

The Role of Flow in the Everglades Ridge and Slough Landscape

Science Coordination Team
South Florida Ecosystem Restoration Working Group
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Executive Summary

The Everglades has at the core of its identity the slow movement of water across the vast, low gradient, wetland landscape. Marjory Stoneman Douglas eloquently immortalized this identity in her descriptions of the “River of Grass” (Douglas 1947). Drainage and compartmentalization efforts during the 20th century for flood control and water supply purposes interrupted this flow, as well as altering water levels, distribution, and seasonal timing. Water flows are closely linked to water levels, and their alterations have caused environmental damage. Efforts to restore the Everglades have focused on re-establishing more natural hydropatterns – the appropriate water levels, and the location, timing, and duration of these water levels. While these natural hydropatterns are widely recognized as being extremely important, much less attention has been paid to the importance of the actual movement of water, the physical and ecological roles that movement of this water plays, and how management activities have altered that flow. Thus, the Science Coordination Team has chosen understanding the science of the role of flow in the Everglades as one of its priorities. The purpose of this paper is to provide a stimulus for increasing the level of understanding and awareness of the role of flow in restoration activities, and to highlight the urgent need for research in this area.

Pre-drainage Everglades hydrology was dominated by a remarkable flow regime – a 30-mile-wide expanse of water moving down the low-gradient wetland landscape from north to south. Surprisingly, although Everglades hydrology has flow as one of its defining characteristics, most discussions of hydrology in the Everglades exclude mention of the role of water movement. The movement of water in aquatic ecosystems such as wetlands is a fundamental construct of ecosystem structure and function, and its ecosystem role is well-established. It is likely that water movement plays a similar vital role in the Everglades.

The ridge and slough landscape, one of several major habitat types in the Everglades, originally consisted of a peat-based system of dense sawgrass ridges interspersed with adjacent and relatively open sloughs. These parallel ridges and sloughs existed in an organized pattern, oriented parallel to the flow direction, on a slightly sloping peatland. Unfortunately, compartmentalization and related water management activities are resulting in the loss of this ridge and slough landscape. This loss is evidenced by replacement of the characteristic ridge and slough landscape with a landscape that is more topographically and vegetationally uniform. It is clear that 1) the Everglades ridge and slough landscape has changed, and is continuing to change significantly; and 2) the landscape changes are having detrimental ecological effects on Everglades plants and animals. It is likely that these changes are the result of altered water flow and hydropattern caused by human-made barriers and shunts, interacting with corresponding changes in water depth and water level fluctuations.

The mechanisms causing the loss of ridge and slough landscape likely are complex, are occurring over a time scale of decades or more, and restoration decisions will have to be made on a time frame shorter than decades. A number of mechanisms for the formation and maintenance of the ridge and slough landscape are proposed, including: sediment transport; changes in water depth under managed conditions; differential rates of peat accumulation and decomposition; erosional formation; extreme hydrological events; fire; underlying bedrock patterns; and microhabitat differences in water chemistry. The presence of flow is necessary for almost all of these mechanisms to operate, and it is likely that a combination of several of these mechanisms operating together is responsible for formation and maintenance of the ridge and slough landscape.

The mechanisms of ridge and slough landscape degradation are not fully understood. However, it is likely that barriers to flow, including levees and canals, contribute significantly to the conversion of the ridge and slough wetland mosaic to more uniform stands of sawgrass. Conversion of the ridge and slough landscape pattern to uniform sawgrass stands has had, and will continue to have, deleterious impacts on Everglades plants and animals. An Everglades landscape increasingly dominated by dense sawgrass stands supports fewer numbers of animals and a lower diversity of animals. The control of vegetation over wading bird ecology is strong enough that Kushlan (1989) states, “Whatever determines vegetation patterns will also, to a large degree, determine bird use of wetlands.” Wading birds are an important component of the Everglades ecosystem. Their foraging and nesting success often are used as indicators of the overall health of the system, and they are one of the most visible and highly regarded fauna of the Everglades. The conversion of ridge and slough landscape to dense sawgrass stands has had a negative impact on wading birds and other important birds of the Everglades. Negative impacts of these landscape changes extend throughout the Everglades food web, including fish, which are important food for wading birds. In addition to altering flow patterns and wetland landscape patterns, barriers to flow serve as barriers to movement of aquatic animals.

Very few research studies have been conducted specifically to determine the role of flow in the Everglades ecosystem. Most of the research projects from which data are presented in this paper, while relevant to the role of flow, were not designed to determine the role of flow. It is precisely for this reason that the Science Coordination Team chose the topic of flow as one of its priorities. Recommendations for future research are prioritized, and include: a multidisciplinary paleoenvironmental study; a thorough geomorphic review; sediment transport studies; synoptic and time series measurements of flow; development of a carbon balance model; remote sensing; and others.

Finally, additional performance measures are recommended for the ridge and slough landscape for the monitoring and assessment of the Comprehensive Everglades Restoration Plan (CERP) progress. These measures, largely based on expanded collection and analysis of remotely sensed images, include: aerial extent and temporal trends of sawgrass ridge, slough, and tree island polygons; edge-to-area ratios for landscape types; average length-to-width ratio and temporal trends of sawgrass ridges or sloughs for a defined area; and spatial orientation of the three landscape types as compared to their historic orientations.

Background

The Everglades, referred to as the “River of Grass” by Marjory Stoneman Douglas in her famous book of the same title (Douglas 1947), has at the core of its identity the slow movement of water across the vast, low gradient, wetland landscape. Drainage and compartmentalization activities for flood control and water supply purposes during the 20th century caused unintended environmental impacts. As restoration of the Everglades has proceeded to reverse these impacts, most of the attention to restoring more natural hydro patterns has focused on water levels, and the timing, duration, and distribution of water levels. Much less attention has been paid to the importance of the actual movement of water through the Everglades, and how management activities have altered that flow. The Science Coordination Team (SCT) has provided this paper as a stimulus for increasing the level of understanding and awareness of the role of flow in restoration activities, and to highlight the urgent need for research in this area.

The SCT, formed in 1997 as a successor to the Science Sub-Group by the South Florida Ecosystem Restoration Task Force, consists of scientists and managers from federal, state, and local government, and two Indian tribes. The SCT’s Charter (SCT Charter 1997) charges the team with ensuring the highest level of communication, coordination, and cooperation in the application of scientific disciplines to the south Florida restoration effort. In 1999, the SCT revised its work plan to more narrowly focus on scientific topics most relevant to present ecosystem restoration efforts. The SCT membership chose five priorities, one of which was to examine the role of flow in the Everglades ecosystem. This priority addresses a specific SCT responsibility stated in the SCT Charter – to identify key gaps in management information and propose research and data collection to address these needs.

As the first step toward examining the role of flow, the SCT sponsored a flow workshop at the Greater Everglades Ecosystem Restoration Science Conference, held in December, 2000, in Naples, Florida (<http://conference.ifas.ufl.edu/everglades>). This workshop included panel presentations, discussions, audience questions, and solicitation of one and five-year research priorities from the 100+ persons in the audience. A summary of that workshop was produced (<http://sofia.usgs.gov/geer>) and contains an overview of the panel presentations and the research priorities that were developed.

As a second step, the SCT prepared this paper, which builds on the flow workshop by examining the role of flow in the ridge and slough landscape. While the focus of this paper is on the ridge and slough physiographic region, the SCT recognizes that flow also occurs widely throughout the freshwater and downstream estuarine regions of the greater Everglades. In general, ideas about the role of flow in these other regions are much less well developed, and are not addressed comprehensively in this paper.

There are two main purposes of this paper: 1) to increase awareness among scientists and resource managers of the importance of flow to Everglades restoration, and 2) to provide scientists with background information and data to stimulate further discussion and research, and to recommend specific areas for future research. This paper does not attempt to prove or disprove the various mechanisms proposed for creation and maintenance of the ridge and slough landscape. In fact, the paper highlights the current lack of scientific data needed for proof.

Rather, it attempts to lay the groundwork for the type of data and research needed, to provide a thoughtful and scientifically sound foundation upon which to better understand the ridge and slough landscape type, and to ensure that it is protected and restored. The SCT envisions that this information will be useful at all levels of restoration effort, including the Comprehensive Everglades Restoration Plan (CERP), the Modified Water Deliveries Project, and other restoration programs at the regional and local levels.

It should be noted that under ideal circumstances, water flow, water levels, and all aspects of the Everglade's natural hydropattern should be restored via implementation of CERP. Because anthropogenic alterations of the historic system are so extensive, it may be difficult to achieve all aspects of hydropattern restoration simultaneously. This difficulty may force tradeoffs when restoration decisions are made. Understanding more about the significance of flows to Everglades restoration will make these resulting tradeoffs easier to evaluate.

Flow is defined as the continuous motion of a fluid (Morris 1992). For the purposes of this paper, flow is the actual movement of water across the Everglades wetland landscape. The time rate of flow is velocity, which is a vector quantity whose magnitude is expressed in units of distance over time, such as inches per second (Morris 1992). In addition, the concept of flow in the Everglades includes consideration of the spatial distribution of that flow across the wetland landscape. It is important to distinguish this definition of flow from discharge (volume of water per unit time), and from the more general concepts of hydropattern, which include water levels, duration of water levels, timing of water levels, and distribution of water levels.

Introduction

The defining characteristics of the Everglades

The Everglades has much in common with other wetland ecosystems in the world, as well as some unique characteristics. The Everglades is characterized by the presence of peat, the importance of water flow, its location in a subtropical climate, and the nutrient limitation that exists, particularly for phosphorus. The presence of peat and nutrient limitation make the Everglades comparable to other peatlands in northern climates (e.g., Foster et al. 1983, Foster and Glaser 1986), as well as regionally specific types such as the Pocosins (Richardson 1981). The role of flow suggests that the Everglades might be viewed as fen (peat marsh with non-acidic soil) rather than an ombrotrophic peatland. However, its subtropical location, and, perhaps, its hydrological connection to Lake Okeechobee, are regional modifiers which distinguish it from other peatlands in the scientific literature.

With respect to vegetation, many of the plant species present in the Everglades are found elsewhere along the Gulf Coast, including the Mississippi River Delta (Penfound and Hathaway 1938). The delta of the Mississippi River also is characterized by moving water, and has plants common to the Everglades such as sawgrass (*Cladium jamaicense*) and maidencane (*Panicum hemitomon*). In addition, there are islands of bald cypress (*Taxodium distichum*) in the coastal marshes of the Mississippi Delta.

The role of moving water in wetlands

The movement of water in flowing water aquatic ecosystems is a fundamental construct of ecosystem structure and function, and its ecosystem role is well-established and studied. Flowing water has the ability to alter the landscape, which, in turn, has the ability to alter the landscape's ecology. Although much less studied in Everglades wetlands, the flow of water across vast expanses of low-gradient marshes was one of the defining characteristics of the river of grass. The flow of water in streams and rivers has been the topic of much research, and stream ecologists are well-versed in the importance of flow. Although water flow is much slower in the river of grass (typically less than one inch per second under present managed conditions [Ray Schaffranek, USGS, unpublished data]), it may be just as important to the ecosystem. Water movement plays a number of roles, including transporting, mixing, and diluting dissolved and particulate materials, the removal of metabolites, and influencing the location and type of aquatic organisms (Allan 1995). Many aquatic organisms orient their bodies to flow and use flow to direct their movements in the flow channel either positively or negatively (Welch 1963, Hynes 1970). The speed of the water flow also determines a number of physical features, including the size of eroded and suspended sediment particles, and the physical force that organisms experience in the water and on the bottom.

Research has been conducted on flow in other wetland systems that bear many similarities to the Everglades (Gregory Pasternack, personal communication). For example, the role of flow in floodplains, river deltas, and tidal marshes has been examined, and they share several characteristics with the Everglades, such as low gradients, dense herbaceous vegetation, fine-grained sediments, abundance of peat, and cohesive bottom substrates. These characteristics result in flow patterns that may be more complex than those of rivers and streams. Flow over a wide vegetated surface has dampened velocity fluctuations, higher turbulent dissipation, a complex vertical velocity profile, and significantly reduced lateral velocity profile relative to open channels.

Historical flow patterns

The historic Everglades was part of a much larger drainage system, originating in south-central Florida in what is now known as the Upper Chain of Lakes near Kissimmee, Florida. The lake system formed the headwaters of the Kissimmee River, a 100-mile-long, meandering, low-gradient river that emptied into Lake Okeechobee (Fig. 1). The lake, much larger than its present-day surface area of 1,750 km², would spill over its southern rim during high water events into the northern part of the Everglades, dominated by vast sawgrass plains. Eventually, the southward movement of water through the sawgrass plains formed the source of water for the ridge and slough landscape. In this sense, the historic Everglades may be viewed as the lower reaches of the Kissimmee River.

The central feature of the pre-drainage Everglades hydrology was a 30-mile-wide expanse of relatively shallow water moving downstream through the low-gradient wetland landscape. The pattern of water flow was remarkable for its regional uniformity across such a broad expanse, and for the absence of any central drainage channel or of any dendritic drainage pattern. Pine flatwoods formed most of the eastern boundary of this flow, and the western boundary was

defined by the Immokalee Rise and the relatively higher wetlands and uplands of what is now the Big Cypress National Preserve. Much of the flow discharged south and west through Shark River Slough, through the mangrove estuaries of the southwestern coast, into the Gulf of Mexico (Fig. 1). South of, and including the New River (Ft. Lauderdale), the pine flatwoods were absent and the Atlantic Coastal Ridge became discontinuous, forming a series of islands separated by coastal rivers (Smith 1848). These rivers thus resulted in a portion of the flow being discharged eastward into Biscayne Bay and the Atlantic Ocean (MacGonigle 1896, Beard 1938). The remainder of the flow discharged southward through Taylor Slough into Florida Bay. Because of Florida's porous geology dominated by limestone overlain by thick peat deposits, the boundaries between surface water and ground water flow are not always distinct.

The Everglades ecosystem is thought to have been formed over the last 5,000 years as sea levels rose and precipitation increased, promoting water retention in a shallow inland basin, and the portion of the basin south of Lake Okeechobee filled in with peat (Gleason and Stone 1984). The result of peat accumulation in this bedrock basin was the formation of a peat surface, level in the east-west direction, and with a slight north-to-south downward slope. The concavity of the bedrock, coupled with the east-west levelness of the peat, resulted in thicker peat deposits in the middle of the basin and thinner deposits along the edges. By the 1880s, peat had accumulated to about 21 feet above sea level along the south shore of Lake Okeechobee (Meigs 1879), and had formed the northern edge of a north-to-south elevation gradient that is now less than 3 inches per mile. The southward flow of water down this gradient is thought to have formed and to maintain the ridge and slough pattern so characteristic of the Everglades (Kushlan 1993).

Everglades plant and animal communities evolved under the conditions imposed by this flow, within a sub-tropical climate, and under the constraints of nutrient limitation. The habitat types that evolved included vast sawgrass plains south of Lake Okeechobee, in the region presently occupied by the Everglades Agricultural Area. South and east of the sawgrass plains was the ridge and slough habitat, including what are now Water Conservation Areas 1, 2, and 3, and Everglades National Park. Marl prairies – short hydroperiod marshes with marl sediments – occupied slightly higher elevations east and west of Shark River Slough. The mangrove zone was located from the Ten Thousand Islands south and east around the tip of Florida's peninsula to the shores of Biscayne Bay.

Surprisingly, most discussions of hydrology in the Everglades exclude mention of the role of water movement. For example, Kushlan (1997) notes that hydroperiod in wetlands typically is defined as the depth, duration, timing, and periodicity of water, but does not include water movement. However, he does note that the wetland water regime can influence the fate of water-borne sediment.

Historical ridge and slough landscape

Originally, the ridge and slough landscape consisted of a peat-based system of dense sawgrass ridges with soil surfaces roughly 2 to 3 feet higher than adjacent and relatively open sloughs (Wright 1912, Baldwin and Hawker 1915). The regular, approximately even spacing and the parallel arrangement of the ridges and sloughs, along with their alignment parallel with the direction of flow, formed a strongly organized pattern. Tree islands of various types formed a

third element of the landscape, rising slightly above the elevation of the sawgrass ridges. The orientation and streamlined shape of the larger tree islands formed a separate pattern, but with the same alignment parallel to the direction of flow. The organized pattern of parallel ridges and sloughs, oriented with flow direction, on a slightly sloping peatland partially resembled other patterned, slightly sloped peatlands such as the circumpolar string bogs (Gore 1983). Historically, the ridge and slough landscape was an extensive pre-drainage landscape, encompassing what are now the Arthur R. Marshall Loxahatchee National Wildlife Refuge, Water Conservation Areas 2A and 2B, Water Conservation Areas 3A and 3B, and Shark River Slough (Fig. 1).

While seemingly small, the 2 to 3-foot difference in elevation between ridge surface and slough bottom was highly significant in the pre-drainage Everglades. During the typical annual rise and fall of wet and dry season water levels, this elevation difference allowed sloughs to remain water-filled throughout the year, while adjacent ridges would be exposed a few months of the year. In the pre-drainage system, native species were adapted to the multiple habitats provided by the tree islands, ridges, and sloughs. Aquatic organisms depended on the sloughs as extensive areas that would remain inundated throughout all but exceptionally dry years.

Drainage and compartmentalization activities

The first major efforts to drain the Everglades came with Hamilton Disston. By the 1890s, he had drained over 50,000 acres of wetlands, opened the Kissimmee River for navigation, and linked the Caloosahatchee River to Lake Okeechobee (Light and Dineen 1994). In addition, he is credited with excavating the first 11 miles of canal south of Lake Okeechobee in the direction of Miami – the precursor to the Miami Canal. By 1917, four major muck-scalped canals transversed the Everglades from Lake Okeechobee to the Atlantic Ocean, short-circuiting the historic, north-to-south pattern of flow and greatly accelerating the removal of water from the Everglades. Unfortunately, flow records prior to disruption of the entire drainage basin are not available. It has been hypothesized that flow magnitudes through the river of grass were significantly higher in the 1800s and early 1900s versus what has been monitored since 1939 (Parker et al. 1955, Jon Woolverton, USGS, unpublished data). Patterns of peat subsidence (Stephens and Johnson 1951), water tables measured in 1915 (Baldwin and Hawker 1915), 1938 (Clayton 1938), and continuously between 1927 and 1939 (Parker et al. 1955), all suggest that these canals substantially lowered water levels in the northern Everglades, often below the peat surface.

Local efforts to surround Lake Okeechobee with a levee began in the early 1900s and were completed with the construction of a levee completely encircling the lake by the mid 1900s. All surface water inflow and outflow points (except one at Fisheating Creek) are now controlled by pumps and/or water control structures.

By the 1910s, Miami was expanding, and plans to drain and develop parts of the Everglades were pursued. Capt. Frank Jaudon, seeking to drain what is now called Northeast Shark Slough, successfully lobbied for creation of Tamiami Trail (Tamiami Trail Commissioners 1928). Objectors at the time (Tatum in Tamiami Trail Commissioners 1928) raised what turned out to be a legitimate concern, that the road bed would act as a dam, blocking the southward flow of water out of what is now Water Conservation Area 3B (c.f. Elliot in Graham 1951). Nevertheless, Tamiami Trail was completed in 1928. Photos from the 1930s show water

occasionally spilling over the top (Matlack 1939), but aerial photos from 1940 (USDA-SCS 1940) suggest that in just 12 years, Tamiami Trail had created two separate landscape types, north and south, where once there had been a continuous landscape type.

Since that time, the ridge and slough landscape has been further compartmentalized. The eastern perimeter levee, stretching from Palm Beach to Miami-Dade county, defined the eastern boundary of the Everglades, and was completed by 1954 (Light and Dineen 1994). This levee became the eastern boundary of Water Conservation Areas 1 and 2, preventing movement of water eastward to agricultural and developing urban areas. By 1959, the Everglades Agricultural Area was separated from the rest of the system by a series of levees, canals, and water control structures. Subsequent levee construction defined the western and northern boundaries of the three Water Conservation Areas, and all three areas were completely surrounded by levees by 1963. A pair of parallel levees (L-67A and L-67C) divided Water Conservation Area 3 into two independent units. These levees, which run almost, but not quite perpendicular to the original sheet flow direction, were intended to reduce groundwater seepage through the highly porous Biscayne aquifer. The western unit, Water Conservation Area 3A, scheduled for higher water levels, serves as a major water supply reservoir. The eastern unit, Water Conservation Area 3B, with lower water levels, reduces the head difference to the developed areas to the east. In 1966, State Road 84 (now Alligator Alley), an east-west highway north of Tamiami Trail, was completed, adding another compartment to Water Conservation Area 3. Water conveyance was provided by bridges at one or more mile intervals.

Although not associated with levees, the so-called “agricultural canals” (e.g., Blue Shanty, Cooperstown) to the north and south of Tamiami Trail created further breaks in the landscape. The Miami Canal, also not associated with a levee, degrades the landscape not as a cross-barrier to flow, but as a shunt concentrating water flow in the canal and short circuiting the landscape.

Loss of ridge and slough landscape

It is clear that the compartmentalization and related water management activities, which have altered flow and other hydrological parameters such as water levels, are resulting in the loss of ridge and slough landscape. Loss is defined here in two ways: 1) a flattening of the landscape due to a decreased difference between ridge elevations and the elevations of the slough bottoms; and 2) an associated blurring of the distinct, directional pattern of ridge and slough vegetation. Evidence for this loss arises from alterations in vegetation patterns over time and indications of altered topography. Satellite images and aerial photography suggest subtle but definite changes in the extent and shape of sawgrass ridges. Where levees, canals, and roadways have separated the landscape into compartments, changes in the landscape are obvious. In areas where the original ridge and slough pattern still is evident, peat topography with identical patterning also is still evident. Where the vegetation pattern has been lost, the distinct topography also has disappeared. The post-drainage alterations in landscape topography show a clear trend from a highly organized, strongly directional pattern to a degraded, more random, and less directional pattern.

Causes of landscape change

Based on these observations, it is apparent that: 1) the Everglades ridge and slough landscape has changed, and is continuing to change significantly; and 2) the landscape changes are having detrimental ecological effects on Everglades plants and animals. It is likely that these changes are the result of altered water flow caused by human-made barriers and shunts, interacting with corresponding changes in water depth and water level fluctuations. These observations can be broken down further, and are discussed in detail in the remainder of this paper:

1. The ridge and slough landscape originally formed, under natural pre-drainage conditions, a continuous, directional, and patterned wetland mosaic.
2. Flow occurred over the full width of this directional, patterned, wetland.
3. The vegetation patterns of this landscape were influenced by water flow, water depth, and hydroperiod differences and their interactions with topographic variations in the peat surface.
4. The original ridge and slough pattern has degraded to varying but substantial degrees throughout the landscape.
5. The type of pattern degradation observed cannot be explained on the basis of altered water depths (or hydroperiods) alone – a change in directional, flow-related processes also must be implicated.
6. Preservation of the ridge and slough pattern and potential restoration of degraded patterns require water movement across the landscape and in the original direction of flow.
7. Conversion of ridge and slough habitat to a uniform, closed landscape of dense sawgrass is having significant, deleterious impacts on the ecology of Everglades plants and animals, including restrictions on dispersal and available habitat for aquatic animals, and limitations on foraging by wading birds and other top predators.
8. If not reversed through restoration of flow, it is possible that the landscape endpoint suggested by current trends would be a uniform, closed landscape of sawgrass.

Evidence of landscape change

Pre-drainage conditions of vegetation, topography, water depth, and water flow, coupled with observation of post-drainage changes, are summarized here from other research (Ingebritsen et al. 1999, Sklar et al. 1999, Sklar et al. 2000, Sklar et al. 2001) and draw on diverse sources such as explorers' journals, historic surveys and maps, and aerial photographs. The study of pre-drainage and pre-compartmentalization landscapes using historical information and indirect evidence might be called forensic ecology. When this type of study is combined with analysis of present-day aerial photographs and topography, natural and disturbed vegetative mosaics, and studies of peat-forming processes, the historical record can provide significant insight into the original, natural state of the ecosystem.

Historical landscape condition

At the regional scale, the peat-based Everglades included two landscapes, the sawgrass plains at the northern end, and the larger ridge and slough landscape in the central and part of the southern

portion (Fig. 1). The distinguishing differences between these two landscapes occur at the local scale, discussed in detail below. In the broader view, both of the landscapes were formed on a base of peat soil filling a bedrock basin. Although difficult to determine exactly, it appears that the pre-drainage elevation of the peat surface was about 3 feet below the elevation of the mineral soil-based edges of the basin, (e.g., the pine flatwoods east of the Everglades) (Van Zee et al. 1998). This elevation difference suggests that the basin peat accumulation probably was linked to average water depth.

The sawgrass plains and the ridge and slough landscape sloped very slightly from an elevation of about 21 feet above sea level at Lake Okeechobee (Meigs 1879) to sea level at Whitewater Bay 100 miles south, a slope of less than 3 inches per mile. Viewed from east to west, the peat-based landscapes were either level or, in some locations, tipped slightly to the east, reflecting drainage toward the Atlantic coast. Overall, at the regional scale and in the direction perpendicular to flow, both landscapes appear to have been very close to level over distances of more than 30 miles.

Sawgrass plains landscape

While the sawgrass plains and ridge and slough landscapes likely had similarly level surfaces at the regional scale, they differed markedly in topography at the local scale. The sawgrass plains formed a remarkably uniform, dense, and nearly monotypic stand of sawgrass, 8 to 12 feet tall. An 1883 expedition sponsored by the New Orleans Times Democrat did manage to penetrate and cross the sawgrass plains, but only by burning the sawgrass ahead of their progress.

“...all jump overboard to begin the usual work of pushing boats through the sawgrass [stubble]... No material change is found in the country through which we travel this day. It is the same through which we have traveled for seven days. Nothing but sawgrass, a little water, plenty of soft, black, slimy mud, and with not a single tree or bush in sight...” (Wintringham 1964).

The uniform sawgrass vegetation and the apparent absence of woody vegetation may reflect a very level peat surface.

Typical water depths in the sawgrass plains can be estimated from actual recorded water levels, from the nature of the soils and vegetation, and from studies of soil cores. The descriptions of a stringy peat with noticeable roots and sufficient structure to resist collapse (Stewart 1907, Harshberger 1914, Baldwin and Hawker 1915) suggest what would now be classified as a Fibric Histosol – a partially decomposed peat (McCollum et al. 1976). The partial decomposition may have resulted from nutrient limitation in the oligotrophic Everglades, and/or from oxygen limitation because the soil was covered with water most of the year. Surface ponding for most, but not all, of the year also would be consistent with the optimal sawgrass growth conditions suggested by the great density and height of the sawgrass canopy.

“[Sawgrass] seems to grow best where water covers the ground for a large portion of the year, but where the water table sinks below the ground late in the dry season. Once established, sawgrass can withstand rather deep water for extended periods, but gradually thins out as water of 3 feet or more is held for periods of 2 - 3 years without drawdown.” (Andrews 1957).

Andrews' observations are consistent with recorded pre-drainage water depths in areas of sawgrass growing on peat (i.e., the sawgrass plains and the peat transverse glades). Water depths in the 6 to 18-inch range, as well as the 24 to 36-inch range, were recorded in these areas. On the basis of pre-drainage soil and vegetation, and from the recorded historical water depths (Meigs 1879, Stewart 1907, Wintringham 1964), we estimate a typical annual variation in pre-drainage water depths between approximately 6 inches below ground surface at the end of the dry season, rising to a typical annual maximum of approximately 1.5 feet above ground at the end of the wet season. As historical descriptions suggest that sawgrass density and canopy height were similar on the ridges of the ridge and slough landscape, the water depth estimates from the sawgrass plains likely are applicable to sawgrass ridges of the ridge and slough landscape as well.

Ridge and slough landscape

In contrast to the uniform vegetation, topography, and hydrology of the uniform sawgrass plains, the ridge and slough landscape formed a distinctly non-uniform, systematically patterned peatland. The local and regional scale of these patterns were recognized clearly during early explorations of the Everglades.

“The surface of the Everglades, taken as a whole, appears to be a level plain, having a slope of three inches per mile toward the south and east, yet this statement is subject to slight modification. Throughout the entire [ridge and slough] area there are numerous winding shallow depressions or channels 100 to 500 feet wide, and one to three feet lower than the land through which they pass. These depressions, locally called 'Strands,' [i.e., sloughs] wind through the 'Glades' in all directions, though their general trend is from north to south. In other places there are slight depressions, like ponds or lagoons, covering one to forty acres. The muck in these depressions is usually less firm than the land on either side. These irregularities of the surface also affect the depth of muck at these points, as the underlying hard material is no lower in these surface depressions than under the adjacent land. These low places are usually filled with water, while the general surface of the Everglades is comparatively dry.” (Wright 1912, p.18-19).

Soil scientists who field-surveyed a 180-square-mile swath through the sawgrass plains and the ridge and slough landscape during the dry season of 1915 introduced the term “ridges and sloughs” to the scientific literature and found substantial differences in elevation between them.

“[The landscape seen to the east and west of the North New River Canal] is very gently undulating or hummocky, owing to a series of ridges and sloughs with local differences of 2 to 3 feet in elevation, having a general northwest-southeast direction. ...” (Baldwin and Hawker 1915, p. 752).

Earlier, in 1907, members of a west to east survey across the Everglades also encountered alternating sawgrass ridges and open water sloughs which showed the same southeastward orientation later noted by Baldwin and Hawker (1915).

“...Chadwick mentioned saw-grass ridges alternating with open leads of water running approximately in a southeastern direction.” (Harshberger 1914).

The photographs reproduced in Figs. 2 and 3 illustrate the ridge and slough landscape described above. They were taken in March, 1917, several months into the dry season. The photographer and explorer, John King, indicated that the Everglades already was drier than they had been prior to drainage. The open sloughs and distinct sawgrass ridges in these photographs are consistent with early descriptions of canoe travel. Col. Harney, and numerous others during the 19th century, found sufficient channels of open water to not only cross the Everglades by canoe, but to do so rapidly (Ives 1856, Dix and MacGonigle 1905, Dimock 1907, Marchman 1947, Church 1949, Anonymous 1960 [1841]). These open sloughs allowed canoe travel, much of it using paddles, rather than the poles more commonly used in shallower waters. The Baldwin and Hawker survey conducted in 1915, a year of apparently normal rainfall, between January and March showed that even during the dry season, water levels apparently were high enough to cover both sloughs and ridges.

“At the time of the survey a few of the higher ridges were above water, but in general the entire surface was inundated. The water in the sloughs in many cases was 2 to 3 feet deep.” (Baldwin and Hawker 1915, p. 788).

The photographs also emphasize a remarkable aspect of early narrative descriptions of the ridge and slough landscape – common pre-drainage observations of a directional, downstream orientation. These early observations are remarkable because the large size of ridges and sloughs makes it difficult to perceive a directional pattern when actually on the ground in the landscape (c.f. Figs. 2 and 3). Present-day helicopter experience suggests that the regional pattern, although partially apparent at lower altitudes, only becomes visibly obvious at altitudes greater than 800-1000 feet. Figure 4 shows an oblique aerial view taken from a dirigible in the 1930s. The altitude is not known, but the pattern of elongated sawgrass ridges and open water sloughs is clearly visible and is very similar to present day oblique aerial views of well-preserved portions of the landscape. The many pre-drainage observations of clear directionality in the landscape suggest that observers perceived the orientation either through the process of traveling through the landscape, or by the visible direction of water flow, often remarked upon.

Having the benefit of aerial views and aerial photographs, hydrogeologist Garald Parker suggested that the directional orientation of the ridge and slough landscape was a natural result of water flow over a peat soil substrate.

“The linear arrangement of this pattern is most noticeable from the air, from which, as Dickerson (1942, p.136-139) says, ‘They reveal a decided ‘grain’ to a broad sweep of country ... as if a great coarse broom had been rudely brushed over the low-lying Everglades region.’

... The ‘grain’ of the Everglades ... is believed to be developed entirely on fresh-water peat and muck... It ... represents a drainage pattern produced on a very gentle sloping surface of organic deposits. The ‘grain’ is composed of tree islands and swales [sloughs] that trend parallel to the regional slope, just as one would expect in an area of consequent drainage.” (Parker et al. 1955).

The ridge and slough pattern is strikingly regular, with evenly spaced ridges (centerline to centerline), and only moderate variation in ridge width. Also striking is the absence of any indication of either a central drainage channel or of any dendritic, hierarchical drainage network. Instead, flow seems to have occurred quite evenly across the full 30-mile width of the Everglades, distributed quite equally across all the numerous sloughs. All of these observations support the regional impression of an unusually level peat surface in the cross-flow (east-west) direction.

The grain mentioned by Parker can be used to create a map of landscape directionality. Figure 5 shows the result of superimposing a 2-mile by 2-mile grid on the earliest available, comprehensive aerial photographs of the Everglades (USDA-SCS 1940), and then visually assigning a landscape direction to each grid cell. The uniformity of the landscape and flow directionality is striking, and reinforces the impression that peat accumulated in equilibrium with a regional water surface that was very level in the cross-flow (approximately east-west) direction. The mapping exercise also reinforces the impression of sheet flow distributed evenly across the full landscape width.

Figure 6 is a stylized depiction (exaggerated vertical scale) of the pre-drainage ridge and slough landscape illustrating the close relation between vegetation and elevation of the underlying peat substrate. Figure 6 helps illustrate the diversity of observations found in different narrative accounts of the pre-drainage Everglades. In particular, descriptions of the Everglades as a “vast lake” on the one hand can be reconciled with other descriptions of an alternating landscape of open water and boggy land on the other hand. At the end of the dry season, there could still be water in sloughs, yet the peat of the ridges could be slightly exposed, yielding boggy conditions on the ridges. In contrast, during the high water at the end of the wet season, water could cover both sloughs and ridges, yielding a continuous water surface – a lake – with emergent sawgrass stems.

Such a range of water depths is consistent with pre-drainage observed depths, soil characteristics, hydrologic preferences of the vegetation, and with hypothesized frequencies of peat fires. Several lines of evidence suggest that under natural, pre-drainage conditions, the water remained in sloughs throughout typical dry seasons. While there certainly is pre-drainage evidence of at least some sloughs drying out, such drying occurred infrequently. Also, there is evidence for year-round presence of surface water within sloughs during typical years, including ability to travel quickly by canoe (Smith 1848), lack of dry camping sites (Sprague 1848, Willoughby 1898, Dimock 1907), and absence of widespread peat fires (Gifford 1911, Cohen 1984).

Water flow

There are many qualitative observations of water flow in the pre-drainage ridge and slough landscape. The majority of sources specifically noted the current of the water in the Everglades, making it clear that they did not observe stagnant areas and most also mentioned the direction of the flow.

“The water is pure and limpid and almost imperceptibly moves, not in partial currents, but, as it seems, in a mass, silently and slowly to the southward.” (Smith 1848).

Soil surveyors working in the spring of 1915 noted a visible current in sloughs, even in the dry season.

“There is a marked current of the water in the sloughs...” (Baldwin and Hawker 1915, p. 788).

The botanist John Davis noted evidence of a current, even in the 1940s.

“The more common aquatic plants are the bonnets, *Nuphar*, swamp-lily, *Crinum americanum* L., white water-lily, *Nymphaea*, and a number of "slough grasses" that bend in the water before the current.” (Davis 1943, p. 266).

Current landscape condition

Post-drainage changes and vegetation patterns in the remaining ridge and slough landscape have been assessed using a variety of remote sensing data, including Landsat Thematic Mapper imagery, infrared aerial photographs, 1940s aerial photographs, and detailed vegetation maps. Float helicopter trips were used to examine the landscape at altitudes up to 1000 feet. GPS-linked photography was used to map particular observations within the overall landscape pattern. At this point, spatial analyses primarily are qualitative. As detailed vegetation mapping presently underway by the South Florida Water Management District is completed for Water Conservation Area 3A, it is expected that quantitative spatial analyses of vegetation polygon attributes will be helpful. The present lack of specific quantitative data at the landscape scale, however, does not negate the overwhelming degree of changes that are recognized easily by visual observation of aerial photographs, digital images, and maps.

Well-preserved landscape

With a template of the original ridge and slough landscape morphology in mind, it is possible to evaluate the condition of the currently remaining landscape. Figure 7 shows a present-day oblique aerial view of central Water Conservation Area 3A. Comparison with pre-drainage descriptions and with 1940s aerial photographs suggests that the original pattern has been well preserved in this area south of Alligator Alley and west of the Miami Canal. The exception to this pattern is a distinct band of altered vegetation immediately south of the Alley. Otherwise, this photograph is remarkable for its similarity with Fig. 4, the dirigible photo from the 1930s. Figure 7 and the area it represents provide our best estimate of an original ridge and slough landscape pattern. Figure 8, a vertical color infrared aerial, also is from central Water Conservation Area 3A. The directional pattern of entire, elongated ridges shown here serves as a good example of well-preserved ridge and slough landscape.

Degraded landscape

In contrast, Figs. 9-14 show oblique and plan view images and maps of degraded ridge and slough landscape. In each case, it is significant that comparison with the well-preserved pattern

suggests a transformation from narrow, linear, and strongly directional polygons, to a post-drainage pattern of more randomly oriented, amorphous, and less directional polygons.

In Fig. 9, the landscape apparently has stayed wet enough to maintain open water and water lily sloughs, but the sawgrass ridges have disintegrated into many small, randomly oriented patches of sawgrass. In an aerial photo of the same region (larger area), faint traces of former sawgrass ridges are apparent (Fig. 10), as in much of the landscape north of Alligator Alley (I-75), and clearly show how much the landscape pattern has disintegrated in this area.

The degradation of the original ridge and slough pattern in this area and along the full length of Alligator Alley illustrates the impact of Alligator Alley construction and related water management practices. As can be seen in Figure 10, extra care was taken with this road to minimize the impacts of a hydrological barrier. Two canals were dredged adjacent to the road, one on each side to provide fill for the road. At every 2.5-mile interval (1-mile intervals, in some places), a small bridge underlies the roadway to connect the two canals and to attempt to make Alligator Alley “hydrologically transparent” within the Everglades landscape to the north and south.

However, despite the conveyance of water across the Alley at discrete intervals, the ridge and slough landscape has degraded substantially (Fig. 10). Negative landscape effects associated with the road have been even more severe farther west, between the Miami and L-28 Canals. The Alligator Alley experience is instructive, particularly given the efforts at maintaining hydrologic connectivity. The degraded ridge and slough landscape suggests that something more than hydrologic conveyance at discrete intervals is needed.

Figures 11 and 12 show a different form of ridge and slough landscape degradation, in which the sawgrass ridges appear to have remained intact. The sloughs, however, appear to be disintegrating, apparently by sawgrass invasion. The random orientation of the invading sawgrass contrasts with the original linear orientation of the ridges and sloughs. Although quantitative data have not been collected, it is possible that the sloughs are filling in with depositional sediments, as well as with vegetation. This process would result in severe degradation of the ridge and slough landscape, with the slough elevation eventually approaching that of the sawgrass ridges.

Figure 13 shows such an example of severe degradation of ridge and slough landscape in which the sloughs almost have been replaced completely by sawgrass. This degradation is typical for much of Water Conservation Area 3B. The pre-drainage expeditions that passed through Water Conservation Area 3B could not have traversed the landscape in its present condition. Figure 14 shows the same information as an excerpt from a vegetation map. A trace of the original directionality can be made out from the aligned remnants of sloughs. Even more complete replacement of ridge and slough landscape by uniform sawgrass has been observed in western Water Conservation Area 2A. Two peat transects (one-half mile each) measured in Water Conservation Area 3B show almost no discernible elevation differences (Chris McVoy, unpublished data). These transects support the relationship between flattening of the peat surface and loss of the characteristic ridge and slough vegetative pattern.

A 1980 vegetation map of part of Shark River Slough (Fig. 15) suggests that the process of ridge and slough landscape degradation and replacement by less directional, more amorphous landscapes also has occurred within Everglades National Park. The contrast in spatial pattern between the old and the new sawgrass is strikingly apparent.

Figure 16 is a satellite image of the western ridge and slough landscape which includes the locations represented in previous figures. This image provides the best available summary indication of the location of well-preserved versus degraded ridge and slough landscape pattern.

Flow in other regions of the greater Everglades

Surface flow obviously occurs in the freshwater and mainland estuarine wetlands of south Florida, and is not restricted to the Everglades ridge and slough system. For example, Tabb (1990) described flow in the broad marl prairies that border the southeastern flank of Shark River Slough. Tabb suggested that this flow occurred primarily during wet seasons when surface water levels in Shark River Slough were elevated enough to carry moving water onto and across the higher elevation prairies. Duever et al. (1979) showed possible flow patterns and directions during periods of high water for the entire Big Cypress National Preserve.

Flows from the Everglades to coastal estuaries are moderated by a coastal topography that has been shaped by water flow. The eastern fringe of the Everglades is bounded by a coastal ridge, interrupted by coastal rivers. On the lower southeast fringe, depressions in the ridge, called transverse glades, once carried fresh water to coastal wetlands, from where it was transported to Biscayne Bay by coastal creeks. Canals and levees lowered the water table, drained the transverse glades, and interrupted the flow of fresh water to coastal creeks. By analyzing aerial photography and sediment cores, Meeder et al. (2000) documented a substantial alteration in coastal creek topography that occurred sometime after 1940. The presence of small, buried oyster reefs near the mouths of these former creeks indicate that nearshore salinities at these sites were seldom greater than 20 ppt before 1940. Meeder et al. (2000) found that the creek bed area, once a topographic low that facilitated the transport of water, is now a topographic high that would retard water flow if water were available. Apparently, the flow of fresh water maintained these coastal creeks, acting as positive feedback that allowed future flow. When flow was redirected, a major landscape change took place. Observations by Glenn Simmons, reported in Simmons and Ogden (1998), suggest that a similar filling in of creeks that had previously facilitated freshwater flow to the coast across a low coastal berm (the Buttonwood Embankment described by Craighead [1971]) may have occurred on the coast bounding northern Florida Bay.

Although it is beyond the scope of this paper to provide a detailed review of the role of flow in these other regions, it should be noted that much less attention has been given to flow in these landscapes than has been the case for the ridge and slough landscape.

Possible mechanisms of ridge and slough formation and maintenance

The mechanisms that are causing the loss of ridge and slough landscape likely are complex. These changes are occurring over a time scale of decades, and restoration decisions will be made

on a shorter time scale. Data collected before compartmentalization activities began, such as continuous time series records of pre-drainage stage, flow direction, and flow velocity, would have been extremely helpful. Unfortunately, the individuals observing the Everglades one hundred years ago had neither the capacity, the foresight, or the inclination to conduct such measurements. This situation forces the use of all available pre-drainage information, including recorded, narrative information, to the fullest. Also, due to the lack of a comprehensive paleoenvironmental study, valuable information that may be contained in the sediment layers is not available at the present time.

The central geomorphological issues regarding the pre-compartmentalized ridge and slough landscape are the mechanisms by which the landscape pattern arose, and the dynamics of landscape pattern over time. While the first issue certainly is of importance, the immediate needs of restoration planning draw attention primarily to the second. It will be necessary to ascertain whether or not landscape patterns naturally shifted over time, and if so, what temporal patterns existed. Also, it will be important to know how human-induced changes in the landscape have altered the natural temporal pattern of landscape dynamics. Regardless of the long-term dynamics, maintenance of the remaining ridge and slough pattern, particularly preventing sloughs from becoming dense stands of sawgrass, is critical for sustaining habitat and dispersal pathways for aquatic animals.

The key geomorphological characteristics of the Everglades are: its peatland base; outcroppings of limestone; a highly cohesive substrate with high clay and organic content; and a floc layer that is more commonly associated with muddy estuaries. These characteristics are in contrast to alluvial systems that have no near-surface bedrock control, very low organic content of sediments, and that beds and banks composed of unconsolidated sand and silt (Gregory Pasternack, personal communication). In addition, the role of vegetation in shaping landscape pattern is important, as well as the feedback mechanisms that likely exist between topography and vegetation.

As in classical geomorphology, there is almost certainly a physical and biological explanation for the particular landscape patterns found in the pre-drainage Everglades and topography in the present Everglades, and they are tied to physical driving forces. On one hand, it is possible that the mechanisms may never be known for certain, particularly given their likely complexity and the long time scale over which they may operate. On the other hand, geomorphic theories have provided reasonable explanations for landscape processes over the full range of time scales, from raindrop erosion to mountain building (Gregory Pasternack, personal communication).

It also is possible that alterations in the ridge and slough landscape result from changes in water quality. In fact, CERP's underlying premise includes water quality as a very important component of Everglades restoration. However, this paper focuses on the hydrological rather than the water quality aspects of ridge and slough formation and maintenance. CERP assumes that restoration of natural flows and levels will be accomplished with water that is not poorer in quality than that of the unimpacted ecosystem.

In the following sections, possible mechanisms of ridge and slough formation and maintenance are presented and discussed. Note that flow is an important component of almost all of them. As

mentioned previously, it is not possible to prove or disprove any of these mechanisms, given the present lack of data and analysis. The possible mechanisms are presented to stimulate discussion and future research. In addition, although the possible mechanisms are presented in separate sections, it is likely that a combination of several of these mechanisms operating together is responsible for formation and maintenance of the ridge and slough landscape.

Sediment transport

One possible mechanism of slough maintenance is net downstream transport of sediments, primarily floc, by water flow prior to compartmentalization. For the purposes of this discussion, floc is defined as loosely consolidated particles that are larger than 0.45 μm in diameter, that are largely organic in nature, and that have densities very close to 1.0. Such a transport mechanism is consistent with the landscape directionality, the shape of ridge outlines, and preliminary indications of floc movement.

Sediment transport by water flow is responsible for maintaining many types of flowing systems. Flows can take multiple paths down gradient and these paths form in the areas of least resistance. As flows increase, these paths widen and there is a velocity distribution across each flow path, with higher velocities in the central (deeper) area and slower velocities on the sides due to friction. Suspended sediments fall out at the slower velocity edges – thus the formation of ridges. The next flow event adds to the process and flow deepens in the center and the ridges grow more. During really large hydrological events, the flow can even be horizontal as the banks overflow and recede, also trapping sediments in the ridge area. As the ridges build, the channel depth increases and the deeper flooding tends to kill off vegetation, making the slough more efficient for water transport and the ridges relatively less efficient.

In the Everglades, because of the normally slow moving water and the peat substrate, floc is likely to make up the bulk of transported sediments. The floc layer can be up to 12 inches thick and is nearly structureless, especially in comparison with the peat soil substrate. Pre-drainage observations of floc in sloughs are available.

“The top soil [of the ridges] is a turf composed largely of saw-grass roots, except in the leads and shallow basins [i.e., sloughs], where the saw-grass does not grow. Here [sloughs] the vegetation is more completely decayed and [the soil] is so loose when saturated with water that one sinks to the bottom sand, or rock.”
(Harshberger 1914, p. 159).

Downstream transport of floc presently found in the remaining ridge and slough landscape might occur either on a slow continual basis, incrementally with individual local storms, or as infrequent high-energy events. Bill Loftus (unpublished data) observed that after Hurricane Andrew in 1992, the floc layer, the periphyton/*Utricularia* mat, and dead vascular plant stems were blown into the sawgrass ridges from the adjacent sloughs. Ridges apparently acted as traps to capture the material. This observation demonstrates how infrequent high-energy events may serve to distribute and deposit materials on the ridges.

In any of these cases, unrestricted flow paths (sloughs) would be critical for uninterrupted downstream transport. The density of floc is very close to that of water, giving floc a low settling velocity. Considering how easily floc is resuspended by physical and biological processes such as gas bubble flotation, bioturbation, and temperature/density effects, it is possible for floc to be carried long distances downstream.

Sedimentation within sloughs subsequent to compartmentalization

Net accumulation in sloughs of organic sediments such as floc might be the process most responsible for the disappearance of open-water habitat, and the increase in the area of dense sawgrass. The shift from net transport of floc prior to compartmentalization to net accumulation of floc subsequent to compartmentalization could be caused by a number of mechanisms, acting separately or together. For example, lowering average water surface elevations decreases water depths, which in turn promotes emergent plant species. Increased emergent growth increases hydrologic resistance to flow, decreasing velocities and floc transport. Increased emergent growth, more so if periphyton coatings are present, also increases filtering of suspended floc. Both decreased water velocities and increased filtering will tend to increase *in situ* accumulation, further decreasing water depths and promoting increased plant growth and stem density. Together, these effects could lead to vegetative as well as topographic filling-in of sloughs.

The onset of such filling-in processes was remarked upon almost fifty years ago. The following is from a Florida Game and Freshwater Fish Commission progress report regarding the then new Water Conservation Areas 2 and 3.

"Prior to intensive drainage much of the Glades area was dissected by relatively deep open water "sloughs." These natural drainage channels permitted traverse into the interior of the Glades by "pole-boat" [probably dugout cypress canoes]. Journey by "pole-boat" for example from Dania on the east coast to the Big Cypress, forty miles to the west, or from Ft. Pierce south through the Glades to Ft. Lauderdale was not uncommon. A "pole-boat" trip such as this would be a remarkable feat indeed at the present time even during periods of high water. The major portion of these open water "sloughs" have now reverted to *Rhynchospora* spp. or maidencane or have been invaded by sawgrass, making navigability possible only by airboat and then only during the wet season.

On the heels of the [State] drainage program and the general drying up of the Everglades came the airboat. The "pole-boat" days were over and a new era was beginning. The development of the airboat permitted entry into any portion of the Glades where the sawgrass was not too dense and a few inches of water could be found. This is the situation in the sawgrass country today. Unless a hunter or a fisherman possesses an airboat he does not venture far into the interior of the Glades [i.e., far away from the canals]." (Wallace 1955, p. 2).

Influence of barriers on flow and sediment transport

Barriers such as roads and levees disrupt continuous flow paths. Perforation by culverts or bridges can connect some sloughs, but the majority of sloughs remain completely blocked, forcing water and sediment laterally across ridges. Areas of stagnation can result between culverts. Suspended sediments likely are deposited in these areas of stagnation upstream and

downstream of the barrier. Higher density sediments would be picked up in the area of accelerated flow velocities upstream of the culverts and that these sediments would be deposited immediately downstream as the water slows and spreads out. For example, this mechanism might explain the pockets of unnatural woody vegetation immediately downstream of the culverts under Tamiami Trail.

Along a linear flow barrier, creation of discrete drainage points connecting upstream and downstream wetland fragments also results in the creation of backwater regions between these discrete points. A backwater wetland receives inflow as water rises, and discharges water as the water surface falls, but backwater wetlands largely are disconnected from their sediment and nutrient sources, and also have reduced flushing. Linear flow barriers with discrete cross connections (e.g., culverts) will develop backwater lobes between these discrete points extending to a distance away from the barrier.

Influence of canals

Canals intercept continuous flow paths and provide short-circuits that connect flow paths that would otherwise have been isolated. Satellite images of areas around canals that do not have associated levees (e.g., Miami Canal, agricultural canals) demonstrate that vegetative shifts do occur across canal boundaries. Canals that are not exactly perpendicular to the flow direction provide preferential flow paths that divert water and cause different hydrologic conditions on either side of the canal. Canals also act to reduce the surface water gradient, and therefore reduce water velocities in adjacent wetlands.

Changes in water levels due to the water management system

Construction of Florida's extensive water management system altered other hydrological parameters in addition to flow. For example, it is possible that unusually high water levels in Water Conservation Area 3A resulting from water management operations upstream caused the loss of most of the tree islands and resulted in the expansion of sawgrass, and that degradation of vegetation patterns in many areas are due to changes in water quality (Terry Rice, personal communication). Regardless of which possible mechanism(s) for ridge and slough formation are correct, it is likely that flow interacts with water depth, hydroperiod, and other hydrological parameters in maintaining landscape heterogeneity in the Everglades.

Although extended periods of unnaturally high water levels can be detrimental, water levels that are too low also can have negative consequences. In shallower waters, emergent species, particularly *Eleocharis cellulosa*, species of *Rhynchospora*, and short and mid-sized sawgrass, replace the floating and submerged slough community. This sequence of wetland plant communities with changing depths is a familiar one found throughout the world. The emergent communities, besides being associated with shallower depths, experience shorter hydroperiods and are subject to increased fire frequencies, as evidenced by the frequency of charcoal in sediments cores. Collectively, these are environmental conditions unfavorable for peat accumulation and consequently this wetland plant guild usually is associated with marl deposits formed by the abundant periphyton found in the same habitat rather than with peat.

The water depths needed to sustain *Nymphaea*-dominated slough communities are hard to define precisely in a variable environment such as the Everglades because water flow and low nutrient-levels also are important factors. However, when water levels began to regularly exceed 2.5 feet in the central Everglades, *Nymphaea* communities began replacing the emergent wet prairies (Goodrick 1984). Cohen et al. (1984) and Herdendorf et al. (1986) suggest that *Nymphaea* is characteristic where year-round water depths range from 1.0 - 3.3 feet and 0.8 - 3.3 feet, respectively. In Shark River Slough, Olmsted and Armentano (1997) and Ross et al. (2001) found that the wettest sites were occupied by *Eleocharis* stands and that slough vegetation was too rare to be mapped. Insights into the influence of water depths can be gained from knowing what depths are too shallow for floating plant communities. Ross et al. (2001) found that in the *Eleocharis* stands, the greatest water depths in the study areas averaged 1.3 - 1.8 feet year-round in an average rainfall year of the 1990s, with maximum 30-day depths being 2.0 - 2.6 feet. In the wetter years, of course, depths were higher.

Variations in water depth also can influence decomposition rates. If peat on ridges experience shorter hydroperiods due to changes in water management, the ability of fungi to serve as the dominant agents of vascular plant decomposition may increase. Fungi are important decomposers of vascular plant material in terrestrial habitats, and are less important in submerged freshwater habitats. Because fungi possess enzyme systems necessary for decay of structural plant material such as lignin, they may out-compete bacteria in these circumstances, and increase the rate of plant decomposition on ridges. This increased rate may contribute to the flattening of the ridge and slough landscape under altered water depth patterns (also, see following section on differential rates of peat accumulation and decomposition).

Although changes in water depth under managed conditions have been suggested as an alternative explanation for decreases in the ridge and slough landscape, changes in water depth alone are not sufficient to account for the observed landscape changes. Comparison of the original and current patterns suggests that a directionally neutral change, such as changes in water depth due to water management practices, while certainly important, would not be sufficient alone to explain the observed changes. Ridges and sloughs exhibit a regional pattern that corresponds with the surface gradient in the Everglades, and the direction and extent of pre-drainage flow patterns. This pattern alone is strong evidence for the role of water movement.

In addition, an examination of water level and vegetation in Shark River Slough and Water Conservation Area 1 suggest that degradation of landscape pattern is not related to changes in water levels. A similar increasing trend of amorphous, non-directional polygons is illustrated in Plate 9 of Davis et al. (1994), both in Shark River Slough and in Water Conservation Area 1 between 1968 and 1984. The vegetation transformations observed in both of these locations are not due to changes in managed water depth; nearby stage gauges indicate no change in water depth patterns or mean water depth over the observed period. All of these examples illustrate a transformation from an originally flowing, directional system to a presently non-flowing, or insufficiently flowing, impounded system.

Differential rates of peat accumulation and decomposition

Peat is created by the accumulation of organic matter over time as organic matter production exceeds decomposition. Labile plant material decays quickly, while refractory plant material decays more slowly. Peat is composed of refractory components of the source vegetation material. If sawgrass decomposes more slowly than water lily and other slough species, this difference alone could account for maintenance of the elevations of the ridges and the lower elevations of the sloughs. Other physical and biological processes interact to control increases in peat elevation. White (1994) uses his process-oriented landscape description to show that peat elevation largely is a consequence of increases from peat accumulation balanced by decreases from fire.

Numerous decomposition studies have been conducted in the peatlands of North America and Europe. Northern bogs are dominated usually by *Sphagnum* mosses, which create the peat of these wetlands. Although different *Sphagnum* species are closely related, they differ in both net primary production and in decay potential. Species that grow in the hollows, the lower elevation and wetter microhabitats, produce biomass at rates up to twice that of mosses growing on the higher, dryer hummocks (Nungesser 1997, Table 2, p. 35). Johnson and Damman (1991) report that in transplant studies, *Sphagnum* moss species that inhabit elevated positions decay more slowly than those that grow in the wetter microhabitats. Labile fractions of *Sphagnum* mosses range from 18% in hummock species to 28% in hollow species (Clymo 1983, Table 4.7, p. 177). The different decay rates reinforce the differences in microhabitat peat depths because peat accumulates faster in the hummocks in spite of a two-fold higher net primary production in the hollows. Therefore, under identical conditions, the hummock species decompose more slowly than the hollow species, producing greater peat accumulation for the same unit of biomass produced, in spite of lower net primary production.

Other peatland research has shown similar results – species that grow in the lower, wetter microhabitats decay at rates two to six times that of species that grow in the elevated, dryer microhabitats (Heal et al. 1978, Rochefort et al. 1990, van Dierendonck 1992, Johnson and Damman 1993). A peatlands microtopography model developed to predict hummock and hollow features indicates that the differences between production and decay of the *Sphagnum* species contributes greatly to generating bog microtopography (Nungesser 1997, Nungesser in press). Under equilibrium conditions, the higher decomposition of the hollow species accumulates less peat than the hummocks species with lower decomposition rates in spite of substantially different productivities. Innate differences in decay rates of peatland species have been reported for other peatlands, as well (Rosswall 1973, Clymo 1983, Morris and Lajtha 1986, Johnson and Damman 1991, Harris et al. 1995).

In the Everglades, similar processes may produce the distinct differences between the ridge and slough microtopography. The dominant ridge species, sawgrass (*C. jamaicense*), is highly resistant to decay relative to the slough species *Nymphaea odorata*. Sawgrass contains much higher proportions of lignin than the floating and submerged slough species. In field litterbag studies, 60% of sawgrass litter in unenriched areas remained after one year (Davis 1991), whereas the *Nymphaea* litter disintegrates within a few months (Shili Miao, personal communication). Harris et al. (1995) reported much lower annual loss of sawgrass mass, 8.7% to

10.8%, in contrast to higher annual loss rates of other plant species found in sloughs (*E. cellulosa*, 45.7% - 84.0%; *P. repens* 36% - 46.5%). These differences would enhance peat accumulation on the ridges relative to the sloughs.

In addition, the presence of unimpeded flow in the pre-drainage Everglades could increase the oxygen concentrations in the bottom of sloughs. More stagnant conditions resulting from decreases in flow could decrease oxygen concentrations in the bottoms. Increased oxygen concentrations would further enhance the rate of decomposition of the more labile submerged vegetation in the slough, resulting in increased differences between ridge and slough bottom elevations. Also, decomposition release nutrients into solution. Increased availability of soluble nutrients and the transport of those nutrients in the presence of unimpeded flow could further increase decomposition rates of slough vegetation (Newman et al. 2001).

Erosional formation of ridge and slough habitat

In contrast to the effects of flow on deposition of organic matter such as floc, it is possible that the ridge and slough habitat was formed originally via erosional processes occurring on a recently uplifted surface (Gregory Pasternack, personal communication). This possibility was first raised by Parker et al. (1955) in a quote appearing previously in this paper.

“... The ‘grain’ of the Everglades ... is believed to be developed entirely on fresh-water peat and muck... It ... represents a drainage pattern produced **on** a very gentle sloping surface of organic deposits. The ‘grain’ is composed of tree islands and swales [sloughs] that trend parallel to the regional slope, **just as one would expect in an area of consequent drainage.**” (emphasis added in bold)

The emphasized text contains very important ideas, particularly regarding the term “consequent.” It is a term that originates with W. Davis, a forefather of geomorphology, in his classic essay entitled, “The Geographical Cycle” (Davis 1909). While Davis’ ideas about landscape origins and evolution recently have been displaced by the Gilbert/Hack dynamic equilibrium theorem (Hack 1960), Davis’ ideas did dominate the early and middle 20th century. His ideas still are viewed as useful, though not generally correct. It is possible that Parker et al. were using their Davisian point of view to suggest a specific hypothesis about the origin and processes at work in the ridge and slough landscape.

A consequent stream is one that forms in proto-troughs on a recently uplifted (or in this case, perhaps, on a peninsula recently exposed by sea level drop) fresh surface. According to Davis, “all the changes which directly follow the guidance of the ideal initial forms may be called consequent; thus a young form would possess consequent divides, separating consequent slopes, which descend to consequent valleys, the initial troughs being changed to consequent valleys in so far as their form is modified by the action of the consequent drainage.” Thus, Parker et al. (1955) were suggesting that the regional surface had an initial roughness of non-aligned proto-troughs that, through the action of water-induced erosion, became connected to form sloughs directed down the regional gentle gradient. It is central to this possible mechanism that the ridge and slough landscape is of an erosional origin, not a depositional origin.

Extreme hydrological events

The Everglades, as are most ecosystems, is influenced by extreme hydrological events. The subtropical setting guarantees occasional impacts from hurricanes, tropical storms, and tropical waves, all of which are capable of producing rainfall events in excess of 20 inches over a relatively short period of time. Because these events typically occur during Florida's wet season (May through September), their impacts may be exacerbated by already saturated soils and existing high water levels. As an example of the potential magnitude of such events, Taylor Alexander relates part of an oral history taken from Fred Dayhoff – an Everglades hunter and angler who later became an Everglades National Park ranger.

“One unique adventure Fred described to me concerned the '47 hurricane, when flood waters as deep as a foot were still running over the Tamiami Trail. Not yet 8 years old, he and his older brother sat on opposite fenders of their '37 Packard, their legs around the fender-mounted headlights, as their father drove slowly. Fred recalled that giant whirlpools marked the submerged north ends of the culverts that passed under the road, and that the floodwater over the road was swift. With their rifle, they took turns shooting bass that were running over the road against the current. Upon each hit, the other brother would jump off and attempt to run the fish down. They had to be quick because the current was fast enough that the fish would be quickly carried into deep water over the sawgrass south of the road. He said the bass were most abundant about where the L-67 levee hits the trail today, in the middle of the Shark River Slough. They ended that day's adventure on Loop Road about eight and a half miles westward from the Trail's 'Fortymile Bend.' The flow there was too swift and deep – about 2 feet he recalled – for them to go farther.” (Lodge, in preparation; excerpted with permission of CRC Press)

These extremes in flow and water depths likely had a profound impact on the Everglades landscape. Increased flow volumes and rates undoubtedly transported particulate and dissolved materials, affecting both upstream source areas and downstream receiving areas. The impact of these events is difficult to assess, particularly without data from a detailed paleoenvironmental study. However, it is certain that following construction of the water management system in the mid-1900s, the magnitude and frequency of extreme hydrological events was decreased. What role these water management changes have on the impact of extreme events is unknown, but worthy of further attention.

Fire

Fire was an important component of the pre-impacted Everglades. Drainage in the Everglades beginning in the late 1800s resulted in a substantial increase in the occurrence of fire in the ridge and slough landscape. It is possible that the linear slough pattern was created by tongues of fire that followed dryer (overdrained) peat lines in a sawgrass-dominated landscape (Craighead 1971). These fires burned out sawgrass rhizomes and peat to create linear pools (sloughs) throughout the ridge and slough system. Fire may explain the sharp separation in vegetation between ridge and sloughs, and the current differences in elevation between ridges and sloughs. More recently, sawgrass is re-invading sloughs where ponded water (levees) has reduced fires.

“Remains of saw grass peat indicate that as late as 1900 saw grass communities may have covered much of the area between the tree islands.” (Craighead 1971; p. 162).

“Accompanying the recent drainage in the dry years, fires burned in long tongues, following the drier peat. Here rhizomes of the saw grass were killed. New plants revegetate slowly, and a sharp line of demarkation [between ridge and slough] remains for many years. Thus, much peat is removed... During the rainy season ponds form in these depressions...” (Craighead 1971; p. 164).

“Ponds in the Shark Slough... large shallow basins floored with marl and flooded in the wet seasons with 18 to 24 inches of water...are the result of fires burning off the peat above the marl base.” (Craighead 1971; p. 169).

Underlying bedrock patterns

Another mechanism that has been suggested is related to changes in sea level. During the past interglacial epoch, when the sea level was higher than present, flow from the Gulf of Mexico likely crossed the southern peninsula of Florida, thus leaving “ripple” deposits. These deposits eventually, through sediment deposition, could have led to elongated ridges in the bedrock. It is possible that underlying bedrock undulations are the base upon which peat deposits are built. Surface geophysics can provide conclusive evidence regarding bedrock configuration and its role in ridge formation and maintenance. Regardless of the specific mechanism(s), the regularity of the ridge and slough pattern suggests the presence of some organizing force acting over the full breadth of the landscape.

Preliminary measurements of peat and underlying bedrock elevations have been made in several transects conducted in ridge and slough and sawgrass plain habitats (Chris McVoy, personal communication). McVoy compared measurements of peat and bedrock elevations to aerial images of the landscape. As expected, peat elevations were higher in areas that would be visually described as sawgrass ridges, based on the presence of sawgrass stands. Conversely, peat elevations were lower in areas that would be visually described as sloughs, based on the presence of open water habitat having sparse emergent vegetation. However, bedrock elevations underneath the peat were variable but generally flatter than peat elevations, and did not correspond to changes in peat elevation. It is possible that bedrock elevations directly beneath the transects would not necessarily correspond to peat elevations along the transects. It may be that, in the presence of unimpeded flow, the bedrock pattern is manifested in the peat pattern at some distance downslope. While these preliminary data do not support the possible mechanism of underlying bedrock influence, more data need to be collected across a broader range of habitats, including degraded and undegraded ridge and slough habitat, to confirm the initial results.

Microhabitat differences in water chemistry due to differences in flow

Anecdotal evidence from northern peatlands suggest the possibility that microhabitat differences in flow may result in microhabitat differences in water chemistry, thereby influencing

Everglades vegetation patterns. The majority of the remaining ridge and slough habitat in the Everglades is in areas in which water quality has not been degraded by inflows from the north. Therefore, small differences in water chemistry could have large effects on biology.

A common form of northern peatlands are raised bogs (the lowest nutrient peatlands), in which the surface is elevated slightly above the surrounding landscape. This elevation results in a very nutrient-poor wetland, with precipitation providing the only water source. In contrast, seepage areas often are found on bogs, and these areas exhibit vegetation tolerant of more eutrophic conditions than vegetation of the main bog expanse. Vegetation in these seepage areas is more typical of nutrient-enriched peatlands than of the raised bogs, but the source water for the seeps is exclusively the upslope parts of the bog. Nutrients are elevated in these seeps (Malmer and Sjors 1955, Heinselman 1963, Ingram 1967, Siegel 1992). Ingram (1964) reported that phosphorus levels in a water track (seep) were 0.148 g m^{-2} compared to 0.057 g m^{-2} from the source bog expanse (upslope). Similarly, potassium was 1.51 g m^{-2} in the water track and 0.99 g m^{-2} in the mire expanse. Malmer and Sjors (1955) similarly reported water tracks that contained higher potassium and calcium levels than the source drainage area of the bog. Ingram (1967) concluded that moving water supports poor fen vegetation while the same water when still supports only bog vegetation. Kulczynski (1949) reported similar findings. Similar relationships were reported by Ingram (1967), who found that the fluctuation of bog water levels is significant in determining site quality; the relationship of his site index with maximum water fluctuations was $r = 0.73$.

These observations suggest that water movement in peatlands provides a means to transport nutrients and to support a richer vegetation type than still water. If this mechanism operates in the Everglades ridge and slough habitat, the slight nutrient enrichment of moving slough water may contribute both to faster growth of slough species and more rapid decomposition of slough litter. Enrichment may occur for a variety of reasons, including groundwater seepage, contact with mineral soils or bedrock, and scavenging of nutrients from decaying peat. Davis (1991) showed that nutrient enrichment in the Everglades increases the decomposition rates of both sawgrass and cattail. With higher decomposition rates of slough species, this slight nutrient enrichment may be one of the feedbacks increasing slough/ridge differentiation. Such a potential mechanism can be tested readily through controlled experiments in slough habitats that examine nutrient levels in flowing water versus still water.

Ecological impacts of ridge and slough degradation

Even though the mechanisms of ridge and slough landscape degradation are not fully known, barriers to flow are resulting in the conversion of the ridge and slough wetland mosaic to more uniform stands of sawgrass. It is likely that this conversion is related to the elimination of flow across the broad expanse in which it once existed. Even though culverts were constructed as part of Alligator Alley, Tamiami Trail, U.S. 27, and other levees to convey water past these barriers, landscape degradation has occurred probably due to the elimination of flow, changes in quantity and distribution of water conveyed, and associated physical and biological components. Conversion of the ridge and slough landscape pattern to uniform sawgrass stands has had, and will continue to have, deleterious impacts on Everglades plants and animals.

Flow may be essential for tree island formation and survival

In addition to the disappearance of the ridge and slough landscape, barriers to flow may have a negative impact on tree islands – an important component of the Everglades landscape. Tree islands now are known to be biodiversity hotspots and critical nesting and foraging habitats for numerous species. Tree islands are tear-shaped islands in the ridge and slough landscape whose long axis normally runs more or less north-south (i.e., upstream-downstream). Both their shape and orientation suggest that water flow has played a major role in their development. The two basic kinds of tree islands in the Everglades are floating tree islands and fixed tree islands. Floating tree islands primarily are found in the Arthur R. Marshall Loxahatchee National Wildlife Refuge and occasionally in other areas with deep peats. Fixed tree islands are found south of the Refuge in Water Conservation Areas 2A, 3A, 3B, and Everglades National Park.

Floating tree islands originate when a large piece of peat, known as a battery, detaches from the bottom during a period of high water and floats to the surface. This new island eventually becomes colonized by a variety of shrubs and trees. The role of flow in this process is completely unknown.

Although there are known exceptions (Loveless 1959), the majority of fixed tree islands are believed to develop because of topographic highs in the limestone bedrock underlying the Everglades. The small bedrock pinnacles or platforms, associated with the heads of the islands, are typically the highest part of a fixed tree island. The tallest trees and shrubs are found on the heads of tree islands. Tails are long, linear mounds of peat that form behind the heads. The elevation of a tail gradually drops from that of the head to that of the surrounding wetland. The vegetation of the tail ranges from tall trees and shrubs immediately downstream of the head, through ever shorter and sparser shrub communities, to a mix of tall sawgrass, ferns, and cattail just before it becomes indistinguishable from the surrounding vegetation. This combination of head and tail gives fixed tree islands a characteristic, elongated tear shape.

Two hypotheses have been proposed to explain the formation of tails – the hydrodynamic and chemo-hydrodynamic hypotheses (Sklar and van der Valk in press). According to the hydrodynamic hypothesis, the tail develops due to litter from the head (or other sources) being deposited in its lee by water currents. According to the chemo-hydrodynamic hypothesis, the tail develops due to the release of nutrients from the head. These nutrients are leached from the head by surface water or shallow groundwater. This leaching creates a plume of nutrients behind the head that increases plant growth and a differential build-up of peat in the plume area when compared to nearby areas outside the plume. Both hypotheses require water flow.

In a study of the size, shape, orientation, and distribution of tree islands in the Arthur R. Marshall Loxahatchee National Wildlife Refuge, Brandt et al. (2000) found that tree islands decreased in size, and that the overall area of tree islands decreased between 1950 and 1991. Photo plots in the interior of the wetland demonstrate a tendency for tree islands to become irregularly shaped, possibly due to the loss of water flow, reduction of pulse magnitude, and ponding of water along the wetland perimeter levees. Pristine tree islands have been described as being small and circular (Loveless 1959) or large and orientated in the direction of water flow (Gleason et al. 1984). It has been hypothesized that the elongated tree islands are found in areas with higher

flow rates, and that reductions in these flows due to compartmentalization have resulted in changes in tree island shape and reduction in size.

When viewed from space, the Everglades is clearly a landscape of large-scale hydrologic gradients. Fixed tree islands are not distributed randomly across the landscape. They seem to be associated with the ridge and slough topography of the Everglades. Although flows are hypothesized to be critical to tree island formation and sustainability (Stone et al. in press, Wetzel in press), the nature of the relationship between the ridge and slough pattern and tree islands is not clear.

The alterations described above in the ridge and slough landscape and in tree islands already have caused major ecological impacts to Everglades ecosystem structure and function. The importance of major landscape features to Everglades ecology and the ecological impacts that result from changes to these features, particularly the loss of open water habitat such as sloughs and wet prairies, are described below.

Sloughs and wet prairies are species rich

Although sawgrass marsh is the predominant wetland plant association in the Everglades, sawgrass marshes in unimpacted regions are interspersed with open water sloughs and wet prairies. An Everglades landscape increasingly dominated by sawgrass, which may exceed 10 feet in height and form an impenetrable mass (Kushlan 1990), will support fewer numbers of animals and a lower diversity of animals. Sawgrass habitats in the southern Everglades are the poorest habitat in both the number of fish species inhabiting them (Loftus and Kushlan 1987) and in the numbers of individuals of those species (Bill Loftus, unpublished data). In contrast, adjacent wet prairie/slough habitats have twice the number of species (Loftus and Kushlan 1987) and much higher densities of organisms (Trexler et al. 2002).

Wet prairies and wet meadows, such as those found in the ridge and slough environment, are wetland types that are associated with high biological diversity. Keddy (2000) notes that in shoreline communities, wet meadows are the least studied community type and most at risk from changes in hydrology. Also, there seems to be a general lack of appreciation among wetland ecologists for how much higher plant diversity is in infertile (nutrient limited) wet prairies and wet meadows than in other wetland habitats. Moore et al. (1989) demonstrate that infertile wet meadows had vastly more species, and more rare species, than other wetland types.

A diverse landscape mosaic is important to the Everglades animal community. Trexler et al. (2002) find that wet prairies and sloughs interspersed among sawgrass ridges are important sources of refugia, particularly for small fishes, during periods of dry down. Periods of dry down are normal features of Everglades hydrology, and Trexler et al. (2002) note that hydrology is a major factor in shaping fish communities. Benefits to the fish community from restoration of more natural hydrology by CERP implementation may be offset by the lack of availability of suitable refugia during dry periods if there are fewer sloughs.

In a study of prawn, crayfish, and small fish distribution in the Arthur R. Marshall Loxahatchee National Wildlife Refuge, Jordan (1996) shows that the wetland is composed of a mosaic of

habitat structure, and that decapod crustaceans and fishes respond to this mosaic. These organisms are important prey of higher trophic levels, and his research indicates that vegetation structure, along with hydroperiod and other factors, govern the availability of prey. With reference to sawgrass stands, Jordan (1996) found fewer prawns and fishes than adjacent wet prairies or sloughs.

Chick and Trexler (in review) find that the large-fish community of Water Conservation Area 3A is dominated by large-bodied predators, such as Florida gar and largemouth bass, whereas the Shark River Slough community consists primarily of less piscivorous species such as lake chubsucker and spotted sunfish. The density of smaller fishes, of the size consumed by many wading bird species, is greater in Shark River Slough than in Water Conservation Area 3A, possibly because of the larger community of predatory fishes in Water Conservation Area 3A. These data suggest that the longer hydroperiod marshes of Water Conservation Area 3A, particularly at its southern end just north of Tamiami Trail, seemed to promote growth of large predatory fish, which, in turn, limit the abundance of small fishes. They suggest that restoration may be best achieved by increasing the spatial extent of long hydroperiod marshes, such as Shark River Slough, to improve marsh quality for wading bird prey.

In summary, the importance of elevation changes in the ridge and slough habitat to the biological community is very important. One of the most dramatic features of wetlands is the degree to which small changes in elevation can allow large numbers of species to coexist (Paul Keddy, personal communication). In one study of coastal plain vegetation in Nova Scotia (vegetation that shares many genera with the Everglades), the distribution of each of more than 30 wetland species was centered upon slightly different elevations along a gradient of less than 5 feet (Keddy 1984). If the topographical variation of the Everglades landscape was lost, there is no doubt that biological diversity of both plants and animals would dramatically decline.

Wading birds need a mosaic of wetland habitats

Wading birds are an important component of the Everglades ecosystem. Their foraging and nesting success often are used as indicators of the overall health of the system. Wading birds also are one of the most visible and highly regarded parts of the Everglades. In fact, the overall decline of wading birds over the last century – to less than one-fifth of their abundance during the 1930s (Davis and Ogden 1994) – has been one of the major factors galvanizing public support for Everglades restoration. Scientists understand the central role that wading birds play in Everglades restoration – so much so that wading bird ecology is being used to define hydrologic targets for restoration, and their population responses to hydrologic restoration will be used as measures of restoration success.

The conversion of ridge and slough landscape to dense sawgrass stands will have a negative impact on wading birds and other important birds of the Everglades. In a study of the factors affecting foraging behavior of wading birds in the Everglades, Peter Frederick (personal communication) states that his researchers did not even attempt to include moderately dense to dense sawgrass habitat in their sampling scheme because they never saw birds in this habitat. The control of vegetation over wading bird ecology is strong enough that Kushlan (1989) states,

“Whatever determines vegetation patterns will also, to a large degree, determine bird use of wetlands.”

Wet prairie habitat is dominated by spikerush, although other plant species include maidencane, beakrush, and arrowheads, with bladderworts and periphyton mats interspersed among the emergent species (Loftus and Eklund 1994). Although these open water habitats do not occupy as much of the unimpacted Everglades as sawgrass marshes, sloughs and wet prairies are more heavily utilized by fish and wading birds (Hoffman et al. 1994).

In a review of systematic reconnaissance flight data collected in the late 1980s, Hoffman et al. (1994) demonstrate that Great Egrets, Great Blue Herons, and White Ibises almost never were associated with dense grass habitats. These types of dense grass habitats only tended to support wading birds when water levels were high, and then only in relatively small numbers. Hoffman et al. (1994) go on to recommend that to improve wading bird habitat, particularly in the Water Conservation Areas, managers should promote the interspersing of slough and wet prairie habitats into areas of dense grass. In addition, Bancroft et al. (1994) suggest that loss of natural connectivity from compartmentalization might have resulted in a reduction of fish prey for wading birds. They hypothesize that levee construction increased the duration of flooding caused by dry season rainfall events, which ultimately hindered the concentration of prey items that occurs during the dry season.

Kushlan (1989) shows that vegetation structure affects wading bird and waterfowl use of wetlands, because different species have different habitat requirements. For example, long-legged species such as Great Blue Herons and Great Egrets feed by wading in shallow open water marsh. Waterfowl that swim require deeper zones without emergent marsh vegetation. Coots, Gallinules, and Grebes feed in open water but remain near the cover of emergent vegetation which they use for nesting (Kushlan 1989). Resident water bird species that nest in swamp forest vegetation depend on nearby marshes for foraging (Kushlan 1990).

The mechanisms by which vegetation structure affects wading birds are the subject of ongoing research. There is strong evidence to suggest that nesting wading birds in the Everglades are limited by prey availability (Gawlik 2002). This hypothesis, termed the Everglades prey-availability hypothesis (Figure 17), was first proposed as an explanation for the decline of the Wood Stork population in south Florida (Kahl 1964), but it has wide support today for several other species of wading birds (Frederick and Spalding 1994, Gawlik 2002). Based on experimental studies, this hypothesis was modified to focus specifically on the occurrence of high-quality landscape patches, or patches with a high availability of prey (Gawlik 2002).

Although there have been no studies examining the influence of flow rates on wading birds in the Everglades, it is hypothesized that water flow may affect the occurrence of high-quality landscape patches indirectly by affecting hydroperiod and characteristics of the environment such as topography and vegetation structure (Figure 17). If water flow is necessary for maintaining the ridge and slough mosaic, then flow could affect high-quality feeding patches via effects on vegetation structure and topography. Fish are most vulnerable to capture by birds where vegetation has an open structure (Surdick 1998). During the wet season, dense sawgrass ridges in the Arthur R. Marshall Loxahatchee National Wildlife Refuge provide habitat for many

fish (Frank Jordan, unpublished data), but they are protected from wading bird predation, which is probably why wading birds avoid that habitat (Hoffman et al. 1994). However, as the dry down progresses and water levels decline, fish on sawgrass ridges are forced to move into more open sloughs where they are vulnerable to capture by wading birds. Also, the concentration of fish from higher elevation ridges to lower elevation sloughs during the drydown increases fish density 20-150 times in the remaining pools of water (Carter et al. 1973, Kushlan 1974, Kushlan 1976, Loftus and Eklund 1994, Howard et al. 1995). Not surprisingly, densities of some wading bird species are highest where slough habitat is most abundant, even after accounting for the effect of water depth (Bancroft et al. 2002). Species that seem to require both high prey densities and vulnerable prey (i.e., Wood Stork, White Ibis, and Snowy Egret) have declined the most since the 1930s (Ogden 1994).

Collectively, these patterns suggest that the interaction of topography, vegetation structure, hydroperiod, water depth, and draw-down rate can determine the quality of feeding patches for wading birds. Changes to this interaction, from flow or other processes, could alter the timing and magnitude of high-quality prey patches resulting from the seasonal drydown. Coincidentally, two major changes in wading bird populations since the 1930s have been the timing and magnitude of nesting effort (Ogden 1994). Frederick et al. (2001) note considerable degradation of active or former wading bird colony substrate in Water Conservation Areas 2 and 3, and hypothesize that this trend imposes limits on available nesting substrates for wading birds. It is known that compartmentalization has resulted in an increase in ponding in the Water Conservation Areas, especially just upstream of levees.

A diverse wetland mosaic is important to birds other than wading birds. The endangered Snail Kite is a highly specialized bird of prey that depends almost exclusively on one species of aquatic snail (apple snail). The presence of relatively sparse emergent vegetation in open-water areas is an important component of Snail Kite foraging habitat, and kites are unable to forage effectively in dense emergent vegetation (Bennetts et al. 1994). Open water habitats also may be important habitat for foraging by the apple snail population. Therefore, suitable Snail Kite foraging habitat is best represented by a mix of emergent vegetation with open-water communities, which includes the ridge and slough habitat type.

Barriers to fish migration

In addition to altering flow patterns and wetland landscape patterns, barriers to flow serve as barriers to movement of aquatic animals. Joel Trexler (unpublished data) conducted analyses of the population structure of three aquatic species (mosquitofish, spotted sunfish, and grass shrimp). These analyses were conducted by examining relative gene flow, which is a measure of the average number of fish in a generation that move from one area to another and successfully reproduce. Relative gene flow was estimated by comparing gene frequencies from fishes collected in different areas of the Everglades and applying standard population genetics theory to interpret the differences observed (Slatkin 1985, Beerli and Felsenstein 1999, Beerli and Felsenstein 2001). Trexler found that the Tamiami Trail limits migration by mosquitofish between Water Conservation Area 3A and Shark River Slough. A comparison of migration within Water Conservation Area 3A and Shark River Slough and between these two regions suggests that migration within these areas is greater than migration between them (Fig. 18).

An ongoing study of aquatic animal use of shallow, peripheral Everglades marshes is beginning to demonstrate how those animals move over the landscape in response to flow direction and rate (Loftus et al. 2001). Even at very slow flows, it is evident that fishes and decapod crustaceans can detect and use flow in their dispersal, and that their orientation to flow appears to be species specific.

Research and data collection recommendations

Very few research studies have been conducted specifically to determine the role of flow in the Everglades ecosystem. Most of the research projects from which data were presented in this paper, while relevant to the role of flow, were not designed to determine the role of flow. It is precisely for this reason that the SCT chose the topic of flow as one of its priorities. Because compartmentalization and drainage of the Everglades almost certainly had a major impact on flow patterns, it is important that appropriate research and data collection occur to best guide future management and restoration decisions. It is with that goal in mind that the following research and data collection recommendations are provided.

It should be noted that listing of these recommendations does not eliminate the need for a thorough science plan for ridge and slough research. It is important that such a plan be developed, with participation by all stakeholders, including restoration managers. The plan should clearly develop priorities for research, so that limited funding can be applied in the most effective manner possible to develop new information. The plan should be revised on a regular basis as new information and knowledge is obtained. Also, because multiple mechanisms of ridge and slough formation and maintenance likely operate, research projects should specifically address the relative importance of the various mechanisms.

The recommendations below are separated into 3 general priorities – higher, medium, and lower – based upon the degree of consensus among the contributors and the reviewers of earlier drafts of this manuscript.

Higher priority

1. A multidisciplinary study of Everglades paleoenvironmental history is essential to determine the historical extent of ridge and slough habitat, the long-term dynamics of this and other landscape types, and more recent dynamics based on impacts from water management activities, barriers to flow, and other disturbance events such as fire. Measurements needed include: sediment stratigraphy; sediment dating; pollen analysis; peat charcoal detection; isotope geochronology; grain size analysis, bulk density measurements; carbon/nitrogen analysis; C3 vs C4 photosynthetic pathways; sediment geochemistry; macrofossil analysis; nitrogen isotope analysis; analysis of lipid biomarker compounds that reveal the origin of organic matter; and analysis of authigenic minerals such as iron sulfides to determine past redox changes.

2. A thorough and broad geomorphic review is necessary to develop competing conceptual models of how the ridge and slough landscape formed and how it is maintained. This review should provide lists of specific questions and hypotheses that would have to be addressed to

evaluate each possible mechanism of formation and maintenance. The review should lead to the selection of a few of the conceptual models that would provide a better foundation for large-scale scientific inquiry. The review should evaluate processes of peat formation and vertical accretion of organic material, as these processes are fairly well understood and relevant.

3. Sediment transport distributions (spatially and temporally) should be quantified as a possible mechanism of ridge and slough formation and maintenance. Measurements needed include: distribution of particle size and density in suspended sediments, including floc; thickness and other specific characteristics of the floc layer, including changes over time; interception of suspended sediment by vegetation; the velocity at which suspended sediments will be deposited (sedimentary velocity); the velocity at which sediments are resuspended (erosive velocity); sediment deposition and decomposition rates in sloughs and sawgrass stands; and the typical elevation differences between ridges and sloughs. Collection of suspended sediments under variable flow regimes, both before, during, and after restoration is needed to support these objectives.

4. Synoptic measurements of flow should be conducted over short time scales and large space scales in order to quantify ranges of flow velocity and direction and to delineate major flow pathways. Flow measurements should be made in both intact and degraded ridge and slough habitat, and should include surface and ground water. Vertical profiling of flow should be conducted at specific times and locations to quantify details of the flow in order to understand the processes involved in sediment transport, erosion, deposition, mixing, and transport, and to correlate point measurements to vertical means. Time series measurements of flow should be conducted over long time scales at a limited number of locations in order to quantify the effect of infrequent events, such as the passage of storms, and the effect of low frequency phenomena, such as seasonal variations. Individual flow measurements, coupled with ecological surveys, should be designed to study the specific processes that are hypothesized to most likely alter the landscape and affect transport and mixing. Examples include flows around tree islands, near culverts, in fire-impacted areas, and in the vicinity of canals.

Medium priority

1. Develop a simple carbon balance model as a basis for understanding the biological and geomorphological processes that may differ between ridge and slough habitats, and to address the possible mechanism of differential rates of peat accumulation and decomposition. Model parameters would include: primary productivity; decomposition; carbon inputs and exports, both dissolved and particulate; and methane export. Obviously, the data collection and research necessary to provide these types of inputs to the model would have to be conducted, and coordinated with the collection of hydrological data suggested elsewhere. From this model development, a thorough, data-based, carbon budget could be established. Such an approach would illustrate any differences that may exist between ridges and sloughs, and would provide insight into factors that control carbon flow.

2. Continued collection and analysis of remotely sensed images, either fixed wing or satellite, is required to track trends in ridge and slough landscape patterns, and to track restoration progress, particularly when barriers to flow are removed. Field studies, remote sensing techniques, and

system models also should be coordinated to provide a thorough understanding of the mechanisms involved. For instance, remote sensing and surface geophysics could be used to identify areas with strong or weak ridge and slough characteristics and depths of sediment deposition on bedrock, and field research could attempt to quantify environmental conditions leading to both landscape types. Field studies should be able to provide the parameters required by the system models.

3. Develop a seasonal water balance for the entire Everglades, illustrating the relative contribution of regional groundwater, direct precipitation, and surface inflows from the north. This balance would allow estimation of flow availability, quantity, and timing to the ridge and slough landscape prior to and after the water management system was constructed. Even if this water balance is available only as a first-order analysis, it would be useful in assessing the historical and present role of flow in creating and maintaining the ridge and slough landscape pattern.

Lower priority

1. Numerical and analytic techniques, including modeling, are needed to determine the mechanisms of ridge and slough formation and degradation. Numerical modeling of water and sediment flows should be conducted at a variety of temporal and spatial scales in order to provide a physics-based interpolation of the flow field on scales of ecological interest. Modeling also is required to evaluate restoration alternatives. System models that investigate the interactions of important landscape mechanisms would improve our understanding of the relative importance of the environmental factors. These models could also assess potential feedback processes between vegetation and hydrology. A specific example of a model is a ridge and slough patterning model. This model is a simple, grid-based simulation model that has been partially developed by South Florida Water Management District staff (Martha Nungesser, personal communication) but not yet implemented. Another possible approach to understanding the nature of flow and these landscape patterns is to build a simple physical model that tracks how slowly flowing water interacts with a peat-type material.

2. Studies should be conducted to assess the potential for recovery from dense sawgrass stands back to a more diverse wetland mosaic once uninterrupted flow patterns are restored. These studies would address whether the system is resilient enough to recover on its own, or further intervention would be required.

3. Research should be conducted to determine steps that must be taken to ensure that existing ridge and slough landscape can be sustained even in compartmentalized areas of the Everglades.

4. The responses of Everglades animals to flow should be studied, particularly how they may use flow to disperse seasonally to recolonize the system and how flow barriers affect that process.

5. Because of the lack of pre-drainage data, additional historical information concerning pre-drainage vegetation conditions should be sought. In particular, interviews should be conducted with individuals having direct experience in the Everglades prior to the majority of human-induced changes. For example, there may be Miccosukee Tribal elders who lived in the Everglades prior to the construction of the Tamiami Trail.

6. Regular workshops, focused on the ecological effects of flow in the Everglades, should be held. These workshops should involve wide participation of hydrologists and ecologists.

Additional recommendations for future research, both at the one and five-year time horizons, are contained in the flow workshop summary, accessible at <http://sofia.usgs.gov/geer>.

Performance measure development

A centerpiece of the overall south Florida restoration effort is CERP. As a restoration priority, CERP includes re-establishment of pre-drainage hydrological parameters shown by a natural systems model. Science is to serve as the foundation of CERP, and CERP managers have chosen to use adaptive assessment as the underlying principle during the three-plus decades of the restoration implementation. Adaptive assessment provides the scientific feedback loop to restoration managers to change direction if desired outcomes are not being realized. A Monitoring and Assessment Plan is under development to provide this feedback during the restoration program, and includes conceptual ecosystem models (including a ridge and slough conceptual model) and performance measures as indicators of restoration success.

During the development of CERP, restoration of water levels, rather than water flows, dominated the consideration of performance measures. Water levels, their distribution, and their timing are vital to the Everglades. Water flow played a lesser role during the Restudy planning process because accurate modeling of water flows is much more difficult than that of water levels, and the consensus view regarding the role of flow presented in this paper was not available to the Restudy planning teams. Understanding of the relationship between water flow and water level is complicated by the presence of flow barriers in the Everglades, which have made interpretations of empirical observations difficult in a compartmentalized system. Because the consensus view presented in this paper now is available and should result in new flow-related research, flow performance measures should be developed accordingly.

Future improvements in performance measures related to flow will depend on additional research as suggested above to expand our knowledge of the role of flow. Several possible performance measures have been explored, but their interpretation is limited by the availability of field-verified quantitative measures. Additional research will allow resource managers to make better decisions when trade-offs between flow and hydroperiod (and any other hydrological parameters) may have to be considered.

Remote sensing provides one of the best tools from which to continually assess trends in ridge and slough landscape characteristics. Possible performance measure metrics to be used from image analysis include: aerial extent and temporal trends of tree island, sawgrass ridge, and slough polygons; edge-to-area ratios for landscape types; average length-to-width ratio and temporal trends of sawgrass ridges or sloughs for a defined area; and spatial orientation of the three landscape types as compared to the historic spatial orientation. Surface geophysics at set transects over time will demonstrate movement of surficial sediments, and enhance performance assessment as restoration measures are implemented.

Refinement of hydrologic models to provide velocity vectors (both magnitude and direction) and water depths would help predict where erosive and sedimentary velocities might occur, where flow directions differ from the natural direction, and where depths might be expected to alter landscape features. Spatial assessments can involve calculating suitability indices to indicate areas with: unnaturally high or slow velocities; unnaturally broad or narrow annual ranges in water depth; unnaturally high peak water levels (or low minimum water levels); and unnatural deviation in flow direction.

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Editor

Nicholas G. Aumen, Everglades National Park

Contributors:

Tom Armentano, Everglades National Park
Nicholas G. Aumen, Everglades National Park
Joan Browder, National Oceanographic and Atmospheric Administration
Elizabeth Crisfield, Everglades National Park
Peter Frederick, University of Florida
Dale Gawlik, South Florida Water Management District
Harry Jenter, US Geological Survey
Jim Kushlan, Smithsonian Institution
Chris McVoy, South Florida Water Management District
Martha Nungesser, South Florida Water Management District
John Ogden, South Florida Water Management District
Gregory Pasternack, University of California - Davis
Mike Ross, Florida International University
Fred Sklar, South Florida Water Management District
Joel Trexler, Florida International University
Jon Woolverton, US Geological Survey

Individual and agency reviewers from which comments on earlier drafts were received:

Sydney Bacchus, public
Ronnie Best, US Geological Survey
Gwen Burzycki, Miami-Dade County
James Duck, compiled comments from the US Army Corps of Engineers, Jacksonville District
Chris Farrell, public
Matt Harwell, US Fish and Wildlife Service
Harry Jenter, US Geological Survey
Brian Keller, National Oceanographic and Atmospheric Administration
Tom Lodge, public
Bill Loftus, US Geological Survey
John Marshall, public
Paul McCormick, Everglades National Park
Jack Moller, public
Mitch Murray, US Geological Survey
John Ogden, South Florida Water Management District
Peter Ortnier, National Oceanographic and Atmospheric Administration
Peter Rauch, public
Terry Rice, Miccosukee Tribe of Indians of Florida
Eric Swain, US Geological Survey
Ken Tarboton, South Florida Water Management District
Mike Waldon, US Fish and Wildlife Service
Jeff Walters, Virginia Polytechnic Institute and State University

Independent peer review panel

Barbara L. Bedford, Senior Research Associate, Department of Natural Resources, Cornell University
Thomas S. Bianchi, Associate Professor, Department of Earth and Ecosystem Sciences, Tulane University
James G. Gosselink, Professor Emeritus, Center for Wetland Resources, Louisiana State University
Paul A. Keddy, Professor of Environmental Sciences, Department of Biological Sciences, Southeastern Louisiana University
Barbara W. Leyden, Professor, Department of Geology, University of South Florida
William H. McDowell, Professor, Department of Natural Resources, University of New Hampshire
Gregory B. Pasternack, Associate Professor, Department of Land, Air, and Water Resources, University of California – Davis

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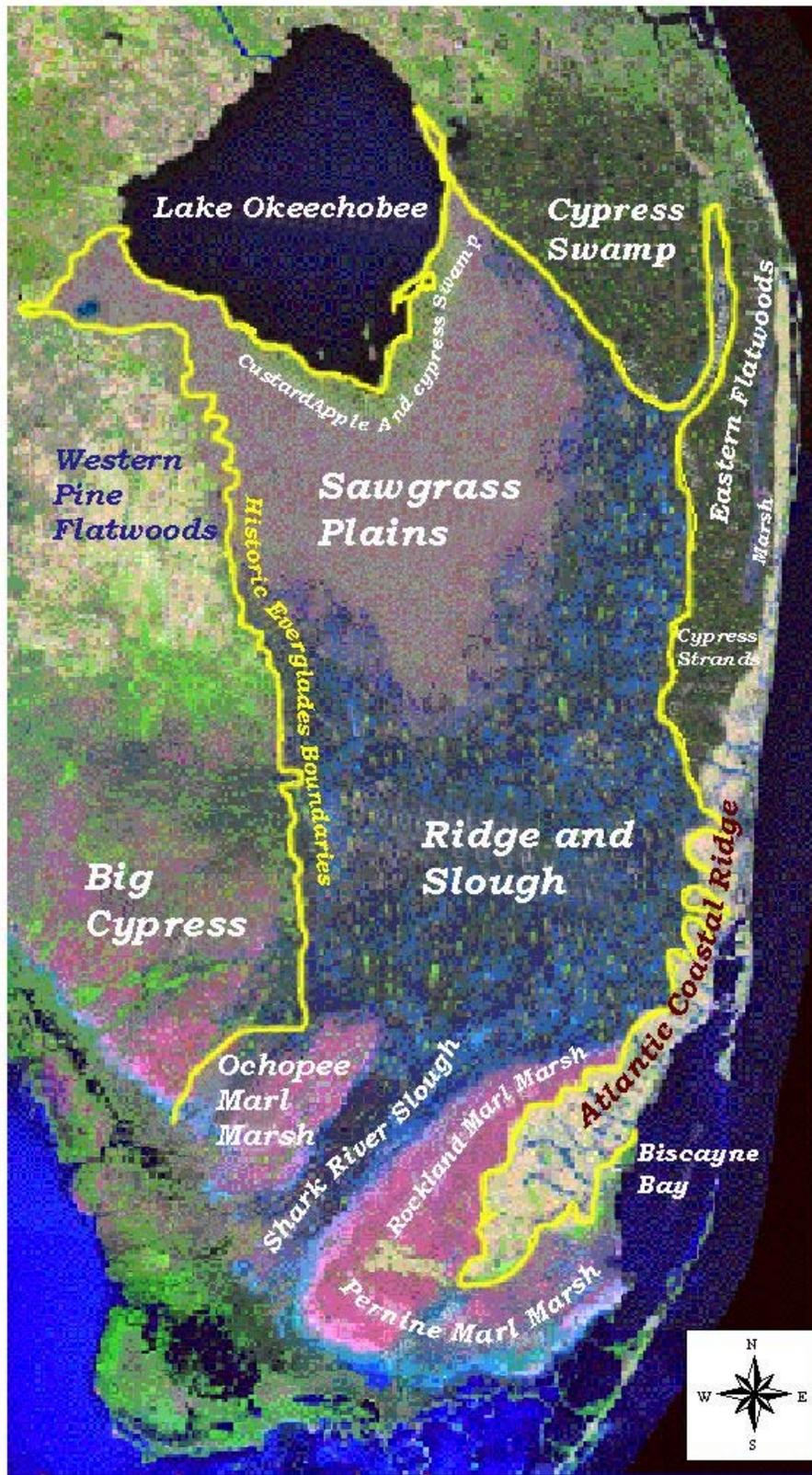


Figure 1. General locations of the major landscape types in the Everglades prior to human intervention.



Figure 2. Ridge and slough landscape in its pre-drainage condition. Note sharp, distinct edges on most sawgrass ridges, and the open water of sloughs, with few emergent plants. Location: present Northeast Shark Slough area.



Figure 3. Ridge and slough landscape in its pre-drainage condition. Note large extent of open water slough. Location: southwest corner of present Water Conservation Area 3B.

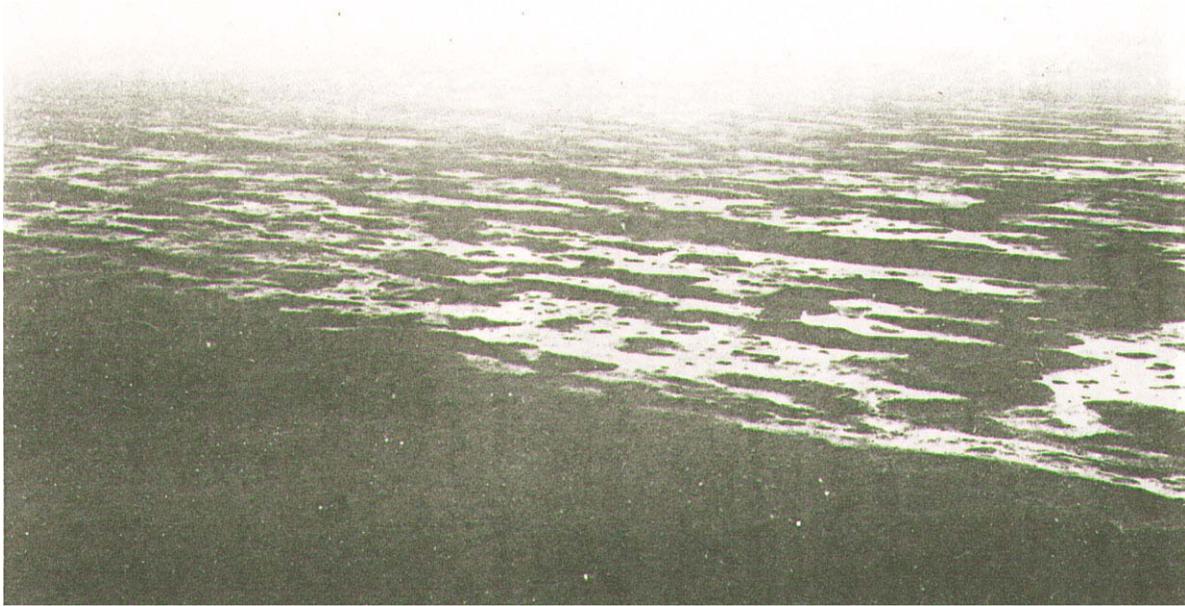


Figure 4. Ridge and slough landscape in its pre-drainage condition (approximate). Oblique aerial view of Everglades from a dirigible, 1930s, looking west. Location: west of Miami, probably south of Tamiami Trail. Note linear pattern of elongated sawgrass ridges (dark) and intervening sloughs (light) (Matlack 1939).

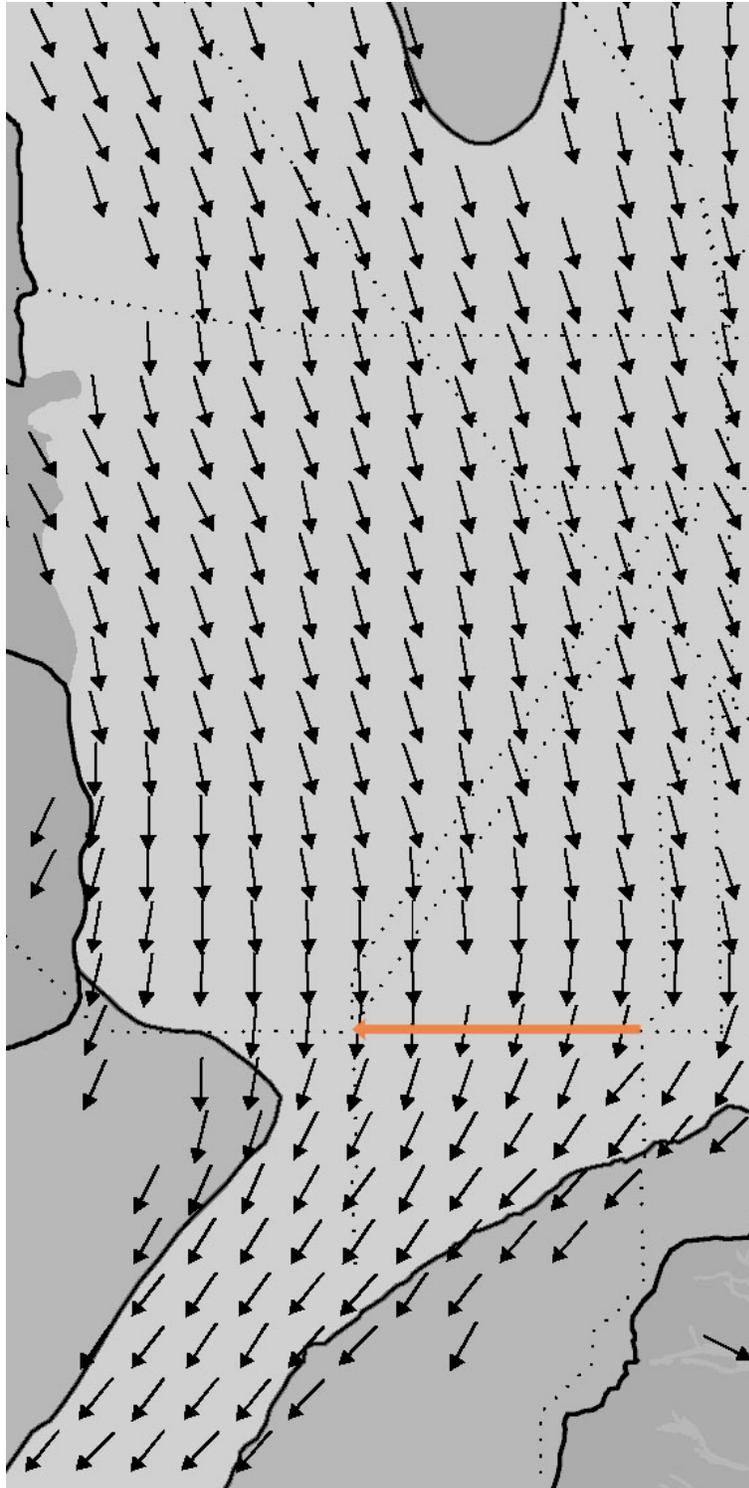


Figure 5. Landscape directionality and estimated pre-drainage flow directions within the western ridge and slough landscape. Mapped from aerial photographs from 1940 (USDA-SCS 1940). Published in Sklar *et al.* (2001), Fig. 2-9. Note continuous flow lines through Water Conservation Areas 3A, 3B, and Northeast Shark Slough. Red line indicates portion of Tamiami Trail between Dade Corners and the intersection of L-67.

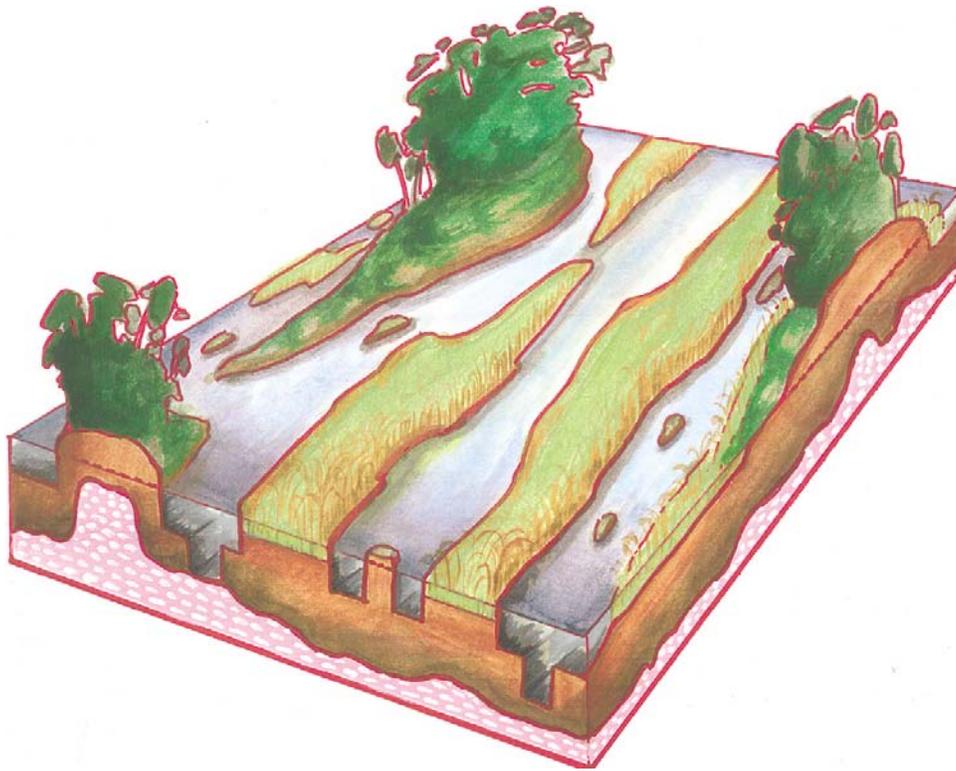


Figure 6. Ridge and slough landscape: artist's reconstruction of pre-drainage condition. Note relation of landscape pattern (plan view) to underlying peat microtopography (vertical profile). Scale: length = 1.5 miles; width = 1.0 mile.



Figure 7. Ridge and slough landscape, considered to be well preserved in its present condition, as seen in a June 2001 aerial view from central Water Conservation Area 3A. Image size approximately 1.5 X 2 miles; North is to left. Gray-green strips are sawgrass ridges; intervening lighter areas are open-water sloughs.

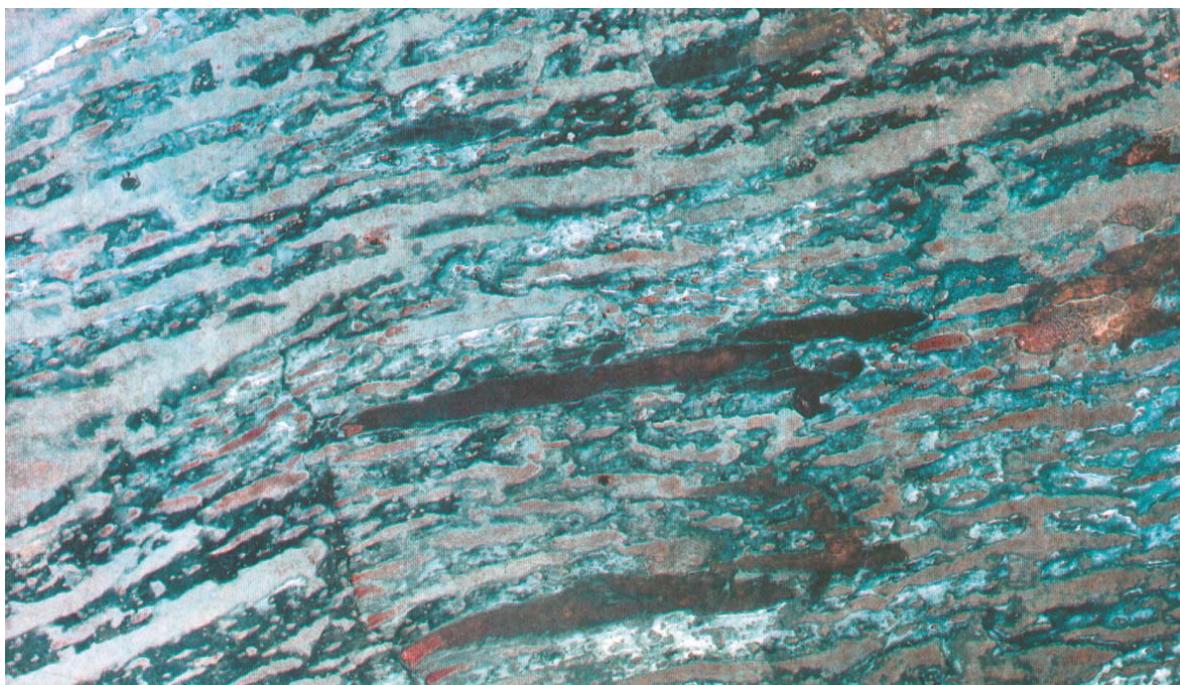


Figure 8. Ridge and slough landscape considered to be well preserved in its current condition, as seen in a 1991 color infrared aerial photo from central Water Conservation Area 3A. Image size approximately 2.5 X 3.75 miles; North is to left. Red indicates woody vegetation; gray strips are sawgrass ridges; darker areas are sloughs, except for two recently burned ridges. An east-west transect through image would cross 15-20 sawgrass ridges. Note well-defined, elongated shape of ridges.



Figure 9. Ridge and slough landscape in its current, degraded condition as seen in a June, 2001 oblique aerial view from the southeast corner of northern Water Conservation Area 3A, north of Alligator Alley (I-75). Gray-green is sawgrass; other areas are slough-like. Note breaking up of sawgrass into numerous, small patches. Photo taken from an altitude of 300-500 feet.



Figure 10. Ridge and slough landscape in its current, degraded condition as seen in a 1991 color infrared aerial photo of the eastern side of Water Conservation Area 3A (intersection of Alligator Alley and US 27) Traces of original NNW-SSE orientation of sawgrass ridges still are visible, but the pattern is unclear, and ridges are breaking up into individual sawgrass patches.



Figure 11. Ridge and slough landscape in its current, degraded condition, as seen in an April 6, 2001, oblique aerial view from northern Water Conservation Area 3A, north of Alligator Alley, looking south. Yellowish-green is sawgrass; gray-green indicates former sloughs, now grown over with wet prairie species. Photo taken from an altitude of about 1000 feet.

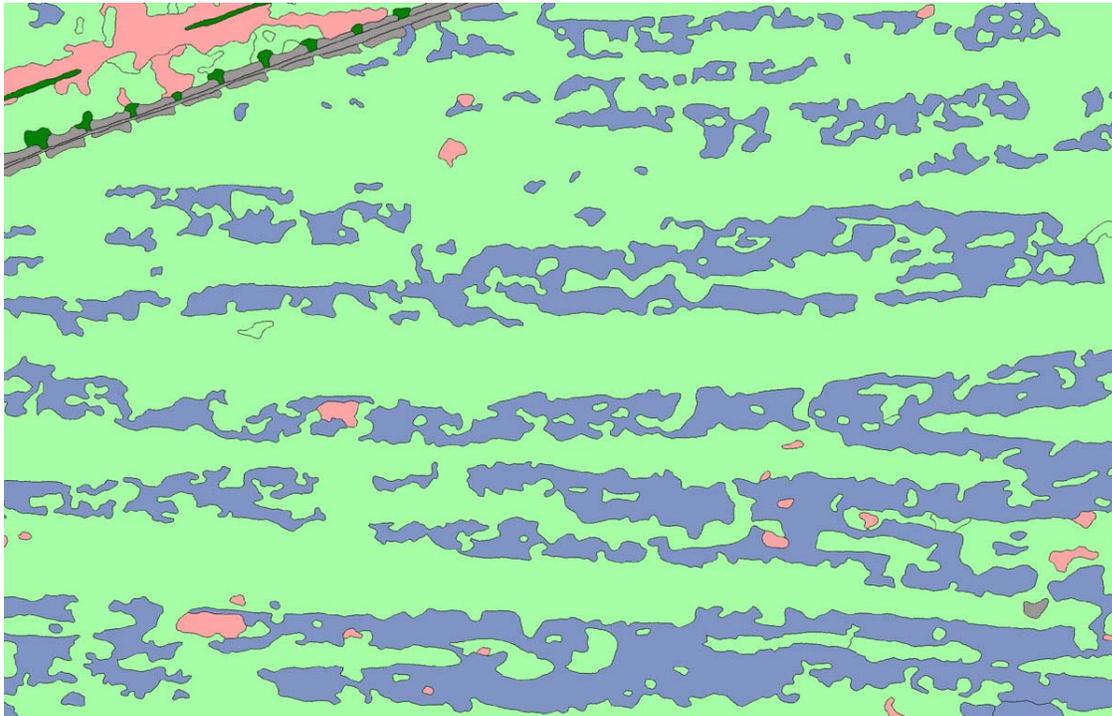


Figure 12. Ridge and slough landscape in its current, degraded condition as seen in detail from a vegetation map of Water Conservation Area 3A, north of Alligator Alley, west of Miami Canal. North is to left. Green indicates sawgrass; blue indicates sloughs. Note breaking up of sloughs, resulting in “moth-eaten” appearance in plan view.



Figure 13. Ridge and slough landscape in its current, degraded condition as seen in Water Conservation Area 3B. Landscape is almost completely covered by sawgrass; slough areas are reduced to minor isolated remnants and directional pattern largely obscured.

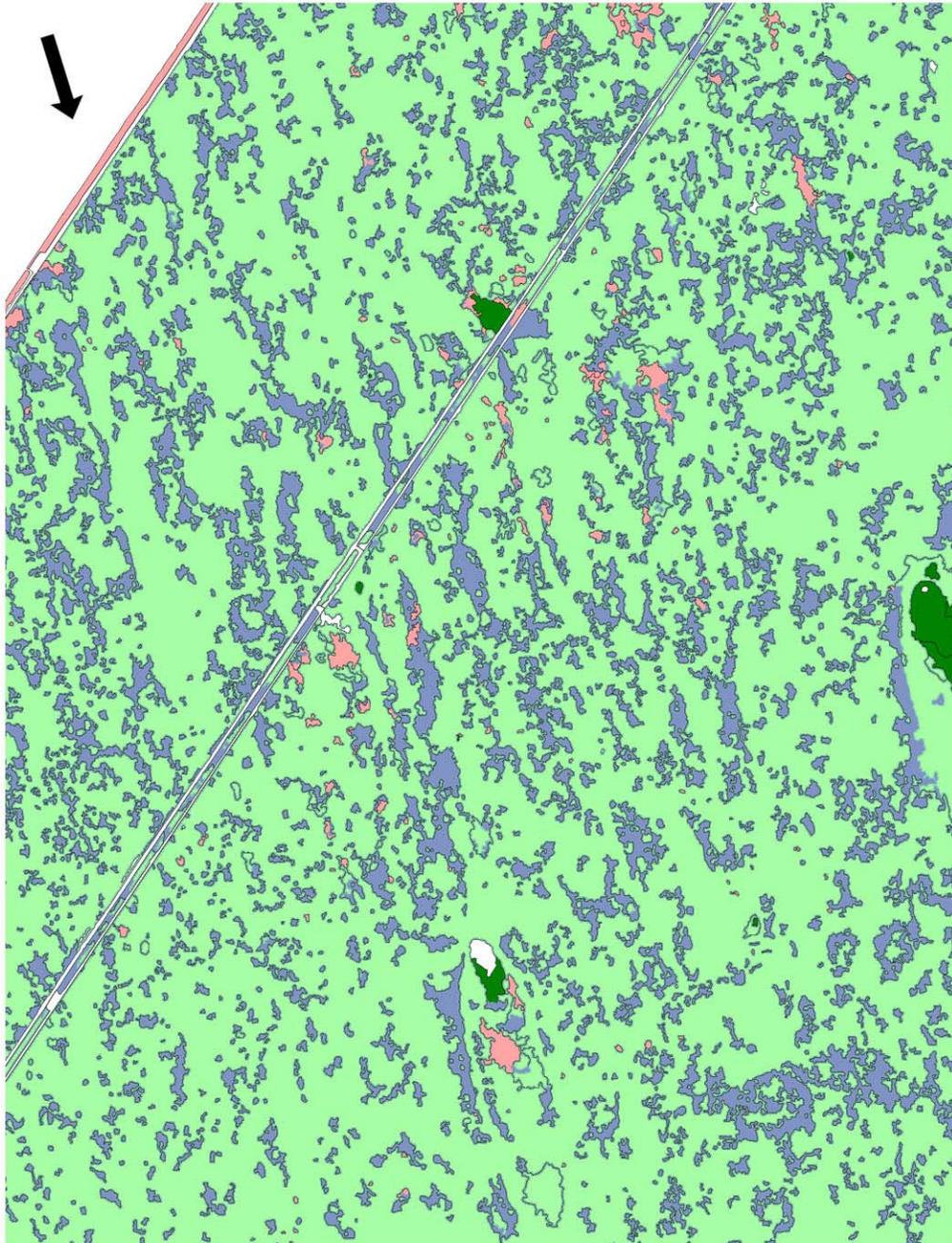


Figure 14. Ridge and slough landscape in its current, degraded condition, as seen in a vegetation map of western Water Conservation Area 3B, along L-67A and L-67C canals. The original pre-drainage NNW-SSE directionality (arrow) still is recognizable faintly (hold at arm's length; rotate image). However, the typical pattern of clear ridges and sloughs has been almost completely obscured, primarily by sawgrass overgrowing the sloughs.

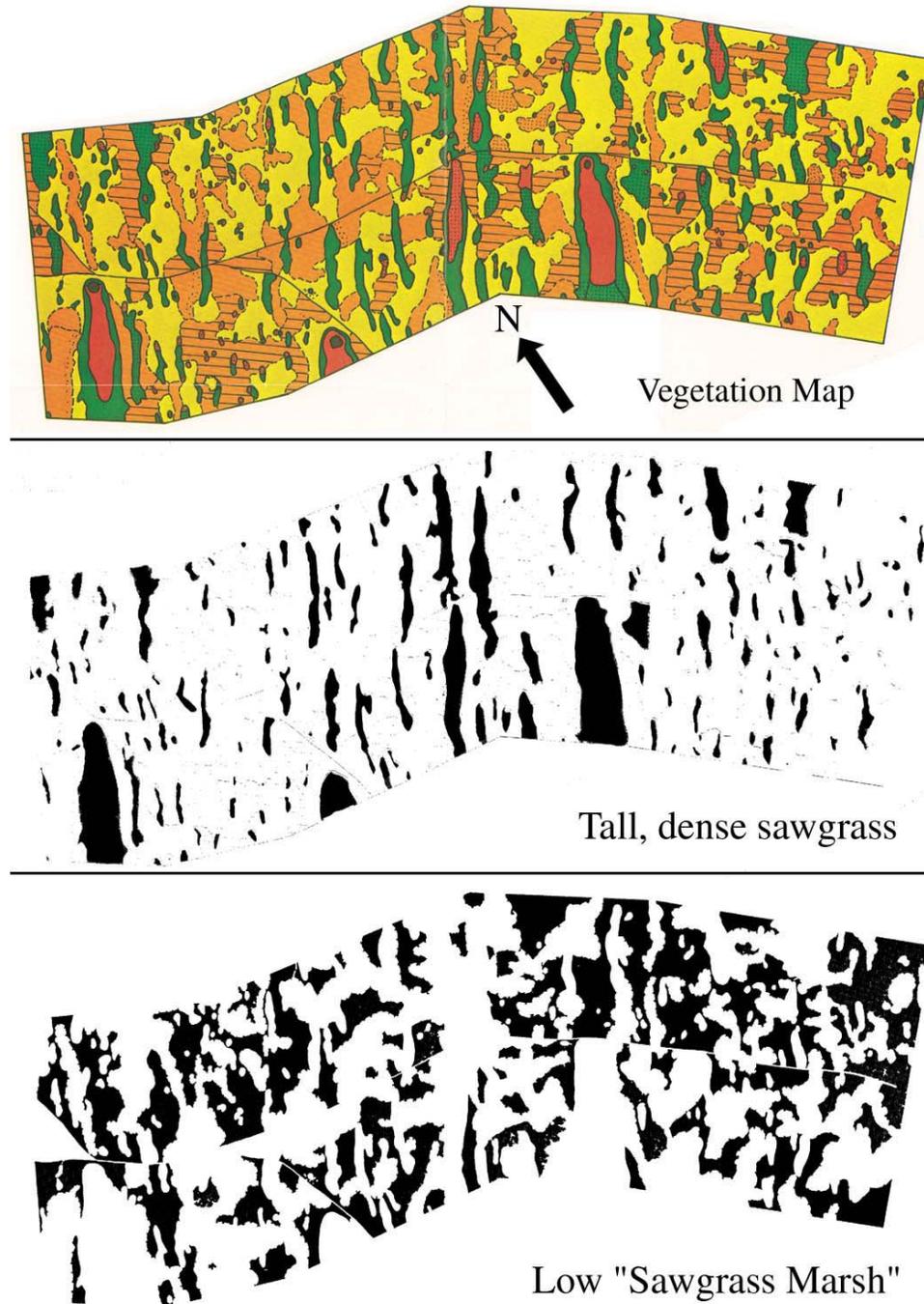


Figure 15. 1980 vegetation map of area within Shark Slough, Everglades National Park (Olmsted and Armentano 1997). Area approximately 3.75 miles wide. Green indicates stands of tall sawgrass, usually very dense and monotypic, slightly elevated above surrounding marsh; yellow indicates sawgrass marsh, with sparse, low stature sawgrass; orange indicates wet prairies; red is bayhead swamp forest. Middle panel shows only tall, dense sawgrass polygons; bottom panel shows sawgrass marsh polygons only. Note contrast in directionality between panels: polygons in middle are directional, with consistent orientation; polygons in bottom panel are amorphous, with random orientation. Middle panel is thought to map original, pre-drainage sawgrass ridge geometry, while bottom panel thought to map post-drainage sawgrass which has randomly colonized sloughs. Random colonization suggests post-drainage absence of a strong directional process.

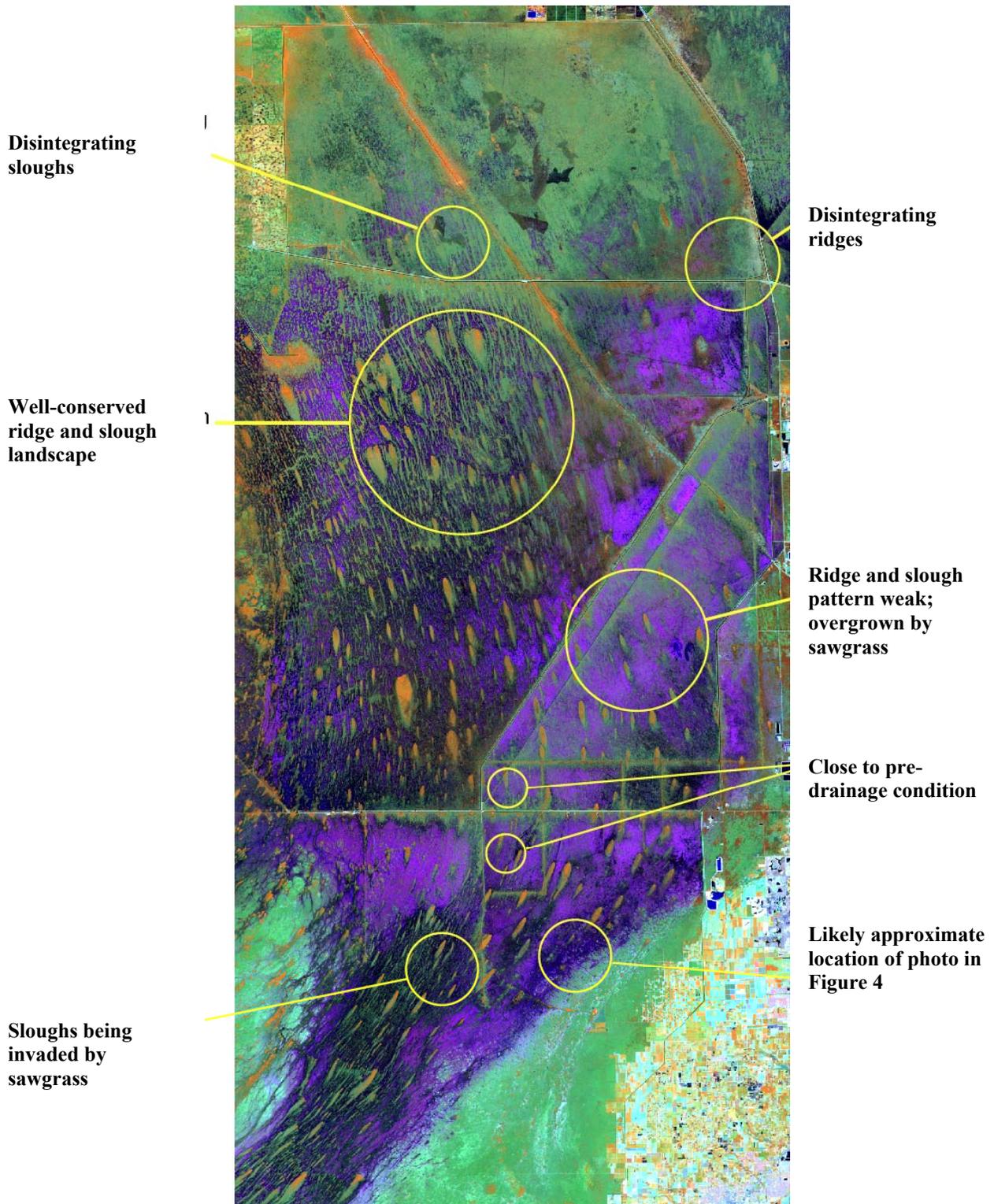


Figure 16. Satellite image of the western ridge and slough landscape, including Water Conservation Areas 3A and 3B, and the Shark Slough/Northeast Shark Slough portions of Everglades National Park. Largest circle indicates portion of landscape which most closely resembles original pattern of ridges and sloughs. Smallest circles show location of 1917 photographs that closely resemble pre-drainage descriptions. Other circles indicate various degraded conditions of present day ridge and slough landscape.

Gawlik In Press

Everglades prey-availability hypothesis

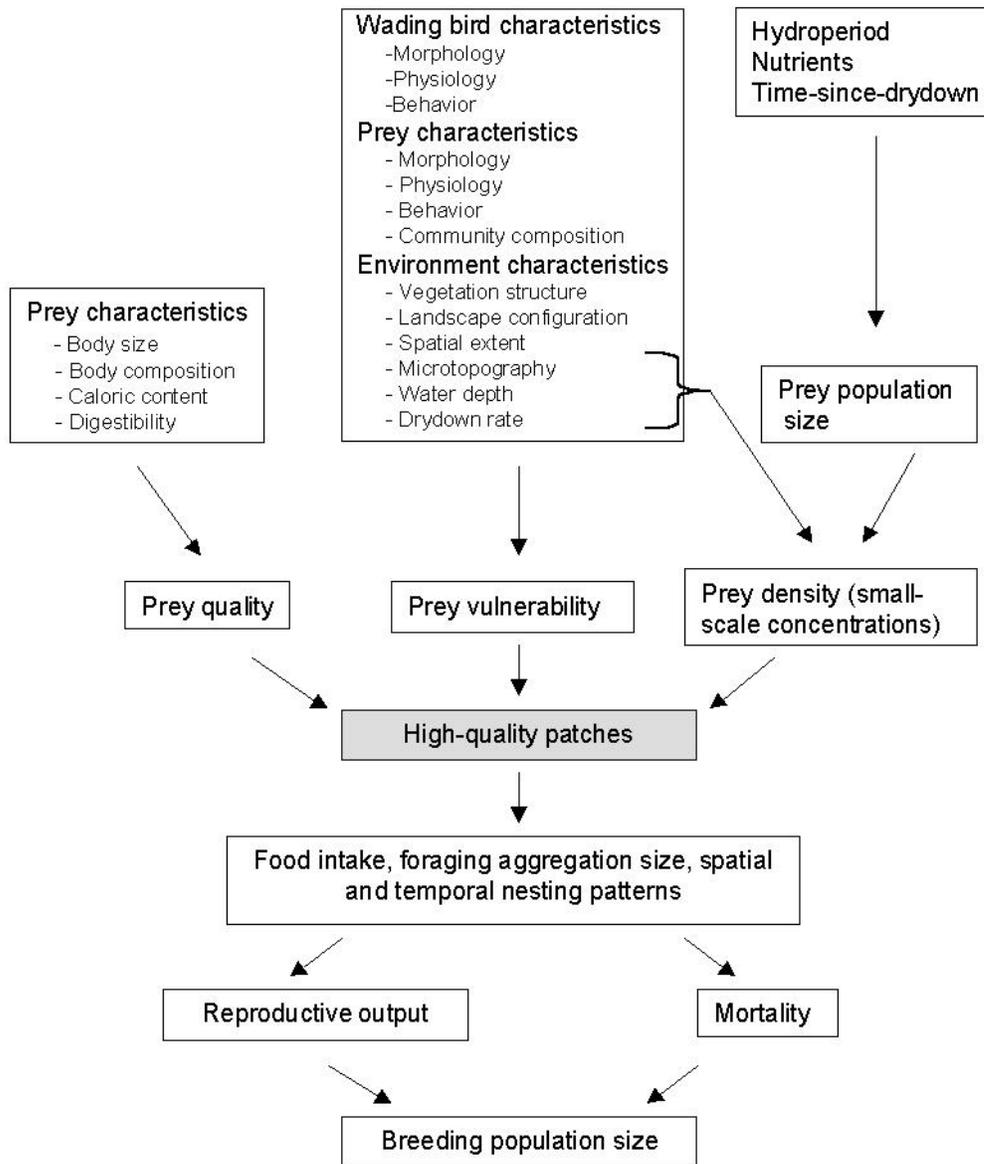


Figure 17. Everglades prey-availability hypothesis (Gawlik in press).

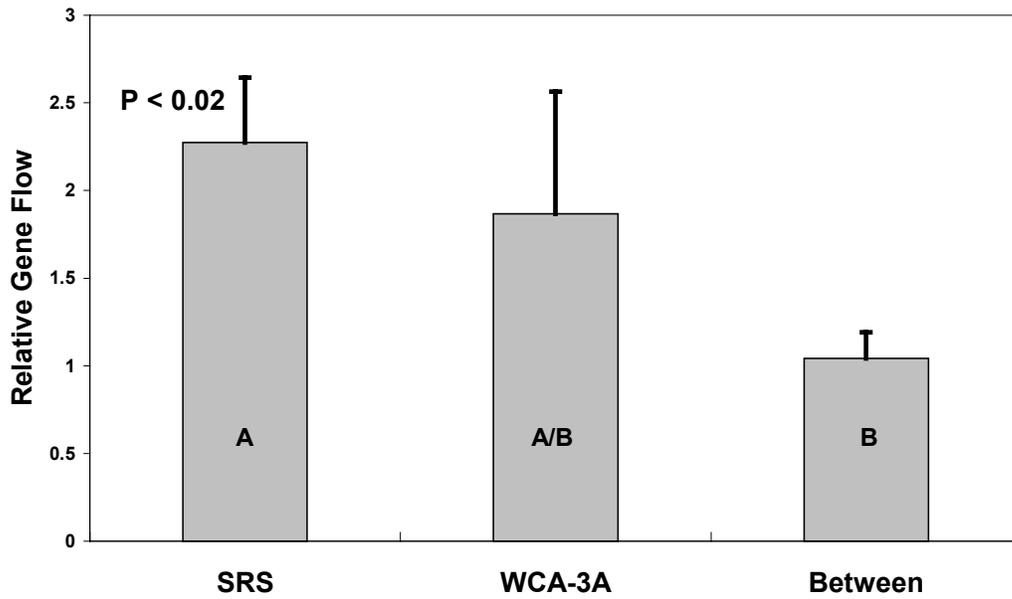


Figure 18. Estimates of migration rate within Shark River Slough and Water Conservation Area 3A, and between the two areas. Sites were chosen to have separations of approximately equal distances within each slough, and between the two sloughs.