SL321

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# Ecological Landscape Modeling: The General Application of an Existing Simulation Framework[1]

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## Introduction

Simulation models are explicit abstractions of reality and at best are tools that should provide insights into a better understanding of a particular problem. In the field of ecology, models can help organize or synthesize our understanding of the ecology of a system, and this understanding may also be applied in making relative comparisons among scenarios of future ecosystem changes. Depending on the objectives, there is a large variety of methods and tools that could be used in such scenario analyses. But because of the difficulty (i.e., time required) in implementing useful models for large or complex systems, it is attractive to employ existing tools.

Just as there are probably no truly "generic" problems in the strictest sense, it is difficult to conceptualize a truly "generic" model. Nevertheless, there are common classes of problems, and a generalized model could serve a useful purpose if the model objectives were pertinent to the class of problem. A highly constrained, well-defined portion of an ecosystem may be best assessed with a very simple model that assumes many ecological processes are unvarying or unimportant to the question at hand. On the other hand, many classes of problems in ecology involve understanding ecosystems that undergo changes at different scales and/or trophic levels, via the direct and indirect interactions inherent among the many components of an ecosystem. In such a class of problem, the requisite understanding may become apparent through modeling the cascading interactions in the system—i.e., its integrated ecology.

Intended for scientists and managers, this document is an overview of an existing, generalized model framework that synthesizes integrated ecosystem dynamics within large spatial domains and across decadal ecological time scales. Some aspects of the physical hydrologic "drivers" of this model framework were targeted to wetland environments, which is emphasized in places. However, the modeling system has been successfully applied to a wider range of terrestrial and aquatic ecosystems at multiple scales within large landscapes.

## *Integrated Ecological Models*

Our landscape modeling framework is intended to be flexible and applicable to a range of scales and

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ecosystems. In synthesizing the dynamic ecosystem interactions across a heterogeneous spatial domain, the model becomes a hypothesis of the physical, chemical, and biological dynamic interactions that are important to the function and structure of a simplified conceptual ecosystem (Figure 1).

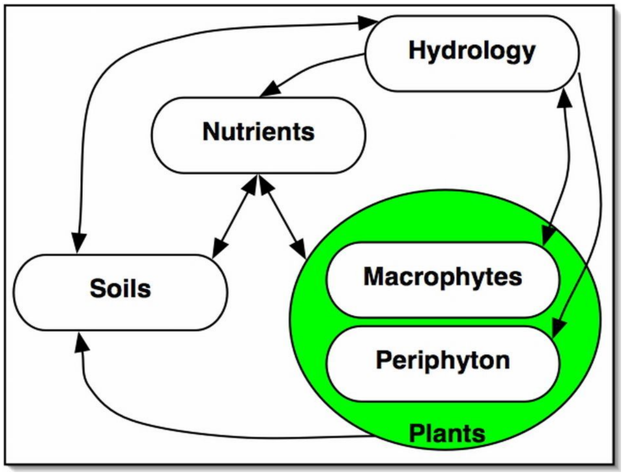


**Figure 1.** The pathways of dynamic interactions among primary modules of a simple conceptual ecosystem are shown.

The feedbacks among hydrology, nutrients, soils, and plants form the basis of the model framework, with the physical hydrology being a principal driver of ecosystem dynamics (e.g., Band 1993; Mitsch and Gosselink 2000). Interacting with these hydrologic dynamics are the nutrient transformations and transport: as the physical and chemical dynamics interact with the biological communities, the cumulative system dynamics define different ecosystem states under different conditions. As shown in earlier results (Fitz et al. 2004), the integrated model effectively simulated the feedbacks among general ecosystem processes, including the resulting patterns of soil properties and vegetative succession at the landscape scale.

### *Wetland Ecological Models*

While wetlands have a wide range of characteristics, ecological models of these systems share at least one general goal: to understand the ecological responses to varying magnitudes and frequencies of flooding (Fitz and Hughes 2008). Regardless of the specific objectives and the level of model complexity, a principal driver of wetland models is flooding and associated surface soil saturation. These wetland physics influence the selection of the implicit or explicit ecological processes to be considered in model development. Hydrology is thus an important consideration in the spatial and temporal scales of the model (Figure 2).

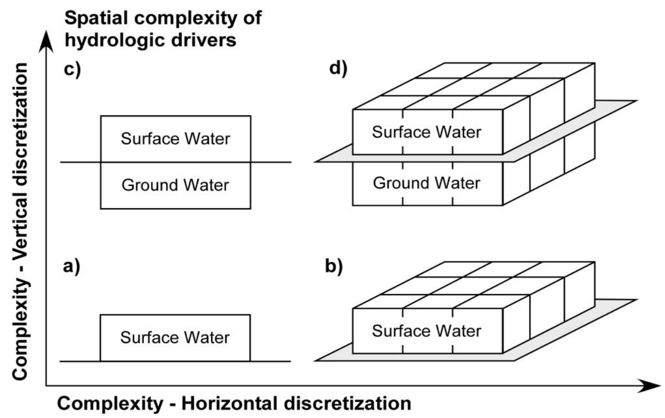


**Figure 2.** Reprinted from Fitz, H. C. 2008. Ecological models: Wetlands. In: S. V. Jorgensen and B. D. Fath (Eds.), *Encyclopedia of Ecology Vol. 5*. Elsevier, Oxford, UK. pp. 3780-3790, with permission from Elsevier. Spatial discretization of the hydrologic component of wetland models largely determines the questions that can be addressed. a) Simplest case, with ponded surface water depths of a single unit area; b) Horizontal extension of surface water across multiple spatial units; c) Vertical stratification of surface and ground water storages; d) Complex case of both vertical and horizontal spatial discretization, which is implemented in the model(s) discussed here.

Horizontal and vertical transport processes establish the basis for biogeochemical transformations of nutrients in shallow surface waters and upper soil layers. Soil accumulation and loss combine with vegetative and algal dynamics to lead to varying trajectories of habitat type in space and time. Integrated models across this spectrum of ecological process complexity are usually limited by our state of knowledge, particularly over long time scales. In combination with directed research and monitoring, the diversity of ecological modeling in wetlands is leading to improved understanding of wetland dynamics. In an era of increased management of wetlands, judicious application of this model-based knowledge should aid in more informed decisions regarding the fate of wetlands.

### *Everglades Modeling Examples*

In planning for Everglades restoration, predictive simulation models are one of the suite of methods being used to evaluate the relative benefits of management alternatives. The primary model used in the original Comprehensive Everglades Restoration Plan (CERP) was the South Florida Water Management Model (SFWMM), which simulates rule-based water management and the resultant water levels in the South Florida urban/agricultural and natural systems (Tarboton et al. 1999). In further evaluating and refining individual CERP projects, hydrologic output from this model continues to be used to predict the relative benefits of alternative scenarios of water management towards system restoration.

In addition to that hydrologic model, ecological and water quality simulation tools were used in the original CERP planning to explore potential ecological dynamics under altered water management. Several spatially explicit species index models and individual (agent)-based models (DeAngelis et al. 1998) estimated the responses of animal species to different water depths among management scenarios. Walker (see Kadlec and Walker 1999) applied a water quality model of Stormwater Treatment Area wetlands to estimate phosphorus loads into the Everglades marshes, and the Everglades Water Quality Model (EWQM, Raghunathan et al. 2001) evaluated the resulting phosphorus fate and transport within the Everglades. Both of those water quality models calculated a simple net loss of total phosphorus from the surface water column, aggregating the multiple biogeochemical processes with several simple equations. While the EWQM was discontinued, significant refinements were subsequently made to the other ecological and water quality simulation tools.

A variety of other models have been developed to help address hydroecological uncertainties within the Everglades marshes. For example, Larsen and colleagues developed fine (local) scale models (Larsen et al. 2007; Larsen et al. 2009) to evaluate hypotheses of the water flow regimes needed to restore the anisotropically patterned peatlands of the ridge and slough habitats of the Everglades. A "next-generation" water management model (Regional Simulation Model, Lal et al. 2005) is starting to be applied by the South Florida Water Management District to selected areas of South Florida. Moreover, a new, process-based water quality model (Jawitz et al. 2008) is being integrated with the Regional Simulation Model for Everglades-wide water quality applications.

## Modeling Framework

The Everglades Landscape Model (ELM, http://ecolandmod.ifas.ufl.edu/models) is a model application that serves as an integrated simulation framework for wetlands and adjacent upland habitats in the greater Everglades region; it is currently the only available tool for evaluating water quality throughout the region. As an existing application that is available for assessing Everglades restoration (http://www.evergladesplan.org) alternatives, it has been thoroughly scrutinized. Most recently it was reviewed by an independent panel of experts, who affirmed its utility for such applications (Mitsch et al. 2007).

While this specific model was refined for Everglades applications, its design was "specifically" crafted to be general to a range of ecosystems and scales. Consisting entirely of open source software, the model uses the highly configurable Spatial Modeling Environment (SME) that solves General Ecosystem Model (GEM) algorithms for a range of ecosystems and scales. With appropriate (GIS-based) map inputs, and changes to database parameters and environmental forcing data, the modeling (code and data) system can be implemented for a variety of landscapes. Indeed, across ecosystem comparisons are one of the research applications of the ELM.

This section is a brief overview of the different component tools that are used in this modeling. The information is mostly from the Everglades application of the SME/GEM; in addition, these modeling tools were used in the watershed of the Patuxent River (Maryland, U.S.A.) to develop the Patuxent Landscape Model (Voinov et al. 1999; Costanza et al. 2002). Related to these efforts are earlier process-oriented landscape simulations in the coastal marshes of Louisiana: the Coastal Ecological Landscape Spatial Simulation, or CELSS, (Sklar et al. 1985; Costanza et al. 1990) and the Barataria-Terrebonne Ecological Landscape Spatial Simulation, or BTELSS, (Reyes et al. 2000; Martin et al. 2002) used simpler "unit" models than described here and specialized computer code for the modeling environment.

### *Spatial Modeling Environment*

The Spatial Modeling Environment, or SME v.2, (Maxwell and Costanza 1995) is the high-level modeling environment that we have used and modified in ELM development. The spatial modeling services of the SME (Figure 3) may be thought of as a comprehensive modeling tool kit for spatial ecological models, with hierarchical modules that perform tasks such as linking spatial map (GIS) data with ecological algorithms and flexible management of input/output. Map data including habitat type, elevation, and canal/river vectors are maintained in GIS layers that are input to the model. Other databases store time series inputs (e.g., rainfall) and parameters that vary with habitat (e.g., growth rates). The comprehensive data structure organizes the information and alleviates the need to recompile the model code when evaluating the results of different model scenarios.

Raster cell surface and groundwater flows in the horizontal dimension are solved using a finite difference, Alternating Direction Explicit technique, providing for propagation of water and water-borne constituents (e.g., salt and nutrients) across space. Vertical integration of surface and groundwater flows are calculated within the groundwater module, using an iterative mass balance approach that evaluates storage potentials following overland and groundwater flows.

Rivers and canal/levees are represented by a set of linked vector objects that interact with a specific set of raster landscape cells. This allows for horizontal flux of water and dissolved constituents over long distances (along multiple grid cells) within a time step. Within each vector (e.g., canal) reach, water and dissolved constituents are distributed homogeneously along the entire reach, with an

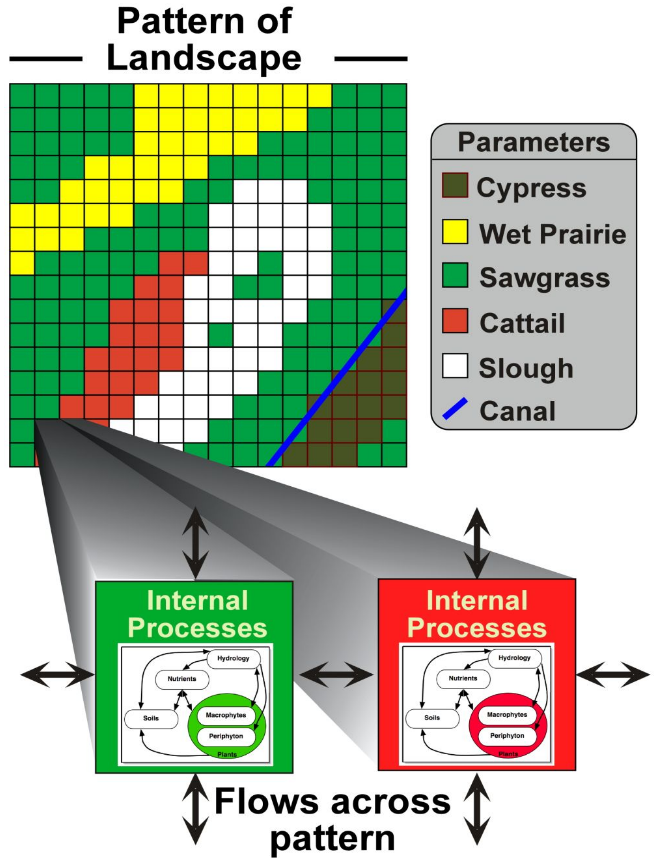


**Figure 3.** The Spatial Modeling Environment (SME) conceptualization of how the "unit" model of general ecosystem dynamics is applied across the heterogeneous spatial grid of different habitat types is shown. Each habitat type within the patterned landscape can be parameterized differently, affecting the internal process dynamics within different grid cells. In turn, the results of the internal processing can affect the direction and magnitude of the flows of water and nutrients across the landscape pattern. Succession, or switching, of habitat types can occur as cumulative conditions warrant.

iterative routine allowing exchange among the grid cells along the vector.

Succession of one habitat type into another is simulated with a simple switching algorithm based on the cumulative effects of environmental variables. For example, in the ELM, counters were incremented based on the time that levels of soil phosphorus concentrations and of ponded water depths exceeded their respective thresholds for each simulated habitat type. Other rules can be quickly encoded to evaluate alternative hypotheses of habitat succession depending on simulation objectives.

### *General Ecosystem Model*

The horizontal fluxes of water and constituents that were described above largely define the 2-D physical transport in a landscape. The vertical solutions of the landscape simulation are calculated in modules of a generic "unit" ecosystem model. An overall goal was to develop a model structure that was generalized enough to make intercomparisons of different ecosystems with one unit model. We avoided structure- or process-specific details that may vary among distinct ecosystems, such as upland forests vs. graminoid wetlands. Instead, we strived to characterize the commonalities in ecosystem processes, keeping the ecosystem model simple and general (Fitz et al. 1996).

The unit model is comprised of linked modules for different ecosystem components, including water, phosphorus, chloride, periphyton, macrophytes, flocculent detritus, and soils (Figure 4). In its spatially distributed application, user-selected modules are executed for each grid cell within a landscape. The grid cells are assigned an initial habitat type, with different habitats potentially having unique parameter values that define processes such as nutrient uptake kinetics or surface roughness for overland flows. Thus, the pattern of habitats in the landscape can influence material fluxes among cells in the landscape, and the within-cell ecosystem dynamics can lead to ecosystem changes and succession that alter the landscape pattern. Within the spatial modeling framework, the model provides an integrated synthesis of ecosystem processes over large time and space domains for use in better understanding and evaluating ecosystems across heterogeneous landscapes.

Applying this in a spatial framework, we have been able to make useful predictions on a wide spectrum of ecological dynamics that describe ecosystem function in various habitat types in temperate and subtropical landscapes (Fitz and Sklar 1999; Voinov et al. 1999; Costanza et al. 2002; Fitz et al. 2004; Fitz and Trimble 2006). Two critical ecosystem drivers in the Everglades landscape are hydrology and nutrient dynamics. As shown in the above manuscripts, we have calibrated and validated the ELM for these dynamics at a range of spatial and temporal scales. With appropriate simulation of the physical and biogeochemical dynamics of the Everglades, we have effectively simulated the response by macrophytes and algal communities, including their feedback on the system physics and chemistry. Evolving the landscape through vegetative succession in a simulation depended strongly on these dynamics.

### *Open Source*

The Open Source code and data necessary to build and run an ELM project is freely available (under the GNU General Public License) on the World Wide Web http://ecolandmod.ifas.ufl.edu/models/getmodel.html. The model is thoroughly documented at a hierarchical level of detail, ranging from the broad goals and concepts targeted to lay audiences to details of code and data that are mostly pertinent to model developers.

No model is complete without data. In the same download of the source code, all data required for implementing the ELM project are freely available on the World Wide Web. Many of those data (e.g., spatial time series database of daily rainfall) are mainly applicable to the landscape of the Everglades. However, many of the ecological parameters may be representative of similar ecosystems in other regions of the world, if only as initial estimates when site-specific data are lacking.

The first complete, public-release version of the ELM (v2.5) in 2006 was associated with a comprehensive documentation report, along with numerous Web-based supplements. Associated with each subsequent public release are updates to that documentation set (ELM v2.8 was released in August 2009). All documentation is found at: http://ecolandmod.ifas.ufl.edu/publications/.

## General Applications

The SME/GEM has been developed for a broad class of ecological landscape model applications, and the ELM is a "mature" and well-tested instance that continues to be refined and applied to the Everglades. With the greater Everglades region encompassing diverse ecosystem types (Fitz 2010), this application

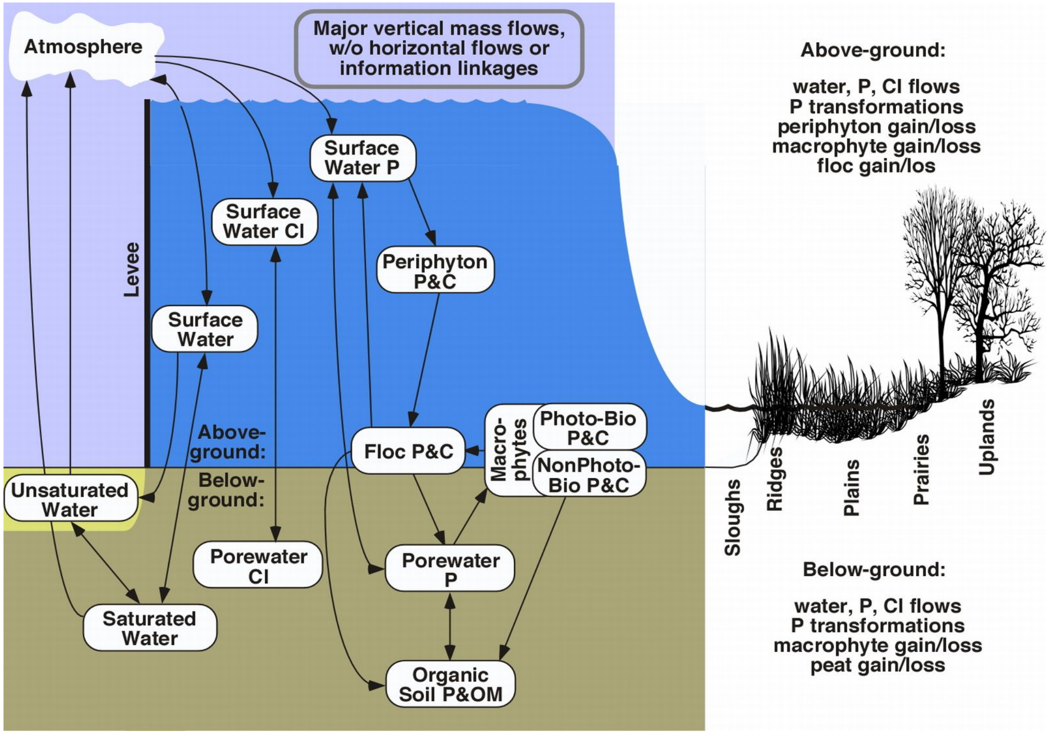


**Figure 4.** The details of the conceptual model of vertical solutions of ecosystem processes are shown. Model state variables are in oval boxes, linked by the major flow pathways among those variables. The periphyton (algal/microbial community) state variables can be considered functionally equivalent to an aquatic algal community. Abbreviations: P = Phosphorus; C = Carbon; Cl = Chloride; OM = Organic Matter; Photo-Bio = Photosynthetic Biomass of macrophytes; NonPhoto-Bio = NonPhotosynthetic Biomass of macrophytes; Floc = Flocculent detritus layer on/above soil.

serves as a useful test bed for continued collaborative developments in landscape modeling in general. From estuarine mangrove forests to freshwater cypress swamps, graminoid marshes, prairies and upland pine habitats, the landscape poses stimulating challenges to ecological synthesis. Given the range of systems that have been modeled, this framework has significant potential for application outside of South Florida.

### *Scalability*

Different problems call for different scales of analysis. In the Everglades, assessment of regional water quality gradients is accomplished using the ELM with a grid resolution of either 500 or 1,000 meters (depending on objectives) across a broad landscape domain larger than 10,000 square kilometers. The same model is being used to explore local ecosystem processes that are responsible for fine-scaled landscape patterns at resolutions of tens to hundreds of meters. Simply changing the input maps and boundary conditions allows the model framework to be used to assess landscapes at a wide range of spatial and temporal scales: the ELM has been applied at annual, decadal, and century time scales; in spatial domains differing by orders of magnitude; to explore research hypotheses; or to support landscape management decisions. To the extent possible, this inherent scalability of applications will be maintained as the model framework is further developed.

### *Module Extensions*

The ecosystem processes considered in the GEM unit model are a core component of the modeling framework, with spatial interactions being integral to understanding the evolution of the landscape. For the Everglades region, and for other applications, there are a suite of extensions and enhancements that have been identified for further development. For example, while "hooks" have been designed for their incorporation into the ELM, spatially explicit fire disturbance modules have not yet been incorporated and are important to exploring vegetative succession in such a fire-impacted landscape. Similarly, the algorithms for succession itself may be enhanced with other rules for neighborhood interactions within a gridded landscape.

More generally, refinements to the vertical solutions of the GEM unit model have been identified. For application within South Florida and elsewhere, particulate sedimentation and erosion in aquatic systems can significantly alter the structure of the landscape. Nitrogen is assumed to be unlimiting in the Everglades application of GEM, and consumer dynamics are not considered. While all of these dynamics were encoded in the original development of the GEM, they were "excised" from the Everglades application for simplicity. For future applications, these modules may be reinstated into the modeling framework. However, a potentially more attractive approach may be to incorporate other more recent modules, making use of libraries of modules (Voinov et al. 2004) that may best meet the overall objectives. For these and other objectives, we hope to obtain guidance from colleagues to best advance the tools available in this framework.

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