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Designing Sustainable Landscapes: Ecological Systems

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A project of the University of Massachusetts Landscape Ecology Lab

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1 Problem Statement

The landscape change, assessment and design (LCAD) modeling approach originally envisioned for the North Atlantic Landscape Conservation Cooperative (NALCC) was based heavily on the use of ecological systems as an organizational framework for implementing landscape change processes (e.g., succession indexed by ecological system) and as the basis for evaluating and summarizing ecological integrity and habitat capability under alternative future scenarios (McGarigal et al 2017). In essence, ecological systems were to provide the overarching framework for the modeling. After thoroughly considering the use of ecological systems and the implications (both advantages and disadvantages) of doing so, it is clear that the use of ecological systems presents some serious challenges, and that modeling changes in their distribution as a function of, for example climate change, may in fact be intrinsically wrong. In this document, we briefly introduce the concept of ecological systems and the challenges of using them as an organizational framework, and then briefly outline four alternatives (that we considered) for their use in the model, including a summary of the advantages and disadvantages of each, and the preferred alternative.

1.1 What are Ecological Systems?

Ecological systems are defined by NatureServe (http://www.natureserve.org/publications/usEcologicalsystems.jsp) as follows:

> "Ecological systems represent recurring groups of biological communities that are found in similar physical environments and are influenced by similar dynamic ecological processes, such as fire or flooding. They are intended to provide a classification unit that is readily mappable, often from remote imagery, and readily identifiable by conservation and resource managers in the field."

At the coarsest level, ecological systems are divided into terrestrial and aquatic systems. NatureServe defines terrestrial ecological systems, for example, as follows:

> "Terrestrial ecological systems are specifically defined as a group of plant community types (associations) that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients. A given system will typically manifest itself in a landscape at intermediate geographic scales of tens to thousands of hectares and will persist for 50 or more years. This temporal scale allows typical successional dynamics to be integrated into the concept of each unit. "

1.2 The challenges of Using Ecological Systems

The concept of ecological systems, while appealing in many respects, offers three major challenges in the context of modeling non-equilibrium landscape dynamics, as follows:

1) Ecological systems are built on the underlying principle that climate and terrain interact to produce an abiotic environmental template upon which biotic processes and disturbance regimes play out to give rise to characteristic plant (and animal) assemblages. Importantly, implicit in this concept is the notion that the resulting spatial heterogeneity is relatively *discrete* at certain spatial and temporal scales, such

that ecological systems can be categorically delineated and mapped in a meaningful manner. Indeed, this is the basic premise of all classification approaches.

However, environmental heterogeneity (e.g., climate and terrain) is typically more continuous than discrete at ecologically relevant spatial and temporal scales, except where it is substantially influenced by human activities (e.g., the boundary between an urban lot and adjacent forest), making it exceedingly difficult to distinguish the boundaries or ecotones between ecosystems and delineate them on a map. Indeed, ecologists have long debated the "continuum" versus "community unit" concepts of ecological heterogeneity and now largely recognize the distinction as one of scale; specifically, that at some scales variation may be meaningfully expressed as discrete even though at finer scales the variation is ultimately continuous. However, if pressed, most contemporary ecologists would argue that in reality ecological relationships exist along continuous gradients at multiple spatial and temporal scales and along multiple ecological dimensions, and that classification and categorical maps are merely for convenience and to facilitate communication.

In light of this dichotomy, we have a choice as to whether to adopt the categorical framework of ecological systems, adopt a gradient approach void of any ecological classification, or adopt a hybrid approach that employs aspects of both paradigms.

2) Ecological systems are conceived as *multidimensional* entities that vary in climate, soils, topography, plant species, etc.. Implicit in the concept of an ecological system is the notion that this dimensionality can be effectively subsumed or collapsed into a single dimension -- the categorical classification. This is a basic premise of all multivariate classification approaches.

   However, techniques exist for preserving the multidimensional aspect of systems. Indeed, maintaining the full dimensionality of the ecological setting space within which ecological systems are defined avoids the errors and loss of information that generally results from reducing the dimensionality of the space. In addition, preserving the full dimensionality of the ecological setting space avoids the need for delineating hard boundaries among artificial classes or categories. Categorical maps subsume large (and typically unknown) amounts of error in the discrete classes. Preserving the original variables (i.e., the raw data) avoids any loss of information and error arising from collapsing the dimensionality and imposing artificial boundaries.

   In light of these considerations, we have a choice as to whether to adopt the one-dimensional categorical framework of ecological systems mapped as discrete entities, adopt a multi-dimensional framework that preserves the raw ecological settings variables and avoids delineating artificial boundaries, or adopt a hybrid approach that employs aspects of both paradigms.

3) Ecological systems were conceived as relatively stable (i.e., long-lived) systems under *dynamic equilibrium* conditions; i.e., where dynamic processes such as disturbance and succession operate within a stable range of variation, such that there is no directional change in the range of variability in ecosystem composition, structure and function. In other words, ecological systems were conceived as relatively static constructs, at least over periods of 50-100 years.

However, under non-equilibrium dynamics driven by directional climate changes, the utility of ecological systems, at least as originally conceived and mapped, comes into question. While climate is clearly a major driver of plant (and animal) distribution (and community development if you believe in communities), it is not the sole driver; terrain (e.g. soils and landform), which is largely unaffected by climate (at least in the short term), plays an important role as well. Moreover, species are differentially sensitive to these drivers, so that any change in any driver will likely affect species differently and at different rates (i.e., time lags in response to changes in drivers will vary among species). Furthermore, owing to differences in life histories and adaptations (e.g., dispersal vectors, mutualistic relationships with other species), species have different intrinsic capacities to expand their range in order to exploit newly favourable environments. For example, although the terrain might be suitable, and climate change models might forecast suitable climate conditions, such that all of the required ecological settings might exist for a cypress swamp in the Connecticut River valley in the year 2080, this outcome is highly unlikely for all the reasons discussed here. Consequently, the predominant view of contemporary ecologists is that under climate change, ecological "systems" and their characteristic species assemblages will slowly disassemble and gradually reassemble in constantly changing and novel ways that we do not understand and cannot predict. Moreover, it is likely that the expected ecosystem changes will be very slow, perhaps on the order of centuries, owing to the longevity of the dominant plant species in most ecosystems (e.g., long-lived trees in forests). Specifically, it is generally believed that barring catastrophic stand-replacing disturbances (which may be the most likely cause of the demise of an existing ecosystem), climate changes will not result in the mortality of the dominant plant species (e.g., trees), but rather will disproportionately affect establishment of new individuals. Consequently, the dominant plants will likely persist for the duration of their lifespan (e.g., centuries), even while the understory is gradually changing in composition. Overall, it is generally accepted that whole ecosystems will not (and cannot) simply uproot and move across the landscape to track changes in climate. Thus, contemporary ecosystems, as described by the dominant organisms, are likely to persist for quite some time.

In light of this realization, we have a choice as to whether to treat ecological systems as static (over the period of our simulation), treat ecological systems as mobile and allow them to move in space over time, or avoid using ecological systems altogether and instead allow points to migrate through a multi-dimensional ecological space independently.

2 Solution Statement

In light of the challenges of using ecological systems discussed above and after carefully considering the advantages and disadvantages of several alternative approaches (described below), we selected an approach in which ecological systems are used variably and only where necessary and deemed useful, but in which they do not provide the dominant organizational framework for the model. In this alternative, the idea is to decide on a case-by-case basis how to best use ecological systems, if at all, in the model process. Thus, some landscape change processes (e.g., succession) index cells by their current ecological system, other processes (e.g., ecological integrity assessment) use current ecological systems, but in a mercenary manner that is relatively insensitive to their precise classification and mapping, and other processes (e.g., urban growth) do not use ecological systems at all. Importantly, in this alternative, we treat ecological systems as static; i.e. they remain unchanged from their initial mapping in timestep 0. This alternative is considered in more detail with the other alternatives in section 6 below.

3 Alternatives Considered and Rejected

The use of ecological systems has bearing on several key components of the LCAD model, including: 1) succession, 2) coarse-filter ecological integrity assessment, 3) focal species assessment, and 4) future natural (e.g., insects, wind, fire) and anthropogenic (e.g., timber harvest) disturbance processes. We considered four alternative approaches regarding the use of ecological systems in the LCAD model. In this section, we briefly describe the advantages and disadvantages of each with regards to the landscape change and assessment components of the LCAD model.

3.1 Static Ecological Systems

In this alternative, ecological systems are used as the overarching organizational framework for the model and are treated as *static* (i.e., unchanging or stationary) over the course of the simulation. Each cell remains in the same ecological system over time in the simulation even though the settings variables change. Thus, the spatial extent and distribution of ecological systems remains constant over time despite climate change, and the model processes rely heavily on the systems for model parameterization. In this alternative, ecological systems play a major role in the model.

- *Succession*.--We derive separate vegetation growth curves for groups of similar ecological systems. Each cell follows the corresponding growth curve, which remains constant over time.
- *Ecological integrity assessment*.--We scale the integrity metrics by ecological system in timestep 0; subsequent timesteps under alternative scenarios are summarized by ecological system, which remains constant over time. Overall results are summarized by ecological system.
- *Focal species assessment*.--We use the ecological systems in the habitat model directly; e.g., by categorically assigning local resource values to each ecological system, which remains constant over time.

Advantages

- Adopts a categorical approach for representing ecological heterogeneity, which most users will find intuitively appealing and familiar, thus rendering the results more accessible to most users.
- Simplest by far to implement.

- Probably more realistic than alternative 2 if we adopt the concept of ecological systems, because time lags will prevent most systems from changing dramatically over a 80-100 year period. In other words, we avoid doing something that is intrinsically wrong -- allowing intact ecological systems to uproot and move to track favourable climate conditions in the near future.
- Makes scaling and assessing change in ecological integrity (coarse filter) relatively simple and straightforward.
- Makes building and parameterizing the habitat models (fine filter) intuitive and easier based on the existing literature and expert knowledge, since biologists often think about habitat associations in a categorical fashion.

Disadvantages

- Adopts a categorical approach for representing ecological heterogeneity, which is probably better represented as a multi-dimensional gradient.
- Intrinsically wrong, since we know that ecological systems cannot remain completely static under climate change -- but perhaps not as wrong as alternative 2 which treats ecosystems as completely mobile.
- Downplays (indeed minimizes) the importance of climate change in the model (especially in phase 1), since the impacts of climate change will be limited to an indirect effect on ecological integrity (via the adaptive capacity attribute) and an indirect effect on habitat (via altered disturbance regimes in phase 2 which change vegetation structure).
- Will not result in a dynamic map of ecological systems, which the Agency probably expects, however unrealistic.

3.2 Non-Stationary Ecological Systems

In this alternative, ecological systems are used as the overarching organizational framework (as in alternative 1) for the model and are treated as completely mobile or *non-stationary* over the course of the simulation. Each cell migrates through ecological setting space and potentially changes ecological system (albeit in a fuzzy classification way) over time in the simulation. Thus, the spatial extent and distribution of ecological systems shifts over time in response to climate change.

- *Succession*.--We derive separate vegetation growth curves for each ecological system. Each cell follows the growth curves for the ecological systems it is classified to based on the fuzzy classification derived from its ecological settings space, which may change over time.
- *Ecological integrity assessment*.--We scale the integrity metrics by ecological system in timestep 0; subsequent timesteps under alternative scenarios are summarized by ecological system based on the fuzzy classification, which may change at each timestep. Overall results are summarized by ecological system.

- *Focal species assessment*.--We use the ecological systems in the habitat model directly; e.g., by categorically assigning local resource values to each ecological system based on the fuzzy classification, which may change over time.

<u>Advantages</u>

- Adopts a categorical approach for representing ecological heterogeneity, which most users will find intuitively appealing and familiar, thus rendering the results more accessible to most users.
- Conceptually simple, since each cell belongs to an ecological system at each timestep (or multiple systems using the fuzzy classification).
- Makes building and parameterizing the habitat models intuitive and easier based on the existing literature and expert knowledge, since biologists often think about habitat associations in a categorical fashion.
- Maximum sensitivity to climate change; reveals the potential magnitude of future range shift in ecological systems and species' habitat -- even if it is not realistic; Agency may find this desirable.

<u>Disadvantages</u>

- Adopts a categorical approach for representing ecological heterogeneity, which is probably better represented as a multi-dimensional gradient.
- Intrinsically wrong, since we know that whole ecological systems cannot uproot and move across the landscape in response to climate change; less realistic than alternative 1 if we adopt the concept of ecological systems, because time lags and other constraints (e.g., static terrain) will prevent most systems from moving significantly over a 80-100 year period. In other words, we will project an unrealistic rate of change in the distribution of ecological systems. We are likely to produce maps of future ecological systems that do not pass the gut check (e.g., baldcypress swamps in Vermont).
- Requires that we derive a statistical model for predicting ecological systems based on the TNC provided map. In order to allow ecological systems to migrate over time, we would need to use a different set of predictor variables in our classifier than were used to derive the original map. Consequently, it is almost certain that we would do a relatively poor job of mapping these systems in a comparable fashion using our settings variables. Moreover, we would have no way of validating the model accuracy, so the results would remain questionable.
- The fuzzy classification of ecological systems makes the ecological integrity and habitat capability assessments much more complicated and computationally expensive.
- Greatly exaggerates the importance of climate change in the model, since the impacts of climate change will be realized as direct effects on ecological integrity and habitat via the shifting extent and distribution of ecological systems.

3.3 Full Gradient Approach

In this alternative, ecological systems are not used other than as a potential overlay on the results. Here, each cell simply migrates through ecological setting space over time in the simulation and is evaluated (in the coarse filter) against other nearby cells in ecological setting space. Note, here we would need to expand our settings variables to capture: 1) dominant vegetation life form (e.g., barren, herbaceous, shrubland, woodland, forest), and 2) composition of conifers versus deciduous species.

- *Succession*.--Unclear how to model this process given extant knowledge. Ideally, we would derive growth curves as a function of the ecological settings variables, so that growth at a cell would be determined by the unique combination of settings at that location and time. However, deriving these growth functions is beyond the scope of this project in phase 1. Alternatively, we derive separate vegetation growth curves for deciduous, coniferous and mixed forest in each ecoregion or geographic unit. Thus, instead of growth curves indexed by ecological system, they would be indexed by gross forest type and geographic location. Each cell follows the growth curves for the gross forest type and geographic location, which remains constant over time. Note, when Forest Vegetation Simulator (FVS) develops the climate module for the northeast, eventually these growth curves could vary with changing climate.
- *Ecological integrity assessment*.--We use gradient scaling of the raw integrity metrics, which are optionally post-hoc summarized by ecological system (which would either remain constant or vary over time as above); subsequent timesteps under alternative scenarios are summarized by ecological system in timestep 0 or by the fuzzy classification at each timestep. Overall results are summarized by ecological system. Note, while the gradient rescaling of the raw metrics is independent of ecological systems, the compositing of the metrics into an overall index of ecological integrity (e.g., intactness) does depend on the ecological models which are indexed by ecological system. Thus, this approach is not entirely free of ecological systems, but their importance is downplayed. We have not figured out a way to be completely free of some land cover classification in the integrity assessment.
- *Focal species assessment*.--Unclear how we would construct habitat capability models under the gradient approach without the use of species distribution data. Ideally, we would construct a statistical model of occurrence using the ecological settings variables as predictors, but even this approach is problematic since future combinations of settings are going to be unprecedented in the current database upon which the statistical models would be derived.

Advantages

- Adopts a multi-dimensional gradient approach for representing ecological heterogeneity, which is probably the correct approach.
- Fundamentally correct, since each cell moves independently through ecological setting space, without the need to classify it into an ecological system. Some dimensions are static (e.g., terrain), while others are dynamic (e.g., climate) -- which is reality.

- Avoids the need to map and/or model ecological systems which is fraught with challenges.
- Probably treats climate change the way it should be; doesn't under or over estimate the importance of climate.

Disadvantages

- Adopts a multi-dimensional gradient approach for representing ecological heterogeneity, which is going to be unfamiliar to most users, thus rendering the results less accessible to most users.
- Unclear how to best model succession; the approach outlined is complicated and thus difficult to understand for most users.
- Unclear how to construct habitat models without the use of empirical data on distribution -- which we are lacking for many species over the NALCC extent. Expert models would be difficult to create without the use of land cover classes.
- The ecological integrity assessment would still need to utilize ecological systems for purpose of constructing the models for ecological integrity; thus, this approach is not entirely free of ecological systems.
- If ecological systems are not used as an organizing framework, then it probably doesn't make sense to summarize results by ecological system, which many users may find unacceptable since many people are hard-wired to use classes.

3.4 Hybrid ecological systems

In this (our selected) alternative, ecological systems are used variably and as necessary and deemed useful, but they do not provide the dominant organizational framework for the model. In this alternative, the idea is to decide on a case-by-case basis how to best use ecological systems, if at all, in the model process. Thus, some landscape change processes (e.g., succession) index cells by their current ecological system, other processes (e.g., ecological integrity assessment) use current ecological systems, but in a mercenary manner that is relatively insensitive to their precise classification and mapping, and other processes (e.g., urban growth) do not use ecological systems at all. Importantly, in this alternative, we treat ecological systems as static; i.e. they remain unchanged from their initial mapping in timestep 0.

- *Succession*.--We derive separate vegetation growth curves for each ecological system. Each cell follows the corresponding growth curve, which remains constant over time. This is identical to alternative 1.
- *Ecological assessment*.--We use gradient rescaling of the raw integrity metrics, use static ecological systems for the models that combine scaled metrics into an index of ecological integrity (e.g., intactness), and post-hoc summarize the results by static ecological system; subsequent timesteps under alternative scenarios are summarized by ecological system at timestep 0. Overall results are summarized by ecological system. Note, this is identical to alternative 3, and is similar to alternative 1 except

here we employ gradient rescaling which downplays the importance of mapped ecological systems.

- *Focal species assessment*.--We use the ecological systems in the habitat model directly; e.g., by categorically assigning local resource values to each static ecological system, and separately develop a climate niche envelope (including abiotic and anthropogenic settings variables). This approach will provide us with change in suitable habitat, determined by ecological systems (static) and urban growth (dynamic), as well as changes in climate niche envelops over time. Thus, we will illustrate the potential disconnect between the spatial distribution of suitable habitat and suitable climate for each timestep. Where these distributions overlap we have high confidence of habitat being provided in the future, where they do not overlap we have low confidence of habitat being provided.

Advantages

- Makes use of ecological systems where they are needed and deemed useful, but does not embrace ecological systems as the sole organizing framework of the model -- which is a practical solution to the dilemma.
- Results will still be summarized by ecological system in the coarse filter ecological integrity assessment, which most users will find appealing, but the systems themselves have only a weak influence on the results because the gradient rescaling is free of dependency on ecological systems.
- Allows us to use ecological systems in the species' habitat models, which is helpful and intuitive to the experts; i.e., makes building and parameterizing the habitat models intuitive and easier based on the existing literature and expert knowledge, since biologists often think about habitat associations in a categorical fashion.
- Produces results in a format expected by the end users (i.e., organized and summarized by ecological system).

Disadvantages

- Conceptually complex; it does not possess a consistent conceptual framework for treating environmental heterogeneity; i.e., lacks purity in conceptual underpinning.
- The use of a hybrid approach makes the methods much more complicated and thus difficult to communicate and understand, which may make the results less accessible to many users.
- Ecological systems per se are treated static; thus, it does not produce a dynamic map of ecological systems over time, which many users probably expect.
- Requires us to create climate niche envelope models for species, which is going to be quite challenging without having data range wide -- which is impractical for many of the settings variables.

4 Major Implementation Constraints

There are no major implementation constraints with the selected approach for using ecological systems. In particular, where ecological systems are used in the model they will be treated as static and thus based on the original input map (http://www.natureserve.org/publications/pubs/NE_Hab_Class&Map_0708_FinalRept.pdf). Importantly, by treating ecological systems as static, we avoid the complex and undoubtedly unsatisfying effort of modeling dynamic ecological systems.

5 Major Risks and Dependencies

The major risk in the selected approach is a slightly underestimated effect of climate on landscape change and ecological assessment. This results because our approach treats ecological systems as static, when in fact they are dynamic -- but to a degree and at a rate of change that we simply don't understand. The uncertainty in predicting future ecological systems is simply too great to warrant treating ecological systems as mobile entities.

Because we are relying on data from outside sources, the accuracy of our model projections are directly dependent upon the accuracy of the ecological systems map -- which to our knowledge has not had a formal accuracy assessment. However, by downplaying the role of ecological systems as an organizational framework for the model, we hope to minimize uncertainty in the model results due to inaccuracies in the ecological systems map.

6 Literature Cited

McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2017. Designing sustainable landscapes products, including technical documentation and data products. https://scholarworks.umass.edu/designing_sustainable_landscapes/