An agent-based model for coastal ecotone dynamics

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Ecosystems are dynamic webs of interacting agents expressing emergent and transformative behaviors. In particular, coastal ecosystems are strongly interconnected to nonstationary environmental dynamics. Attempting to understand such systems with reductionist or linear paradigms is likely to be problematic. Here, we develop an agent-based model of coastal ecotone vegetation dynamics at the southern terminus of the Florida peninsula.

Ecotone | Coastal Dynamics | Agent-based model

Introduction

Coastal ecotone dynamics express the adaptation of terrestrial, estuarine and marine ecosystems to morphological landscape changes in response to perpetual and nonstationary environmental dynamics. Such changes are based on a web of complex interactions and feedbacks between the biota and environment. Given the inherent nonlinearity and interdependence expressed in such dynamics, one would expect that linear systems analysis is likely to provide unsatisfying results [1]. As noted by Jiang et al. [2]: "While habitat transitions can be abrupt, modeling the specific drivers of abrupt change between halophytic and glycophytic vegetation is not a simple task. Correlative studies, which dominate the literature, are unlikely to establish ultimate causation for habitat shifts, and do not generate strong predictive capacity for coastal land managers."

To illustrate this, Jiang et al. [2] developed a simplified coastal ecotone transition model with cellular automata containing positive feedbacks wherein species can change environmental conditions towards niche optimums, demonstrating that both abrupt environmental gradients and internal positive feedbacks can generate sharp ecotonal boundaries. Further, recognition of the need to engage analytical paradigms not reliant on linear constraints has been provided by DeAngelis [4], wherein recent developments in application of nonlinear dynamical systems theory are advocated. For example, Ye et al. [5] demonstrate the identification and clarification of sockeye salmon population and environmental interactions with empirical dynamical modeling (EDM), and Ushio et al. [6] identify dynamical changes in interaction networks of multispecies fish communities.

We are motivated to develop an agent-based model to identify and quantify coastal ecotone vegetation and landscape feedbacks both structurally, and informatically, eventually leading to an information-theoretic framework of nonlinear systems dynamics.

Vegetation Mapping. As a component of the Comprehensive Everglades Restoration Plan (CERP), the Department of Interior conducts a comprehensive vegetation mapping project [3]. This effort leverages the emergent power of remote sensing and spatial information processing, providing unprecedented levels of ecosystem detail and specificity. Figure 1 shows the vegetation mapping regions within Everglades National Park.

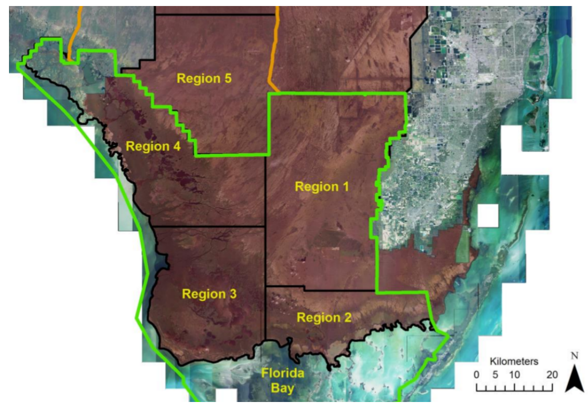

Fig. 1: Vegetation mapping regions within Everglades National Park.

The vegetation assessment assigns a landscape characterization code, the *vegetation code*, to 50 m x 50 m patches throughout a region. The vegetation codes derive from a tree of descriptors starting with one of seven overall landscape types, with additional code elements providing increasing levels of landscape and ecosystem specificity as illustrated in table 1.

Table 1: Vegetation code examples.

Code	Description	Code	Description
A	Aquatic	AM	Aquatic Marsh
F	Forest	FH	Hardwood Hammock
E	Exotic	Es	Brazilian Pepper
C	Scrub	CS	Swamp Scrub
S	Shrub	SMa	Black Mangrove Shrubland
M	Marsh	MFG	Graminoid Freshwater Marsh
W	Woodland	WM	Mangrove Woodland
O	Other	ONS	Barren Salt Flat

Everglades Region 2. Ruiz et al. [3] recently completed a comprehensive vegetation survey of the southern Everglades coastal (Region 2, figure 1). A map of the relative species composition is shown in figure 2, where the inset in red demarcates a subset of Region 2 where the agent-based model is applied.

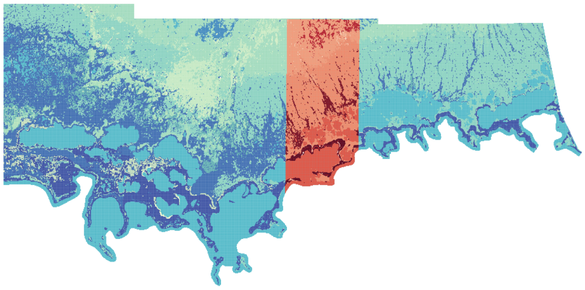

Fig. 2: Region 2 domain (blue) with subset (red).

Agent-based modeling

Agent-based modeling can be viewed as an evolution of cellular automata [7], finding good success in the analysis of ecosystem complexity and interactions [8]. Agent-based models consist of dynamically interacting rule-based agents operating in a decentralized, interconnected paradigm accommodating emergence and natural complexity. NetLogo is a programmable modeling environment for simulating complex phenomena in an agent-based framework [9], and is the modeling platform we employ to investigate coastal ecotone dynamics.

NetLogo distinguishes four types of agents: Patches, Turtles, Links, and Observers. Patches represent the world in a grid of cells. Turtles represent agents that operate in the world, interacting with patches and each other. Links provide connections between agents. Observers allow interaction between agents within, and external to the model domain. Our model defines agents for the dominant vegetation species (turtles), agents for the landscape cells (patches), and interactions between agents as described below.

Model Domain. The model is applied to the Region 2 subset shown by the irregular polygons in figure 3. The rectangular grid along the top of the region represents the 400 x 400 m grid of the Everglades Depth Estimation Network (EDEN) providing timeseries data on landscape water depths [10].

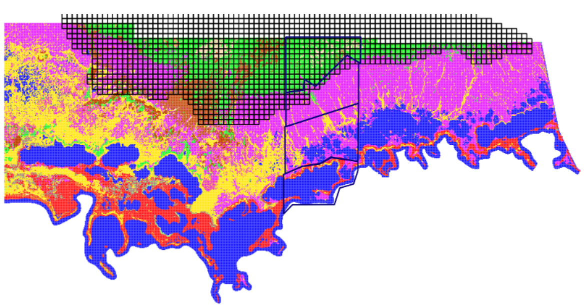

Fig. 3: Region 2 with EDEN grid (top) and subset domain.

The model domain in NetLogo is a grid of 32,214 patches (118 x 273) corresponding to a spatial domain of 5,900 x 13,650 m. Patches correspond to the same 50 x 50 m vegetation classification map developed by Ruiz et al. The domain wraps horizontally, but not vertically. The patch origin is `(x=0, y=0)` in the lower left corner.

The vegetation map specifies vegetation codes on each cell, but a vegetation code represents a landscape classification with possibly multiple species. Since we are interested in species and landscape interactions, we desire model agents that represent individual species. We therefore transform the vegetation map into a species-centric representation with species binomem explicitly identified on each 50 x 50 m cell of the map. A table of the primary fields in the transformed GIS table is shown in table 2.

In our model, turtles represent vegetation species. Turtles are initially sprouted on patches according to the transformed GIS vegetation map. Turtle behaviors governing their interaction with the environment are codified in rules, which may be probabilistic. Patches also have behaviors, and there is no limit between the interactions and feedbacks that can be expressed in behaviors between agents.

Table 2: GIS database fields.

Vegetation GIS Table		Timeseries GIS Table	
Field	Value	Field	Value
Species	Sawgrass	Salinity_G	LM
Binomen	Cladium jamaicense	Stage	Cell_5_183
Veg_Code	MFGcSD	Zone	EDEN
Abundance	70		
MinAbundan	50		
MaxAbundan	100		
MaxHeight	2		
CoHabit	NA		
Matrix	NA		
Description	Short Sawgrass Marsh		
NAVD88_Ft	-0.208		

Model Data. Environmental data are informed through the NetLogo `time` extension, with daily mean water levels and salinities provided as timeseries input to patch agents. The link between timeseries and patches is specified in a separate timeseries GIS layer as noted in table 2. For each patch in the model domain, water depth and salinity are read from the input timeseries files according to the `Stage` and `Salinity_G` field values in the GIS layer as shown in figure 4. The rectangular cells along the top correspond to 3 x 3 blocks of EDEN cells, with the daily water level extracted from the center EDEN cell of the 3 x 3 block. The lower three irregular polygons correspond to relatively uniform topographic contours, with access to hydrographic station data within each zone. For example, the Little Madeira (LM) observational station in the lower zone.

Note that model patch topographic and water level elevation data are with respect to the NAVD88 in centimeters.

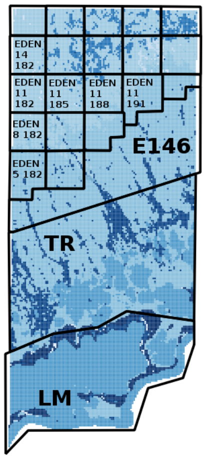

Fig. 4: Agent-based model domain with zones for water level and salinity timeseries input.

Model Methods. As a programming language, NetLogo combines aspects of procedural programming with automata-based programming. Procedural programming relies on procedures or subroutines to change the state of variables and model elements, arranged in a modular hierarchy. Automata-based programming can be viewed as a generalization of finite state machines, with aspects of event-driven programming. NetLogo programs conventionally have `setup` and `go` procedures, the latter being executed in a loop sequencing through the agent procedures.

The `setup` procedure loads the timeseries input data, loads the GIS shapefiles representing the vegetation map and timeseries zones, initializes patches with data from the GIS layers, and sprouts turtles on the patches according to the GIS vegetation map species for each cell. The `go` procedure iteratively calls the vegetation agents and a `propagation` agent governing species succession as vegetation dies in response to environmental feedbacks.

A typical vegetation agent (turtle) assess whether the vegetation on a particular patch has been stressed enough to die. For example, *Cladium jamaicense* (sawgrass) contains assessments of hydroperiod (greater than 180 days dry), water depth (greater than 90 cm), and porewater salinity (greater than 5 parts-per-thousand for 20 days). All of these assessments can be made probabilistically to simulate individual plant tolerances.

The `propagation` agent queries the surrounding patches to see what vegetation species are neighbors. If vegetation on the patch has died, and environmental conditions are conducive for the neighboring species, then a neighboring species can establish on the vacant patch according to a probabilistic rule.

A useful aspect of the model is that as vegetation turtles die, the date of death and reason are logged in the turtle variables.

Model application. The model user interface and display is shown in figure 5. The user can specify the start and end dates, and the number of days for each timestep.

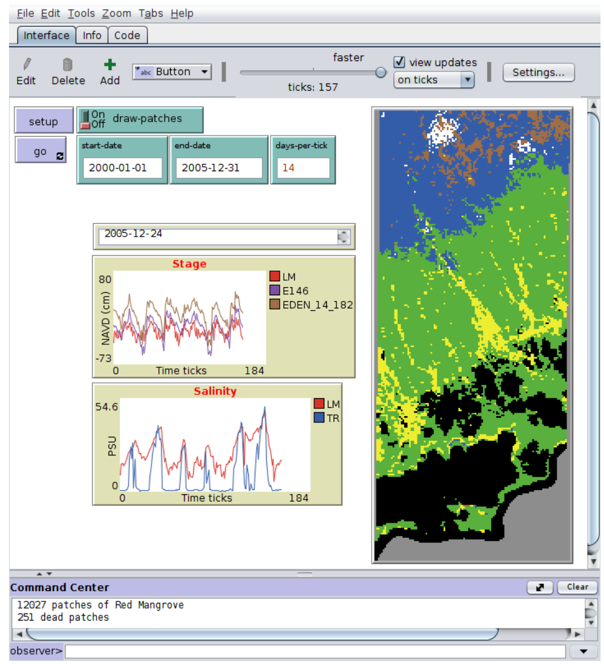

Fig. 5: User interface for the agent-based model.

Input data for patch water level elevation and salinity span the period from June 1, 1994 to May 15, 2017. Examples of the input data tables are shown in table 3. These tables can be updated or replaced to represent different environmental forcing scenarios.

Table 3: Example timeseries input data.

	Water Salinity (ppt)				
Date	LM	MK	TR		
1994-06-01	27.6	37.0	18.1		
1994-06-02	26.9	35.6	15.1		
2017-05-14	33.1	41.5	29.2		
2017-05-15	33.3	41.3	30.6		
	Water Elevation NAVD88 (cm)				
Date	LM	TR	E146	Cell_5_183	Cell_5_185
1994-06-01	-19.44	-9.84	-8.84	11.86	21.66
1994-06-03	-26.64	-12.94	-11.54	12.76	22.86
2017-05-14	-19.42	-16.04	-18.84	-1.94	4.96
2017-05-15	-18.77	-15.04	-19.64	-2.94	3.56

Model Access. The model is accessible *via* GitHub at https://github.com/SoftwareLiteracyFoundation/Ecotone.

Conclusion

The model is currently in development. Additional expertise and collaboration is needed to complete the agent behaviors, conduct model assessments, suggest and enact model improvements, and to document model applications.

Future intentions are to "calibrate" the model corresponding to observed vegetation changes over time [11] so that anticipated coastal change scenarios can be forecast. Additionally, quantification of dynamic feedbacks between agents can be assesed leading to structural information of ecotone dynamics. These feedbacks and morphological changes can be analyzed in a multidimensional phase-space using empirical dynamical modeling to empirically determine causal links between agents.

1. Kruger J., and Dunning D., Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. Journal of Personality and Social Psychology, Vol 77(6), pg. 1121-1134 http://psycnet.apa.org/journals/psp/77/6/1121/ (1999).

2. Jiang Jiang, Donald L. DeAngelis, Su-Yean Teh, Ken W. Krauss, Hongqing Wang, Haidong Lie, Thomas J. Smith III, Hock-Lye Koh. Defining the next generation modeling of coastal ecotone dynamics in response to global change. Ecological Modelling, 326, 24 April 2016, 168-176. https://doi.org/10.1016/j.ecolmodel.2015.04.013 (2016).

3. Pablo L. Ruiz, Helena C. Giannini, Michelle C. Prats, Craig P. Perry, Michael A. Foguer, Alejandro Arteaga Garcia, Robert B. Shamblin, Kevin R. T. Whelan, Mary-Joe Hernandez. The Everglades National Park and Big Cypress National Preserve Vegetation Mapping Project, Interim ReportSoutheast Saline Everglades (Region 2). Everglades National Park Natural Resource Report NPS/SFCN/NRR2017/1494. August 2017. https://irma.nps.gov/DataStore/DownloadFile/583479 (2017).

4. Donald L. DeAngelis and Simeon Yurek, Equation-free modeling unravels the behavior of complex ecological systems. PNAS 112 (13) 3856-3857. https://doi.org/10.1073/pnas.1503154112 (2015).

5. Ye H., et al. Equation-free mechanistic ecosystem forecasting using empirical dynamic modeling. Proc Natl Acad Sci USA 112:E1569E1576. http://www.pnas.org/content/112/13/E1569 (2015).

6. Ushio M., Hsieh C., Masuda R., Deyle E., Ye H., Chang C., Sugihara G., Kondoh M. Fluctuating interaction network and time-varying stability of a natural fish community. Nature, 554, 360. http://dx.doi.org/10.1038/nature25504 (2018).

7. Schiff, Joel L. *Cellular Automata: A Discrete View of the World*. Wiley & Sons, Inc. ISBN 9781118030639. (2011).

8. Grimm V., Railsback S. *Individual-based Modeling and Ecology*. Princeton University Press. pp. 485. ISBN 978-0-691-09666-7 (2005).

9. Wilensky, U. NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL. http://ccl.northwestern.edu/netlogo/ (1999).

10. Telis P.A., Xie Zhixiao, Liu Zhongwei, Li Yingru, and Conrads P.A., The Everglades Depth Estimation Network (EDEN) Surface-Water Model, Version 2: U.S. Geological Survey Scientific Investigations Report 2014-5209, 42 p., doi 10.3133/sir20145209. (2015).

11. M. S. Ross, J. F. Meeder, J. P. Sah, P. L. Ruiz and G. J. Telesnicki, The Southeast Saline Everglades Revisited: 50 Years of Coastal Vegetation Change. Journal of Vegetation Science, 11(1), 101-112. http://www.jstor.org/stable/3236781 (2000).