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# A Framework for Modeling the Linkages between Ecosystems and Human Systems

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# A Framework for Modeling the Linkages Between Ecosystems and Human Systems

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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 developed and initial dynamic, multiscale, spatial model that illustrates some of the core concepts of the framework. We are in the process of 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 are doing a particularly poor job of managing many natural resources sustainably way over the long term (Ludwig et. al. 1993). **Sustainability** is a concept that broadly refers to the persistence of the integrity and structure of any system over time. There is considerable debate 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 difficulty 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 for the future.

Therefore, what often pass as *definitions* of sustainability are frequently *predictions* that particular actions taken today will lead to sustainability. For example, keeping harvest rates of a resource system below rates of natural renewal should, one can argue, lead to a sustainable extraction system—but that is a prediction, not a definition. It is, in fact, the foundation of MSY-theory (maximum sustainable yield), for many years the basis for management of exploited wildlife and fisheries populations (Roedel 1975). As learned in these fields, the sustainability of a system can only be known after sufficient time has passed to observe if the prediction holds true. So much uncertainty exists 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, 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).

We hypothesize that the causes of many sustainability problems lie in "scale problems." 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 phenomena are particularly prevalent in both many natural resource systems and many human institutions, and we argue that our failure to recognize this fact has led to persistent problems.

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 *(e.g.,* small plots in ecology, individuals or single firms in economics) and that information is then often used to build models at radically different scales *(e.g.,* 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) showed 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. Any missing piece or assumption could render the model useless. On the other hand, if ecosystems could be partitioned into relatively 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. Further, the variety of regulatory responses can be increased if each subunit responds independently to local disturbances thus enhancing the overall regulatory capability of the system (Ashby 1960).

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 and practical understanding of the system can be divided into tractable smaller problems. Just as important, the day to day 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 a 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. This independence is constrained, however, 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 could improve our analytic ability. 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 prices they 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 about the relevant circumstances at that scale

The lobster fishery in the northeastern U.S. provides an interesting example of how management at inappropriate scales has created both biological and social problems. In the State of Maine, fishermen have for many years voluntarily marked egg-bearing lobsters with a "v-notch" in one of the tail flippers. The State of Maine had passed legislation making v-notched lobsters illegal for sale in the State. The mark remains on the lobster for two or three molts or four to six years. The hoped-for effect of v-notching is to reserve a fairly large population of mature females for stock reproduction purposes. Because mature lobsters tend to migrate, however, each fall a large number pass by Cape Cod. Until recently, they were caught and sold by a small group of Provincetown fishermen since the State of Massachusetts did not have a prohibition on the sale of v- notchers. Maine fishermen, concerned by this, claimed their only response is to stop v-notching. The scale of the v-notch activity did not match the scale of lobster migration. In 1994, the State of Massachusetts recognized this problem and now enforces the v-notching policy, removing the scale mismatch.

## 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.

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. Legislative language is often open to interpretation. It is thought that regulations are easier to write and enforce if they are stated in clear, black and white, absolutely certain terms.

Most contemporary, environmental regulations, particularly in the United States, *demand certainty*. When scientists are pressured to supply this nonexistent commodity, not only does frustration and poor communication follow 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 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. And, we need to stress the importance of developing institutions that tend to generate accurate information about ecosystem structure and use so that the edge of uncertainty is slowly pushed backward over time.

## 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 Problem: Sustainable Ecosystems and Human Systems

Thus, there are several underlying causes for the mismanagement of natural resources. We have identified those associated first with missing or failed institutions and secondly with scale mismatches among institutions.

1. Missing Institutions: human institutions do not exist at the appropriate scale or have not established effective controls of ecosystem stocks and flows.
2. Scale Mismatches: potentially effective institutions exist at the appropriate scales, but
   A. Missing Connections: decision-making linkages between scales are ineffective
   B. Incorrect Scale of Information: decisions are based on information aggregated at the wrong scale, even though information may exist at the appropriate scale

Effective institutions may be missing completely (#1, the *"missing institution"* hypothesis), which typically results in open access systems, and frequently resource degradation. Sometimes current governance or management systems are too large or too small for the ecosystem to which they are related. 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 who consider their individual costs and benefits fail to consider the full (including social) 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.

Another factor promoting overuse of resources in ecosystems has to do with the poor design of institutions and incentives in some 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. This is a variant of the missing institutions hypothesis. There are various reasons for this failure:

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 expected 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 consistent with 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.

In addition to the problem of missing or failed institutions, there are problems of mismatched systems that can go awry in more than one way. Sometimes current governance or management systems are unconnected to other parts of the human system at larger or smaller scales — (#2A, the *"Missing Scale: missing connection"* hypothesis). An example of this difficulty solved by constructing a multi-scale model is the General Ecosystem Model of Fitz et al (1995). Sometimes decision-makers rely on ecological information aggregated at too small or too large a scale (#2B, the *"incorrect scale of information"* hypothesis). For example, in the cod fisheries of eastern Canada, local fishermen reported changes in the size distribution of the fish they were capturing, reflecting lowered recruitment, but catch data considered by governmental officials were aggregated to include both off-shore and in-shore information. The local information was swamped by the aggregation process.

Human systems may fail to maintain ecosystems when 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. Interested parties can identify what they perceive to be 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 lkm 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 (Maler 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.

## Resolution and Predictability

Stocks and flows can vary greatly across space and over time, and whatever predictability they exhibit may not be easy for resource users to perceive. Many, if not most, systems contain significant non-linear relationships, and these raise interesting questions about the influence of *resolution* (including spatial, temporal, and component) on the description of data and on the performance of models, in particular their predictability. For example, the relationship between the number of components included and the predictability of models is an important input to model design. Hofmann (1991) discusses this concern in the context of scaling coastal models to the global scale. It is difficult to use aggregate models that integrate over many details of finer resolution models, because the aggregated models may not be able to represent biological processes on the space and time scales necessary. Hofmann suggested that detailed models which were "coupled," in which the output of one model becomes the input for another, may be a more practical method for scaling models to larger systems. The Everglades Landscape Model, discussed below, is such a model.

Considerable effort has been directed toward more formal measures of predictability. Colwell (1974) defined predictability as the reduction in uncertainty about one variable given knowledge of others using categorical data. He developed a quantative index of predictability based on information theory concepts. Colwell's index varies from 0 (totally unpredictable) to 1 (totally predictable) and is divided into two components - constancy (C) and contingency (M). For example, an annual rainfall pattern would be more predictable the more knowledge of the month or season told you the amount of rainfall. It could be predictable because it was constant over time (every month had the same reainfall) or because it was periodic and contingent (i.e. every June is 20 cm, every January is 5 cm), or some combination. The predictability of resources, not just their variability or heterogenity, is very important to humans and other animals in terms of how they use the resource. A predictable resource is generally easier to utilize.

One can define predictability in both space and time, and for a whole host of resources. One can also distinguish between "data" or descriptive predictability within a data series, and "model" predictability when one is comparing a model with data. For example, rainfall data will exhibit a certain predictability. Particular models of rainfall will also exhibit differing abilities to predict the rainfall data. For example, in the spatial domain one can define spatial *auto-predictability* ($P_a$) as the reduction in uncertainty about the state of a pixel in a scene, given knowledge of the state of adjacent pixels in that scene, and spatial *cross-predictability* ($P_c$) as the reduction in uncertainty about the state of a pixel in a scene, given knowledge of the state of corresponding pixels in other scenes. $P_a$ is a measure of the internal pattern in the data, while $P_c$ is a measure of the ability of a model to represent that pattern.

Cross-predictability ($P_c$) can be used for pattern matching and testing the fit between map scenes. In this sense it relates to the predictability of models versus the internal predictability in the data revealed by $P_a$. While $P_a$ generally increases with increasing resolution (because more information is being included), $P_c$ generally falls or remains stable (because it is easier to model aggregate results than fine grain ones). Costanza and Maxwell (1994) 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 modeling those patterns accurately. Thus we can define an optimal resolution for a particular modeling problem that balances the benefit in terms of increasing data predictability *($P_a$)* as one increases resolution, with the cost of decreasing model predictability *($P_c$)*. Figure 1 shows this relationship in generalized form. There may be limits to the predictability of natural phenomena at particular resolutions, and "fractal like" rules that determine how both "data" and "model" predictability change with resolution.

# Human-Ecosystem Relationships: 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. 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.

A major goal of this paper is to begin development of a common framework and to sketch out how it may be used. Figure 2 represents a general schema of parallels between human and ecological systems, and the nature of their interactions. Both ecological and social systems have attributes of stocks, flows, and their interactions even though 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 2). By structuring the human and ecological systems, and their interactions, in parallel forms, we hope to facilitate comparisons of multiple levels.

## Stocks

By stocks we refer to elements in the system that can potentially accumulate or decumulate. The stocks (Fig. 2) of ecosystems, for example, include **organisms and species** 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 by the biomass and volume of living material or the volume of non-renewable resource.

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 counted as natural income.

We can differentiate two broad types of natural capital: (1) renewable (biotic) or active natural capital and (2) nonrenewable (abiotic) 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). When left in place, they yield a flow of ecosystem services (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).

Individuals and aggregations of individuals are **the human actors** who make choices among actions leading to different outcomes. Human 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. If no limits are placed on human actions, however, unconstrained short-term self interest can lead to unsustainable ecological results. A person with constrained property rights is likely to have fewer short-term options than someone who holds an unconstrained set of rights, but these limits 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. Many scholars differentiate among two broad types of human-made capital: physical and human capital. One is the factories, buildings, tools, and other physical artifacts usually associated with the term "capital." This form of capital is inactive unless humans activate it through the decisions and actions they take. A second form of human-made capital is the stock of education, skills, culture, and knowledge stored in individual 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-man capital that has been discussed and analyzed more recently is "social capital (Coleman 1988), the commonly shared and understood relationships that can enhance the mutually beneficial outcomes of a process. These include shared knowledge, skills, power, connections, trust, monetary resources, and bundles of property rights. The organizational structures of social capital are regularized patterns of linking actors in more or less predictable and patterned sets of relationships and must be shared among individuals rather than be anything possessed by a single individual. 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 and temporal extent, its history, the assets it controls, its information generating and processing capability, its production technology, etc.

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. In addition, we have the important distinction between renewable and non-renewable natural capital, and for some purposes we can lump manufactured, human and social 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 heterogeneity 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 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) (Crawford and E. Ostrom, 1995). 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. 2). The number of attributes that potentially affect the capacity of human actors to manage resources sustainably is very large. We concentrate here on a limited number of attributes which capture important variation in functionally significant ways: heterogeneity, predictability, resilience, decomposability, extent in space and time, and productivity. **Heterogeneity** reflects the degree to which variety exists in the attributes of various entities in a system. Heterogeneity is low (homogeneous) when most human or ecosystem entities are similar in structure and value and high when many entities differ in structure and/or value. 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. Extent in space **and time** reflects the size of geographic region covered by stocks of ecological or human systems or the length of time considered. The terms 'patchiness' and 'grain' are used to reflect scale in terms of area. Productivity characterizes the amount of outflow obtainable from a particular combination of stocks, inflows, and controls.

All of the above attributes can be measured in both human and ecosystems. When human and ecosystems interact (Figure 2) an additional set of attributes is important that characterizes the relationships between human systems and ecosystems. One is then interested in measuring 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. **Knowledge** represents the level of understanding of those using a resource system of how the system is structured and the relevant values of key variables. The level of knowledge about a particular system may vary from full certainty to considerable uncertainty. 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. This attribute is frequently referred to as subtractbility of the flow of benefits or the rivalness of the benefits produced. Sustainability 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 observe fishers on the fishing grounds or if they do not return to the same harbor, it may be difficult to monitor the equipment they use or the amount they catch and thus to enforce catch rules, again leading unsustainability. Fish catches are inherently divisible; but other ecosystem stocks, such as the stratosphere, are not — and this can create further problems. Sustainability, 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. If those making harvesting and investment decisions have relatively complete and certain information about the structure of the ecosystem and good information about the values of key variables, the likelihood of achieving long-term sustainability is enhanced.

## Space and Time

As useful as it is to link human and ecosystem terms for comparison and analysis, what we have introduced so far reflects only a single spatial unit at a single moment in time. Obviously, ecosystem characteristics vary spatially and temporally — and so do human systems. To deal with such complexity, any model must eventually make such variation explicit. In Figure. 3 we show an hypothetical system in which there is variation in both natural habitats in an ecosystem (variation in natural capital — species present, their growth rates, degree of external pertubations) and human systems (variation in human actors, human-made capital, selection mechanisms, and rules in use).

Here is the heart of the problem of scale mismatch. As we show in the next section, human and ecosystem stocks, flows, controls and attributes are interdependent. If either human of ecosystems are modelled without understanding both the interdependence and spatio-temporal variation, mismatches of information and misunderstanding will be common. Fortunately, as we noted above, even large and complex systems can typically be analysed as a set of smaller units, each with specified rules, which have flows among them. If we can model the human system, the ecosystem, and the interactions appropriately within each unit, and link them, we will have a powerful tool.

# "Beijer World 1": A Dynamic, Spatial, Multiscale, Integrated Model

We developed a generalized interactive simulation game based on the general framework described above to help understand the general dynamics of linked ecological economic systems, including natural capital depletion, property rights regimes, and trade-offs between economic efficiency, equitable distribution, and ecological sustainability. The model consists of a unit model containing 2 state variables; natural capital and human-made capital, which is replicated for each of three spatial cells, meant to represent areas of land or water. A second scale is included as "higher level capital" meant to represent a generalized governance function - either a formal government or a less formal governance system. Figure 4 is a diagramatic representation of the model. A complete description of the model and its behaviors is given in Costanza et al. (in prep). This model emphasizes generality at the expense of realism and precision in the terms discussed above.

Even though the model is fairly simple, it produces a very rich array of behaviors, that cover many of the general situations encountered in natural resource management. For example there are three basic cases that the model can deal with:

(1) Isolated systems: when transfers (externalities) between cells are small the three cells operate as relatively independent systems. In this case, the maximum sustainable harvest rate in each cell depends completely on the local conditions in that cell's ecosystem. Three separate property rights regimes (one for each cell) are appropriate in this case.

(2) Large externalities and no higher level control: this corresponds to an open access resource where free riding and over explotation are possible. If a shared property regime can be developed and enforced covering all three cells, this is the most simultaneously efficient, equitable, and sustainable way to manage this case.

(3) Large externalities and no shared property: if shared property cannot be implemented then to avoid crashing the resource there must be effort to control flows between cells (externalities) using higher level (government) enforcement. This is costly and can be inequtable, sacrificing the efficiency and equity goals for sustainability. If control is insufficient in the interest of maximizing efficiency, the system will not be sustainable.

The model can also be played as an interactive game so that users can experiment with the various trade-offs themselves. Figure 5 shows a typical user interface screen for the model in this mode. We also used the model as an experimental system, and statistically analyzed the causes of variance in the system. The results of this analysis showed that because the model (like the real world) has discontinuities and thresholds it was very difficult to predict sustainability from the "independent" variables of the model's parameter settings. But using only those runs which were sustainable, a multiple regression model could explain about 75% of the variation in total capital (natural plus human-made) in the system. The best guarentee of obtaining a sustainable run was to have all harvest limits in the model adequately below a safe threshold, or, in other words, to apply the precautionary principle. This generally implied an equitable distribution of resource use and an only modest sacrifice of economic production in the long run.

# Additional Modeling Studies

There are various ways to elaborate the basic model we have described to increase realism and/or precision. One way to add realism is to add complexity to the ecosystem component. For example, we have developed a General Ecosystem Model (GEM) that is designed to simulate a variety of ecosystem types at a relatively high level of complexity 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.

A second way to increase realism is to increase the spatial resolution of the model. 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

The usefulness of models depends, ultimately, on their ability to predict events and conditions in the real world. Empirical data are essential for testing models, and the hypotheses underlying them. We envision at least three sorts of empirical databases that would prove useful in this context. 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 are included representing stock, flows, controls, and attributes for ecosystems and human systems. Initial studies demonstrate that various types of institutional arrangements (human system controls) do affect ecosystems in both positive and negative fashion (Becker et. al, forthcoming; Gibson et al, forthcoming). Measurements over time are being obtained for a sample of forest ecosystems within multiple, countries. Data from an initial set of forest ecosystems have already been collected in Bolivia, India, Nepal, Uganda, and the U.S. The database already has capabilities of capt uring 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.

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 will include criteria of reliability and data quality for each variable (Costanza et al. 1992).

Finally, 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 propose 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.

# Conclusions

In this paper we have argued that problems associated with the failure to manage many natural resources in a sustainable way over the long-run have to do with a fundamental mismatch between the structure and attributes of ecosystems and the structure and attributes of connected human systems. To explore these mismatches, however, requires that ecologists and social scientists develop a common language and framework for studying complex, hierarchical systems which involve considerable uncertainty. Thus, a major emphasis of the current paper has been on the development of a coherent framework that can be used by both ecologists and social scientists when modeling these kinds of coupled systems over time. We have now developed several models of increasing complexing using the language we have developed. We report on these elsewhere. And, we are in the process of developing a complex, multi-tiered database for examining hypotheses derived from these models related to the governance and management of forest ecosystems.

The empirical and modeling studies will address many of the policy issues raised above and particularly the effect of diverse ways of organizing human systems on the sustainability of complex ecosystems. We will examine, for example, the comparative performance (in terms of economic efficiency, equity, and ecosystem sustainability) of decision making systems that are local and independent as contrasted to either centralized systems located external to an ecosystem or human systems that share decision-making capability among multi-level, nested human organizations. 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. 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 Junction* 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

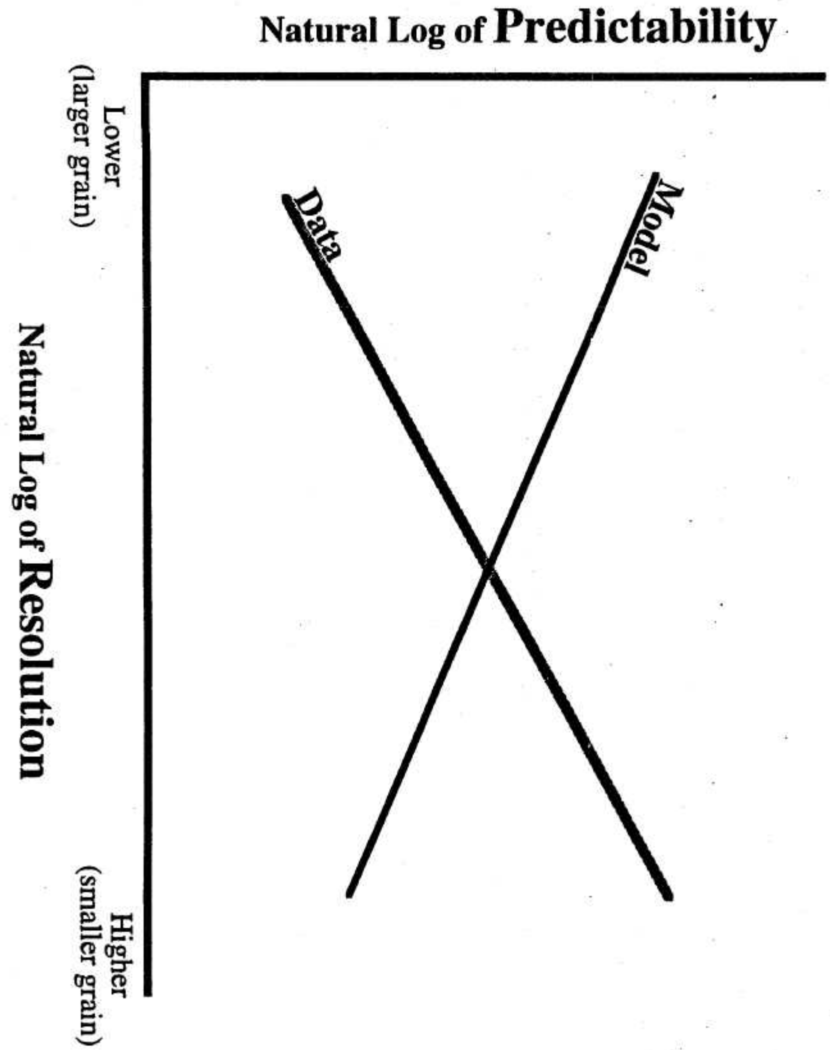
Figure 1. Relationship between resolution and predictability

Figure 2. A framework for analyzing human and ecosystem interactions. Note the parallel entities and processes in both ecological and human systems.

Figure 3. Spatial and temporal depiction of ecosystem and human system characteristics and their variation over a landscape.

Figure 4 A STELLA diagram of a generalized dynamic, spatial, multiscale, integrated model. See text for further explanation.

Figure 5. A typical user interface screen for the Beijer World model showing variables that the user can change simply by sliding the control with the mouse.



Natural Log of Predictability
Natural Log of Resolution
Lower
(larger grain)
Higher
(smaller grain)
Data
Model

# Framework for Ecosystem and Human System Linkages

**Ecosystem Characteristics**

**Stocks**
- Species and Organisms
- Natural Capital

**Flows**
- External Inputs & Outputs
- Internal Flows

**Controls**
- Physical & Behavioral Laws
- Natural Selection
- Ecological Relationships

**Attributes**
- Heterogenity
- Predictability
- Resilience
- Decomposability
- Extent in Space and Time
- Productivity

**Interaction Characteristics**

**Flows**
- Harvest
- Pollution
- Enhancement
- Non-Consumptive Uses

**Controls**
- Transformations
- Transactions

**Attributes**
- Excludability
- Observability
- Knowledge
- Enforceability
- Divisibility
- Sustainability
- Equity
- Efficiency

**Human System Characteristics**

**Stocks**
- Human Actors
- Human-Made Capital

**Flows**
- External Inputs & Outputs
- Internal Flows

**Controls**
- Physical & Behavioral Laws
- Selection Mechanisms
- Rules in Use

**Attributes**
- Heterogenity
- Predictability
- Resilience
- Decomposability
- Extent in Space and Time
- Productivity

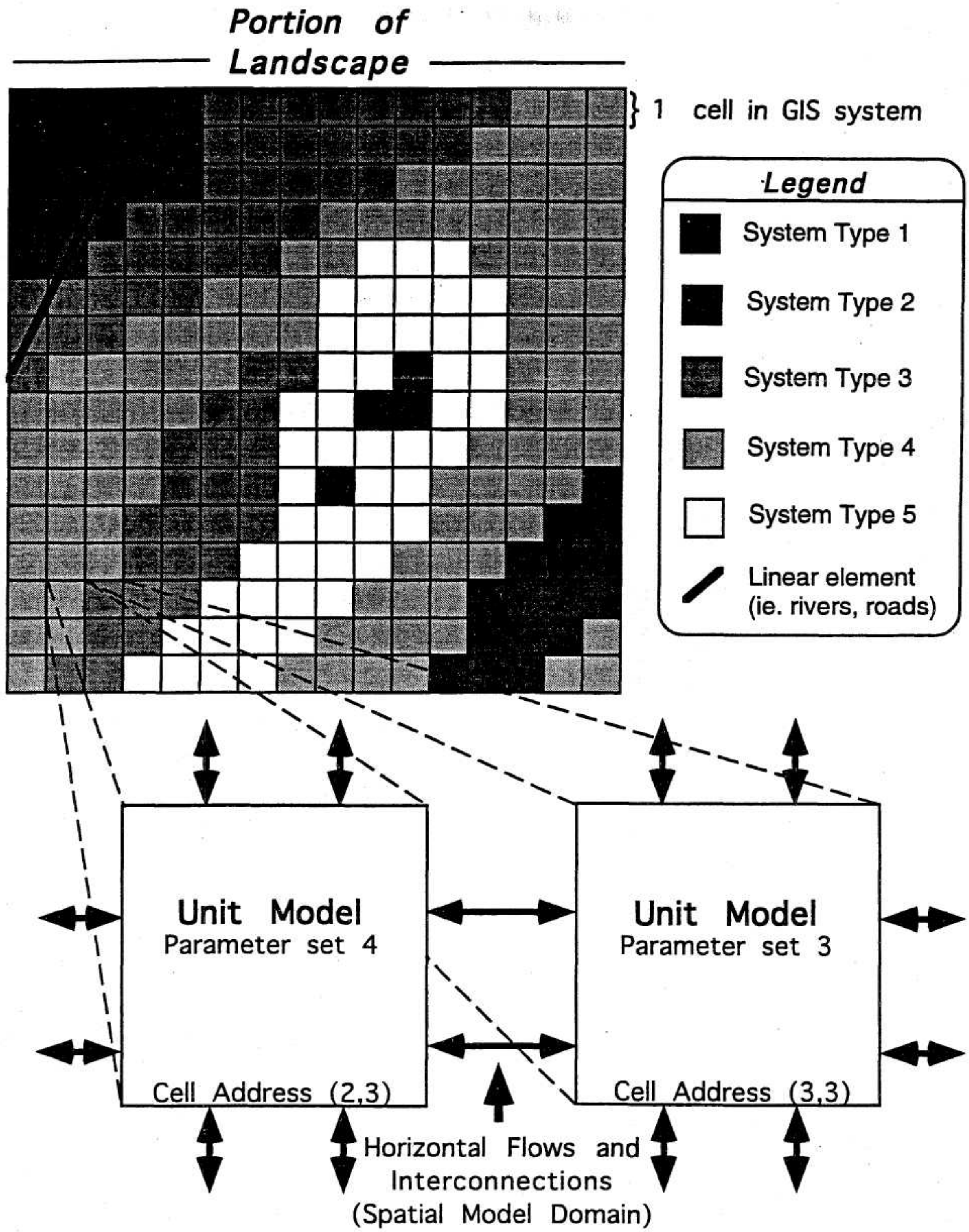
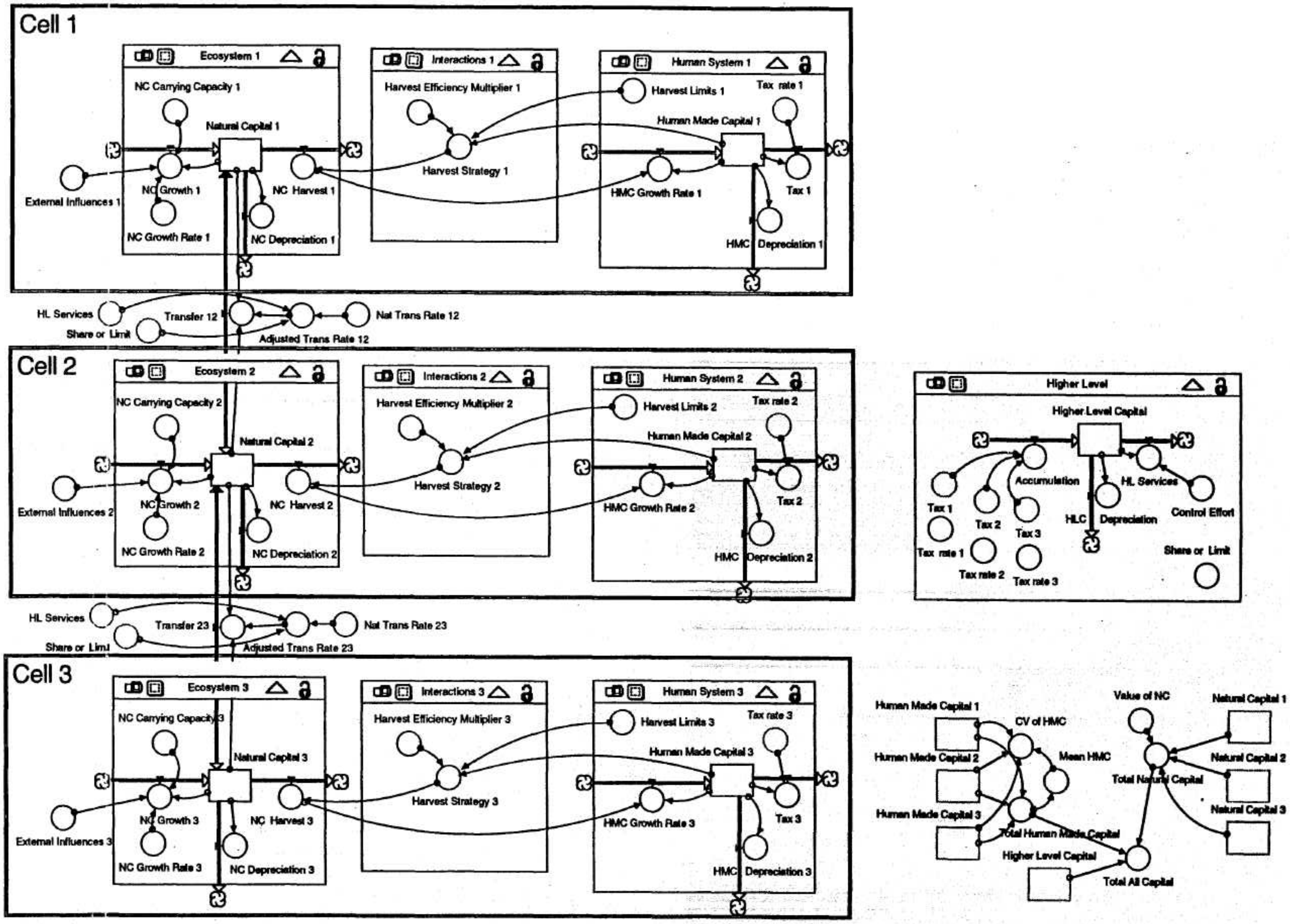
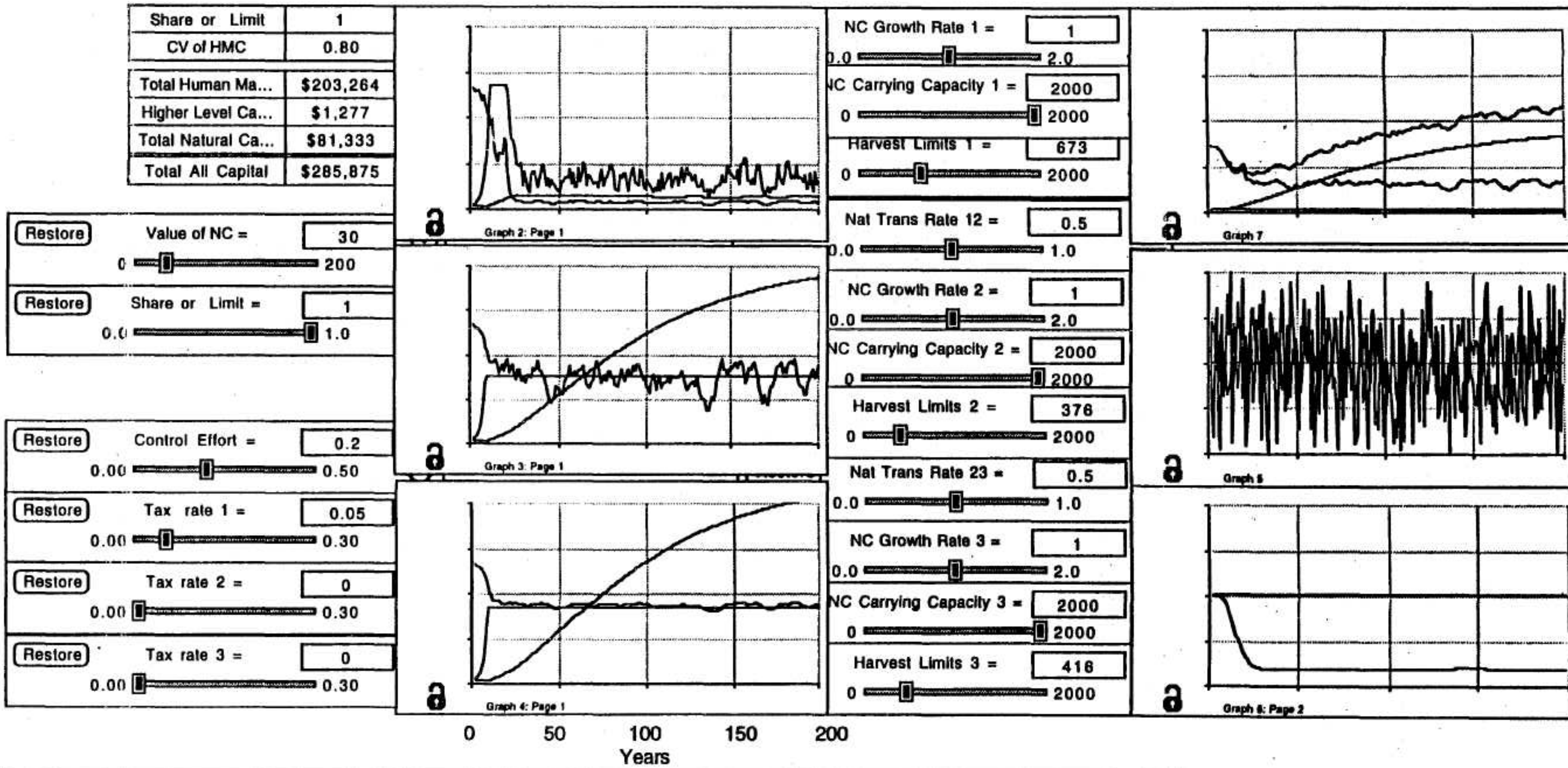



Figure 3 The unit model simulates the dynamics for each of the cells. Cells are connected over the landscape.

Beijer World 1: A Two Scale, Dynamic, Model of a Linked Ecosystem and Human System



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