Relative Importance of Hydro-Ecological Processes Governing Self-Organization of the Everglades Ridge and Slough Landscape

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The flow-parallel ridges and sloughs of the central Everglades formed centuries ago and remained relatively stable until relatively recently. Although degradation of a large area of ridge and slough during the past century is well documented – the actual processes responsible for degradation are much less certain. The origin of the ridge and slough landscape is hypothesized to involve complex feedbacks between hydrologic and ecological processes, including flow and vegetative flow resistance and its role in redistributing sediment from topographically lower to higher areas, influences on differential rates of peat accretion, and corresponding adjustments of the plant communities. The National Research Council recently highlighted the need to incorporate measurements of flow and suspended sediment in the performance measures being used to judge restoration progress. Two of the key uncertainties are the velocity threshold for entraining organic sediment in sloughs, and the net exchange of suspended sediment between sloughs and ridges. USGS measurements are focused on quantifying these and other uncertainties in field measurements and experiments, and also modeling the connections between flow and transport and ecological processes on longer timescales ranging to centuries. Our ridge and slough simulation model is being used to identify the key factors responsible for both origin and degradation of ridge and slough pattern that will help prioritize the most fruitful restoration strategies. What follows is a synthesis of the USGS team's recent research and its implications for restoration.

- Average ambient velocities measured in the Everglades are typically on the order of 0.3 cm s^{-1} in central WCA-3A and 0.7 cm s^{-1} in Shark Slough.
- Flow was primarily through sloughs at our study location in central WCA-3A. The average flow velocity was 30% higher and the flow discharge per unit-width was more than 100% higher in sloughs compared with ridges over the 3-year measurement period. The ridge-slough difference in flow velocity was small relative to 2 - 3 times greater velocities associated with gravity waves that propagate through WCA-3A as a result of sudden pulses of water released from WCA-2A through water control structures. Severe storms such as Hurricane Wilma also locally increased flow velocity for short periods of time (by as much as 10 times).
- In general the most effective management actions that increase flow velocity will be the ones that increase water-surface slope rather than those that simply increase water depth. Pulsed flow operations at water control structures are potentially an effective means to increase water-surface slope and flow velocity, although the high velocities needed for floc entrainment possibly can only be restored for short periods of time and only in small areas of the Everglades, i.e. similar to what can be expected from severe storms.
- Our field flume experiment with enhanced flow determined that relatively fine particles associated with plant stems are entrained at a flow velocity between 0.38 and 1.73 cm s^{-1}, in other words, at relatively high velocities but not untypical conditions in the present-day Everglades. Fine suspended particles are important in transporting carbon and

phosphorus (P) downgradient, although their ultimate role in ridge and slough landscape processes remains uncertain.

- Entrainment of the larger floc particles from the sediment bed occurred at substantially higher velocities (between 3.3 and 6.4 cm s^{-1}) that are rare in the present-day Everglades. The critical bed shear stress threshold for floc entrainment in the Everglades is 1.0×10^{-2} Pa, with the greatest increase in entrainment flux occurring between this threshold and bed shear stresses of 2.0×10^{-2} Pa. Depth-averaged velocities at which these bed shear stresses are obtained vary with vegetation community, flow depth, and water surface slope. Under current water-surface slopes in the Everglades, floc entrainment by flow will never occur in densely vegetated *Eleocharis* sloughs and will rarely occur in sparser deep-water sloughs. However, redistribution of floc from sloughs to ridges by flow can be restored by a combination of reducing *Eleocharis* abundance and releasing pulses of water from impounded areas that temporarily increase water surface slope. Above surface-water depths of approximately 45 cm, bed shear stresses vary little with water level but remain highly sensitive to water surface slope.

- 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 reinforce 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. At a bed shear stress of 2.0×10^{-2} Pa, two weeks of flows that induce sediment transport will result in an annual scour rate in sloughs equivalent to the spatially averaged rate of peat accumulation throughout the ridge and slough landscape.

- Water management has decreased surface water levels across large areas of the Everglades, and vegetation patterns in many of those areas responded with expansion of *Cladium* and *Eleocharis.* Although the feasibility of promoting dieback of *Cladium* just by increasing water level has been demonstrated, we predict that it will not be feasible to restore a ridge and slough pattern just by increasing water level. Increasing surface water slope and water depth are necessary to restore and maintain sediment redistribution patterns, but may not be sufficient without reducing vegetation frontal areas in remnant sloughs with at least a "one-time" mechanical removal of *Cladium* and *Eleocharis*. Once vegetation frontal area is removed from remnant sloughs, our modeling suggests that surface-water slope and depth can be successfully managed to maintain a topographically and vegetatively heterogeneous ridge and slough landscape with high habitat connectivity.

- Suspended sediment holds an important proportion of surface water total P, in relatively labile forms, despite its low abundance. Higher discharge results in greater downstream transport of labile particulate P with sloughs transporting more material than ridges. Everglades water quality models should more routinely consider the transport and fate of dissolved and particulate forms of P.

- Our measured concentrations and other characteristics of suspended sediment and associated nutrients were similar in adjacent ridge and slough under the current hydrologic regime. This finding was not predicted by our modeling of a stable ridge and slough system, which suggests that the present-day ridge and slough system is not sustainable with present velocities.
- Restoration of greater water flow through the Everglades likely will result in faster spread of P from the phosphorus hotspot in northern WCa-2A through increased particulate and dissolved P transport to down-gradient areas. Our modeling indicates that along with diminished flows, increased P is also a primary factor promoting loss of Everglades ridge and slough landscape structure. As a result, the goal to contain excess P may interfere with the goal of restoring increased flows.

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