A Process-Based Cellular Automata Model of Ridge and Slough Landscape Evolution

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The ridge and slough landscape is a longitudinally patterned, topographically and vegetationally heterogeneous portion of the Everglades that has experienced widespread degradation over the past century. Degraded ridge and slough landscape exhibits a loss of heterogeneity (typically, a loss of sloughs) and slough connectivity. The landscape is now a focus of restoration efforts, and a firm process-based understanding of ecohydrological feedbacks governing landscape evolution is needed. Leading hypotheses of dominant processes in the ridge and slough landscape include a differential peat accretion feedback in ridge and slough vegetation communities responding primarily to surface-water depth, duration, and frequencies, and a sediment redistribution process governed by flow that affects peat topography and vegetation distribution. A cellular automata model of the differential peat accretion feedback and flow/sediment feedback was formulated as a means of testing whether these processes could individually or together reproduce actual landscape structure. The model was based on laboratory and field experiments and high-resolution, partial differential equation-based solutions of velocity profiles to ensure that it captured essential physical details while remaining computationally efficient.

Separate modules within the cellular automata model simulated flow in longitudinal and lateral dimensions, the entrainment, deposition, and transport of floc, the net balance between in-place organic matter production and decomposition, and vegetative propagation of *Cladium*. The flow module was simplified but based on the depth-averaged Navier-Stokes equations and was dominated by the balance between gravitational forcing and vegetative resistance. Mean flow velocities and bed shear stresses were solved using two-dimensional lookup tables based on high-resolution Reynolds-averaged Navier-Stokes simulations of velocity profiles in ridge and slough vegetation communities. Simulated bed shear stresses were coupled to a partial differential equation for advection, dispersion, settling, and entrainment of suspended floc. Both the functional relationship between bed shear stress and entrainment flux and the single effective floc diameter were determined from laboratory experiments that quantified the entrainment, settling, and aggregation of floc. Differential peat accretion on ridge and slough was simulated using a regression relationship with water depth as the independent variable. The regression relationship was based on a numerical model of the differential peat accretion feedback, which was parameterized using results of field and laboratory experiments. Lastly, a vegetative propagation rule ultimately responsible for lateral expansion of peat was formulated.

Natural-system simulations covered a range of surface-water depths and flow velocities representative of pre-drainage conditions. For certain combinations of uncertain fitting parameters, the model predicted emergence of a ridge and slough landscape with dimensions very similar to well-preserved portions of the actual landscape. At early time steps, ridge locations shifted and some of the nascent ridges disappeared, consistent with paleoecological studies of the ridge and slough landscape. However, at later time steps, ridges remained permanent fixtures, and the relative coverage of *Cladium* asymptotically stabilized. Ridge morphology lay on a continuum between features dominated by flow, which were narrow, closely spaced, and highly linear, and features dominated by vegetation growth and expansion, which were more rounded and irregular. A strong flow influence produced landscapes in which the major axis of ridges was within $< 5^{o}$ of the flow direction, ridges had high length-to-width ratios, and sloughs remained interconnected over the long term. While no-flow runs preserved landscape heterogeneity through a simple feedback between water level and the volume of the model domain occupied by peat, *Cladium* features produced in these runs were amorphous, had high variability in orientation, and surrounded isolated sloughs.

Perturbing a well-developed ridge and slough landscape by decreasing mean water level or flow velocity resulted in a rapid expansion of ridges into sloughs, similar to the widespread expansion of *Cladium* observed throughout the actual landscape in the past century. Over the range of surface-water depths and velocities practical for the Everglades under current bed slopes but restored flows, conversion of slough cells to mature ridge cells was irreversible, due to the difficulty of attaining bed shear stresses above the entrainment threshold in dense *Cladium*. However, if vegetational heterogeneity were re-initialized, model results predict its long-term maintenance under restored flow conditions through differential peat accretion and flow/sediment transport feedbacks.

In summary, the cellular automata model qualitatively predicts how the ridge and slough system responds to hydrologic forcing. Key findings of the model that are relevant to restoration are:

- Feedback between two distinct mechanisms is needed to explain the evolution of the ridge and slough landscape. First is the differential peat accretion mechanism that introduces topographic heterogeneity through an autogenic peat accumulation process, and second is a feedback caused by interactions between topographic heterogeneity, vegetation, and flow that reinforces landscape morphology through redistribution of sediment from sloughs to ridges. Individually these mechanisms are not sufficient to explain the origin of the ridge and slough landscape. In addition, episodic events such as hurricanes are not a necessary precursor for the sediment redistribution that supports landscape formation and maintenance.
- Topographic and vegetative heterogeneity of the landscape can be preserved by water level management alone, but flows that induce sediment transport are necessary for interconnected sloughs to persist. However, if sufficient in magnitude, these flows can be intermittent, of a total duration less than 3 weeks/year.
- Vegetation pattern structure responds rapidly to shifts in water level, with decreased surface water levels causing an expansion in the relative coverage of *Cladium.*
- It will not be feasible to restore sloughs to *Cladium* monocultures by manipulating water level and surface water slope alone. However, once *Cladium* is removed by other means, appropriate management of surface-water hydrology could potentially maintain a topographically and vegetationally heterogeneous landscape with high habitat connectivity over the long term.

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