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Modeling biocomplexity – actors, landscapes and alternative futures

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Abstract

Increasingly, models (and modelers) are being asked to address the interactions between human influences, ecological processes, and landscape dynamics that impact many diverse aspects of managing complex coupled human and natural systems. These systems may be profoundly influenced by human decisions at multiple spatial and temporal scales, and the limitations of traditional process-level ecosystems modeling approaches for representing the richness of factors shaping landscape dynamics in these coupled systems has resulted in the need for new analysis approaches. New tools in the areas of spatial data management and analysis, multicriteria decision-making, individual-based modeling, and complexity science have all begun to impact how we approach modeling these systems. The term ‘‘biocomplexity’’ has emerged as a descriptor of the rich patterns of interactions and behaviors in human and natural systems, and the challenges of analyzing biocomplex behavior is resulting in a convergence of approaches leading to new ways of understanding these systems. Important questions related to system vulnerability and resilience, adaptation, feedback processing, cycling, non-linearities and other complex behaviors are being addressed using models employing new representational approaches to analysis. The complexity inherent in these systems challenges the modeling community to provide tools that capture sufficiently the richness of human and ecosystem processes and interactions in ways that are computationally tractable and understandable. We examine one such tool, EvoLand, which uses an actor-based approach to conduct alternative futures analyses in the Willamette Basin, Oregon.

Keywords: Complexity; Resilience; Adaptation; Simulation

1. Introduction

The term ‘‘biocomplexity’’ is used to describe the complex structures, interactions and dynamics of a diverse set of biological and ecological systems, often operating at multiple spatial and temporal scales. The study of biocomplexity reflects an intention to understand fundamental principles governing global behavior of these systems, expressed in terms of biological, physical, ecological and human dimensions, in terms of the interactions and resulting patterns and structures that collectively define system responses (Colwell, 1998; Levin, 1998; Manson, 2001). Several decades of study and appreciation of the rich nature of the interactions that drive many systems of vital interest to humanity have led to an increasingly sophisticated set of hypotheses on how these systems respond to the many perturbations and cycles that they are exposed to. The scientific community is being asked to bring to bear these advances in our collective understanding of systems impacted by anthropogenic influences to improve management and planning of these systems, resulting in the need for new approaches to incorporating human behavior as an important component of ecological and environmental systems behaviors. As human impacts stress the ability of many systems to deliver the wealth of ecological, social and economic goods and services societies rely on, terms such as ‘‘vulnerability’’ and ‘‘resilience’’ have come into common use as ways

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to think about system response and the implications of human modification of these systems in maintaining functions perceived as important for human and natural uses. The study of biocomplexity identifies and defines a set of concepts, hypotheses and approaches for understanding and characterizing the rich patterns of interactions and behaviors in these systems, with the goal of providing new insights into important questions related to system vulnerability and resilience, self organization and adaptation, feedback processing, cycling, and non-linearities. The modeling community is developing new approaches to representation and analysis that are allowing exploration of complex systems in ways that are beginning to answer questions about how these systems interact, evolve, and transition to new, often unexpected, behaviors.

The challenges of representing and analyzing biocomplex behavior are resulting in a convergence of approaches leading to new ways of understanding these systems. Recent developments in mathematics related to complex systems analysis have provided a variety of new tools and strategies for exploring complex system dynamics (Bak and Chan, 1989; Holland, 1995; Kauffman, 1969; Fernandez and Sole, 2003). Key insights arising from these analyses focus on questions related to identifying system properties that result in self-organizing or emergent behavior, the nature of interactions that can lead to highly non-linear behaviors in a range of systems, and the circumstances in which ‘‘surprises’’ in system response may be observed. As these concepts have been expanded from their initial focus on primarily physical phenomena to the examination of increasingly rich ecological, economic and social systems, ecological and environmental modeling efforts have become correspondingly more focused on incorporating biocomplexity considerations in their approaches and analyses. Most of these approaches embody the concept that complex behavior arises from the collective interactions of large numbers of relatively simple entities (Holland, 1995; Arthur et al., 1997). Alternatively, the recently proposed theory of Panarchy (Holling, 2001; Gunderson and Pritchard, 2002) proposes an alternative hypothesis that states that complex behavior results from a small number of controlling processes operating at multiple spatial and temporal scales. While full articulation of the underpinnings of these approaches is beyond the scope of this paper, they clearly suggest that new modeling and analysis paradigms are needed, and modelers are beginning to incorporate concepts of self-organization, adaptation, multi-scalar interactions and multiple actors alongside more traditional process-based approaches to develop new classes of models able to more fully characterize and simulate biocomplex systems.

Systems scientists have presented many examples of biocomplexity conceptualizations spanning purely ecological (Walker et al., 1969; Carpenter and Cottingham, 1997), social (Emery and Trist, 1965; Bella, 1997), economic (Arthur et al., 1997) and coupled human/natural systems (Sheffer et al., 2002.) However, these broad conceptualizations have not lent themselves to the modeler's need for reasonably concrete, well-articulated and operational definitions amenable to computation and analysis. For example, a Google search using the phrase ‘‘ecosystem resilience’’ returns on the order of 75 000 ‘‘hits’’, most of which discuss resilience of particular systems or classes of systems with broad brush strokes, describing in somewhat vague, fuzzy terms the general concept of a system being robust to change. Examined closely, what constitutes ‘‘change’’ generally becomes somewhat nebulous. In some cases, a change in the composition of the system is implied, without reference to the magnitude of the change in question, or whether the compositional change implies a change of function, e.g. the capacity of the system to provide a particular set of goods and services. In other cases, the focus is on examining system behavior, to better understand circumstances in which perturbations of the system will either be absorbed or send the system off in a new direction.

We are seeing a transition from conceptual to more quantitative methods for describing and analyzing these systems (Carpenter and Cottingham, 1997; Carpenter et al., 1999; Lepperhoff, 2002; Chattoe, 1998), and a rich literature is emerging in this area. A variety of methodologies building on and extending complex analysis of simpler physically-based systems to quantitatively describe and model biocomplex human and natural system behaviors are emerging, based on more traditional stability analyses applied to non-linear systems. These analyses examine state spaces defined in terms of stability basin structure, distributions of attractors in state space, and ability of perturbations to move the system into alternate stability domains. Extending these concepts into the biocomplexity realm, we can define operationally useful descriptors of complex behavior that are relevant to management. For example, system resilience can be defined as the capacity of a system to absorb perturbations while continuing to operate within it current stability domain. Models that sufficiently characterize the structure of the state space with respect to attractor basin geometries can provide insight to managers on regions where vulnerability of a system to provide specific productions may be high. However, additional challenges exist: real state spaces may be highly multidimensional, dynamic, and non-linear or even folded, making analysis of their structure difficult. Further, where management is based on multiple criteria (reflected by multiple model outputs), these outputs may have substantially different state space structures. Nevertheless, these concepts are being used to examine more realistic systems and applied to the management realm.

2. Alternative futures

In parallel to the emergence of biocomplexity as an analysis paradigm, a number of studies have recently focused on alternative futures analyses (e.g. Baker et al., 2004; Hulse et al., 2000; Santlemann et al., 2001; Steinitz and McDowell, 2001; Voinov et al., 1999; Noth et al., 2000). This has resulted largely from a need and desire to utilize analytical approaches, generally using process-level models synthesizing multiple landscape elements, to predict a particular set of responses of the target landscape to a particular set of perturbations reflecting alternative landscape management. These efforts generally incorporate stakeholder involvement in determining the nature, pattern and scale of the perturbation(s) considered, and resulting modeled landscapes or landscape trajectories are used to assess the outcome behaviors. While these efforts can be very effective for moving models into the policy and management arena and can provide insight into the implications of specific management strategies, they raise a number of issues related to our ability to effectively model the myriad of potential interactions and behaviors that may (or may not) lead to surprising and unforeseen results. While opening the door for modelers to interject current understanding of important processes and interactions into the management of coupled human/natural systems, alternative futures analyses can place additional burdens on the modeler, particularly related to identifying and incorporating interactions across multiple processes, possibly across multiple spatial and temporal scales. For example, a model-based assessment of stream biological production based on vegetative pattern at a site may generate questionable results when the broader influences of channel migration, wood production from upstream areas, or large, low-periodicity flood events can substantially alter that pattern (Van Sickle et al., 2004). The utility of incorporating additional complexity in a model is often unclear; particularly in situations that are data limited or mechanisms are not well understood, simpler models may be more reliable predictors of system response (National Academy of Sciences (NAS), 2001). Representing human decision making, and at least indirectly, human values, in the landscape may be necessary to incorporate the influence of and feedback to the human component of these systems, and can be accomplished through a stakeholder process (Hulse et al., 2004) or modeled (Etienne et al., 2003).

3. Actor-based approaches to simulating landscape change

3.1. Overview

Landscape change modeling is at the core of most alternative futures analyses, and the last decade had seen considerable activity in this area (see Parker et al., 2003 for an excellent review). This activity is in part a result of the widespread availability of GIS-based platforms and datasets, complimented by a rapid increase in computing power and sophistication of representational tools for software development resulting from a convergence of approaches derived from individual-based modeling and complexity analysis. In particular, actor-based approaches have become a commonly-used tool for representing human interactions driving landscape change, as well as many other types of systems in which collective behavior arises from collective behavior. Actor-based models typical explicitly represent: 1) a landscape as a collection of decision units, defined by spatial properties and attributes relevant to the decision making criteria relevant to the task addressed by the modeler; and 2) entities that make decisions and/or take actions that result in landscape change. While the term ‘‘agent’’ is used commonly in the literature to describe these entities, we prefer the term ‘‘actor’’, since ‘‘agent’’ has a number of connotations in computer science distinctly different than the usage described here, and ‘‘actor’’ has a clearer semantics consistent with common usage of the term in a non-modeling context.

An appeal of an actor-based approach for landscape change modeling is that modeled actors can be based in large part on actual actors contributing to behaviors of the real system which the model is attempting to capture, increasing the realism of the model. Simulated actors may be based on individual decision makers, collections of individuals acting as a homogeneous entity (i.e. an institution), or as abstractions with no specific real-world counterpart (e.g. organizational structures reflecting collective actions that are not captured in specific real-world organizations). From a modeling perspective, the task of the modeler involves determining an appropriate set of characteristics that represent the attributes of the actor relevant to the model, and a set of actor behaviors that capture the decisions or actions of the actors in the system. While the set of necessary actor attributes is highly dependent on the problem being addressed, behaviors typically consist of some form of decision rules that related site and/or system characteristics to a particular actor action and resulting landscape change. Determining an appropriate set of actors and their corresponding behaviors is a significant modeling challenge, and may involve expert knowledge, surveys, demographic and population behavior analysis, and other methods; this is an active area of research.

Self-organization and adaptation are key aspects of many types of complex behavior generally, and landscape change specifically. Adaptation implies that a system modifies its behavior, or ‘‘learns’’, through the processing of feedback describing the success of current strategies at achieving desired outcomes. Adaptive mechanisms may occur at multiple scales and may operate though a variety of distinct pathways. At an actor level, adaptation may involve changing decision behavior, reflecting changes in landscape production, actor goal satisfaction and other decision criteria. At a system level, adaptation may manifest as higher-order changes in actor composition, changes in decision spaces and system process reorganization. Relatively few current models explicitly incorporate adaptive processes into their representations; this is another area of active development.

3.2. An example alternative futures modeling framework – EvoLand

A number of frameworks for complex systems and alternative futures analyses have been developed (Noth et al., 2000; Sengupta and Bennett, 2003; Maxwell and Costanza, 1995; Daniels, 1999), each providing a specific set of capabilities for representing and manipulating supported representations of the system of interest. These frameworks can simplify implementation of models and provide standard methods for data management, model integration, and analysis. *EvoLand* (for Evolving Landscapes) is an example of a modeling tool that supports development of spatially explicit, actor-based approaches to landscape change and alternative futures analysis.

EvoLand provides a framework for representing: 1) a landscape consisting of a set of spatial containers, or *integrated decision units* (IDU's), modeled as a set of polygon-based geographic information system (GIS) coverages containing spatially-explicit depictions of landscape attributes and patterns; 2) a set of actors operating on a landscape, defined in terms of a *value system* that couples actor behavior to global and local production metrics and in part determine policies the actor will select for decision making; 3) a set of *policies* that constrain actor behavior and whose selection and application results in a set of outcomes modifying landscape attributes; 4) a set of autonomous process descriptions that model non-policy driven landscape change; and 5) a set of *landscape evaluators* modeling responses of various landscape production metrics to landscape attribute changes resulting from actor decision making. EvoLand provides a general-purpose architecture for representing landscape change within a general paradigm incorporating actors, policies, spatially explicit landscape depictions, landscape feedback, and adaptation; application-specific components are ''plugged in'' to EvoLand as required to model particular processes.

The fundamental organizational structure used in EvoLand is shown in Fig. 1. Key elements in this organizational scheme are Policies, Actors, Actions, Policy and Cultural Metaprocesses, Autonomous Landscape Change processors, and Landscape Evaluators. Definitions for these key elements are provided below. Taken together, these elements provide a basic platform for assembling actor-based models of landscape change. Because many of these elements are ''pluggable'' software components, the basic EvoLand platform can be used with application-specific actor definitions, policy sets, autonomous process descriptions, and landscape evaluators.

3.2.1. Policies

Policies in EvoLand provide a fundamental construct guiding and constraining actor land use/land management decision making. Policies capture rules, regulations, and incentives and other strategies promulgated by public agencies in response to social demands for ecological and social goods, as well as factors used by private landowners/land managers to make land and water use decisions. They contain information about site attributes defining the spatial domain of application of the policy, whether the policy is mandatory or voluntary, goals the policy is intended to accomplish, and the duration the policy, once applied, will be active at a particular site. As actors assess alternative decisions about land management, they weigh the relative utility of potentially relevant policies to determine what policies they will select to apply at any point in time/space, is any. Once applied, a policy outcome is triggered that modifies one or more site attributes, resulting in landscape change.

Policies are characterized by two types of decision variables: (1) those required to be satisfied before the policy can be considered (also known as non-compensatory attributes or *constraints*); and (2) compensatory factors defining the intention of the policy at addressing specific goals, which can be ''traded off'' against other objectives in decision making using a multiobjective decision making algorithm. Further, policies may optionally be constrained to operating only with selected actor classes (e.g., all home owners, farmers with streams flowing through their property, forest owners with anadromous fish in adjacent streams).

3.2.2. Actors

In EvoLand, actors are entities (individuals or groups) that make decisions about the management of particular landscape units (IDU's) for which they have management authority, based on balancing a set of objectives reflecting their particular values, mandates, and the policy sets in force on the parcels they manage. They do this within the scope of ''policy sets'' that are operative on particular landscape elements over which they have decision making control. Fundamentally, actors are characterized by the values they express through their

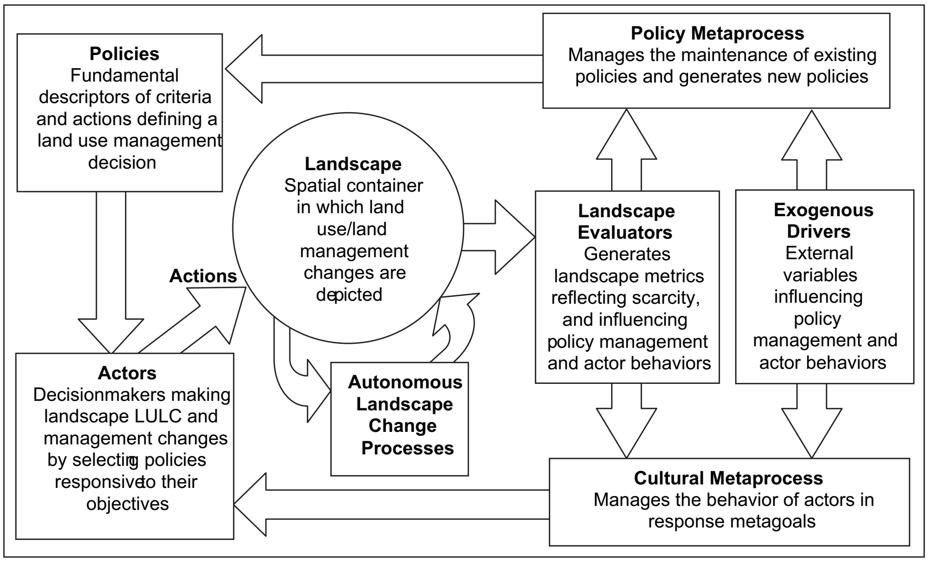

Fig. 1. Conceptual framework for EvoLand.

behaviors; examples might include ecosystem health, economic production, or property rights. These values are correlated with demographics characteristics and, in part guide the process actors use to select policies to implement; policies with intentions consistent with the actors' values are more likely to be selected by the actor for application.

In addition to actor values, EvoLand supports interaction between actors via two mechanisms: 1) neighbor influence on decision making; and 2) actor membership in *organizations* promoting a specific value system and capable of promulgating new policies consistent with the organization's values. Neighbor influence is intended to capture the concept of diffusion of innovation: i.e. if an actor observes a neighbor utilizing policies that result in a successful outcome consistent with the actor's value system, the actor is more likely to implement that policy. "Neighbor" is defined in terms of spatial proximity of the two actors; an alternative approach would generalize the location metrics to include non-spatial definitions of proximity, e.g. proximity of values systems.

Actor decision making is based on a stochastic multicriteria model that considers multiple factors to select policies the actor will implement. These factors include the consistency of the policy intention with the actor's values (based on the degree of self-interest the actor exhibits), the alignment of the policy intention with global measures of scarcity of various landscape productions (based on the degree of altruism the actor exhibits), and the degree of actor interaction with other actors successfully employing the policy. EvoLand allow the modeler to experiment with the relative weightings of these factors in exploring their effects on system behavior.

3.2.3. Policy Metaprocess

EvoLand employs two *metaprocesses* that reflect feedback loops that modify system behavior at a high level. The first of these, the Policy Metaprocess, modifies the policy set that is available to actors. The second, the Cultural Metaprocess, modifies actor behavior.

The Policy Metaprocess is responsible for generating new policies, modifying existing policies, and removing existing policies that are no longer relevant. An evolutionary model is employed to manage the adaptation and creation of policies responsive to scarcity measures, i.e. a *marketplace of policies* is created, where policies compete for success, defined in terms of measures such as: 1) the frequency with which a given policy is employed; and 2) the utility of the policy in addressing current scarcity issues. The Policy Metaprocess is an example of an adaptive process, using genetic operators (selection, crossover, mutation, and genesis) to evolve new policies based on recombination of successful policies, where the success ("fitness") of a policy is defined via the Landscape Evaluator metrics. This approach doesn't capture actual policymakers in the real system, but focuses more on metrics of policy success independent of who or what is actually creating those policies.

3.2.4. Cultural Metaprocess

The Cultural Metaprocess is responsible for adaptively modifying the behavior of actors in the systems. Actor behavior is defined by the value system used to guide decision making and its connections to other actors. The Cultural Metaprocess uses output from the Landscape Evaluator to change an actors values in response to shifting societal measures of scarcity, and manages the interactions between actors described previously.

The specific steps used by the Cultural Metaprocess are similar to that used by the Policy Metaprocess, and focus on allowing actors to adaptively modify their behaviors based on landscape feedback and interactions with other actors. The Cultural Metaprocess may (optionally) adjust actor values in response to changes corresponding to broad societal shifts in values as resources and production become scarce. Alternatively, the Cultural Metaprocess may manifest cultural processes though actor interactions, capturing the concept that as scarcities manifest themselves, the actor population responds through "experiments" that may/may not alleviate the scarcity, and that "successful" experiments spread through diffusion adoption resulting from actors observing successes achieved by other "nearby" actors with similar goals. These experiments are conducted through genesis and evolution of new policies, applied locally. Successful policies then have an opportunity to expand globally as an adaptive process. In essence, the system "learns" successful policies through experimentation by individual actors, with successful policies adopted by other actors as landscape attributes and actor interactions allow.

3.2.5. Autonomous landscape change processes

Landscapes change in response to a variety of factors other than human decision making. EvoLand support plug-in components that periodically change the underlying landscape, reflecting autonomous processes that occur independently of human actions. From an alternative futures modeling perspective, this enables EvoLand to incorporate these processes into the simulated trajectories of change. Examples of autonomous process models that have been developed for application using EvoLand include vegetative succession, river channel restructuring and meandering in response to flood events, or external human population influx and distribution. EvoLand provides a basic framework for incorporating application-specific autonomous processes into a landscape change model, and managing the interactions of these processes with policy-driven landscape modifications. Together, these provide a robust representation of change processes that can be adapted to a wide variety of situations.

3.2.6. Landscape evaluators

These components allow EvoLand to evaluate landscape production of metrics relevant to actor decision making. They are typically spatially explicit models that take a landscape, represented as an attributed coverage of IDU's, as input, and generate a suite of metrics related to a specific type of system production (e.g. ecological population abundances and diversity measures in the case of an ecosystem health-oriented goal; jobs and wealth production in the case of an economically-oriented goal.) The models provide measures of landscape performance and serve as a primary form of feedback considered by EvoLand. They also provide a point at which more traditional approaches to modeling may intersect with actor-based approaches, since these models do not directly interact with actors, but reflect actor influences on landscape change as well as indirectly influencing actor behavior via other mechanisms previously noted. In EvoLand, these models are plug-in components, allowing alternative representations to be readily compared to better understand the implications of specific representations and factors on system behavior, and allowing the extension of EvoLand into additional domains of consideration. Currently, EvoLand includes evaluators for aquatic macroinvertebrate habitat, riparian vegetative structure, fish species abundance and richness, terrestrial habitat, and market value of land.

3.2.7. Biocomplexity analyses

A primary rationale for an alternative futures model, as with any modeling effort, is to provide insights on system behavior. The traditional tools of model analysis (e.g. sensitivity analysis, model verification) are equally applicable to actor-based models. However, the intrinsic complexity typically captured in these models, and the generally long time frames they encompass, suggest a shift in emphasis from rigorous validation to a more exploratory approach to model use. In alternative futures analyses, we are typical more concerned with providing reasonable estimates of the bounds of system behavior than with prediction of specific outcomes, suggesting a Monte Carlo or similar approach focusing on characterizing the likelihood of realizing qualitatively distinct system behaviors. From a complexity perspective, the emphasis typically shifts again; analyses focus on system stability, identifying attractors in behavioral space, the nature and strength of these attractors, and the factors that tend to drive the system from one basin of attraction to another characterized by fundamentally different controlling processes, productions and behaviors.

Within EvoLand, we are just starting to experiment with various biocomplexity analyses; our current efforts focus on: 1) defining a set of experiments addressing the effects of various mechanisms of feedback processing and actor interactions on system behavior; 2) exploring mechanisms of policy evolution and capacity to generate innovative and effective policies as an adaptive process; and 3) characterizing the nature of the landscape state spaces to identify dominant attractors that persist under dynamic trajectories of change and the circumstances under which the landscape may move to an alternate attractor basin, and 4) vulnerability of landscapes to change under various policy scenarios.

3.3. Applying EvoLand – a case study in the Willamette Basin, Oregon

EvoLand is currently being used to conduct a series of alternative futures analysis in selected areas of Oregon's Willamette River Basin, aimed at better understanding the relationships and interactions between ecological, economic and social drivers of change to improve management of these areas. We are focusing on the confluences of major tributaries along the mainstem of the Willamette River, historically areas of both ecological richness and high anthropogenic impact. The study areas are characterized using spatial datasets incorporating land use and land cover, soils and hydrography, demographic, political and related cultural and physiographic datasets. The IDU's are determined using parcel-level information in combination with other vector coverages relevant to decision making, including floodplain delineations and riparian buffers. Actors are defined primarily through an analysis of demographic patterns; we are currently exploring the use of additional datasets to more richly characterize actor behavior. A number of goals/values are being considered, including ecosystem health, economic production, and landscape-level land use goals; each is represented by a landscape model that compute a set of metrics relevant to the particular goal considered. For example, ecosystem health is modeled using a suite of submodels that consider fish abundance and diversity, riparian vegetative structure, and upslope habitat quality; economic production submodels include wealth production expressed as market value of parcels. An initial set of policies are crafted based on current operative policies in the study areas as well as policies that are currently being contemplated. We focus primarily on land use/land cover change, using a 50 year analysis period and a stochastic analysis approach, using trajectories and patterns of change to determine likely development patterns, vulnerability of specific landscape areas to changes in capacity to provide ecological, economic and social productions of concern. Here, we address specifically the effects of policies that promote the development and conservation of riparian forests, or alternatively, urban development, near the edges of an urbanizing area in the Willamette River Basin. We are using EvoLand to: 1) explore the impacts of various feedback loops and interactions on system behavior, expressed though trajectories of change and the nature of the resulting attractor basins of the system productions described above; 2) identify policy characteristics that lead to more or less vulnerable landscapes; and 3) understand the critical linkages between the coupled human/natural systems that collectively generate landscape change.

Fig. 2 shows the initial (current) land use/land cover configuration of the study area, at the confluence of the McKenzie and Willamette Rivers. The initial land distribution in the study area was 36% urban, 32% rural (includes rural, agriculture, and other vegetation), 13% forest, 10% water, and 9% roads. EvoLand was set up to consider two alternative management strategies for lands in the riparian corridors of the study area. The first emphasized policies that establish and conserve forest land uses in these areas. The second emphasized urban development in these riparian corridors. Both policy sets were run independently for a 50-year planning horizon. Predicted landscape configuration for the forest-oriented policy set is shown in Fig. 3, and for the urban development-oriented policy set in Fig. 4.

After 50 years of promoting forest growth outside the urban growth boundary, the study area was predicted to contain 36%

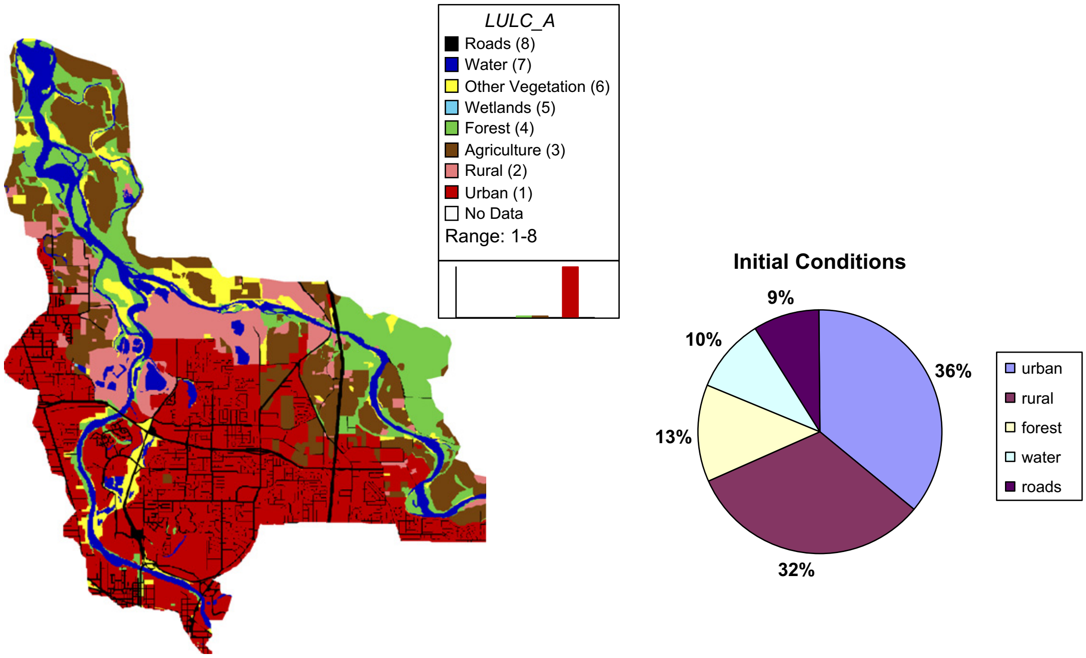

Fig. 2. Initial land use/land cover conditions for the McKenzie study area. Scale is approximately 15 km by 15 km.

urban, 6% rural, 40% forest, 10% water, and 9% road land uses. After 15 years, habit for fish improved, with results delayed reflecting the time needed for new forests to become mature (Fig. 5). Economic conditions moved more rapidly and were more cyclical, reflecting changes in urban areas. The urban area accommodates a population increase of 65% increasing urban population density from 15.5 persons/ha to 25.5 persons/ha. The value of forest land almost triples, while rural lands lose three-fourths their value. In this scenario rural activities shift to forestry, the total real market value (RMV) of land is a quarter greater at the end of the 50-year run. While this type of transition from agriculture to forestry has not occurred in the Willamette Valley, it is occurring in the nearby Coast Range of Oregon, and the modeling suggests that if the public wants fish and a viable rural sector, a shift to forestry is an option.

In November 2004, Oregonians passed a ballot measure that may limit the utility of urban growth boundaries to limit

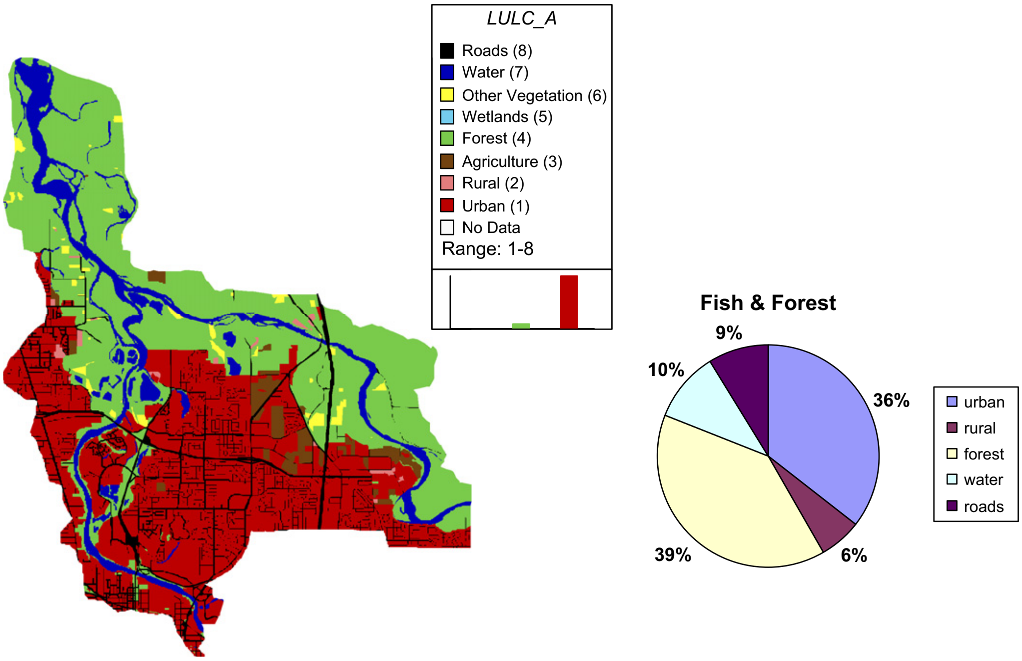

Fig. 3. Simulated land use/land cover conditions after 50 years under policy sets that promote forest establishment and conservation along riparian corridors.

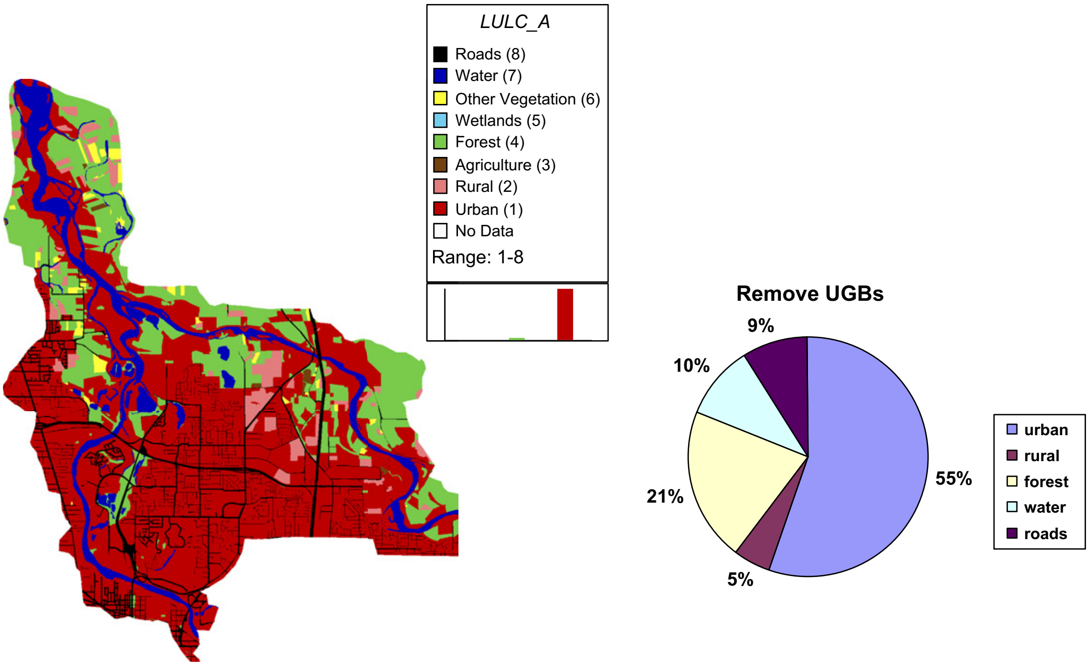

Fig. 4. Simulated land use/land cover conditions after 50 years under policy sets that promote urban development along riparian corridors.

urbanization. This is reflected in the second scenario where policies favoring urbanization (while also trying to grow forests and protect fish) are employed. This scenario shows the urban area expanding to 55% of the land base, rural uses decreasing to 5%, and forest uses growing to 21%. Urban population density increases by 1 person/ha. The RMV of forest lands increase, but not enough to offset the decline in agriculture. With roughly half the forest cover and people's preference to build along rivers, small stream health remains constant, but after 15 years, floodplain health declines precipitously by year 35 (Fig. 5).

The model questions whether the goal of urban growth boundaries to preserve agricultural lands and natural resources like fish is possible. Shifting the rural economy to forest products can improve rural economic health and fish health. Removing urban growth boundaries is predicted to result in the loss of fish and farms without a corresponding increase in the rural economy. Ecological effects in either scenario take on the order of 15 years to develop. Here, EvoLand results do not predict reality, but suggest possible consequences of actions and hypotheses to consider, and EvoLand provides a vehicle for beginning to explore these consequences and understand the drivers and feedbacks that may determine landscape change in a way that is extensible and amenable to multiple feedbacks.

Analyses such as these are fundamentally multiperspective, integrative, and spatially distributed; an actor based approach appears well suited to capturing the rich set of individual behaviors, distributed across a spatially heterogeneous landscape, that collectively result in the system-level patterns these systems display. EvoLand provides a reasonably flexible framework that allows adaptation of existing evaluative models into an actor-based modeling paradigm, and facilitates analysis of feedbacks, adaptive processes, and system behavioral response patterns. Significant issues exist, particularly related to sufficiency of actor characterization, model validation, and interpretation of the rich sets of spatial and temporal information produced by the model. The modeling community has yet to develop a broadly accepted set of approaches to these issues.

4. Future challenges

There remain many issues and challenges related to the use of actor-based models of biocomplex systems. Despite the wealth of discussions in the literature related to both biocomplexity and actor-based modeling approaches, few concrete examples of the use of actor-based models addressing biocomplexity issues have been presented; still fewer of these incorporate adaptive mechanisms and internal experimentation as fundamental aspects of representation. A key issue at this point is whether these approaches represent only a current fad, extensions to previous methodologies, or fundamentally new approaches to modeling and understanding complex systems. The complexity analysis models drawing from simpler physical systems have yet to be convincingly demonstrated to have real-word relevance to the more complex adaptive systems ecological and environmental modelers typically address. Our current models, particularly those addressing alternative futures analysis, are difficult to verify in any traditional way and new approaches and datasets are needed to validating these models. This will be a key challenge to allow more widespread acceptance of these models for real-world applications. We have yet to develop well-specified operational definitions of key concepts like resilience, vulnerability, and adaptation, although current models are beginning to make progress in

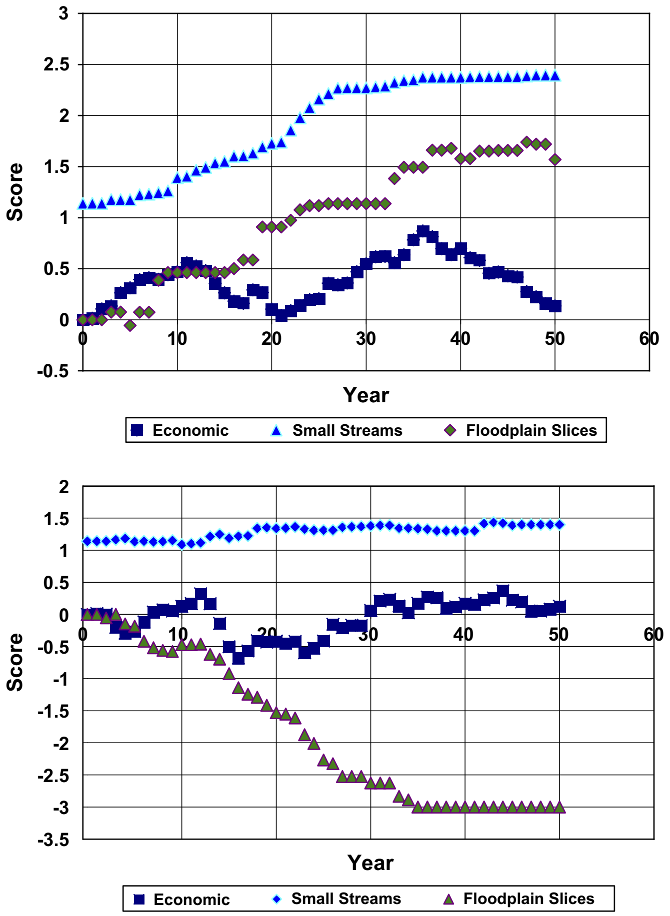

Fig. 5. Comparison of landscape evaluations for economic, small stream habitat, and floodplain vegetation results for forest establishment and conservation policies (top) and urban development (bottom) policy sets over 50 year simulation period. Scale is −3 to +3, with higher scores reflecting increasing production of the metric.

this area (e.g. Carpenter et al., 1999). Indeed, no widely accepted general theoretical framework for expressing biocomplexity concepts currently exists, much less a common set of approaches for representing this complexity in our models of these systems. However, a number of approaches are being developed and being applied to the analysis of real systems. In particular, actor-based modeling approaches are beginning to emerge and appear to provide a powerful tool for representing the wealth of individual decisions, actions, and interactions that frequently characterize these systems, particularly as adaptive processes are explicitly represented in these models. Models such as EvoLand provide examples for which operational approaches to representing and characterizing actors, adaptive processes, and interpretation of biocomplex responses are being developed.

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