems for natural resource management (Atran 1993, McCay and Acheson 1987, Wilson 1990). Several questions present themselves:

1. Which current management systems are unsustainable?
2. Can we identify the causes of unsustainability in these systems?
3. How can we fix these systems?

We hypothesize that the causes of many sustainability problems lie in "scale mismatches." Large-scale ecosystems are not simply small scale systems writ large, nor are micro-scale ecosystems mere microcosms of largescale systems. The driving forces and the feedback mechanisms operative at different levels exhibit distinct patterns of their own. What this means is that management systems that produce perfectly acceptable outcomes when applied to ecosystems at one level can and frequently do produce disruptive or destructive results when applied to higher level or lower level systems. Management practices that do well in handling traditional resource uses at the local level, for example, cannot be expected to do equally well in handling activities organized at a continental or global scale. Even more important, when local systems are superseded by national or international management practices, local ecosystems frequently suffer. The problem, then, is to match ecosystems and management systems in such a way as to maximize the compatibility between these two types of systems.

This essay seeks to build on this fundamental insight. In this paper we define the key terms and begin the exploration of an analytic model. In the future we intend to develop a broad global data base to test hypotheses about relationships between ecosystems and social institutions, and to investigate ways to repair the damage caused by scale mismatches. A particularly valuable tool in this effort will be the use of simulation games to explore the consequences of changing social institutions in a controlled manner.

Hierarchy and Scale Problems

In modeling complex systems, the issues of scale and hierarchy are central (O'Neill et al. 1989). Some claim that the natural world, the human species included, contains a convenient hierarchy of scales based on interaction-minimizing boundaries; scales ranging from atoms to molecules to cells to organs to organisms to populations to communities to ecosystems (including economic, and/or human dominated ecosystems) to bioregions to the global system and beyond (Allan and Starr 1982, O'Neill et al. 1986).

The term "scale" in this context refers to both the resolution (spatial grain size, time step, or degree of complication of the model) and extent (in time, space, and number of components modeled) of the analysis. Resolution refers to how finely grained or demarcated space, time or complexity of a system is. Extent refers to the scope of a system in terms of space, time or complexity. Multi-scale phenomenon are particularly prevalent in both many natural resource systems and in many human institutions. The process of "scaling" refers to the application of information or models developed at one scale to problems at other scales. In both ecology and economics, primary information and measurements are generally collected at relatively small scales *(i.e.* small plots in ecology, individuals or single firms in economics) and that information is then often used to build models at radically different scales *(i.e.* regional, national, or global). The process of scaling is directly tied to the problem of aggregation, (the process of adding or otherwise combining components) which in complex, non-linear, discontinuous systems (like ecological and economic systems) is far from a trivial problem (O'Neill and Rust 1979, Rastetter et al. 1992). For example, in applied economics, basic data sets are usually derived from the national accounts, which contain data that are linearly aggregated over individuals, companies, or organizations, Sonnenschein (1974) and Debreu (1974) have shown that, unless one makes very strong and unrealistic assumptions about the individual units, the aggregate (large scale) relations between variables have no resemblance to the corresponding relations on the smaller scale. Only recently, however, has serious work been undertaken to develop multi-scale models of either ecosystems or human institutional systems.

If ecosystems actually functioned as a seamless web with no practical subdivisions, understanding and managing such systems would require a massive, centralized modeling, measurement and monitoring effort. On the other hand, if ecosystems ccould be partitioned into separable parts that can be largely understood on their own merits, measurement and monitoring requirements might be no less than in a seamless system, but the ability to partition the problem into manageable parts would make the understanding and management of the overall system much more tractable. More importantly, the need to pass large amounts of information along to a centralized management structure could be reduced greatly with little loss of understanding or management capability.

Fortunately most ecosystems do appear to function as partitionable systems. For example, Allen and his colleagues suggest that for all practical purposes ecosystems function as connected subsystems, or holons. Each holon which might exist in a certain place for a certain time of the year, a nursery ground for example, can be treated as a separate entity during that period. If this is the case, the scientific understanding of the system can be divided into tractable smaller problems and, just as important, practical management of a large number of ecosystem functions can be assigned to local management units with no need to pass information about the condition or state of the particular holon on to more central and removed management authorities. If there are no human institutions at a small level, it is impossible to utilize information effectively about diversity and local variation.

Nevertheless, subsystems or holons cannot be managed with complete independence; they are connected to the rest of the system which is heavily dependent on the sum of all such connections. Put differently, events within a subsystem can be treated as independent up to a point; however, this independence is constrained by the system-wide need for the contributions of the various subsystems and by the dependence of the subsystem itself upon contributions from the wider system. The results of events within holons are transmitted to the rest of the system through larger scale events such as migration, dispersal, temperature changes, and so on. If there are no human institutions at the level of these larger systems, it is impossible to regulate the effects of migration, dispersal, and other transboundary phenomena.

The Everglades of south Florida provide an interesting example of how partitioning might work. The agricultural areas south of Lake Okeechobee have been suggested as possible sites for combined wet agriculture (using wet adapted strains of sugar cane and other crops) and water storage (which, incidentally, tends to reduce or stop the subsidence of soils and diminish the phosphorus load of waters entering the sawgrass regime). Management of this 'subsystem' might proceed almost independently of the rest of the ecosystem so long as it operated under the constraint of having to release water to lower parts of the system in appropriate seasonal flows. A market-like arrangement, in which water managers for the system used variable monthly water storage lease prices might work very effectively as a signal for the times when water was required in the lower part of the system, i.e., as a means to integrate the functioning of the agricultural areas with the rest of the ecosystem.[1] Managers working at the scale of the hydrology of the entire system would need to know only how much water was being held and would be in a position to alter that total amount by varying the pricesthey were willing to pay to lease storage. Events at the scale of individual fields would remain under the control of individual farmers — those most knowledgeable abou the relevant circumstances at that scale

The lobster fishery in the northeastern U.S. provides an interesting example of how management at inappropriate scales can create both biological and social problems. In the State of Maine, fishermen voluntarily mark egg-bearing lobsters with a "v-notch" in one of the tail flippers, making the lobster illegal for sale in the State. The mark remains on the lobster for two or three molts or four to six years. The presumed effect of v-notching is to reserve a fairly large population of mature females for stock reproduction purposes. Because mature lobsters tend to migrate, each fall a large number pass by Cape Cod, where they are caught and sold by a small group of Provincetown fishermen (the State of Massachusetts does not have a prohibition on the sale of v-notchers). Maine fishermen, concerned by this, claim their only response is to stop v-notching. The scale of the v-notch activity does not match the scale of lobster migration.

Thus, scale mismatches of various kinds can be seen to be a major cause of the mismanagement of natural resources (Lee 1993). Scale mismatches can occur between spatial, temporal, or functional scales. They can also occur for one of three reasons:

1. because human institutions do not exist
2. because they exist, but not at the appropriate scales
3. because the linkages and information transfer between scales does not work effectively

Limited Information and Misplaced Certainty

Another problem in managing natural resources is dealing with limited information and uncertainty. To understand the scope of the problem, it is necessary to differentiate between *risk* (which is an event with a *known* probability, sometimes referred to as statistical uncertainty) and *true uncertainty* (which is an event with an *unknown* probability, sometimes referred to as indeterminacy). Most important environmental problems suffer from true uncertainty, not merely risk.

Science treats uncertainty as a given, a characteristic of all information that must be honestly acknowledged and communicated. Over the years scientists have developed increasingly sophisticated methods to measure and communicate the uncertainty arising from various causes. It is important to note that the progress of science has, in general, uncovered *more* uncertainty rather than leading to the absolute precision that the lay public and some policy makers often mistakenly associate with "scientific" results.

The scientific method can only set boundaries on the limits of our knowledge. It can define the edges of the envelope of what is known, but often this envelope is very large and the shape of its interior can be a complete mystery. Science can tell us the range of uncertainty about global warming, the potential impacts of toxic chemicals, or the possible range of fish population dynamics, and maybe *something* about the relative probabilities of different outcomes, but in most important cases it cannot tell us which of the possible outcomes will occur with any degree of accuracy.

Our current approaches to environmental management and policy making, on the other hand, abhor uncertainty and gravitate to the edges of the scientific envelope. The reasons for this are clear. The goal of policy is making unambiguous, defensible decisions, often codified in the form of laws and regulations. While legislative language is often open to interpretation, regulations are much easier to write and enforce if they are stated in clear, black and white, absolutely certain terms.

As they are currently set up, most environmental regulations, particularly in the United States, *demand certainty* and when scientists are pressured to supply this nonexistent commodity there is not only frustration and poor communication but mixed messages in the media as well. Because of uncertainty, environmental issues can often be manipulated by political and economic interest groups. Uncertainty about global warming is perhaps the most visible current example of this effect. In order to rationally use science to make policy we need to deal with the whole envelope of possible futures and all their implications, and not delude ourselves that certainty is possible.

Conflicts of Interest

Conflict over resource acquisition is universal among living organisms; in a finite world, resources are a zero-sum game. Genetic conflicts of interest exist among all living organisms: individuals strive to increase their own inclusive fitness (Hamilton 1964, Grafen 1991: 9-13), in a finite world, at the expense of non-related individuals. Cooperation, in both human and non-human systems, seems to be more likely under specific conditions: where the number of actors is smaller rather than larger, where interactions are repeated, and where actors are able to detect cheating and punish offenders. Both the ecological and the social science literature are converging on such findings (e.g., Ostrom 1990, Keohane and Ostrom 1995, deWaal 1984, 1986, Alexander 1987, Low 1992).

Although management initiatives often tend to assume a unified bureaucratic actor and a unified community of resource users, conflicts are common among and within units at every scale. At the smallest unit of analysis, even within households men and women may have different and occasionally conflicting rather than complementary resource use systems. (Low 1994, Peters and Guyer 1982, Carney and Watts 1990, Schroeder 1993). For example, men who invest their wealth in livestock may come into conflict with women concerned with cultivation of the same land. At higher scales, stratification of communities on the basis of religion, occupation, wealth/class, ethnicity, and longevity of residence can result in conflicting rather than complementary resource use (Cernea, 1985, Nhira 1994, Briscoe 1979, Brown 1995).

At even higher scales, examples abound of conflict between different communities trying to use the same resource: conflicts over water use in arid zones, overfishing in both coastal waters and the high seas. For decades scholars of bureaucracy have documented fragmentation, parochialism, and conflict both within and among units of bureaucracies in societies of all types. Different units of a government's bureaucracy may work smoothly enough with their own interest group clients — say, the U.S. Forest Service with the timber industry and the U.S. Park Service with environmentalists — but will have conflicts over how best, and how much, to use a resource. *The obvious implication of such conflicts is that not only must resource management systems be examined at different scales but that the activities, interests, and outcomes for different categories of actors in units at the same scale must be differentiated.*

The Policy Problem: Sustainable Ecosystems and Human Systems

We identify three major reasons why human systems fail to sustain ecosystems. First, the scale and structure of human systems frequently correspond poorly with the scale and structure of ecosystems. Human systems consist of rules and mechanisms for coordination and control that are rooted in history and reflect past and present struggles over the distribution of wealth. These path dependent social forces have divided and partitioned property rights in various ways that only partly correspond to the scale and structure of ecosystems. Migratory species of fish in the ocean frequently travel from the jurisdiction of one national state to another. Systematic use of these stocks requires cooperation and contracting between sovereign states, which often is problematic because mechanisms for credible commitments and effective enforcement are lacking. For instance, if the fishers of state A know that particular fish stocks are about to leave their fisheries zone for the jurisdiction of state B, the fishers (and their government) have a strong incentive to decimate the stocks before they migrate. When valuable fish are found in waters outside all national fisheries zones, contracting for the rational use of these stocks also is problematic. Even when current users succeed in constraining their own behavior, the agreement can act as an incentive for outsiders to enter these waters. Within national states, property rights are partitioned between internal political jurisdictions (for instance, between central and regional authorities), which can create difficulties comparable to those found in international relations. However, states usually have better means than the international community to solve their internal conflicts. All these problems share a common feature: because control does not match the scale and structure of the ecosystem, the actors fail to consider the full costs and benefits of their actions. The remedy involves changes in the structure of effective control to reduce these external effects, but the solution may involve intractable political issues.

The second factor promoting overuse of resources in ecosystems has to do with the design of institutions and incentives in human systems. A polity may have full jurisdiction over a particular ecosystem and still introduce a system of rules, coordination and enforcement that fails to sustain ecosystems. There are various reasons for this:

a) The cost of establishing and enforcing an effective system of property rights can be greater than the benefits as perceived by the members and the leaders of the polity (Eggertsson 1990). In other words, the opportunity cost of measurement and enforcement is greater than the community is willing to bear. Only events that change the costs (or benefits) of establishing and operating an effective system will lead to changes in behavior.

b) The (political) system for aggregating preferences or for collective action may produce outcomes that are not rational in terms of the individual preferences of the actors involved. Modern political theory has dealt extensively with such inconsistencies. In addition to voting problems there are issues related to systems of representation (including over representation by certain districts in a legislature), rational ignorance of voters, agenda control and other strategic use of parliamentary procedures. The remedies here involve structural changes of collective action mechanisms.

c) Finally, the problem need not be related to costly measurement and enforcement or perverse outcomes of the political process, but the actors involved fundamentally may not desire to bear the opportunity cost of sustaining a particular ecosystem. Change in behavior will require a new perception of costs and benefits. Particularly complex situations may arise, when the users of a resource are asked by outsiders to bear all the cost of reducing the rate of utilization, for instance because the outsiders want to protect a particular species. In some cases, the outsiders may be willing to share in the cost of reduced utilization, but transaction costs and problems with jurisdictions prevent contracting between insiders and outsiders. In other cases, the outsiders may be unwilling to make the required sacrifice to compensate the users for lower rates of utilization (which corresponds to our case c)). Finally, the outsiders may be ready to use force (trade-sanctions or even violence) to change the users' behavior.

The third reason why human systems may fail to maintain ecosystems is that the actors lack appropriate knowledge about the nature and structure of ecosystem or even the nature of the social systems. In the 1960s and 1970s, textbooks in economics frequently claimed that centrally managed societies would be more likely to protect the environment than decentralized market economies because the central mangers would internalize all relevant costs and benefits. The experience in Eastern Europe has shown that this optimism was unfounded. Similarly, the impact of industrial development on ecosystems is only partly understood and so are various linkages and processes in ecosystems. Rapid feedback and appropriate selection mechanisms can compensate for lack of knowledge by decision makers. However, in the interaction between ecosystems and human systems such processes are often slow, ambiguous and may come too late.

Modeling in the Natural and Social Sciences

How can models help us understand the complexities of ecological and human systems and the relationships between them? Conceptual and quantitative models developed to address the problems of scale and uncertainty in complex systems can serve as the basis for multi-scale models of institutions (and the ecosystems they depend on) that inform us about regimes of sustainable resource management (Costanza et al. 1993).

Purposes of models

Models are analogous to maps. Like maps, they have many possible purposes and uses and no one map or model is right for the entire range of uses (Levins 1966, Robinson, 1991). It is inappropriate to think of models or maps as anything but crude (but in many cases absolutely essential) abstract representations of complex territory, whose usefulness can best be judged by their ability to help solve the navigational problems faced. Models are essential for policy evaluation, but are often also misused since there is "...the tendency to use such models as a means of legitimizing rather than informing policy decisions. By cloaking a policy decision in the ostensibly neutral aura of scientific forecasting, policy-makers can deflect attention from the normative nature of that decision..." (Robinson, 1993).

Models are tools to build consensus on contentious and highly uncertain environmental problems. Each interested party can identify what they perceive are the key variables, the direction and strength of relationships among variables, and the important areas of uncertainty. A model can take the best available information and generate a range of possible outcomes that are bound by uncertainty about the ecological and institutional constraints identified by the actors. For example, the conceptual model of Folke et al. (1994) attempts to build consensus between ecologists and economists by describing the "ecological plimsoll line." That line identifies the range of uncertainty about the quantity and quality of natural and human capital that is possible and desirable as envisioned by the two groups. Similarly, the dynamic simulation model of Hall et al. (19XX) generates a range of ways to manage the water resources of the Flathead Lake, Montana based on the needs of utilities, landowners, sport fishers, and native Americans. That model includes the effects of uncertainty about the hydrology and ecology of the region and the conflicting demands of the users to build a consensus about how to manage the water flow through the region.

Classifying Different Types of Models

Three criteria often are used to classify and evaluate models (Holling, 1964; Levins, 1966; Costanza et al., 1993). *Realism* describes the degree to which a model represents system behavior in a qualitatively realistic way. *Precision* describes the degree to which a model represents behavior in a quantitatively precise way. *Generality* describes the degree to which a single model can represent a broad range of systems' behaviors. No single model can maximize all three of these goals and the choice of which objectives to pursue depends on the fundamental purposes of the model. Examples of models in ecology, economics, political science, and anthropology demonstrate the various ways in which trade-offs are made between realism, precision, and generality.

High-generality conceptual models Conceptual models often describe the qualitative relationship between a few important variables and relationships. They do so by simplifying relationships and/or reducing resolution, and thereby gain generality at the expense of realism and/or precision. Simple linear and non-linear economic and ecological models tend to have high generality but low realism and low precision (Clark and Monroe 1975, Brown and Swierzbinski 1985, Lines 1989, 1990b, Kaitala and Pohjola 1988). Examples include Holling's "4-box" model (Holling 1987), Folke et al.'s (1994) three scenarios of the future, the "ecological economy" model of Brown and Roughgarden (1992), most conceptual macroeconomic models (Keynes 1936, Lucas 1975), economic growth models (Solow 1956) and the "evolutionary games" approach. For example, the "ecological economy" model of Brown and Roughgarden (1992) contains only three state variables (labor, capital, and "natural resources") and the relationships between these variables are highly idealized. But the purpose of the model was not high realism or precision, but rather to address some basic, general questions about the limits of economic systems in the context of their dependence on an ecological life support base.

High-precision analytical models Often, one wants high precision (quantitative correspondence between data and model) and is willing to sacrifice realism and generality. One strategy here is to keep resolution high, but to simplify relationships and deal with short time frames. Some models strive to strike a balance between mechanistic small-scale models which trace small fluctuations in a system and more general whole-system approaches which remove some of the noise from the signal but do not allow the modeler to trace the source of system changes. The alternative some ecologists have devised is to identify one or a few properties that characterize the system as a whole (Wulff and Ulanowicz 1989). For example, Hannon and Joiris (1987) used an economic input-output model to examine relationships between biotic and abiotic stocks in a marine ecosystem and found that this method allowed them to show the direct and indirect connection of any species to any other and to the external environment in this system at high precision (but low generality and realism). Also using input-output techniques, Duchin's (1988, 1992) aim was to direct development of industrial production systems to efficiently reduce and recycle waste, in the manner of ecological systems. Large econometric models (Klein 1971) used for predicting short run behavior of the economy belong to this class of models since they are constructed to fit existing data as closely as possible (at the sacrifice of generality and realism).

High-realism impact analysis models High-realism models seek to represent accurately the underlying processes in a specific system, rather than precisely matching quantitative behavior or being generally applicable. Dynamic, non-linear, evolutionary systems models at moderate to high resolution generally fall into this category. Coastal physical-biological-chemical models (Wroblewski and Hofmann 1989) which are used to investigate nutrient fluxes and contain large amounts of site-specific data fall into the this category, as do micro models of behavior of particular business activities. Another example is Costanza et al.'s (1990) model of coastal landscape dynamics that included high spatial and temporal resolution and complex non-linear process dynamics. This model divided a coastal landscape into $1km^2$ cells, each of which contained a process-based dynamic ecological simulation model. Flows of water, sediments, nutrients, and biomass from cell to cell across the landscape were linked with internal ecosystem dynamics to simulate long-term sucessional processes and responses to various human impacts in a very realistic way. But the model was very site-specific and of only moderate numerical precision.

Moderate-generality and moderate-precision indicator models In many types of systems modeling, the desired outcome is to determine accurately the overall magnitude and direction of change, trading off realism for some moderate amount of generality and precision. Some econometric models fall into this category. Cleveland (1991) develops a model that describes the factors determining the long run cost of oil production. The results are reasonably precise, and the specification of the model describes a general relationship between resource depletion and technical change that can be applied to other resources. Other examples are aggregate measures of system performance such as standard GNP, environmentally adjusted net national product (or "green NNP") that includes environmental costs (Mäler 1991), and indicators of ecosystem health (Costanza et al. 1992). The microcosm systems employed by Taub (1989) allow some standardization for testing ecosystem responses and developing ecosystem performance indices. Taub (1987) notes, however, that many existing indicators of change in ecosystems are based on implicit ecological assumptions that have not been critically tested, either for their generality, realism, or precision.

Evaluating the Performance of Models

We often are interested in how well a model "works." An essential part of the evaluation of model performance is the tradeoff between the resolution of a model and how well it predicts the phenomena of interest (Costanza et al., 1993). Resolution may have spatial, temporal, and component aspects. Predictability measures the reduction in uncertainty about one variable given knowledge of others using categorical data (Colwell 1974).

Costanza and Maxwell (1993) provide an example of the tradeoff between resolution and predictability in spatial modeling. They analyzed the relationship between spatial resolution and predictability and found that while increasing resolution provides more descriptive information about the patterns in data, it also increases the difficulty of accurately modeling those patterns. In the next section we discuss this tradeoff in generalized form. Our analysis suggests that we can define an optimal resolution for a particular modeling problem that balances the benefit in terms of increasing data predictability as one increases resolution, with the cost of decreasing model predictability.

Human-Ecosystem Relationships: A Framework

To help us understand and model the relationships between ecosystems and human systems, we need a common language and an adequate conceptual framework within which to work. The lack of this framework has hindered communication between the relevant disciplines and has limited progress on sharing data, concepts, models, and results. A major goal of this paper is to begin development of a common framework and to sketch out how it may be used. Figure 1 represents a general schema of parallels between human and ecological systems, and the nature of their interactions. Both ecological and social systems have "stocks," "flows" among those stocks, and "controls" of those flows. Both systems also have attributes of the stocks, flows, and their interactions. Particulars differ: in an ecosystem, the biomass of, for example, fish comprises one stock. Stock can flow from the fish population into a fisheries catch, a flow that can be predictable or unpredictable. In such an example, the human and ecosystems interact, and all such interactions also have flows, controls, and attributes (Figure 1). By structuring the human and ecological systems, and their interactions, in parallel forms, we hope to facilitate comparisons of multiple levels. Bringing the two together is thus an even more challenging task.

One cannot develop a common theoretical structure and tie work relevant to the behavior of an ecosystem to the behavior of human systems unless a shared language exists. Developing a lexicon of key terms is an essential part of our task since many of the important concepts used in the diverse, relevant sciences are not known and understood in different disciplines. If there is to be a serious joint effort by scholars from diverse disciplines that goes beyond working on different parts of a large project, those participating have to start using concepts in a broadly similar way. We are developing a glossary, and will be glad to share it with interested colleagues.

Stocks

The **stocks** (Fig. 2) of ecosystems include **species and organisms,** which have structure and organization. Individual organisms are the actors of ecological systems; they interact not only with conspecifics (as in human political and social interactions), but also with individuals of other species (e.g., in predator-prey interactions). As a result, species persist, increase/decrease over time, and shift in geographical distribution. **"Natural capital"** is represented by the biomass and volume of living material. Since "capital" is traditionally defined as produced (manufactured) means of production, the term "natural capital" needs explanation. It is based on a more functional definition of capital as "a stock that yields a flow of valuable goods or services into the future." What is functionally important is the relation of a stock yielding a flow — whether the stock is manufactured or natural is in this view a distinction between kinds of capital and not a defining characteristic of capital itself. Natural capital may also provide services like recycling waste materials or water catchment and erosion control, which are also counted as natural income.

We can differentiate broad types of natural capital: (1) renewable or active natural capital and (2) nonrenewable or inactive natural capital. Renewable natural capital is active and self maintaining using solar energy. Ecosystems are renewable natural capital. They can be harvested to yield ecosystem goods (like wood) but they also yield a flow of ecosystem services when left in place (like erosion control and recreation). Nonrenewable natural capital is more passive. Fossil fuel and mineral deposits are the best examples. They generally yield no services until extracted. Renewable natural capital is analogous to machines and is subject to entropic depreciation; nonrenewable natural capital is analogous to inventories and is subject to liquidation (El Serafy, 1989).

In human systems, individuals and aggregations of individuals make choices among actions potentially leading to different outcomes. These actors are the parallel of organisms in ecosystems. The expectations, and values that actors associate with activities, affect their outcomes. Individuals hold perceptions (information, beliefs, and models) about causal processes and about the state of particular variables. The models used by individuals differ in such attributes as the degree of completeness, accuracy, fineness, and complexity, as well as how much information is retained in memory and how information about the past is integrated. In a rich ecological system, humans may have many more options for how they obtain flows of resources that enable them to achieve valued outcomes (see example below and Figure 2). If no limits are placed on human actions, however, unconstrained short-term self interest can lead to unsustainable ecological results. A person with limited property rights is likely to have fewer short-term options than someone who holds many bundles of rights, but these very constraints may contribute to long-term sustainability.

Human-made capital (assets) are the (organized and structured) material and non-material resources upon which actors can draw in pursuing activities. These include knowledge, skills, power, connections, trust, monetary resources, and bundles of property rights. We can differentiate broad types of human-made capital. One is the factories, buildings, tools, and other physical artifacts usually associated with the term "capital." A second is the stock of education, skills, culture, and knowledge stored in human beings themselves. This latter type is usually referred to as "human capital" while the former we will call simply "manufactured capital." A final sort of human capital is "social capital (coleman 1988) the commonly shared and understood relationships that can enhance the mutually beneficial outcomes of a process. Thus we have four broad types of capital: natural, human, manufactured, and social. The first three correspond roughly to the traditional economic factors of production of land, labor, and capital. Social capital is not captured by the traditional factors; its organizational structures are regularized patterns of linking actors in more or less predictable and patterned sets of relationships. Families, clans, firms, and governments are all examples ~ from an immense array of potential types of single organizational structures. Each type of organizational structure has distinctive patterns of stratification, dominance, capabilities, and limits. Any particular organizational structure will be characterized by the number of its members, its geographic extent, its history, the assets it controls, its information generating and processing capability, its production technology, etc. In addition, we have the important distinction between renewable and non-renewable natural capital, and for some purposes we can lump both human and manufactured capital together as "human-made capital."

Flows

Flows (Fig. 2)are the transactions or exchanges of material assets or information from one stock to another in all ecosystems. **External inputs and outputs** of energy are universal in ecosystems. **Internal cycles** of energy, and flows of matter, vary in scale and speed across ecosystems. Failure to recognize these rate differences is, as we note above, one source of problems of "scale mismatch." For example, a stock or population of trees or fish provides a flow or annual yield of new trees or fish, a flow which can be sustainable year after year. The sustainable flow is "natural income," the stock that yields the sustainable flow is "natural capital." Since the flow of services from ecosystems requires that they function as whole systems, the structure and diversity of the system is an important component in natural capital.

From a human point of view, particular ecological outputs of interest for consumption include, e.g. volume (biomass) of particular species of fish, or of lumber from specified tree species, etc. These flows are **harvest,** or removal and consumption of natural material from the ecosystem. Other outputs, that arise from the interactions of the human and ecological systems, include **pollution,** or the return of waste products from transformations of material and energy to the ecosystem; **enhancement,** or investment in maintenance or restoration of resource quality and resource productivity; and **non-consumptive uses,** such as certain kinds of recreation.

Controls

All systems involve controls (Fig. 2). In ecosystems, **physical/behavioral laws** control many processes (e.g. temperature controls the speed at which many reactions can occur). **Natural selection,** the rules governing the existence and reproduction of all living things, interacts with physical laws to constrain the life histories and behavior of living components of ecosystems. Thus, in consistently cold regions of the Arctic, we know that the survival and reproduction of fish species, for example, has been shaped over time by cold conditions, and the differential success of cold-tolerant versus other individuals. **Ecological relationships** (e.g., competition, predator-prey, mutualism) both result from the interaction of physical laws and natural selection, and further constrain the type and complexity of interactions that can occur in ecosystems.

In human systems, controls include **physical/behavioral laws, selection mechanisms,** and **rules in use.** Behavioral laws include determinant or probabilistic responses to stimulus —"knee-jerk" responses, limits on human attention and cognition, and psychological responses to "charismatic" traits. Human selection mechanisms are processes that select some individuals or organizations from an available population to be rewarded or punished, and thus increase or decrease their likelihood of persistence. Examples include entrance examination for college, job requirements, and profitability in economic systems. Rules in use are enforceable constraints on actions and outcomes placed by humans on themselves and others. They exist at multiple levels, and always in the context of the community in which they are jointly understood, accepted, and enforced. Rules define the actions that individuals may, must, or must not take (our definition here is not equivalent to formal laws, which are formulations made by legislatures, executives and administrative agencies, and courts). When we refer to a human system as one governed by the rule of law, we usually mean that there is a close correspondence between rules-in-form *(dejure)* and rules-in-use *(de facto)* [2]

In the interactions between human and ecosystems, two controls are of central importance. **Transformations** are physical changes of inputs into outputs; production and consumption represent two major transformations when humans interact with ecosystems. **Transactions** are the transfers from one party to another in exchange relationships of rights to inputs, outputs, and assets. For example, when someone harvests timber or produces paper, these are transfomations; when they hire workers or sell timber or paper, these are transactions; the instruments they use (labor contracts, bills of exchange or sale) record the transactions.

Attributes

Attributes are the characteristics of stocks, flows and controls, and their relationships (Fig. 1). To capture the important variation in functionally significant ways, we consider the following attributes: heterogeneity, predictability, resilience, and decomposability. **Heterogeneity** reflects the degree to which any variable exhibits internal variance; in ecological systems, both spatial and temporal variations exist and can complicate analysis. In human systems, individuals vary along important continua, including age, wealth, skill, and strength. Such differences clearly can affect demands made on an ecosystem, conflict among individuals and groups, and the challenge of crafting institutions and incentives to increase sustainability. **Predictability** measures the degree to which any entity's behavior can be forecast as a measure of the degree to which it remains constant, or, if it changes, the degree to which those changes can be predicted as a function of some other variable or entity (e.g., are the fluctuations seasonally cyclic?). **Resilience** measures the magnitude of disturbances than can be absorbed before a system centered on one locally stable equilibrium flips to another (Holling 1987). For example, if there is unsustainable harvesting of a commercial fish species, "trash fish" may increase in numbers and replace the commercial species. Resilience measures the resistance of systems to such shifts. **Decomposability** measures the degree to which distinct components of the system can be broken down into smaller, homogeneous discrete aspects. A perfectly decomposable organization is entirely hierarchical and vertical, with all subsystems fully contained within the larger systems of which they are a part. There are no horizontal connections among subsystems that are part of different systems. The physical **Area or extent** reflects the size of geographic region covered by stocks of ecological or human systems. The terms 'patchiness' and 'grain' are used to reflect scale in terms of area. **Growth rates** measure changes in stocks and flows over time. **Turnover time** is the relationship between stocks and flows in any system, measuring the rate of replacement of a stock, given a particular rate of flow

All of the above attributes can be measured in both human and ecosystems. When human and ecosystems interact (Figure 1) an additional set of attributes is important, and what we are interested in measuring is the **costs and benefits** of these attributes: excludability, observability, enforcement, divisibility, and durability. **Excludability** refers to the capability and cost of keeping some individuals from benefiting from a system. **Observability** is the capability of detecting and measuring human actions and their consequences on ecosystems and human systems. **Enforceability** is the feasibility and cost of achieving conformance to rules. **Divisibility** refers to the separability of a resource into units that can be used by different individuals. **Durability** measures the persistence of a stock over time as it is used. All physical depreciate over time as a function of the second law of thermodynamics.

The complex relationships between ecosystems and human systems cannot be understood in terms of a few generalizations. Therefore, we must limit ourselves to analzing aspects of the phenomena and model the critical characteristics of the relationships. But they vary vary with the resource questions being investigated. The main contribution of our theoretical framework is to define the main categories of our efforts and processes that are involved in the interactions between the two systems.

Consider a fisheries as an example of human-ecosystem interaction. If excludability is impossible or too costly, free riders can destroy the system even if no other problems exist. If one cannot monitor catch or stock, or enforce catch rules, the system similarly will be unsustainable. Fish catches are inherently divisible; but other ecosystem stocks, such as the stratosphere, are not — and this can create further problems. Durability, the persistence of fish stocks when under fishing pressure, will vary with the ecology of the particular fish species as a function of reproductive or recruitment rate, for example. Similarly, if local rules are devised in response to local conditions, but larger-scale ecological factors have influence, or larger-scale social systems intervene, sustainability may be hard to achieve.

The Fish Game: A Simple Example

We developed a simple example that shows the basic elements of the framework above. We are in the process of developing more complete examples (see also Hannon and Ruth 1994). The example can be played as a game with a group of players, and can also be simulated in a dynamic modeling program such as STELLA. This example is intended to be the simplest system that still shows the basic behaviors we are interested in. In its preliminary form, it is totally deterministic and predictable; later we will show how changing these attributes affects the system.

Consider the diagram and equations shown in Figure 3. The stocks in the system are **fish** (natural capital) and **fisher assets** (human-made capital). The fish stock reproduces itself in a very simple way:

Reproduction = if Total_Fish_Stock > 1000 then 0 else Total_Fish_Stock

This means that if the fish stock is above its "carrying capacity" (set in the model as 1000) then it does not reproduce. If it is below the carrying capacity, it simply doubles itself (adds an amount equal to the current fish stock) during a time step. When playing this game without a computer, one can simply create markers with colored paper to represent different amounts of fish. We set the initial fish stock at 150 arbitrary units.

The fish are harvested by the fishers according to some harvest strategy. In this initial example, the fishers' objective is to maximize their total assets at the end of the game. Since assets increase as harvest increases, but over-harvesting causes the fish stock to crash, successful fishers are those who can balance these factors.

The aggregate harvest is set equal to the harvest strategy, with the limitation that if the aggregate harvest cannot be greater than the total fish stock.

Aggregate_Harvest = if Total_Fish_Stock < 0 then 0 else Harvest_Strategy

The total fisher assets (initially 10 units) grows in proportion to the aggregate harvest. In the model we have half of the harvest converted into fisher assets:

Growth_of_Assets = Aggregate_Harvest/2

Fishers can harvest fish in proportion to their total assets, the harvest per unit of assets (i.e.. the efficiency of the boats and gear) and any catch limits that may be in place. Catch limits are one sort of rule-in-use that fishers can use to increase the probability of sustaining their fishery over time.

Harvest_Strategy = if Total_Fisher_Assets < Catch_Limit then Total_Fisher_Assets * Gear_Efficiency_Multiplier else Catch_Limit

When playing the game without a computer, one can have a number of fishers, each with their own stock of assets. They can take fish from the pool in proportion to their assets at each time step. For example, if a player has 10 units of assets, they can take up to a maximum of 10 units of fish during that time step, half of which are converted into additional fisher assets, so they now have a total of 15 units of assets and can take a maximum of 15 units of fish the next time step.

Behavior of the Model

Figure 4 shows some of the basic behavior of the model. In these runs the units of time are years, the model is run for 40 years, and for this series of runs the the Gear_Efficiency_Multiplier was held constant at 1. Figure 4a shows the behavior when there is no catch limit (CatchJLimit set to 100,000 in the model). Fisher assets and aggregate harvest grow quickly until year 13, when the fishery crashes due to overharvesting. If a catch limit is imposed at various levels, one gets the behaviors shown in figures 4 b-d, which have the catch limit set at 400, 500, and 600 units, respectively. With a catch limit set at 400 units the system is sustainable. At a catch limit of 500 units, total fisher assets are larger and the fishery is still sustainable . But at 600 units the fishery ultimately collapses due to overharvesting after about 25 years. This is because as fisher assets grow, the maximum rate of harvest by fishers grows and they can more quickly deplete the stock. If the catch limit is set too high this can totally deplete the stock in one time step.

Figure 5 shows the behavior of the model when the catch limit is held constant (at 500 units) and the Gear_Efficiency_Multiplier is varied (mimicking efficiency changes due to technical improvements in fishing equipment). As the Gear_Efficiency_Multiplier is increased from a value of 1 (figure 5a) to 2 (figure 5b) the fishery remains sustainable and the Total_Fisher_Assets increase from $8,077 to $9,140. As the Gear_Efficiency_Multiplier is further increased to 2.6 (Figure 5c) the Total_Fisher_Assets continue to increase to $9,394, but at a setting of 2.7 (Figure 5d) a threshold is reached and the fishery crashes in year 9, with Total_Fisher_Assets reduced to only $1,632. Thus, if gear efficiency increases so that more fish are caught per unit of assets, the fishery can collapse even with catch limits in place, because the fishers can totally deplete the stock in one time step.

When playing the game with a group (in a laboratory or field setting), the central problems are those of setting catch limits and efficiency of gear (how much each fishing boat, or unit, can catch or, alternatively, when harvesting is allowed). If the players do not communicate with each other it is very difficult to establish and enforce a catch limit. Even if they do communicate with each other and agree on catch limits, the pressure to defect is large and someone can easily defect and cause the fishery to collapse. Recent laboratory experiments show that cooperation is more difficult when the assets of harvesters are high or asymmetric, when it is costly to communicate, when information about defections is not available, and when the cost of sanctioning is high. Field research yields similar findings (Ostrom et al., 1994).

Implications of the Model

Even this simple initial model raises the problem of scale mismatches. Neither fishers nor government officials usually have as much accurate information about the structure and dynamics of a local, inshore fishery as someone who plays the Fishing Game has. Through trial and error, fishers harvesting from a particular inshore fishery over a long period of time might eventually learn how to regulate technological efficiency and total catch limit so as to manage such a fishery in a sustainable manner. As we have seen, however, small changes in control variables in the crucial range can have dramatic effects several years latter on the sustainability of a system. Further, some control settings appear to work well for the first two decades but cause a crash in the third or fourth decade. Thus, even local users will find it difficult to control complex ecosystems when strong incentives exist to attempt to accumulate maximum assets. Officials who were responsible for a very large number of such inshore fisheries -- each with their own different system structure would be making decisions about control variables based on aggregated information across a variety of differently structured local ecosystems. A control parameter set by a larger unit for all local ecosystems within that unit, would most likely lead to lower asset accumulation or the collapse of some of the fisheries in the larger jurisdictions.

Another problem of scale mismatch occurs whenever human systems are organized only on a small scale but the relevant ecosytem is much larger in extent. The Fishing Game illustrates the tension between decisions made by individual fishers, such as the purchase of more efficient fishing gear, and the decisions made by a community, such as the catch limit. Tensions can also exist between any of the human decisions, and ecological factors such as reproductive/recruitment rates offish species, predictability of ecological events that have impact of the fish population, etc. Future models will more overtly analyze problems of scale mis-match and how nesting of systems at diverse levels may help to cope more effectively with these problems.

Implementing the Framework

A broad framework of the type discussed can be used in a variety of ways. A key use of such a framework is simply fostering communication among scholars trained in the array of disciplines needed for any systematic study linking human system characteristics to ecosystem characteristics. The simple fish game presented above draws on this framework to illustrate how stocks and flows of both human systems and ecosystems affect one another in a dynamic setting. The behavior of this system depends on controls exercised by both the human and the natural systems. Setting the control variables for the human systems for even this simple model (which is totally predictable) so that the system is sustainable over time turns out to be a non-trivial problem. There are obviously many more complex implementations of the framework possible, that include more of the attributes of real world system, both in terms of modeling studies and empirical studies. We are working on a hierarchy of implementations of the framework as discussed below.

Modeling Studies

Expanding the Fish Game

There are several ways to expand our simple fish game to make it more realistic. We curently have a version that allows several players to interact in managing a fishery. Players are asked to play the role of fishermen. Their individual objectives are to maximize their income. In order to do this over the long run (usually less than 10 iterations - years - of the model) they must develop rules for mutual restraint, otherwise the fishery collapses. Each year, or iteration, players are asked to make two decisions: (1) how many boats to buy and (2) how many boats of those they own, to operate. Players can buy boats from the instructor ($20,000 - $30,000 is a reasonable charge per boat); they may also buy and sell boats among themselves, if it occurs to them to do so. The operator can buy back boats but should do so in a pecunious way. If players feel they have bought too many boats and can't sell them they can cut their costs some by not operating all their boats.

After the players provide the operator with their decisions, the information is entered in the program and the program is run the appropriate number of periods. The results are printed - each player is given a separate sheet of output corresponding to their operation - and players are asked to repeat their decision process. This continues until the fishery collapses or until the players, through rules they adopt, have managed to stabilize and sustain the fishery. This implementation focuses on the process of rule development by individual fishermen in the search for sustainable rules.

A second way to expand the simple fish game is to focus on elaborating the ecosystem charististics. We can begin this by allowing the fish stock to behave in more realistic ways, including uncertainty and unpredictability, limited relilence, variable growth rates, multiple species, the existence of refugia, etc. These elaborations are underway, as is work on linking with much more elaborate and realistic ecosystem models as discussed below.

A More Realistic Ecosystem Model

We have developed a General Ecosystem Model (GEM) in Stella, that is designed to simulate a variety of ecosystem types using a fixed model structure (Fitz et al. 1995). Driven largely by hydrologic algorithms for upland, wetland and shallow-water habitats, the model captures the response of macrophyte and algal communities to simulated levels of nutrients, water, and environmental inputs. The GEM model contains 15 state variables. It explicitly incorporates ecological processes that determine water levels, plant production, nutrient cycling associated with organic matter decomposition, consumer dynamics, and fire. While the model may be used to simulate ecosystem dynamics for a single homogenous habitat, our primary objectives are to link it to human system models, to use it as the basis for interactive games with human players, and to replicate it as a "unit" model in heterogeneous, grid-based dynamic spatial models using different parameter sets for each habitat. Thus, we constrained the process (i.e., computational) complexity, yet targeted a level of disaggregation that would effectively capture the feedbacks among important ecosystem processes. A basic version has been used to simulate the response of sedge and hardwood communities to varying hydrologic regimes and associated water quality. Sensitivity analyses provided examples of the model dynamics, showing the varying response of macrophyte production to different nutrient requirements, with subsequent changes in the sediment water nutrient concentrations and total water head. The GEM's modular design facilitates understanding the model structure and objectives, inviting variants of the basic version for other research goals. Importantly, we hope that the generic nature of the model will help alleviate the "reinventing-the-wheel" syndrome of model development, and we are implementing it in a variety of systems to help understand their basic dynamics. Linking the GEM to human system models is a primary goal for the future.

Adding Spatial Articulation

We have several ongoing projects in which we are using the GEM model in a spatially articulated way, linked to GIS data. These modeling efforts are outgrowths of the coastal ecological landscape spatial simulation (CELSS) model developed by Costanza et al. (1990). This modeling approach has been applied in two previous studies. The model was first implemented in the Atchafalaya Delta Area of coastal Louisiana, where it was developed to model spatial ecosystem processes, succession, and land loss problems and used to evaluate the impacts of management strategies and specific projects designed to alleviate coastal erosion problems (Costanza et al. 1990). In this case the spatial articulation was 2749 1 km^2 cells. A more sophisticated version of the model is currently being implemented in the Water Conservation Areas and Everglades National Park in Florida to examine the repercussions of management strategies on elements of the ecosystem such as water levels, nutrients, and plant successional patterns (Fitz et al. 1993). This implmentation uses 13,000 1 km^2 cells. In the Patuxent River drainage basin in Maryland, we are attempting to apply integrated ecological and economic modeling and analysis in order to improve our understanding of regional systems, assess potential future impacts of various land-use, development, and agricultural policy options, and better assess the value of ecological systems (Bockstael et al. 1995). Starting with an existing spatially articulated ecosystem model of the Patuxent River drainage basin in Maryland that contains 5,896 0.4 km^2 cells (Debellevue et al 1993), we are adding modules to endogenize the agricultural components of the system (especially the impacts of agricultural practices and crop choice) and the process of land-use decision making. The integrated model will allow us to evaluate the indirect effects over long time horizons of current policy options. These effects are almost always ignored in partial analyses, although they may be very significant and may reverse many long-held assumptions and policy predictions. These initial efforts will be extended to include more elaborate interactions with the human system components, especially property rights regiems.

Empirical Studies

Cross-Ecosystem Studies.

Long-term, empirical, studies that will evolve over time are part of the International Forestry Resources and Institutions (IFRI) research program undertaken by an international network of scholars with a home base at Indiana University. This program has developed a complex, relational database that already has made a serious effort to include variables related to ecosystem and human system characteristics and their interaction. Variables representing stock, flows, controls, and attributes exist for ecosystems and human systems. Initial studies demonstrate that various types of institutional arrangements (human system controls) do impact on ecosystems in both positive and negative fashion (Becker et. al, forthcoming; Gibson et al, forthcoming). Over-time measurements will be obtained for a sample of forest ecosystems within multiple countries. Data from an initial set of forest ecosystems has already been collected in Bolivia, India, Nepal, Uganda, and the U.S. The database already has capabilities of capturing multi-layered human structures and organizations at a sub-national level. Since the IFRI database was not initially conceptualized using the framework elucidated in this paper, we will add any missing variables that are identified as important in the modeling efforts described above.

Cross-Cultural Studies.

Less-detailed data are available for various resource bases (agriculture and land tenure, fishing, pastoral practices, forest resource use) in a wide variety of cultures. The Standard Cross-Cultural Sample (Murdock and White 1969) is a sample of 186 societies, stratified by geographic region, and within region by language group (to avoid problems of sample bias, and cultural diffusion), for which ethnographic records are produced by qualified ethnographers who have lived in the society for a substantial period of time. Many of these ethnographies are collected in the Human Relations Area Files, where they are cross-referenced by topics, including property rights, inheritance, ownership of moveable property, dispute resulution, gathering, hunting, fishing, animal husbandry, and agriculture. We are coding these societies for analysis of distribution and maintenance of common-property resources cross-culturally (see also Low 1990a,b). The categorizations by the HRAF are appropriate, but since the actual ethnographic data are variable in quality, we are including criteria of reliability and data quality for each variable (Costanza et al. 1992).

Cross-National Studies.

Further, in order to develop the capacity to analyze multi-level human and ecosystem relationships, as well as examining relationships among human and ecosystems at a national level, we will build a national-level, relational database capable of incorporating the ecosystem data contained in the IFRI database and some aspects of the HRAF database. To do this we will draw on existing datasets that capture stocks, flows, controls, and attributes of human and ecosystems especially those that contain data for multiple periods of time. Many hypotheses concerning multiple-level ecosystem and human system linkages cannot be addressed at the current time because no multi-level, temporal database currently exists containing data related to the framework described in Figure 1.

Policy Issues

We began by proposing that a variety of ecological policy difficulties and dilemmas may arise from scale mismatches of one sort or another. Sometimes current governance or management systems are too large or too small for the ecosystem to which they are related (e.g. the Maine lobster fishery above); we call this the "missing scale" hypothesis. Sometimes current governance or management systems are unconnected to other human systems at larger or smaller scales — hte "missing connection" hypothesis. And sometimes they are relying on ecological information aggregated at too small or too large a scale, the "incorrect scale of information" hypothesis. An example of the third difficulty solved by constructing a multi-scale model is the General Ecosystem Model ofFitzetal (1995).

To examine these working hypotheses, we need to develop:

1. a broad framework that links key components of human and ecosystems through the various structures and processes (e.g. Fig. 1);

2. a glossary of common terms (in progress);

3. a initial models of linked human and ecosystems to analyze at multiple scales. We have shown a very simply example of a fisheries for explication, but models such as Wilson (pers. comm) and the GEM model (Costanza et al 1995) are more useful.

4. design of multi-level empirical database

The empirical and modeling studies will address many of the policy issues raised above. We will be particularly interested in studying systems where the extent of an ecosystem is substantially smaller or larger than the extent of any linked humanly organized system. This is particularly puzzling where there are substantial conflicts among the users of such systems. We will also study the impact of differently structured incentive systems when the scale of human and ecosystems are relatively well matched. And, finally, we will be particularly interested in studying complex, nested systems where it is extremely different for any actor to obtain appropriate knowledge about the nature and structure of ecostyems and humans systems and thus, their dynamic behavior over time.

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ENDNOTES

[1] A leasing system of this sort would effectively alter the costs of production of wet and dry crops favoring wet crops. This same change in relative costs would also encourage experimentation with new and/or untried wet crops and, if supported by appropriate plant breeding programs, would provide the incentives for the gradual transformation of agriculture i the area.

[2] The following are seven key types of rules that affect the structure of organizational arrangements: Entry/exit, Position, Authority, Scope, Information, Aggregation, Payoff. Definitions and examples of these rules include the following taken from Chapter 2 of *Rules, Games, and Common-Pool Resources by Elinor Ostrom, Roy Gardner, and James Walker (1994).*

1. Position rules specify a set of *positions* and how many participants are to hold each position.
   EXAMPLE: Farmers who constitute an irrigation association designate positions such as member, water distributor, guard, member of a tribunal (to adjudicate disputes over water allocation), and other officers of the association.

2. Boundary rules specify how *participants* enter or leave these positions.
   EXAMPLE: An irrigation association has rules that specify how a farmer becomes a member of the association and the qualifications that individuals must have to be considered eligible to hold a position as an officer of the association.

3. Authority rules specify which *set of actions* is assigned to which position at each node of a decision tree.
   EXAMPLE: If a farmer challenges the actions taken by another farmer or the water distributor, the rules of an irrigation association specify what a water distributor or guard may do next.

4. Aggregation rules specify the *transformation function* to be used at a particular node, to map actions into intermediate or final outcomes.
   EXAMPLE: When a decision is made at a meeting of an irrigation association about changing association rules, the votes of each member present and voting are weighted (frequently each vote is given equal weight, but it may be weighted by the amount of land owned or other factors) and added. When 50 percent plus one of those voting (presuming a quorum) vote to alter legislation, the rules are altered. If less than 50 percent plus one vote for the change, the rules remain unchanged.

5. Scope rules specify the *set of outcomes* that may be affected, including whether outcomes are intermediate or final.
   EXAMPLE: Rules that specify that the water stored behind a reservoir may not be released for irrigation if the level falls below the level required for navigation or for generating power.

6. Information rules specify the *information* available to each position at a decision node.
   EXAMPLE: Rules that specify that the financial records of an irrigation association must be available to the members at the time of the annual meeting.

7. Payoff rules specify how *benefits and costs* are required, permitted, or forbidden in relation to players, based on the full set of actions taken and outcomes reached.

EXAMPLE: Rules that specify whether a farmer may sell any of the water received from an irrigation system, what crops may be grown, how guards are to be paid, and what labor obligations may be involved to keep the system maintained.

Figure Legends

Figure 1. A framework for analyzing human and ecosystem interactions. Note the parallel entities and processes in both ecological and human systems.

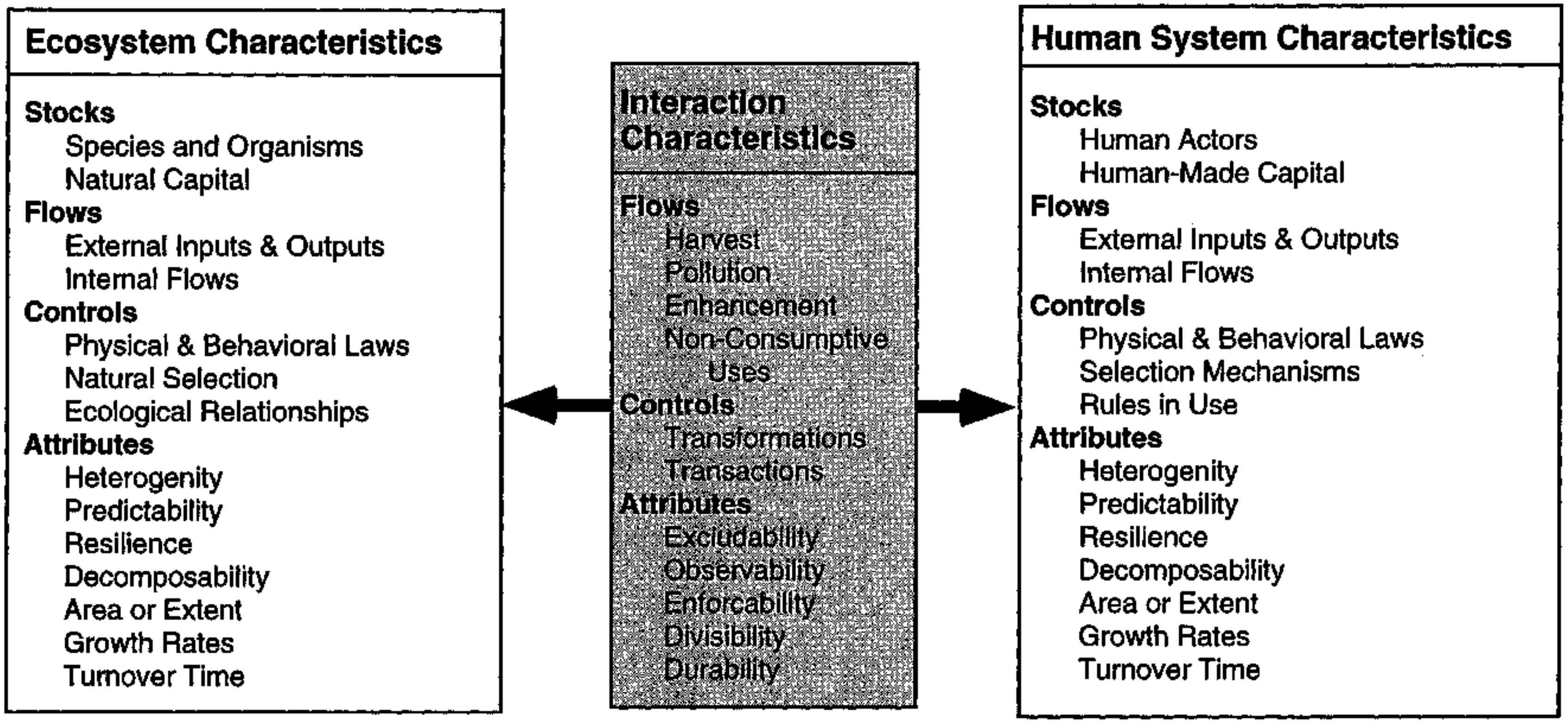
Figure 2. A very simple model of a system. Stocks (both ecological and human) are shown as rectangles. Flows are shown as double "pipes," and controls are shown as circles. This is a simple, deterministic model, but unexpected complexity can result. See text for further explanation.

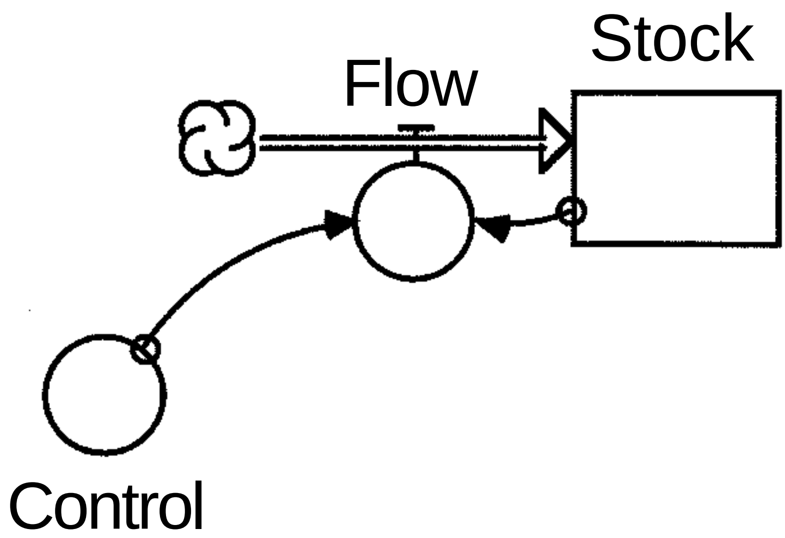
Figure 3. A simple model of a fishery, in which both ecological and human stocks, flows, and controls can vary. See text for further explanation.

Figure 4. Results of the fishery model (Figure 3) in which only the catch limit is allowed to vary, (a) No catch limit; (b) Catch limit=400; (c) Catch limit=500; (d) Catch limit=600. Gear efficiency multiplier= 1.0 in all cases.

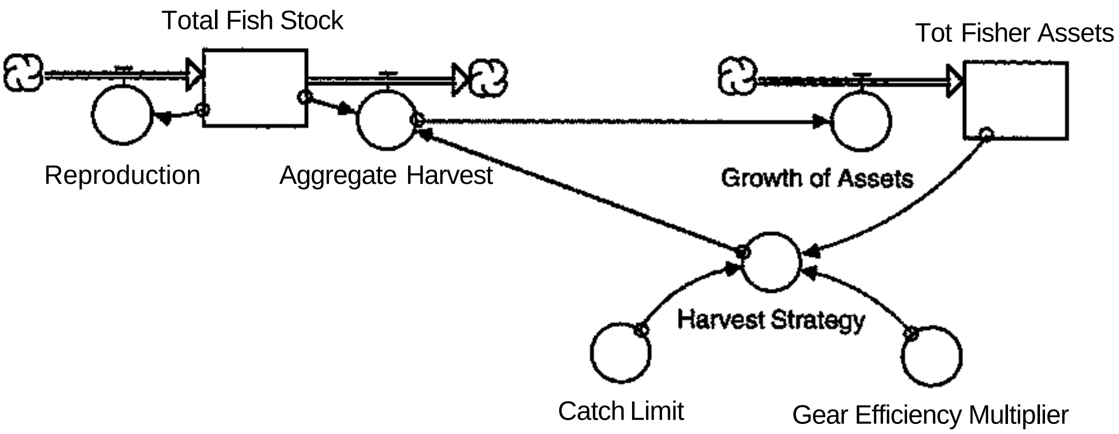
Figure 5. Results of the fishery model (Figure 3) in which only the gear efficiency multiplier is allowed to vary. (Catch limit=500). (a) Gear efficiency multiplier= 1.0; (b) Gear efficiency multiplier=2.0; (c) Gear efficiency multiplier=2.6; (d) Gear efficiency multiplier=2.7.

Framework for Ecosystem and Human System Linkages




Stock
Flow
Control

Diagram



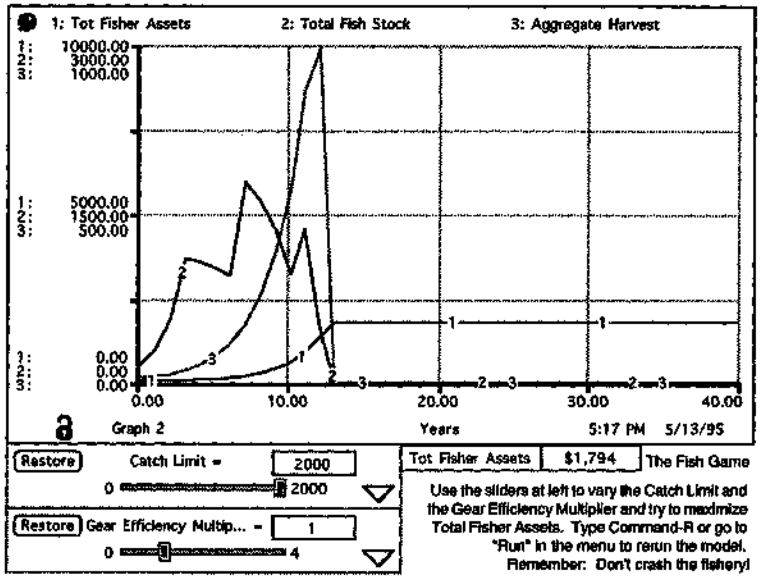
Equations

Total_Fish_Stock(t) = Total_Fish_Stock(t - dt) + (Reproduction - Aggregate_Harvest) * dt
INIT Total_Fish_Stock = 150

Reproduction = if Total_Fish_Stock > 1000 then 0 else Total_Fish_Stock
Aggregate_Harvest = if Total_Fish_Stock < 0 then 0 else Harvest_Strategy

Tot_Fisher_Assets(t) = Tot_Fisher_Assets(t - dt) + (Growth_of_Assets) * dt
INIT Tot_Fisher_Assets = 10

Growth_of_Assets = Aggregate_Harvest/2
Catch_Limit = 2000
Gear_Efficiency_Multiplier = 1
Harvest_Strategy = if Tot_Fisher_Assets < Catch_Limit then Tot_Fisher_Assets * Gear_Efficiency_Multiplier else Catch_Limit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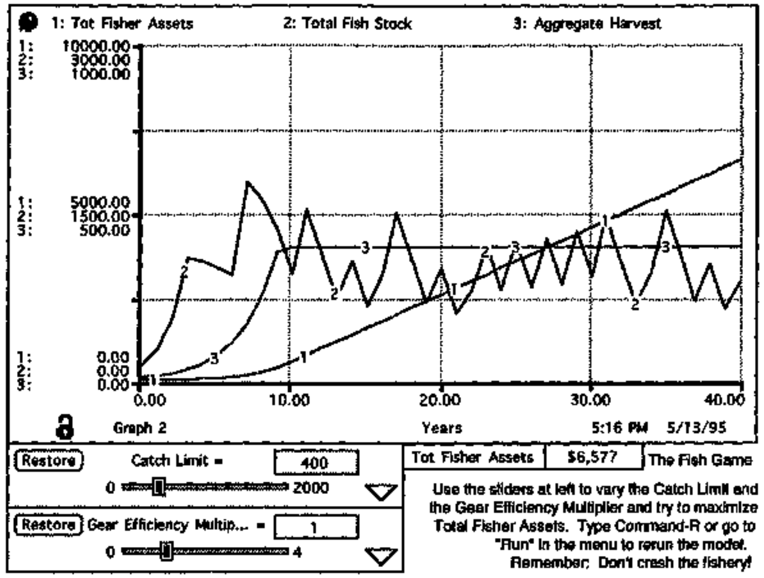
2: Total Fish Stock
3: Aggregate Harvest
10000.00
3000.00
1000.00
5000.00
1500.00
500.00
0.00
0.00
0.00
0.00
10.00
20.00
30.00
40.00
Graph 2
Years
5:17 PM 5/13/95
Restore
Catch Limit =
2000
Tot Fisher Assets
$1,794
The Fish Game
Restore
Gear Efficiency Multip... =
1
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

A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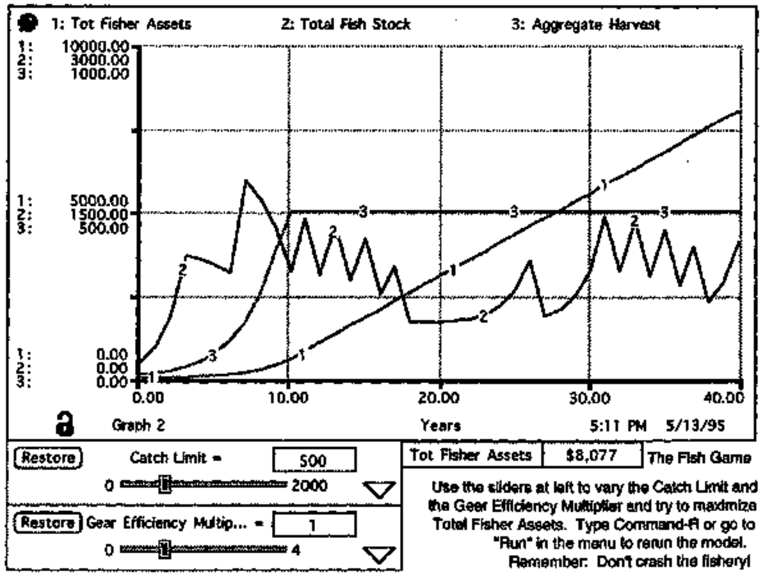
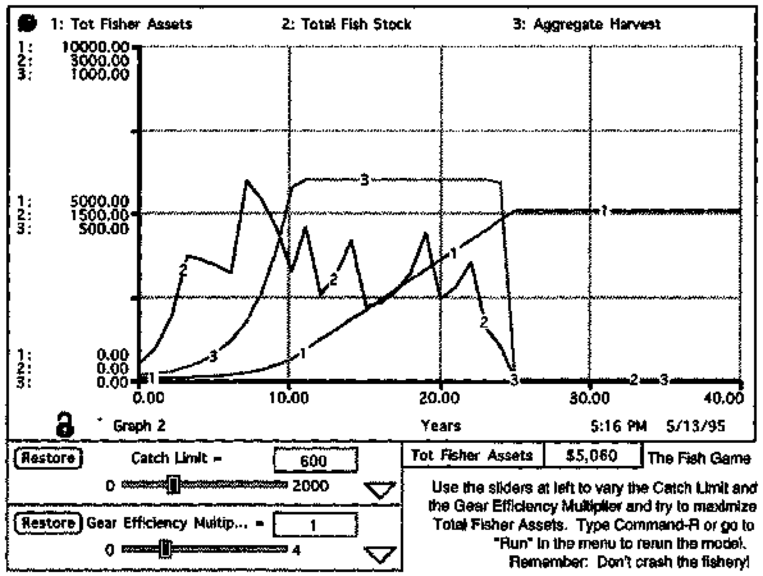
2: Total Fish Stock
3: Aggregate Harvest
10000.00
3000.00
1000.00
5000.00
1500.00
500.00
0.00
0.00
0.00
0.00
10.00
20.00
30.00
40.00
Graph 2
Years
5:16 PM 5/13/95
Restore
Catch Limit =
400
Tot Fisher Assets
$6,577
The Fish Game
Restore
Gear Efficiency Multip... =
1
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

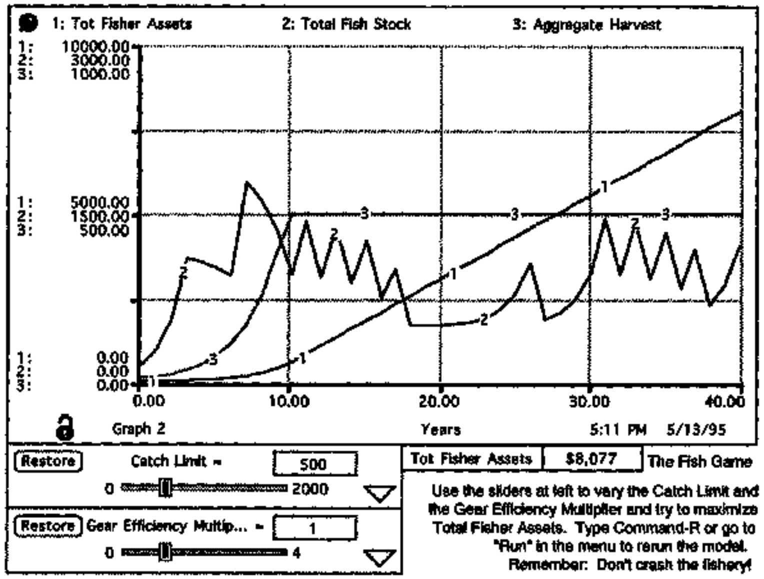
B


1: Tot Fisher Assets
2: Total Fish Stock
3: Aggregate Harvest
10000.00
3000.00
1000.00
5000.00
1500.00
500.00
0.00
0.00
0.00
0.00
10.00
20.00
30.00
40.00
Graph 2
Years
5:11 PM 5/13/95
Restore
Catch Limit =
500
Tot Fisher Assets
$8,077
The Fish Game
Restore
Gear Efficiency Multip... =
1
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

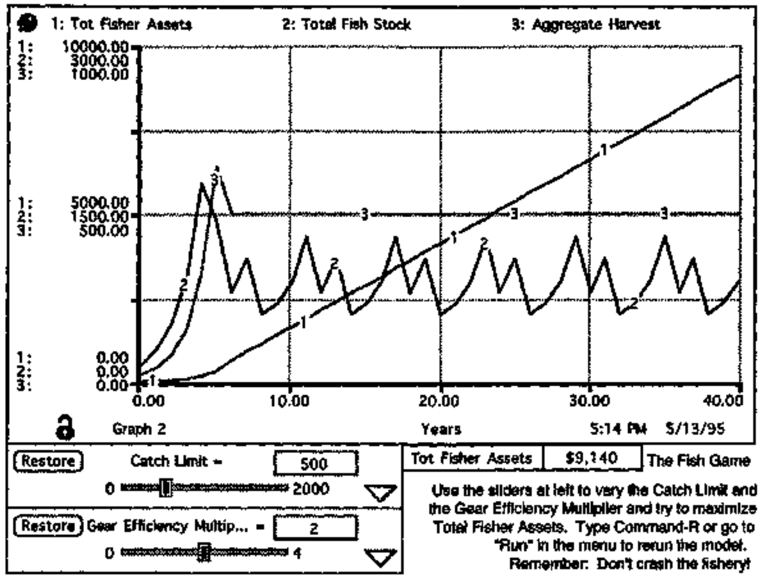
C


1: Tot Fisher Assets
2: Total Fish Stock
3: Aggregate Harvest
10000.00
3000.00
1000.00
5000.00
1500.00
500.00
0.00
0.00
0.00
0.00
10.00
20.00
30.00
40.00
Graph 2
Years
5:16 PM 5/13/95
Restore
Catch Limit =
600
Tot Fisher Assets
$5,060
The Fish Game
Restore
Gear Efficiency Multip... =
1
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

D


1: Tot Fisher Assets
2: Total Fish Stock
3: Aggregate Harvest
Graph 2
Years
5:11 PM 5/13/95
Restore
Catch Limit = 500
Restore
Gear Efficiency Multip... = 1
Tot Fisher Assets $8,077
The Fish Game
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

A


1: Tot Fisher Assets
2: Total Fish Stock
3: Aggregate Harvest
Graph 2
Years
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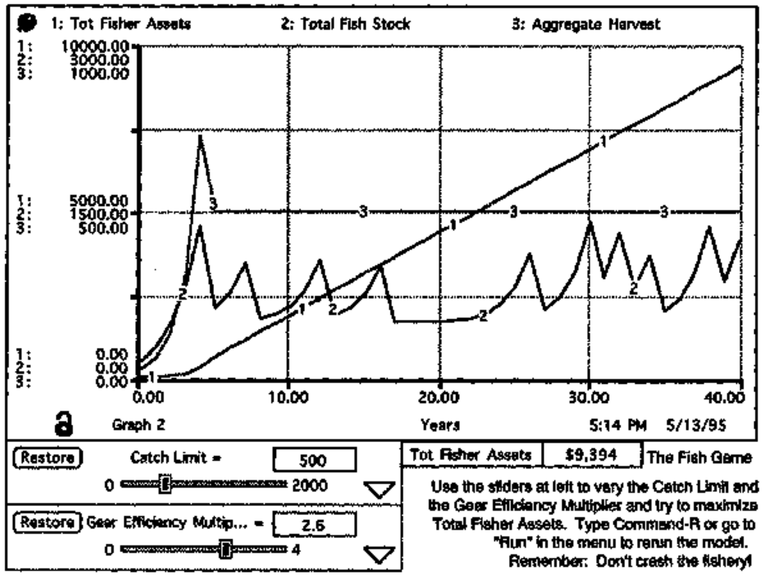
Restore
Catch Limit = 500
Restore
Gear Efficiency Multip... = 2
Tot Fisher Assets $9,140
The Fish Game
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

B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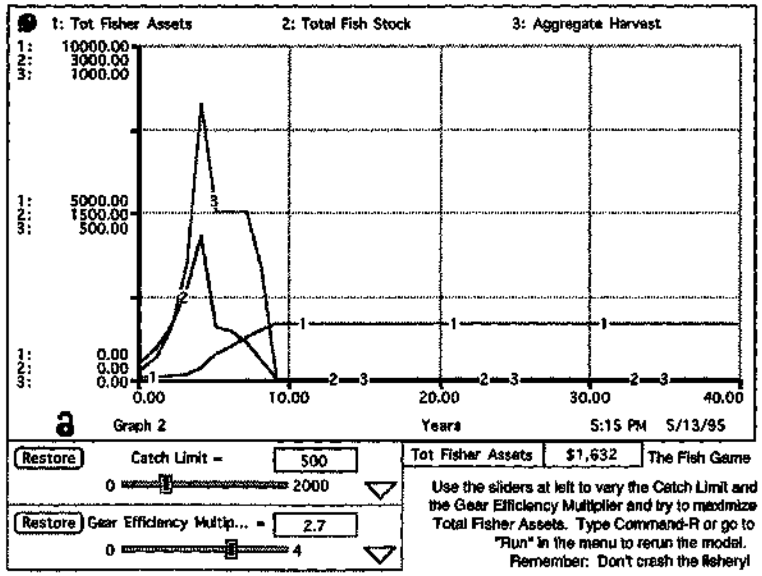
2: Total Fish Stock
3: Aggregate Harvest
Graph 2
Years
5:14 PM 5/13/95
Restore
Catch Limit = 500
Restore
Gear Efficiency Multip... = 2.6
Tot Fisher Assets $9,394
The Fish Game
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

C


1: Tot Fisher Assets
2: Total Fish Stock
3: Aggregate Harvest
Graph 2
Years
5:15 PM 5/13/95
Restore
Catch Limit = 500
Restore
Gear Efficiency Multip... = 2.7
Tot Fisher Assets $1,632
The Fish Game
Use the sliders at left to vary the Catch Limit and the Gear Efficiency Multiplier and try to maximize Total Fisher Assets. Type Command-R or go to "Run" in the menu to rerun the model.
Remember: Don't crash the fishery!

D