United States
Environmental Protection
Agency

Office of Water
Office of Science and Technology
Washington, DC 20460

EPA-822-R-07-004
September 2007
www.epa.gov

Nutrient Criteria Technical Guidance Manual

Wetlands

Full Guidance Document available in full at:
http://www.epa.gov/waterscience/criteria/nutrient/guidance/

APPENDIX A. ACRONYM LIST AND GLOSSARY

ACRONYMS

ACOE/ACE/COE - Army Corps of Engineers
AGNPS - Agricultural Nonpoint Source Pollution model
ARS - Agricultural Research Service
BACI - Before/After, Control/Impact
BMP - Best Management Practice
BuRec - Bureau of Reclamation
CCC - Commodity Credit Corporation
CENR - Committee for the Environment and Natural Resources
CGP - Construction General Permit
CHN - Carbon-Hydrogen-Nitrogen
CPGL - Conservation of Private Grazing Land
CPP - Continuing Planning Process
CREP - Conservation Reserve Enhancement Program
CRP - Conservation Reserve Program
CSO - Combined Sewer Overflow
CWA - Clean Water Act
CZARA - Coastal Zone Act Reauthorization Amendment
DIP - Dissolved inorganic phosphorus
DO - Dissolved oxygen
DOP - Dissolved organic phosphorus
DRP - Dissolved reactive phosphorus
ECARP - Environmental Conservation Acreage Reserve Program
EDAS - Ecological Data Application System
Eh - Redox potential
EMAP - Environmental Monitoring and Assessment Program
EQIP - Environmental Quality Incentive Program
FDEP - Florida Department of Environmental Protection
FIP - Forestry Incentive Program
GIS - Geographic Information System
GPS - Geospatial Positioning System
GWLF - Generalized Watershed Loading Function
HEL - Highly erodible land
HGM - Hydrogeomorphic approach

HSPF - Hydrologic Simulation Program - Fortran
MPCA - Minnesota Pollution Control Agency
NAAQS - National Ambient Air Quality Standard
NASQAN - National Stream Quality Assessment Network
NAWQA - National Water Quality Assessment
NIS - Network Information System
NIST - National Institute of Standards and Technology
NOAA - National Oceanic and Atmospheric Administration
NPDES - National Pollution Discharge Elimination System
NPP - Net primary production
NRCS - Natural Resources Conservation Service
NSF - National Science Foundation
NWI - National Wetlands Inventory
OH EPA - Ohio EPA
ONRW - Outstanding Natural Resource Waters
PCB - Polychlorinated biphenyls
PCS - Permit Compliance System
PIP - Particulate inorganic phosphorus
POP - Particulate organic phosphorus
PSA - Particle size analysis
QA/QC - Quality Assurance/Quality Control
QC - Quality Control
REMAP - Regional Environmental Monitoring and Assessment Program
RF3 - Reach File 3
SCS - Soil Conservation Service
SPARROW - Spatially Referenced Regressions on Watersheds
SRP - Soluble reactive phosphorus
STORET - Storage and Retrieval System
SWAT - Soil and Water Assessment Tool
TKN - Total Kjeldahl Nitrogen
TMDL - Total Maximum Daily Load
TP - Total Phosphorus
TWINSPAN -
USDA - United States Department of Agriculture
USEPA - United States Environmental Protection Agency
USFWS - United States Fish and Wildlife Service
USGS - United States Geological Survey
WEBB - Water, Energy, and Biogeochemical Budgets
WHIP - Wildlife Habitat Incentive Program
WLA - Wasteload Allocation
WQBEL - Water Quality Based Effluent Limit
WQS - Water Quality Standard
WRP - Wetlands Reserve Program

GLOSSARY

biocriteria
(biological criteria) Narrative or numeric expressions that describe the desired biological condition of aquatic communities inhabiting particular types of waterbodies and serve as an index of aquatic community health. (USEPA 1994).

cluster analysis
An exploratory multivariate statistical technique that groups similar entities in an hierarchical structure.

criteria
Elements of State water quality standards, expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that supports a particular use. When criteria are met, water quality will generally protect the designated use (40 CFR 131.3(b)).

designated use(s)
Uses defined in water quality standards for each waterbody or segment whether or not the use is being attained (USEPA 1994).

detritus
Unconsolidated sediments comprised of both inorganic and dead and decaying particulate organic matter inhabited by decomposer microorganisms (Wetzel 1983).

ecological unit
Mapped units that are delineated based on similarity in climate, landform, geomorphology, geology, soils, hydrology, potential vegetation, and water.

ecoregion
A region defined by similarity of climate, landform, soil, potential natural vegetation, hydrology, and other ecologically relevant variables.

emergent vegetation
"Erect, rooted herbaceous angiosperms that may be temporarily to permanently flooded at the base but do not tolerate prolonged inundation of the entire plant; e.g., bulrushes (Scirpus spp.), saltmarsh cordgrass" (Cowardin et.al., 1979).

eutrophic
Abundant in nutrients and having high rates of productivity frequently resulting in oxygen depletion below the surface layer (Wetzel 1983).

eutrophication
The increase of nutrients in [waterbodies] either naturally or artificially by pollution (Goldman and Horne 1983).

GIS (Geographical Information Systems)
A computerized information system that can input, store, manipulate, analyze, and display geographically referenced data to support decision-making processes. (NDWP Water Words Dictionary)

HGM, hydrogeomorphic

Land form characterized by a specific origin, geomorphic setting, water source, and hydrodynamic (NDWP Water Words Dictionary)

index of biotic integrity (IBI)
An integrative expression of the biological condition that is composed of multiple metrics. Similar to economic indexes used for expressing the condition of the economy.

interfluve
An area of relatively unchannelized upland between adjacent streams flowing in approximately the same direction.

lacustrine
"Includes wetlands and deepwater habitats with all of the following characteristics: (1)
situated in a topographic depression or a dammed river channel; (2) lacking trees, persistent emergents, emergent mosses or lichens with greater than 30% areal coverage; and, (3) total area exceeds 8 ha (20 acres). Similar wetland and deepwater habitats totaling less than 8 ha are also included in the Lacustrine System if an active wave-formed or bedrock shoreline feature makes up all or part of the boundary, or if the water depth in the deepest part of the basin exceeds 2 m (6.6 feet) at low water...may be tidal or nontidal, but ocean-derived salinity is always less than 0.5%" (Cowardin et.al., 1979).

lentic
Relatively still-water environment (Goldman and Horne 1983).

limnetic
The open water of a body of fresh water.

littoral
Region along the shore of a non-flowing body of water.

lotic
Running-water environment (Goldman and Horne 1983).

Macrophyte
(Also known as SAV-Submerged Aquatic Vegetation) Larger aquatic plants, as distinct from the microscopic plants, including aquatic mosses, liverworts, angiosperms, ferns, and larger algae as well as vascular plants; no precise taxonomic meaning (Goldman and Horne 1983).

µg/L
micrograms per liter, 10^{-6} grams per liter

mg/L
milligrams per liter, 10^{-3} grams per liter

mineral soil flats
Level wetland landform with predominantly mineral soils

minerotrophic
Receiving water inputs from groundwater, and thus higher in salt content (major ions) and pH than ombrotrophic systems.

mixohaline
Water with salinity of 0.5 to 30%, due to ocean salts.

M
Molarity, moles of an element as concentration

multivariate
Type of statistics that relates one or more independent (explanatory) variables with multiple dependent (response) variables.

nutrient ecoregion
Level II ecoregions defined by Omernik according to expected similarity in attributes affecting nutrient supply (http://www.epa.gov/OST/standards/ecomap.html).

oligotrophic
Trophic status of a waterbody characterized by a small supply of nutrients (low nutrient release from sediments), low production of organic matter, low rates of decomposition, oxidizing hypolimnetic condition (high DO) (Wetzel 1983).

palustrine
"Nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses orlichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5%. It also includes wetlands lacking such vegetation, but with all of the following four characteristics: (1) area less than 8 ha (20 acres); (2) active wave-formed or bedrock shoreline features lacking; (3) water depth in the deepest part of basin less than 2 m at low water; and, (4) salinity due to ocean-derived salts less than 0.5%" (Cowardin et.al., 1979).

peatland
"A type of wetland in which organic matter is produced faster than it is decomposed, resulting in the accumulation of partially decomposed vegetative material called Peat. In some mires peat never accumulates to the point where plants lose contact with water moving through mineral soil. Such mires, dominated by grasslike sedges, are called Fens. In other mires peat becomes so thick that the surface vegetation is insulated from mineral soil. These plants depend on precipitation for both water and nutrients. Such mires, dominated by acid forming sphagnum moss, are called Bogs." (NDWP Water Words Dictionary)

periphyton
Associated aquatic organisms attached or clinging to stems and leaves of rooted plants or other surfaces projecting above the bottom of a waterbody (USEPA 1994).

pocosin
Evergreen shrub bog, found on Atlantic coastal plain.

riverine wetland
A hydrogeomorphic class of wetlands found in floodplains and riparian zones associated with stream or river channels.

slope wetland
A wetland typically formed at a break in slope where groundwater discharges to the surface. Typically there is no standing water.

trophic status
Degree of nutrient enrichment of a waterbody.

waters of the U.S.
Waters of the United States is defined at 40 CFR § 230.3(s)) as including:
a. All waters that are currently used, were used in the past, or may be susceptible to use in interstate or foreign commerce, including all waters that are subject to the ebb and flow of the tide;
b. All interstate waters, including interstate wetlands; and,
c. All other waters such as interstate lakes, rivers, streams (including intermittent streams), mudflats, sandflats, wetlands, sloughs, prairie potholes, wet meadows, playa lakes, or natural ponds the use, degradation, or destruction of which would affect or could affect interstate or foreign commerce including any such waters:

1 That are or could be used by interstate or foreign travelers for recreational or other purposes;
2 From which fish or shellfish are or could be taken and sold in interstate or foreign commerce; or,
3 That are used or could be used for industrial purposes by industries in interstate commerce;

d. All impoundments of waters otherwise defined as waters of the United States under this definition;
e. Tributaries of waters identified in paragraphs (a) through (d) of this definition;
f. The territorial sea; and,
g. Wetlands adjacent to waters (other than waters that are themselves wetlands) identified in paragraphs (a) through (f) of this definition.
For further information regarding the scope of 'waters of the U.S.' in light of the U.S. Supreme Court's 2006 decision in Rapanos v. United States, see "Clean Water Act Jurisdiction Following the U.S. Supreme Court's Decision in Rapanos v. United States & Carabell v. United States," which was jointly issued by the U.S. Environmental Protection Agency and the Army Corps of Engineers and is available at: http://www.epa.gov/owow/wetlands/.

wetland(s)
Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions [EPA, 40 CFR§ 230.3 (t)/USACE,33 CFR § 328.3 (b)].

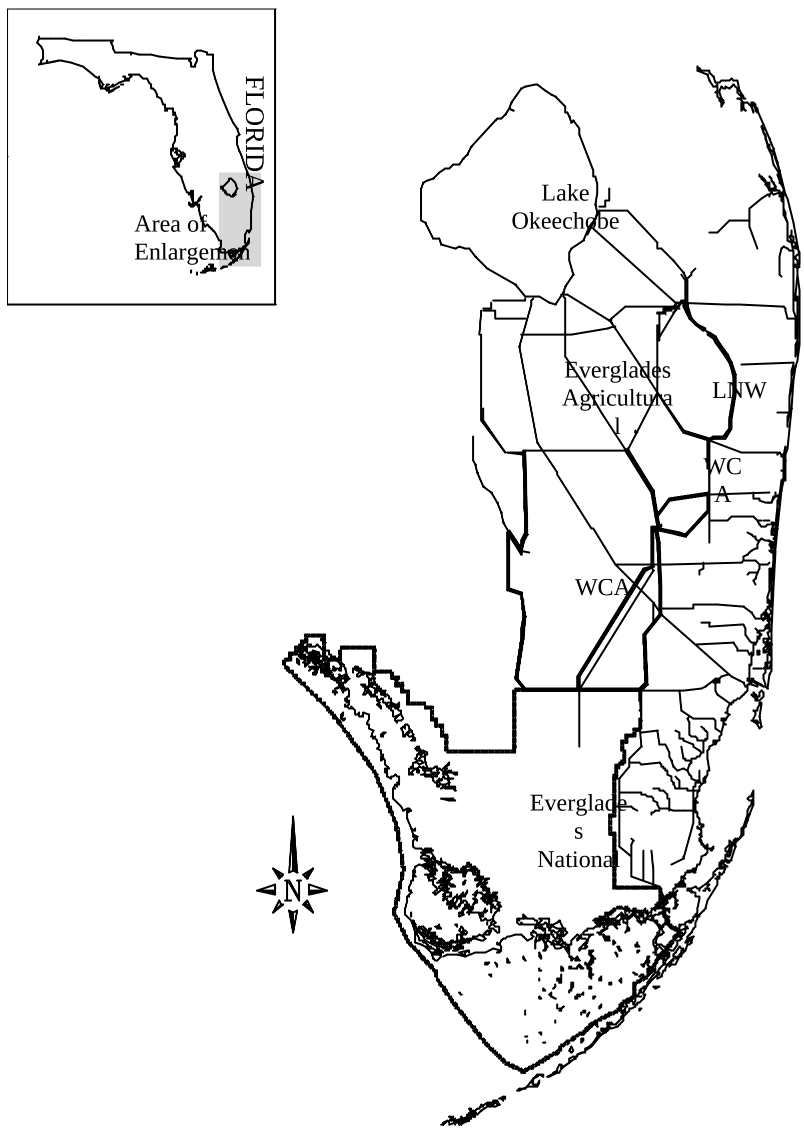
APPENDIX B. CASE STUDY: DERIVING A PHOSPHORUS CRITERION FOR THE FLORIDA EVERGLADES

INTRODUCTION

The Everglades (Figure B1.1) is the largest subtropical wetland in North America and is widely recognized for its unique ecological character. It has been affected for more than a century by rapid population growth in south Florida. Roughly half of the ecosystem has been drained and converted to agricultural and urban uses. Among other changes, the conversion of 500,000 acres of the northern Everglades to agriculture (the Everglades Agricultural Area or EAA) and the subsequent diking of the southern rim of Lake Okeechobee eliminated the normal seasonal flow of water southward from Lake Okeechobee. Furthermore, the construction of a complex network of internal canals and levees disrupted the natural sheetflow of water through the system and created a series of impounded wetlands known as “Water Conservation Areas” or WCAs. This conversion from a hydrologically open to a highly managed wetland occurred gradually, beginning with the excavation of four major canals during the 1900-1910 period and culminating with the construction of the Central and South Florida Flood Control Project (CSFFCP) during the 1950s and 60s (Light and Dineen 1994).

The remnant Everglades is managed for multiple and often conflicting uses including water supply, flood control, and the hydrologic needs of the natural ecosystem. Water management operations have altered the quantity, quality, timing, and delivery of flows to the Everglades relative to the pre-disturbance system; some parts of the system have been damaged by overdrainage, excessive flooding in other areas has stressed native vegetation communities. Changes to the seasonal pattern of flooding and drying have influenced many ecological processes, including changes in the dominant micro- and macro-phytic vegetation, declines in critical species, and the nesting success of wading bird populations that rely on drawdowns during a narrow window of time to concentrate fish prey. Canal inputs containing runoff from agricultural and urban lands contribute roughly 50% of flows to the managed system and have increased loads of nutrients and contaminants. In particular, phosphorus (P) has been identified as a key limiting nutrient in the Everglades and increased inputs of this nutrient have been identified as a significant factor affecting ecological processes and communities.

The primary source of P to the pre-disturbance Everglades was rainfall, although seasonal flows from Lake Okeechobee likely contributed significant P to the northern fringe of the wetland. Prior to the implementation of P control efforts in the late 1990s, canal flows were estimated to contribute more than half of the P load to the managed Everglades (SFWMD 1992). Discharge from the EAA is the main source of water to the Everglades, with approximately 500,000 acres of farmland draining southward via SFWMD canals, and is the major source of anthropogenic P. Significant inputs also come from Lake Okeechobee, a naturally mesotrophic lake that has also been enriched by agricultural runoff. Several other agricultural and urban catchments contribute



Appendix B1. Figure B1.1. Major hydrologic units of the remnant Florida Everglades (shaded region) including (from north to south) the A.R.M. Loxahacthee National Wildlife Refuge (LNWR), Water Conservation Area (WCA) 2A, WCA 3A, and Everglades National Park. Shaded lines represent the regional canal and levee system that conveys water southward from Lake Okeechobee and the Everglades Agricultural Area to the Everglades and urban areas along the coast.

smaller amounts of P via canal discharges into various parts of the Everglades. However, in general, canal P concentrations and loads (and associated wetland concentrations) decline from north to south.

The history of P enrichment and associated ecological impacts is not well documented but probably occurred at a limited scale for much of the last century. Early reports by the South Florida Water Management District (e.g., Gleason et.al., 1975, Swift and Nicholas 1987) showed an expansion of cattail and changes in the periphyton community in portions of the northern Everglades receiving EAA runoff. The severity and extent of P impacts were more fully recognized by 1988 when the Federal Government sued the State of Florida for allowing P-enriched discharges and associated impacts to occur in the Everglades. Settlement of this lawsuit eventually resulted in the enactment of the Everglades Forever Act by the Florida Legislature in 1994, which required the Florida Department of Environmental Protection (FDEP) to derive a numeric water quality criterion for P that would "prevent ecological imbalances in natural populations of flora or fauna" in the Everglades. These legal and legislative events provided the basis for numerous research and monitoring efforts designed to better understand the effects of P enrichment and to determine levels of enrichment that produced undesirable ecosystem changes.

Research and monitoring were initiated by the State of Florida (the Florida Department of Environmental Protection and the South Florida Water Management District) and other university research groups (e.g., Duke University, Florida International University, University of Florida) to better understand ecological responses to anthropogenic P inputs and to identify a P concentration or range of concentrations that result in unacceptable degradation of the Everglades ecosystem. This case study reviews research and monitoring conducted by the State to derive a P criterion for the Everglades. This criterion was proposed by the FDEP in 2001 and approved in 2003. This process is divided into three parts:

1. Define the reference (i.e., historical) conditions for P and the oligotrophic ecology of the Everglades;

2. Determine the types of ecological impacts caused by P enrichment; and,

3. Identify wetland P concentrations that produce these impacts,and determine a criterion that will protect the resource from those impacts.

DEFINING THE REFERENCE CONDITION

Several sources of information were used to characterize reference conditions across the Everglades. Sampling in minimally impacted locations (i.e., reference sites) believed to best reflect historical conditions provided the quantitative basis for establishing reference conditions with respect to P concentrations and associated ecological conditions. Where possible, this characterization was augmented by historical evidence. Written accounts of surveys conducted during the 1800s and early 1900s provided useful qualitative data on past ecological conditions. Early scientific literature contained substantial information on large-scale vegetation patterns (e.g., Davis 1943, Loveless 1959). Paleoecological assessments, including the dating and analysis of soil cores with respect to nutrient content and preserved materials such as pollen provided, further information (e.g., Cooper and Goman 2001, Willard et.al., 2001).

Predisturbance Everglades exhibited significant spatial and temporal variation, and, while its conversion to a smaller, more managed wetland resulted in the loss of some of this heterogeneity, the legacy of past variations in hydrology, chemistry, and biology remain in many areas. Legislation mandating the development of a P criterion stipulated that natural variation in P concentrations and ecological conditions within the remnant ecosystem be considered. This required that sampling efforts encompass the expected range of background variability in the remnant ecosystem. To ensure that spatial variation in P conditions were considered, sampling was conducted in all four major hydrologic units: The Loxahatchee National Wildlife Refuge (LNWR), WCA-2A, WCA-3A, and Everglades National Park (see Figure B1.1).

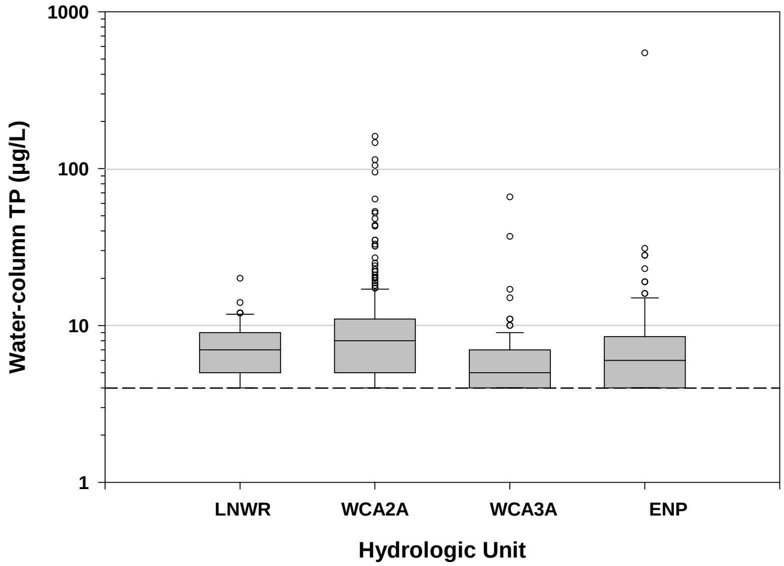
Water Column Phosphorus

Nutrient inputs to the Everglades were historically derived primarily from atmospheric deposition (rainfall and dry fallout), which is typically low in P. Historical loading rates have been estimated from annual atmospheric P inputs in south Florida and reconstructions of P accumulation in Everglades soils and probably averaged less than 0.1 g P m^{-2} y^{-1} (SFWMD 1992). Atmospheric inputs of P were augmented by inflows from Lake Okeechobee, which was connected by surface-water flows to the northern Everglades during periods of high water (Parker et.al., 1955). While inflows from this historically eutrophic lake were undoubtedly enriched in P compared with the Everglades, the influence of these inputs were likely limited to wetlands along the lake's southern fringe (Snyder and Davidson 1994) as is demonstrated by the limited extent of pond apple and other vegetation that require more nutrients for growth than the sawgrass (*Cladium jamaicense)* that dominates most of the Everglades.

Interior areas of the Everglades generally retain the oligotrophic characteristics of the predrainage ecosystem and, thus, provide the best contemporary information on historical P concentrations. Water chemistry data were available for several interior locations that had been sampled by the State for many years. Median water-column TP concentrations at these stations ranged between 4 and 10 µg L^{-1}, with lowest concentrations occurring in southern areas that have been least affected by anthropogenic P loads (Figure B1.2). Phosphorus concentrations >10 µg L^{-1} were measured periodically at many of these sites. Isolated high P concentrations at reference stations were attributed to P released as a result of oxidation of exposed soils, increased fire frequency during droughts, and difficulties in collecting water samples that are not contaminated by flocculent wetland sediments when water depths are low. Data from reference sites may represent an upper estimate of historical TP concentrations in the Everglades since several stations are located in areas that either have been overdrained, a condition which promotes soil oxidation and P release, or so heavily exposed to canal inflows (e.g., WCA 2A) that some P inputs have likely intruded even into interior areas. However, in the absence of reliable historical data these values were deemed as best available for defining reference condition.

Soil Phosphorus

Extensive soil mapping projects across interior portions of the central and northern Everglades indicate a reference range for soil TP in the surface 0-10 cm of soil of between 200 and 500 mg kg^{-1} on a mass basis (DeBusk et.al., 1994, Reddy et.al., 1994a, Newman et.al., 1997, Richardson et.al., 1997a, Newman et.al., 1998). Fewer data are available from ENP, but available evidence indicates background concentrations of < 400 mg kg^{-1} (Doren et.al., 1997). Soil P content also varies volumetrically as a function of changing soil bulk density. The typical bulk density of flooded Everglades peat soils is approximately 0.08 g cm^{-3}, whereas soils that have been subjected to extended dry out and oxidation can have bulk densities greater than 0.2 g cm^{-3} (Newman et.al., 1998). Increases in volumetric nutrient concentrations resulting from increased bulk density can have a stimulatory effect on plant growth even in the absence of external P inputs (see Chapter 2). Following correction for the varying bulk densities in the peat soils of the Everglades, a historical TP concentration of <40 µg cm^{-3} may be applicable for most regions (DeBusk et.al., 1994, Reddy et.al., 1994a, Newman et.al., 1997, Newman et.al., 1998, Reddy et.al., 1998). In the LNWR, most of the interior area has soil TP < 20 µg TP cm^{-3} (Newman et.al., 1997).



Appendix B1. Figure B1.2. Box plots showing surface-water P concentrations at long-term monitoring stations in each major hydrologic unit that illustrate the minimally impacted (i.e., reference) condition of the Everglades with respect to P. The top, mid-line, and bottom of each box represents the 75th, 50th (median), and 25th percentile of data, respectively; the error bars represent the 90th and 10th percentiles; open circles are data outside the 90th percentile; the dashed line is the analytical limit for TP (4 µg L^{-1}).

REFERENCE ECOLOGICAL CONDITIONS

The Everglades is perhaps the most intensively studied wetland in the world and, therefore, the ecological attributes that defined the predisturbance structure and function of this ecosystem are well understood compared with most wetlands. Clearly, not all of the valued ecological attributes of this or any other wetland are affected directly by P enrichment. Thus, in order to define the reference condition of the ecosystem with respect to the role of P, this assessment focused on those processes and communities that are most sensitive to P enrichment. Based on available information and preliminary scoping studies, five ecological features were selected as biotic response variables. These features included three indicators of ecosystem structure, one indicator of ecosystem function, and one indicator of landscape change. Structural indicators included the periphyton community, dominant macrophyte populations, and the benthic macroinvertebrate community. Diel fluctuations in water column DO provided an important indicator of shifts in aquatic metabolism. The landscape indicator of change was the loss of open-water slough-wet prairie habitats—areas of high natural diversity and productivity.

Periphyton

Aquatic vegetation and other submerged surfaces in the oligotrophic Everglades interior are covered with periphyton, a community of algae, bacteria and other microorganisms. Periphyton accounts for a significant portion of primary productivity in sloughs and wet prairies (Wood and Maynard 1974, Browder et.al., 1982, McCormick et.al., 1998), and floating and attached periphyton mats provide an important habitat and food source for invertebrates and small fish (Browder et.al., 1994, Rader 1994). These mats store large amounts of P (approaching 1 kg TP m^{-2} in some locations) and, thus, may play a critical role in maintaining low P concentrations in reference areas (McCormick et.al., 1998, McCormick and Scinto 1999). Periphyton biomass and productivity peak towards the end of the wet season (August through October) and reach a minimum during the colder months of the dry season (January through March). Periphyton biomass in open-water habitats can exceed 1 kg m^{-2} during the wet season (Wood and Maynard 1974, Browder et.al., 1982, McCormick et.al., 1998) when floating mats can become so dense as to cover the entire water surface. Aerobic conditions in slough-wet prairie habitats is maintained by the high productivity of this community and the capacity of dense algal mats to trap oxygen released during photosynthesis (McCormick and Laing 2003).

Two types of periphyton communities occur in reference areas of the Everglades. Mineral-rich waters, such as those found WCA 2A and Taylor Slough (ENP), support a periphyton assemblage dominated by a few species of calcium-precipitating cyanobacteria and diatoms, while the soft-water interior of LNWR contain a characteristic assemblage of desmid green algae and diatoms. Waters across much of the southern Everglades (WCA-3A and portions of ENP) tend to be intermediate with respect to mineral content and contain some taxa from both assemblages.

The chemical composition of periphyton in the oligotrophic Everglades is indicative of severe P limitation. Periphyton samples from reference areas of major hydrologic units within the Everglades are characterized by an extremely low P content (generally <0.05%) and extremely high N:P ratios (generally >60:1 w:w). This observational evidence for P limitation is supported by experimental fertilization studies that have shown that: 1) periphyton responds more strongly to P enrichment than to enrichment with other commonly limiting nutrients such as nitrogen (Scheidt et.al., 1989, Vymazal et.al., 1994); and, 2) periphyton changes in response to experimental P enrichment mimic those that occur along field nutrient gradients (McCormick and O’Dell 1996). Thus, it is well-established that periphyton is strongly P-limited in reference areas of the Everglades.

Dissolved Oxygen

Interior Everglades habitats exhibit characteristic diel fluctuations in water-column dissolved oxygen (DO), although aerobic conditions are generally maintained throughout much or all of the diel cycle (Belanger et.al., 1989, McCormick et.al., 1997, McCormick and Laing 2003). High daytime concentrations in open-water habitats (i.e., sloughs, wet prairies) are a product of photosynthesis by periphyton and other submerged vegetation. These habitats may serve as oxygen sources for adjacent sawgrass stands, where submerged productivity is low (Belanger et.al., 1989). Oxygen concentrations decline rapidly during the night due to periphyton and sediment microbial respiration and generally fall below the 5 mg L^{-1} standard for Class III Florida waters (Criterion 17-302.560(21), F.A.C.). However, these diurnal excursions are characteristic of reference areas throughout the Everglades (McCormick et.al., 1997) and are not considered a violation of the Class III standard (Nearhoof 1992). In fact, a site specific criterion for DO has been adopted by the State; a copy of the technical support document (Weaver 2004) can be found at:
http://www.dep.state.fl.us/water/wqssp/everglades/docs/DOTechSupportDOC2004.pdf.

Vegetation

The vegetation communities characteristic of the pristine Everglades are dominated by species adapted to low P, seasonal patterns of wetting and drying, and periodic natural disturbances such as fire, drought, and occasional freezes (Duever et.al., 1994, Davis 1943, Steward and Ornes 1983, Parker 1974). Major aquatic vegetation habitats in oligotrophic areas include sawgrass wetlands, wet prairies, and sloughs (Loveless 1959, Gunderson 1994). The spatial arrangement of these habitats is dynamic and controlled by environmental factors such as fire, water depth, nutrient availability, and local topography (Loveless 1959).

Sawgrass (*Cladium jamaicense*) is the dominant macrophyte in the Everglades, and stands of this species compromise approximately 65 to 70% of the total vegetation cover of the Everglades (Loveless 1959). Wet prairies include a collection of low-stature, graminoid communities occurring on both peat and marl soils (Gunderson 1994). Dominant macrophyte taxa in these habitats include *Rhynchospora*, *Panicum*, and *Eleocharis* (Loveless 1959, Craighead 1971). Sloughs are deeper water habitats that remain wet most or all of the year and are characterized by floating macrophytes such as fragrant white water lily (*Nymphaea odorata*), floating hearts (*Nymphoides Aquaticum*), and spatterdock (*Nuphar advena*) (Loveless 1959, Gunderson 1994). Submerged aquatic plants, primarily bladderworts (*Utricularia foliosa* and *U. purpurea* in particular), also can be abundant in these habitats and, in the case of *U. purpurea*, provide a substrate for the formation of dense periphyton mats.

Several studies have concluded that macrophyte communities in the Everglades are P-limited. Sawgrass is adapted to the low-P conditions indicative of the pristine Everglades (Steward and Ornes 1975b, Steward and Ornes 1983). During field and greenhouse manipulations, sawgrass responded to P enrichment either by increasing the rate of growth or P uptake (Steward and Ornes 1975a, Steward and Ornes 1983, Craft et.al., 1995, Miao et.al., 1997, Daoust and Childers 1999). Furthermore, additions of N alone had no effect on sawgrass or cattail growth under low-P conditions (Steward and Ornes 1983, Craft et.al., 1995). Recent experimental evidence in the Everglades National Park (Daoust and Childers 1999) has shown that other native vegetation associations such as wet prairie communities are also limited by P.

Historically, cattail (*Typha* spp.) was one of several minor macrophyte species native to the Everglades (Davis 1943, Loveless 1959). In particular, cattail is believed to have been associated largely with areas of disturbance such as alligator holes and recent burns (Davis 1994). Analyses of Everglades peat deposits reveal no evidence of cattail peat, although the presence of cattail pollen indicates its presence historically in some areas (Gleason and Stone 1994, Davis et.al., 1994, Bartow et.al., 1996). Findings such as these confirm the historical presence of cattail in the Everglades but provide no evidence for the existence of dense cattail stands covering large areas (Wood and Tanner 1990) as now occurs in the northern Everglades. In contrast, sawgrass and water lily peats have been major freshwater Everglades soils for approximately 4,000 years (McDowell et.al., 1969).

Macroinvertebrates

Aquatic invertebrates (e.g., insects, snails, and crayfish) represent a key intermediate position in energy flow through the Everglades food web as these taxa are the direct consumers of primary production and, in turn, are consumed by vertebrate predators. Invertebrates occupy several functional niches within the Everglades food web; however, most taxa are direct consumers of periphyton and/or plant detritus (e.g., Rader and Richardson 1994, McCormick et.al., 2004). Rader (1994) sampled both periphyton and macrophyte habitats in this same area and, based on the proportional abundance of different functional groups, suggested that grazer (periphyton) and detrital (plant) pathways contributed equally to energy flow in low-nutrient areas of the Everglades.

The macroinvertebrate fauna of the Everglades is fairly diverse (approximately 200 taxa identified) and is dominated by Diptera (49 taxa), Coleoptera (48 taxa), Gastropoda (17 taxa), Odonata (14 taxa), and Oligochaeta (11 taxa) (Rader 1999). Most studies have focused on a few conspicuous species (e.g., crayfish and apple snails) considered to be of special importance to vertebrate predators, and relatively little is known about the distribution and environmental tolerances of most taxa. An assemblage of benthic microinvertebrates (meiofauna) dominated by Copepoda and Cladocera is also present in the Everglades (Loftus et.al., 1986), but even less is known about the distribution and ecology of these organisms.

Invertebrates are not distributed evenly among Everglades habitats but, instead, tend to be concentrated in periphyton-rich habitats such as sloughs. In an early study, Reark (1961) noted that invertebrate densities in ENP were higher in periphyton habitats compared with sawgrass stands. Rader (1994) reported similar findings in the northern Everglades and found mean annual invertebrate densities to be more than six-fold higher in sloughs than in sawgrass stands. Invertebrate assemblages in sloughs were more species-rich and contained considerably higher densities of most dominant invertebrate groups. Functionally, slough invertebrate assemblages contained similar densities of periphyton grazers and detritivores compared with a detritivore-dominated assemblage in sawgrass stands. Higher invertebrate densities in sloughs were attributed primarily to abundant growths of periphyton and submerged vegetation, which provide oxygen and a source of high-quality food.

QUANTIFYING P IMPACTS

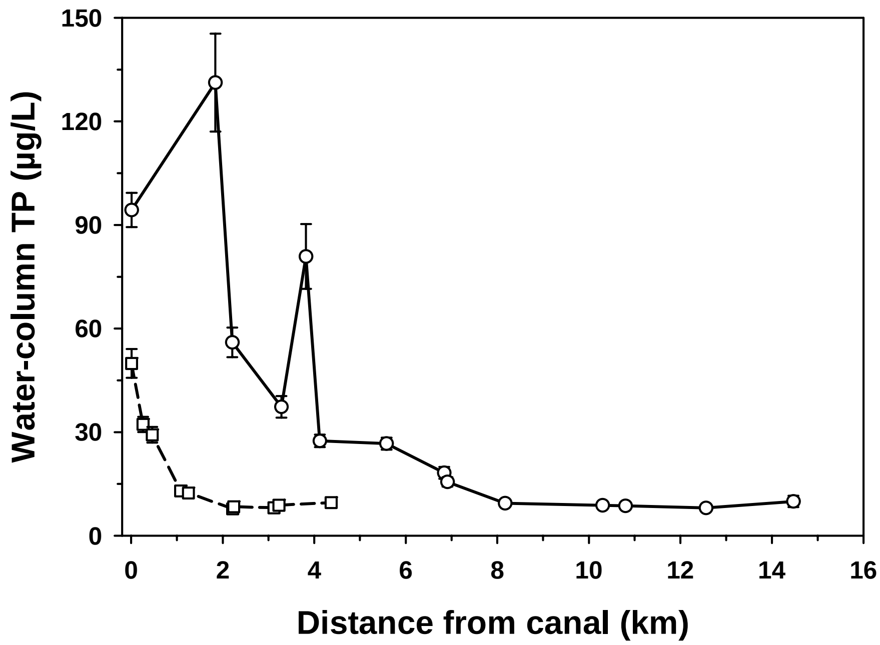
A targeted design (see Chapter 4) was used to quantify changes in key ecological attributes in response to P enrichment. Discharges of canal waters through fixed water-control structures are the primary source of anthropogenic P for the Everglades and produce P gradients that extend several kilometers into the wetland in several locations. These gradients have existed for several decades and provided the clearest example of the long-term ecological impacts associated with P enrichment. Monitoring was conducted along gradients in different parts of the Everglades to assess ecological responses to P enrichment. Fixed sampling stations were located along the full extent of each gradient to document ecological conditions associated with increasing levels of P enrichment. Intensive monitoring was performed along gradients in two northern Everglades wetlands, WCA 2A and the LNWR. WCA 2A is a mineral-rich, slightly basic peatland and contains the most pronounced and well studied P gradient in the Everglades, whereas LNWR is a soft-water, slightly acidic peatland. These two wetlands represent the most extreme natural water chemistry conditions in the Everglades and support distinct periphyton assemblages and macrophyte populations while sharing dominant species such as sawgrass and water lily. Less intensive sampling along gradients in other parts of the Everglades (WCA 3A and ENP) to confirm that P relationships were consistent across the wetland.

Chemical and biological conditions were measured at each sampling station along the two intensively sampled gradients. Repeated sampling, sometimes over several years, was performed to ensure that temporal variation in each metric was considered in the final data analysis. Monthly surface-water sampling and less frequent soil sampling were performed to quantify P gradients in each area. Diel DO regimes, periphyton, and benthic macroinvertebrates were sampled quarterly when surface water was present. Macrophyte sampling included ground-based methods to document shifts in species composition and remote sensing to determine changes in landscape patterns. The hydrology of each site was characterized to determine whether P gradients were confounded with hydrologic gradients, which can also exert a strong influence on ecological patterns.

Numerous field experiments have been conducted to quantify ecological responses to P enrichment and to better understand how interactions between P enrichment and other factors such as hydrology may affect these responses. The design of these experiments varied in complexity with respect to size and dosing regime depending on the specific objective of each study and has included enclosed fertilizer plots (e.g., Craft et.al., 1995), semi-permeable mesocosms receiving periodic P additions to achieve fixed loading rates in the form of periodic additions (e.g., McCormick and O'Dell 1996), flumes receiving semi-continuous enrichment at a fixed rate (Pan et.al., 2000), and flumes receiving flow-adjusted dosing to achieve constant inflow concentrations (Childers et.al., 2002). These experiments were useful in establishing the causal nature of responses to P enrichment documented along the P gradients described above.

GRADIENT P CONCENTRATIONS

Strong gradients in P concentrations were documented downstream of canal discharges into most Everglades wetlands (Figure B1.3). Inflow TP concentrations in from 1996-1999 have averaged as high as 100 µg L^{-1} as compared with reference and pre-disturbance concentrations $\leq$ 10 µg L^{-1}. The degree and spatial extent of P enrichment varies among areas depending on the source and magnitude of inflows. The most extensive enrichment has occurred in the northern Everglades near EAA inflows, while southern areas (e.g., ENP) have been relatively less affected. The most extensive enrichment has occurred in WCA-2A, which, unlike other areas, receives most of its water from canal discharges. Soil TP was strongly correlated with surface-water concentrations and exceeded 1500 mg kg^{-1} at the most enriched locations as compared with concentrations < 500 mg kg^{-1} in reference areas. In general, this enrichment effect is limited to the surface 30 cm of soil depth (Reddy et.al., 1998).



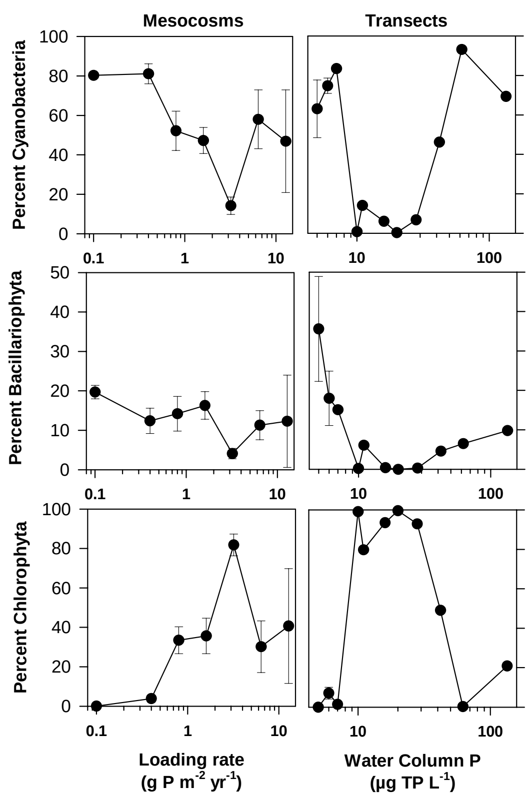
Appendix B1. Figure B1.3. Mean water-column TP concentrations (1996-1999) at long-term monitoring stations downstream of canal discharges in two northern Everglades wetlands, WCA 2A (circles connected by solid line) and LNWR (squares connected by dashed line). Error bars are ± 1 SE.

ECOLOGICAL RESPONSES TO P ENRICHMENT

Periphyton

Periphyton responses to P enrichment include changes in productivity, biomass, and species composition. Periphyton rapidly accumulates P from the water (McCormick et.al., 2001, Noe et.al., 2003), and, thus, a strong relationship between P concentrations in the water and periphyton is maintained along the P gradients (Grimshaw et.al., 1993, McCormick et.al., 1996). In fact, increases in periphyton P may provide one of the earliest signals of P enrichment (e.g., Gaiser et.al., 2004). Rapid increases in periphyton photosynthetic activity and growth rates occur in response to P enrichment (e.g., Swift and Nicholas 1987, McCormick et.al., 1996, McCormick et.al., 2001). All of these responses are consistent with the P-limited nature of Everglades periphyton.

Paradoxically, these physiological responses are associated with sharply lower periphyton biomass in P-enriched areas due to the loss of the abundant community of calcareous cyanobacteria and diatoms that is indicative of mineral-rich reference areas. This community is replaced by a eutrophic community of filamentous cyanobacteria, filamentous green algae, and diatoms in areas having even slightly elevated P concentrations. For example, McCormick and O'Dell (1996) found that the calcareous assemblage that existed at low water-column P concentrations (TP = 5 to 7 µg L^{-1}) was replaced by a filamentous green algal assemblage at moderately elevated concentrations (TP = 10 to 28 µg L^{-1}) and by eutrophic cyanobacteria and diatoms species at even higher concentrations (TP = 42 to 134 µg L^{-1}). These results are representative of those documented by other investigators (e.g., Swift and Nicholas 1987, Pan et.al., 2000). Taxonomic changes in response to controlled P enrichment in field experiments have been shown to be similar to those documented along field enrichment gradients (Figure B1.4), thereby providing causal evidence that changes in the periphyton assemblage were largely a product of P enrichment (McCormick and O'Dell 1996, Pan et.al., 2000).



Appendix B1. Figure B1.4. Changes in percent biomass (as biovolume) of major algal groups in field enclosures dosed weekly with different P loads (left panel) and along a P enrichment gradient downstream of canal discharges (right panel) in WCA 2A. From McCormick and O'Dell (1996).

Community metabolism and dissolved oxygen concentrations

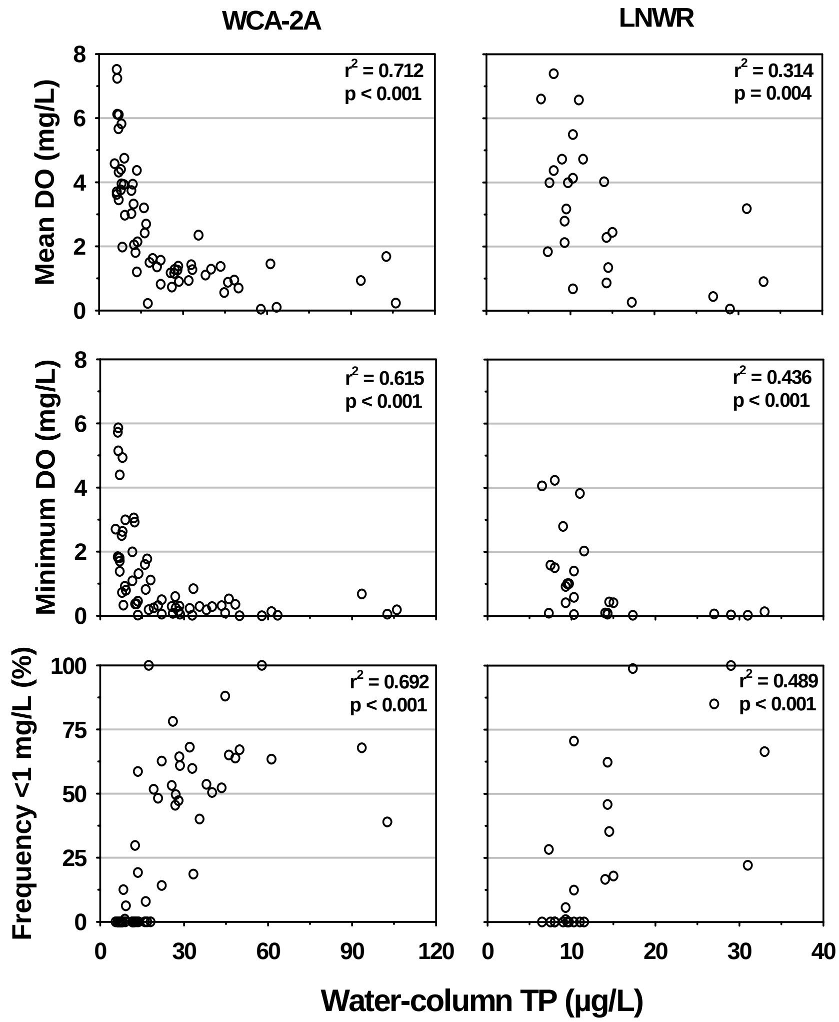
Phosphorus enrichment causes a shift in the balance between autotrophy and heterotrophy in the water column as a result of contrasting effects on periphyton productivity and microbial respiration. Rates of aquatic primary productivity (P) and respiration (R) are approximately balanced (P:R ratio = 1) across the diel cycle in minimally impacted sloughs throughout the Everglades (Belanger et al., 1989; McCormick et al., 1997). In contrast, respiration rates exceed productivity by a considerable margin (P:R ratio << 1) at enriched locations. This change is related primarily to a large reduction in areal periphyton productivity as a result of shading by dense stands of cattail (*Typha domingensis*) that form a nearly continuous cover in the most enriched areas (McCormick and Laing, 2003). Increased cattail production also stimulates microbial respiration (e.g., sediment oxygen demand) (e.g., Belanger et.al., 1989) due to an increase in the quantity and decomposability of macrophyte litter.

The shift towards dominance of heterotrophic processes with P enrichment, in turn, affects dissolved oxygen (DO) concentrations in enriched areas. For example, DO concentrations at an enriched site in WCA 2A rarely exceeded 2 mg L^{-1} compared with concentrations as high as 12 mg L^{-1} at reference locations (McCormick et al., 1997). Depressed water-column DO concentrations have subsequently been documented in enriched areas of WCA 2A and the LNWR (Figure B1.5) and confirmed in experimental P-enrichment studies (McCormick and Laing 2003). Declines in DO along field P gradients were steepest within a range of water-column TP concentrations roughly between 10 and 30 µg L^{-1}. Lower DO in enriched areas are associated with other changes including an increase in anaerobic microbial processes and a shift in invertebrate species composition toward species tolerant of low DO, described later in this study.

Macrophytes

Nutrient enrichment initially stimulates the growth of existing vegetation as evidenced by increased plant P content, photosynthesis, and biomass production, as it does for periphyton. Persistent enrichment eventually produces a shift in vegetation composition toward species better adapted to rapid growth and expansion under conditions of high P availability. Two major shifts in Everglades plant communities have been documented along P gradients, including: 1) the replacement of sawgrass stands by cattail; and, 2) the replacement of slough-wet prairie habitat by cattail.

Sawgrass populations in the Everglades have life-history characteristics indicative of plants adapted to low-nutrient environments (Davis 1989, Davis 1994, Miao and Sklar 1998). Sawgrass responses to P enrichment include an increase in tissue P, plant biomass, P storage, annual leaf production and turnover rates, and seed production (e.g., Davis 1989, Craft and Richardson 1997, Miao and Sklar 1998). Cattail is characterized by a high growth rate, a short life cycle, high reproductive output, and other traits that confer a competitive advantage under enriched conditions (Davis 1989, Davis 1994, Goslee and Richardson 1997, Miao and Sklar 1998).



Appendix B1. Figure B1.5. Relationship between water-column DO metrics and TP concentration at several stations and time intervals along P gradients downstream of canal discharges into two northern Everglades wetlands (see Figure 1 for map). Total P concentrations are mean values for all samples (n = 3 to 6) collected during the three-month period preceding DO measurements, which were typically collected over 3-4 diel cycles using dataloggers. Correlation coefficients are Spearman rank coefficients based on all data in the plot. Adapted from McCormick and Laing (2003).

Measurements and controlled enrichment experiments have shown that cattail growth rates exceed those of sawgrass under enriched conditions (Davis 1989, Newman et.al., 1996, Miao and DeBusk 1999). The replacement of sawgrass by cattail in P enriched areas may be facilitated by disturbances such as flooding or severe fires that weaken or kill sawgrass plants and create openings. Consequently, sawgrass distributional patterns were not as clearly related to P gradients as were other ecological indicators of enrichment.

Sloughs and wet prairies appear to be particularly sensitive to replacement by cattail under P-enriched conditions, possibly due to the sparser vegetation cover in these habitats. The process of slough enrichment and replacement by cattail as shown in satellite imagery is supported by ground-based sampling methods (McCormick et.al., 1999) that documented changes in slough vegetation and encroachment of these habitats by cattail in areas where soil TP concentrations averaged between 400 and 600 mg kg^{-1} and water-column TP in recent years averaged > 10 µg L^{-1}. *Eleocharis* declined in response to increased soil P, and *Nymphaea* was stimulated by enrichment and was dominant in slightly enriched sloughs. Increased occurrence of cattail in sloughs was associated with a decline in *Nymphaea*, probably as a result of increased shading of the water surface. These findings are consistent with those of Vaithiyanathan et.al., (1995) who documented a decline in slough habitats along this same nutrient gradient and the loss of sensitive taxa such as *Eleocharis* at locations where soil TP exceeded 700 mg kg^{-1}. As discussed by McCormick et.al., (2002), loss of these open-water areas is a sensitive landscape indicator of P enrichment (Figure B1.6).

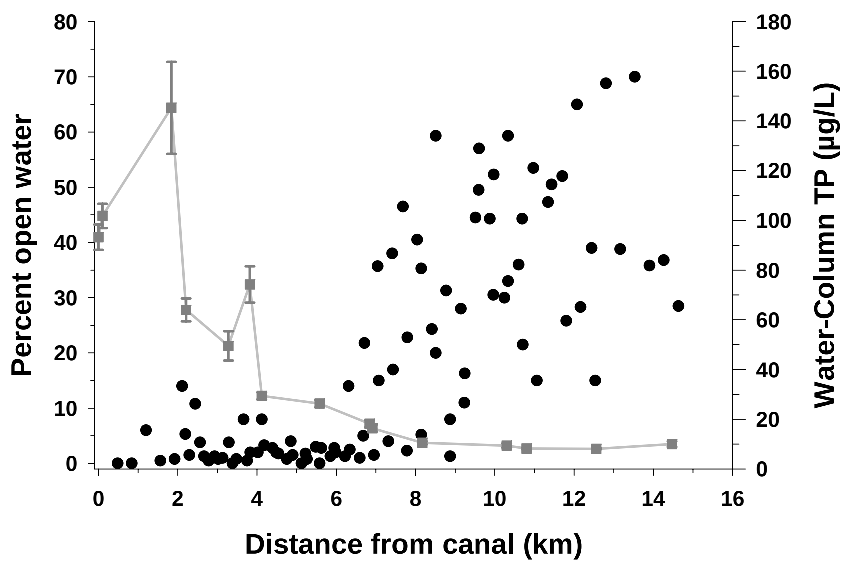


Figure B1.6. Changes in the percentage of open-water (i.e., sloughs, wet prairies, or other opening caused by natural disturbance or airboats) cover at 94 locations along a P enrichment gradient in WCA 2A as determined using aerial photography. Gray line shows the mean (± 1 SE) water-column TP concentration (1996-1999) at 15 long-term monitoring stations along the gradient.

Benthic Macroinvertebrates

Macroinvertebrates are the most widely used biological indicator of water quality impacts, and several changes that occur in this community along P enrichment gradients in the Everglades are similar to those documented in response to eutrophication in other aquatic ecosystems. Several studies have documented an overall increase in macroinvertebrate abundance with increasing P enrichment (Rader and Richardson 1994, Trexler and Turner et.al., 1999, McCormick et.al., 2004). However, differences in sampling methodology have apparently produced conflicting results with respect to changes in species richness and diversity. For example, Rader and Richardson (1994) documented an increase in both macroinvertebrate species richness and diversity with P enrichment in open-water (i.e., low emergent macrophyte cover) habitats and concluded that enrichment had not impacted this community. McCormick et.al., (2004), however, using a landscape approach that involved habitat-weighted sampling, found little change in either species richness or diversity in response to enrichment. This latter study accounted for the decline in the cover of habitats such as sloughs and wet prairies, which contain the most diverse and abundant macroinvertebrate communities (Rader 1994). McCormick et.al., (2004) also documented a pronounced shift in community composition with increasing P enrichment as taxa characteristic of the oligotrophic interior of the wetland are replaced by common pollution-tolerant taxa of oligochaetes and chironomids. These changes were indicative of habitat degradation as determined using biotic indices derived by the Florida DEP to assess stream condition based on macroinvertebrate composition (results available at http://www.epa.gov/owow/wetlands/bawwg/case/fl2.html).

As for many other P-induced biological changes, the greatest change in the macroinvertebrate community occurred in response to relatively small increases in P concentration. Along field enrichment gradients, community shifts were associated with increases in water-column TP above approximately 10 ug L^{-1} (McCormick et.al., 2004). Similarly, Qian et.al., (2004) documented several shifts in community structure and function in response to long-term experimental dosing at average concentrations of approximately 10-15 ug L^{-1}.

ESTABLISHING A P CRITERION

The FDEP was charged with reviewing and analyzing available P and ecological data collected throughout the Everglades to establish a numeric P criterion. A brief summary of this process is provided here, and more detailed information can be found in Payne et al., (2000, 2001a,b; available at http://www.dep.state.fl.us/water/wqssp/everglades/pctsd.htm; and, 2002, 2003, available at http://www.sfwmd.gov/sfer/previous_ecr.html).

The narrative nutrient standard for Class III Florida waters such as the Everglades states that “in no case shall nutrient concentrations of a body of water be altered so as to cause an imbalance in natural populations of aquatic flora or fauna." The FDEP approach to detecting violations of this standard with respect to surface-water P concentrations in the Everglades was to test for statistically significant departures in ecological conditions from those at reference sites (i.e., interior sampling locations with background P concentrations). Biological and chemical data collected along anthropogenic P gradients throughout the Everglades were analyzed to determine P concentrations associated with such departures. Results showed that sampling sites with average (geometric mean) surface-water TP concentrations significantly greater than 10 ppb consistently exhibited significant departures in ecological condition from that of reference sites. A key finding supporting this concentration as the standard was the fact that multiple changes in each of the major indicator groups—periphyton, dissolved oxygen, macrophytes, and macroinvertebrates—all occurred at or near this same concentration (e.g., Payne et.al., 2001).

Data from field and laboratory experiments conducted by various research groups provided valuable supporting information for understanding responses to P enrichment. While such experiments were not used directly to derive the P criterion, they established cause-effect relationships between P enrichment and ecological change that supported correlative relationships documented along field P gradients. For example, McCormick and O'Dell (1996) and Pan et.al., (2000) showed that major shifts in periphyton species composition documented along field P gradients matched those elicited by controlled P dosing in field enrichment experiments. McCormick and Laing (2003) confirmed that controlled P enrichment produced declines in water-column DO similar to those measured along the gradients. Macroinvertebrate community changes were documented experimentally, Qian et.al., (2004).

While the criterion established a surface-water concentration of 10 ug L^{-1} TP as protective of native flora and fauna, the methodology used to measure compliance with the criterion needed to normalize background fluctuations in concentration. Additional analyses of P data collected over several years at reference sites was used to set both a longer-term average concentration and a shorter-term maximum concentration for each site. Based on these analyses, the FDEP concluded that annual maximum concentrations at a given sampling location should not exceed 15 ug L^{-1} TP over the long-term, while five-year average concentrations should not exceed 10 ug L^{-1} TP. These limits would be applied to reference areas to ensure no further degradation and to areas already impacted by P enrichment to gauge the rate and extent of recovery in response to a suite of P control measures, including agricultural BMPs and the construction of treatment wetlands to remove P from surface runoff prior to being discharged into the Everglades. Additional information on Florida's progress in assessing and implementing the adopted standard can be found on the South Florida Water Management District Web site: www.sfwmd.gov.

LITERATURE CITED

Bartow, S. M., Craft, C. B., and Richardson, C. J. 1996. Reconstructing historical changes in Everglades plant community composition using pollen distributions in peat. *Journal of Lake and Reservoir Management*. 12:313.

Belanger, T. V., Scheidt, D. J., and Platko, J. R. II. 1989. Effects of nutrient enrichment on the Florida Everglades. *Lake and Reservoir Management*. 5:101.

Browder, J. A., Cottrell, D., Brown, M., Newman, M., Edwards, R., Yuska, J., Browder, M., and Krakoski, J. 1982. Biomass and Primary Production of Microphytes and Macrophytes in Periphyton Habitats of the Southern Everglades, Report T-662, Homestead, FL: South Florida Research Center.

Browder, J. A., Gleason, P. J., and Swift, D. R. 1994. Periphyton in the Everglades: spatial variation, environmental correlates, and ecological implications. *Everglades: The Ecosystem and Its Restoration.* Davis, S. M. and Ogden, J. C., eds., Delray Beach, FL: St. Lucie Press. p. 379.

Childers, D. L., R. D. Jones, J.vC. Trexler, C. Buzzelli, S. Dailey, A. L. Edwards, E. E. Gaiser, K. Jayachandaran, A. Kenne, D. Lee, J. F. Meeder, J. H. K. Pechman, A. Renshaw, J. Richards, M. Rugge, L. J. Scinto, P. Sterling, and W. Van Gelder, 2002. Quantifying the effects of low level phosphorus enrichment on unimpacted Everglades wetlands with in situ flumes and phosphorus dosing. Porter, J. and Porter, K., eds. The Everglades, Florida Bay and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. Boca Raton, FL: CRC Press. pp. 127-52.

Cooper, S. R., and Goman, M. 2001. Historical changes in water quality and vegetation in WCA-2A as determined by paleoecological analyses. *An Integrated Approach to Wetland Ecosystem Science: The Everglades Experiments,* Richardson, C. J., ed. New York, NY: Springer-Verlag (in press.)

Craft, C. B., Vymazal, J., and Richardson, C. J. 1995. Response of Everglades plant communities to nitrogen and phosphorus additions. *Wetlands*. 15:258.

Craft, C. B., and Richardson, C. J., 1997. Relationships between soil nutrients and plant species composition in Everglades peatlands. *Journal of Environmental Quality.* 26:224.

Craighead, F. C., 1971. *The Trees of South Florida Vol I: The Natural Environments and Their Succession.* Coral Gables, FL: University of Miami Press.

Daoust, R. J., and Childers, D. L. 1999. Controls on emergent macrophyte composition, abundance, and productivity in freshwater Everglades wetland communities. *Wetlands*. 19:262.

Davis, J. H., Jr. 1943. *The Natural Features of South Florida, Especially the Vegetation, and the Everglades*. Bulletin No. 25, Florida Geological Survey.

Davis, S. M., 1989. Sawgrass and cattail production in relation to nutrient supply in the Everglades, in *Freshwater Wetlands and Wildlife*, Sharitz, R. R., and Gibbons, J. W., eds., USDOE Office of Scientific and Technical Information, Oak Ridge, Tennessee, p. 325.

Davis, S. M., Gunderson 1994. L. H., Park, W. A., Richardson, J., and Mattson, J., Landscape dimension, composition, and function in a changing Everglades ecosystem. *Everglades: The Ecosystem and Its Restoration*, Davis, S. M., and Ogden, J. C., eds., Delray Beach, FL: St. Lucie Press. p. 419.

DeBusk, W. F., Reddy, K. R., Koch, M. S., and Wang, Y. 1994. Spatial distribution of soil nutrients in a northern Everglades marsh - Water Conservation Area 2A. *Soil Science Society of America Journal.* 58:543.

Doren, R. F., Armentano, T. V., Whiteaker, L. D., and Jones, R. D. 1997. Marsh vegetation patterns and soil phosphorus gradients in the Everglades ecosystem. *Aquatic Botany*. 56:145.

Duever, M. J., Meeder, J. F., Meeder, L. C., and McCollom, J. M. 1994. The climate of south Florida and its role in shaping the Everglades ecosystem, in *Everglades: The Ecosystem and Its Restoration*, Davis, S. M. and Ogden, J. C., eds. Delray Beach, FL: St. Lucie Press. p. 225.

Gaiser, E. E., L. J. Scinto, J. H. Richards, K. Jayachandran, D. L. Childers, J. C. Trexler, and R. D. Jones. 2004. Phosphorus in periphyton mats provides the best metric for detecting low-level P enrichment in an oligotrophic wetland. *Water Research*. 38:507-16.

Gleason, P. J., Stone, P. A. 1994. Age, origin, and evolution of the Everglades peatland, *Everglades: The Ecosystem and Its Restoration*, Davis, S. M. and Ogden, J. C., eds., St. Lucie Press, Delray Beach, FL, p. 149.

Gleason, P. J., Stone, P. A., Hallett, D., and Rosen, M. 1975. Preliminary report on the effect of agricultural runoff on the periphytic algae of Conservation Area 1, Unpublished report, Central and Southern Flood Control District, West Palm Beach, FL.

Goslee, S. C., and Richardson, C. J. 1997. Establishment and seedling growth of sawgrass and cattail from the Everglades. *Effects of Phosphorus and Hydroperiod Alterations on Ecosystem Structure and Function in the Everglades.* Richardson, C. J., Craft, C. B., Qualls, R. G., Stevenson, R. J., Vaithiyanathan, P., Bush, M., and Zahina, J. Duke Wetland Center publication #97-05. Report to the Everglades Agricultural Area Environmental Protection District. Chapter 13.

Grimshaw, H. J., Wetzel, R. G., Brandenburg, M., Segerblom, M., Wenkert, L. J., Marsh, G. A., Charnetzky, W., Haky, J. E., and Carraher, C. 1997. Shading of periphyton communities by wetland emergent macrophytes: decoupling of algal photosynthesis from microbial nutrient retention, *Archive für Hydrobiologie.* 139:17.

Gunderson, L. H. 1994. Vegetation of the Everglades: determinants of community composition, *Everglades: The Ecosystem and Its Restoration*, Davis, S. M., and Ogden, J. C., Eds., St. Lucie Press, Delray Beach, FL. p. 323.

Light, S. S., and J. W. Dineen. 1994. Water control in the Everglades: an historical perspective. Pages 47-84 in S.M. Davis and J.C. Ogden, eds. *Everglades: the ecosystem and Its restoration*. Delray Beach, FL: St Lucie Press.

Loftus, W. F., Chapman, J. D., and Conrow, R. 1986. Hydroperiod effects on Everglades marsh food webs, with relation to marsh restoration efforts. *Fisheries and Coastal Wetlands Research*. Larson, G., and Soukup, M., eds. Vol. 6 of the Proceedings of the 1986 Conference on Science in National Parks. U.S. NPS and The George Wright Society, Ft. Collins, CO. p. 1.

Loveless, C. M. 1959. A study of the vegetation of the Florida Everglades. *Ecology.* 40:1.

LOTAC 1972

McCormick, P. V., Chimney, M. J., and Swift, D. R.. 1997. Diel oxygen profiles and water column community metabolism in the Florida Everglades, U.S.A. *Archive für Hydrobiologie*. 140: 117.

McCormick, P. V., and Laing, J. 2003. Effects of increased phosphorus loading on dissolved oxygen in a subtropical wetland, the Florida Everglades. *Wetlands Ecology and Management*.

McCormick, P. V., Newman, S., Miao, S. L., Reddy, K. R., Gawlik, D., Fitz, C., Fontaine, T. D., and Marley, D. 1999. Ecological needs of the Everglades, *Everglades Interim Report*, South Florida Water Management District, West Palm Beach, FL. Chapter 3.

McCormick, P. V., and O'Dell, M. B. 1996. Quantifying periphyton responses to phosphorus enrichment in the Florida Everglades: a synoptic-experimental approach, *Journal of the North American Benthological Society*. 15:450.

McCormick, P. V., Rawlik, P. S., Lurding, K., Smith, E. P., and Sklar, F. H. 1996. Periphyton-water quality relationships along a nutrient gradient in the northern Everglades. *Journal of the North American Benthological Society*. 15:433.

McCormick, P. V., and Scinto, L. J. 1999. Influence of phosphorus loading on wetlands periphyton assemblages: a case study from the Everglades, *Phosphorus Biogeochemistry of Subtropical Ecosystems*, Reddy, K. R., O'Connor, G. A., and Schelske, C. L., eds., Boca Raton, FL: CRC/Lewis Publishers. p. 301.

McCormick, P. V., Shuford, R. B. E. III, Backus, J. B., and Kennedy, W. C. 1998. Spatial and seasonal patterns of periphyton biomass and productivity in the northern Everglades, FL, USA. *Hydrobiologia*. 362:185.

McCormick, P. V., Shuford, R. B. E. III, and Rawlik, P. S., 2004, Changes in macroinvertebrate community structure and function along a phosphorus gradient in the Florida Everglades. *Hydrobiologia* 529:113-132.

McCormick, P. V., O'Dell, M. B., Shuford III, R. B. E., Backus, J. B. and Kennedy, W. C. 2001. Periphyton responses to experimental phosphorus enrichment in a subtropical wetland. *Aquatic Botany*. 71:119-39.

McDowell, L. L., Stephens, J. C., and Stewart, E. H. 1969. Radiocarbon chronology of the Florida Everglades peat. *Soil Science Society of America Proceedings*. 33:743.

Miao, S. L., Borer, R. E., and Sklar, F. H. 1997. Sawgrass seedling responses to transplanting and nutrient additions, *Restoration Ecology*. 5:162.

Miao, S. L., and DeBusk, W. F. 1999. Effects of phosphorus enrichment on structure and function of sawgrass and cattail communities in Florida wetlands, in *Phosphorus Biogeochemistry of Subtropical Ecosystems*, Reddy, K. R., O'Connor, G. A., and Schelske, C. L., eds. Boca Raton, FL: CRC/Lewis Publishers. p. 275.

Miao, S. L., and Sklar, F. H. 1998. Biomass and nutrient allocation of sawgrass and cattail along a nutrient gradient in the Florida Everglades. *Wetlands Ecology and Management*. 5:245.

Nearhoof, F. 1992. Nutrient-induced impacts and water quality violations in the Florida Everglades. Water Quality Technical Series 3(24), Bureau of Water Facilities Planning and Regulation, Department of Environmental Regulation, Tallahassee, FL.

Newman, S., Grace, J. B., and Koebel, J. W. 1996. Effects of nutrients and hydroperiod on *Typha*, *Cladium*, and *Eleocharis*: implications for Everglades restoration, *Ecological Applications*. 6:774.

Newman, S., Reddy, K. R., DeBusk, W. F., Wang, Y., Shih, G., and Fisher, M. M. 1997. Spatial distribution of soil nutrients in a northern Everglades marsh: Water Conservation Area 1. *Soil Science Society of America Journal*. 61:1275.

Newman, S., Schuette, J., Grace, J. B., Rutchey, K., Fontaine, T., Reddy, K. R., and Pietrucha, M. 1998. Factors influencing cattail abundance in the northern Everglades. *Aquatic Botany*. 60:265.

Noe, G. B., Scinto, L. J., Taylor, J., Childers, D. L., Jones, R. D. 2003. Phosphorus cycling and partitioning in an oligotrophic Everglades wetland ecosystem: a radioisotope tracing study. *Freshwater Biology*. 48:1993-2008.

Pan, Y., Stevenson, R. J., Vaithiyanathan, P., Slate, J., and Richardson, C. J. 2000. Changes in algal assemblages along observed and experimental phosphorus gradients in a subtropical wetland, USA. *Freshwater Biology*. pp. 339-53.

Parker, G. G. 1974. Hydrology of the pre-drainage system of the Everglades in southern Florida. *Environments of South Florida: Past and Present*. Gleason, P. J., ed., Memoir No. 2., Miami Geological Society, Coral Gables, FL. p. 18.

Parker, G. G., Ferguson, G. E., and Love, S. K. 1955. *Water Resources of Southeastern Florida with Special Reference to the Geology and Groundwater of the Miami Area*, Water Supply Paper 1255, United States Geological Survey, U.S. Government Printing Office, Washington, D.C..

Payne, G., T. Bennett, and K. Weaver. 2001. Development of a Numeric Phosphorus Criterion for the Everglades Protection Area. Chapter 3 in the 2001 Everglades Consolidated Report. South Florida Water Management District, West Palm Beach, FL.

Payne, G., T. Bennett, and K. Weaver. 2002. Development of a Numeric Phosphorus Criterion for the Everglades Protection Area. Chapter 5 in the 2002 Everglades Consolidated Report. South Florida Water Management District, West Palm Beach, FL.

Payne, G., K. Weaver, and T. Bennett. 2003. Development of a Numeric Phosphorus Criterion for the Everglades Protection Area. Chapter 5 in the 2003 Everglades Consolidated Report. South Florida Water Management District, West Palm Beach, FL.

Qian, S. S., R. S. King, and C. J. Richardson. 2003. Two statistical methods for the detection of environmental thresholds. *Ecological Modeling*. 166:87-97.

Rader, R. B. 1994. Macroinvertebrates of the northern Everglades: species composition and trophic structure. *Florida Scientist*. 57:22.

Rader, R. B. The Florida Everglades: Natural Variability, Invertebrate Diversity, and Foodweb Stability. *Freshwater Wetlands of North America: Ecology and Management*. Batzer, D. P., Rader, R. B., and Wissinger, S. A., eds. New York, NY; John Wiley and Sons. p. 25.

Rader, R. B., and Richardson, C. J. 1994. Response of macroinvertebrates and small fish to nutrient enrichment in the northern Everglades. *Wetlands*. 14:134.

Reark, J. B.1961. Ecological investigations in the Everglades, 2nd annual report to the Superintendent of Everglades National Park, University of Miami, Coral Gables, FL.

Reddy, K. R., Wang, Y., DeBusk, W. F., and Newman, S. 1994. Physico-chemical properties of soils in the water conservation area 3 (WCA-3) of the Everglades, Report to South Florida Water Management District, University of Florida, Gainesville, FL.

Reddy, K. R., Wang, Y., DeBusk, W. F., Fisher, M. M., and Newman, S. 1998. Forms of soils phosphorus in selected hydrologic units of Florida Everglades ecosystems, *Soil Science Society of America Journal*. 62:1134.

Richardson, C. J., Craft, C. B., Qualls, R. G., Stevenson, J., Vaithiyanathan, P., Bush, M., and Zahina, J. 1997a. Effects of Phosphorus and Hydroperiod Alterations on Ecosystem Structure and Function in the Everglades, Duke Wetland Center publication #97-05, report to the Everglades Agricultural Area Environmental Protection District.

Scheidt, D. J, Flora, M. D., and Walker, D. R. 1999. Water quality management for Everglades National Park, *American Water Resources Association.* September Issue, p. 377.

SFWMD, Draft Surface Water Improvement and Management Plan for the Everglades, 1992 Supporting Information Document, South Florida Water Management District, West Palm Beach, FL.

Snyder, G. H., and Davidson, J. M. 1994. Everglades agriculture - past, present, and future, in *Everglades: The Ecosystem and its Restoration*, Davis, S. M., and Ogden, J. C., eds., Delray Beach, FL: St. Lucie Press p. 85.

Steward, K. K., and Ornes. W. H. 1975a. Assessing a marsh environment for wastewater renovation. *Journal of the Water Pollution Control Federation*. 47:1880.

Steward, K. K., and Ornes, W. H. 1975b. The autecology of sawgrass in the Florida Everglades. *Ecology*. 56:162.

Steward, K. K., and Ornes, W. H. 1983. Mineral nutrition of sawgrass (*Cladium jamaicense* Crantz) in relation to nutrient supply. *Aquatic Botany*.16:349.

Swift, D. R., and Nicholas, R. B., Periphyton and water quality relationships in the Everglades Water Conservation Areas, 1978-1982, Technical Publication 87-2, South Florida Water Management District, West Palm Beach, FL. 1987.

Turner, A. M., Trexler, J. C., Jordan, C. F., Slack, S. J., Geddes, P., Chick, J. H., and Loftus, W. 1999. Targeting ecosystem features for conservation: standing crops in the Everglades, *Conservation Biology*. 13:898.

Vaithiyanathan, P., Zahina, J., and Richardson, C. J. 1995. Macrophyte species changes along the phosphorus gradient, in *Effects of Phosphorus and Hydroperiod Alterations on Ecosystem Structure and Function in the Everglades*, Richardson, C. J., Craft, C. B., Qualls, R. G., Stevenson, J., Vaithiyanathan, P., Bush, M., and Zahina, J., Duke Wetland Center publication #95-05, report submitted to Everglades Agricultural Area Environmental Protection District, p. 273.

Vymazal, J., Craft, C. B., and Richardson, C. J. 1994. Periphyton response to nitrogen and phosphorus additions in the Florida Everglades. *Algological Studies*.73:75.

Willard, D. A., Weimer, L. M., and Riegel, W. L. 2001. Pollen assemblages as paleoenvironmental proxies in the Florida Everglades. *Review of Palaeobotany and Palynology*. 113:213.
:
Wood, E. J. F., and Maynard, N. G. 1974. Ecology of the micro-algae of the Florida Everglades, in *Environments of South Florida: Past and Present*. Gleason, P. J., ed., Memoir No. 2. Miami Geological Society. Coral Gables, FL. p. 123.

Wood, J. M., and Tanner, G. W. 1990. Graminoid community composition and structure within four Everglades management areas. *Wetlands*. 10:127.