External Panel Report to the Florida Department of Environmental Protection

Overview and Evaluation of Everglades Nutrient Threshold Research

for the period October, 1996 to October, 1997

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Executive Summary

The contents of this report are based on (a) reviews of published documents provided to the Panel by Florida DEP, SFWMD, Duke Wetland Center, and the Florida International University research group; (b) two workshops and two site visits to three research areas in the Everglades; (c) the published literature on wetlands; (d) visits to several web sites relevant to the Everglades; (e) several rounds of interactive review of drafts of this report by the research groups and DEP staff. Review of the three research groups was sometimes complicated by the fact that each began its efforts at a different time and is thus in a different stage in its research program. In addition, it was not always clear to the Panel that some research was started for purposes other than its utility in determining nutrient thresholds. Therefore, we may be critical of some research activities, although they were useful to a different research agenda than the present one. Review of the research was also impeded by the fact that most members of the Panel had not seen the research sites prior to conducting the workshops. The following recommendations are based on the main points from the Summary of Recommendations section.

A. While it appears that analytical quality assurance for phosphorus analysis is largely under good control, it is unclear whether all participating analytical laboratories possess minimum detection limits for dissolved reactive P low enough to evaluate adequately the natural variation in ambient concentrations in relatively unimpacted areas (3.2).

B. Interaction among the three research groups has increased greatly during the past three years. However, the three research programs should interact more closely on data sharing for modeling and other concerns. Duke and FIU have a vast amount of data that are not being utilized, so far as the Panel is aware, in model implementation and validation. In final review of this report, SFWMD states that it is using available Duke data to calibrate the ELM model. Panel believes, however, that there is a pressing need for implementation of better data-sharing procedures (4.2.1).

C. The panel is concerned that it is not presently known how similar or dissimilar the various research sites are to each other and how they relate to other areas within the Everglades Protection Area. This concern deals primarily with issues of the generality and applicability of results from past, present, and future research to other areas within the Everglades and to spatial variability among sites within the same vegetation type. The panel recommends that the three research groups, or a contractor working closely with the groups, utilize existing available hydrologic, biological, and chemical data to conduct multivariate analyses to determine the similarities and dissimilarities between the research sites that SFWMD, FIU, and Duke have studied to date. Results of this effort will not only provide information on site comparability and spatial variability but could provide a foundation for development of a set of reference sites throughout the Everglades. A larger geographically based set of reference wetland sites could be used to demonstrate the relationship between the current research sites and other areas within the system that have not been or are not likely to be studied as extensively (6).

D. Simulation modeling is a major component of Everglades research by SFWMD, planned research by FIU, and by Duke who have provided data for some of the modeling done by SFWMD. The groups agree conceptually that simulation modeling is one of several necessary components that together constitute an overall successful research program. The District has used models to design its overall Everglades research program. They have progressed from conceptual models to a series of simulation models that have helped the District redesign experiments and monitoring. It is the Panel's opinion that at this time the District's modeling would benefit from re-examining the level of detail of the P cycle and conducting rigorous model validation. To be valuable in helping to set P concentration limits, the models should include as many details of the P cycle as necessary (uptake, sorption, precipitation, organic-inorganic transformations, dissolved-particulate transformations, solid-aqueous equilibria) to capture system dynamics and to enable the appropriate "what if" questions to be evaluated. The FIU group is urged to begin simulation modeling immediately with the best information currently available. Their models can be modified later to incorporate new data. This will enable the group, and others, to use the models as guidance for experimentation and monitoring (4.1).

E. Does the Everglades have a phosphorus assimilation capacity, if so, is it the same everywhere and how well can it be quantified? By assimilation capacity we mean a capacity to process and sequester additional P without a significant change in ecological structure or function (4.1).

F. All research groups should cooperate in developing a statistically rigorous budget of standing stocks of all forms of phosphorus in each of several sections of the Everglades. Only after compiling these budgets will we know the existing P content of the system. The value of the findings of all research groups, in terms of mass balance of phosphorus, will be limited unless accurate measurements of atmospheric inputs are obtained. During review of this report we were informed that this work is in progress. The same is true for inorganic (reactive) phosphorus. This should not be construed as a suggestion that every detail of phosphorus chemistry need be modeled. What we are suggesting is not a modeling exercise (3.1).

G. Under the natural "sheet-flow" movement of water in the Everglades, to what extent does phosphorus move with water flow in dissolved or particulate forms or, alternatively, what other mechanisms transport phosphorus through the Everglades (4.1, ¶4)?

H. No rapid bio-indicator of responses to additional phosphorus has yet been clearly identified. The three research groups should work together to design and implement a program to evaluate indices (such as ATP, adenylate ratio, alkaline phosphatase activity), rates of processes (such as microbial growth, respiratory rates, substrate uptake) and changes in size, shape, or biomass of fast-growing species along P gradients and/or in existing flumes and mesocosms (5; 10.4).

I. Because periphyton appears to be a major component in the primary production of the Everglades ecosystem, and because periphyton community composition appears to be highly sensitive to phosphorus enrichment, the Panel believes that additional work is needed in terms of quantifying (1) periphyton response to P enrichment, (2) the effect of periphyton on P sequestration in sediments, and (3) the role of periphyton in Everglades food webs and how changes in community composition would alter food web dynamics (5).

J. Gradient analysis is an important component of the nutrient threshold research. Within this context it is important to better define and quantify threshold changes in organisms, functional groups, or communities. All research groups are therefore urged to look for and measure parameters sensitive to changes in concentrations of nutrients.

K. Wet-prairie habitats with marl soils are important in the Everglades but are not being studied as part of nutrient-threshold research. However, we were informed during final review of this report that it is a part of other research activities.

1. General overview of research in progress.

During the past year, two workshops have been convened with the three groups that are doing nutrient threshold research in the Everglades. In addition, the members of the peer-review panel have read published literature and unpublished reports by the three research groups and publications by other scientists relevant to the ongoing nutrient threshold research. This report has gone through two rounds of review by the research groups and their sponsoring organizations, and the Panel chairperson met with representatives of the sponsors to discuss this report prior to its finalization. Comments from the researchers and sponsors have been carefully considered by the panel, and a number of corrections have been made in response to new information. The review interactions have been a useful part of the process. Moreover, in some instances the panel sees significant changes in projects as the result of comments made during workshops and field trips or in response to our first draft of this report, which was circulated in May, 1997. In this final report, we specifically call attention to additional actions the Panel believes are needed by one or more of the researchers or sponsors.

Bringing the three research groups together to discuss specific elements of the research program with the Panel has served to expedite inter-group exchange of information and probably also is stimulating more cooperative research. The panel views all three research groups as highly skilled professionals, the quality of whose work fully meets the usual standards of peer-reviewed science. The quality of the research also has been validated by active publication of the results in respected, peer-reviewed scientific journals. Each group has its special strengths, and fortunately these complement one another to give breadth to the nutrient threshold research. This critique of ongoing and planned research should be viewed as constructive criticism of a strong and very active program. In the remainder of the report we highlight some areas of concern that we believe need to be addressed while also noting where good progress is being made. The panel understands the strict limits of its own mandate, which is to review and evaluate the ongoing nutrient threshold research. As with much applied research, this program has quickly reached the limits of basic knowledge, so much of the work is concerned with understanding how the Everglades ecosystem functions and how changes in the nutrient regime affect it. Judgments have to be made about which and how much basic information is required to guide the future regulatory decisions. Since the panel's role is advisory, nothing in the report should be construed as directing either research or rule making, but we try to be specific about shortcomings as we see them.

The level of detail at which we can evaluate specific research projects is limited by the level of detail at which they have been presented to us at the workshops, on the field trips, and in reports and published literature. Although initially there was some discussion of having Panel members actually be present during hands-on laboratory and field work, this has not proven practical for a number of reasons, including funding limitations and time available for such purposes among and within the three research groups and the panelists. SFWMD has provided peer-reviewed research proposals against which we can judge the results and scope (Fontaine et al. 1996), but, except for the FUI flume study, we do not have comparable documents for the other research groups. The level of detail at which research methods and results have been revealed to us is, to say the least, uneven. We are aware of relevant activities by some or all groups about which we have had no briefing at all (e. g. greenhouse studies, collection and evaluation of rainfall and dryfall P data), and it is likely that there are other relevant research activities of which we remain unaware. We are also aware of relevant activities by other research groups that probably fill some gaps that we perceive in the work shown to us (e. g. USGS work in WCA-3A; EPA's Athens, Ga based Everglades studies). The panel's difficulties in discovering what research is being done in some areas serve to underscore what we see as a major problem: communication, cooperation, and integration among the research groups and the agencies funding the research.

Lean et al. (1992) suggested that the research effort should (1) assess responses of the Everglades to nutrient inputs and (2) determine maximum levels of nutrients that will not cause significant ecological changes. Although where the nutrients are located in the system is not defined by them, Lean et al. clearly took an ecosystem view of the problem, and this is reflected in the ongoing research. The Panel agrees that this is the best scientific approach. The Panel's evaluation of ongoing research is based on the assumption that a system view of the problem is being taken by the research groups. That is an important criterion for evaluating the relevance of specific investigations. In review of this report, one or more sponsors disagreed with the use of the Lean et al. report as the procedural basis for research. It is the Panel's view, however, that most of the ongoing research is justified only if a system approach, like that advocated by Lean et al, is accepted as correct. In any interacting system, modification of one attribute often results in changes in other attributes throughout the system. The Panel views the current research efforts as being directed toward understanding as quantitatively as possible how changes in inputs of phosphorus are reflected in other parts of the system and how they may interact with other variables such as hydrology. This information will greatly improve the ability to judge what long-term level of inputs of phosphorus to the Everglades is possible without resulting in significant changes in other system attributes.

Lean et al. further stated, "This study will determine the threshold level for total phosphorus concentration in marsh waters." The Panel believes achieving that goal will require attention to total system phosphorus, its distribution, and its tendency to move and change chemical form, and we focus on that issue in some of the following sections. The research is appropriately following the lead of Lean et al. in taking a system view of the problem and the potential solutions. In advocating a systems approach Lean et al. correctly indicated that details of the approach have to be developed as work and understanding progresses. In many respects, notably modeling, more probably is being done than was anticipated by Lean et al. However, the panel notes in Section 3 what it feels are significant omissions and problems we have not been able to address.

During review of this report, all sponsors requested that the Panel comment in more detail on specific research components of each research group. The Panel respectfully points out that it has not been able to observe the research first hand, has not visited laboratories, and in general has not been presented with the research in sufficient depth to make what would be essentially a quality-assurance evaluation. The Panel has provided comment and criticism at the level at which the projects have been presented to it.

2. Research Approaches

Three different research approaches are being used to determine effects of P on the structure and function of the Everglades ecosystem: (1) Analysis of patterns observed along P gradients that have resulted from past and current P inputs via the hydrologic control structures, (2) experimental P addition studies conducted in semi-static mesocosms or flow-through flumes located in situ, and (3) simulation modeling using water and nutrient inputs as forcing functions. Each approach has strengths and limitations, and it is the combination of approaches used in a comparable manner in each of the major Everglades subsystems (WCA's, Everglades National Park) that will provide the maximum potential for addressing the question of P loading effects on the ecosystem.

In our previous report (Pomeroy et al. 1995b) we presented a matrix of research approaches in distinct Everglades environments to illustrate the needs for research. That is updated in Table 1 to show how ongoing and planned research is filling in the matrix. The major remaining omission appears to be wet-prairie marl soils. However, we were informed during final review of this report that research on wet-prairie marl soils is being done as part of other research initiatives. The tree-island category has been dropped from the matrix, but we have been advised that research on tree islands as potential foci of phosphorus inputs by birds and alligators is in progress. The research elements in Table 1 are taken largely from Lean et al. (1992).

Table 1. Matrix describing the distribution of research projects using four levels of experimental design to study the response of different habitats in the Everglades to nutrient enrichment.

1 - Duke Studies; 2 - FIU Studies; 3 - SFWMD Studies
O = Ongoing; P = Proposed; C = Completed
S = Slough communities
E = Emergent macrophyte communities (either Sawgrass or Cattails)

Research Element	PEAT SOILS								MARL SOILS	
	WCA-1		WCA-2A		WCA-3A		ENP		Wet Prairie	
	S	E	S	E	S	E	S	E	S	E
Gradient Analysis	2C, P 3O	2C, P 3O	1O 2C,P 3O	1O, 2C,P 3O	1P 2C, P	1P 2C, P	2C,P	2C, P	2O	2O
Paleoecology Studies			1O 3P	1O						
Dosing- Mesocosm	3O		1O 3O	1O			2O	2O		
Dosing- Flume	2O		1O				2O			
Greenhouse Studies	3O	3O		3O 1C,O						
Unit/Flume Modeling	2P	2P	1P				2P	2P		
Landscape Modeling	3O	3O	3O	3O	3O	3O	3O	3O		
Remote Sensing/EPA	3O	3O	3O	3O	3O	3O	3O	3O		

The mesocosms-greenhouse category in Table 1 refers to experimental systems that are located in more controlled environments than field conditions and that may have a number of treatments applied including nutrient dosing, hydroperiod, and salinity. Thus dosing studies in the field, that are considered mesocosm studies, fall under the batch dosing experiments in contrast to the flume dosing studies. To remove this confusion, the mesocosm-greenhouse category will be referred to as 'greenhouse studies' to minimize confusion. The panel felt that it was necessary to identify specifically the location of soils and plants used in greenhouse studies of ecological processes. Landscape observations are those that involve some remotely sensed information such as low-altitude mapping or satellite interpretation of landscape patterns in vegetation. This will be termed remote sensing; but the key is that it is information that is being used for the landscape modeling of the Everglades Protection Area.

Analyses of patterns along spatial gradients in surface water or sediment P are being performed primarily in WCA-2A by the Duke and SFWMD research groups, in WCA-1 by FIU and SFWMD, and in the ENP by FIU. The strength of this approach is its realism and high degree of relevance to the question of thresholds in ecosystem response to added P over relatively long periods of time. In effect, the historical loading of P resulting from hydrological and agricultural activities provides the "experiment." Actual responses of the Everglades ecosystem to decades of increased P input are measured along the gradient of P input. Limitations of this approach involve difficulty in determining past P loading rates or concentrations at each location along the gradient and whether current ecosystem characteristics are primarily a consequence of current P loading or some different level of past P loading. Another limitation to this approach is the difficulty in separating effects of changes in other factors in addition to changes in P (e. g. hydrology). The gradient approach has provided a considerable amount of data useful for identifying relationships between P concentration in either water or sediments and structural ecosystem characteristics (e.g., biomass, coverage, species composition). Future work by all three groups should also emphasize functional ecosystem characteristics along P gradients (e.g., areal gross primary production, community respiration, dissolved oxygen dynamics, P cycling) as well as initiate such studies in areas of the Everglades other than WCA-2A where major P gradients can be found (e.g., WCA-3A, and perhaps ENP). The limitations of the gradient approach, described above, are being addressed through a combination of flume or mesocosm studies (for short-term responses) and paleo-ecological studies (for very long-term responses).

Experimental P addition studies include two types, (1) semi-static mesocosms with pulsed weekly additions of different concentrations of P, and (2) flow-through flumes with continuous addition of different concentrations of P. The mesocosm experiments are currently being conducted by SFWMD researchers in WCA-1 and WCA-2A sloughs, also by FIU in ENP, and a large set of structural and functional characteristics are being monitored to determine a broad array of ecological responses to P addition (Table 1). The strengths of the mesocosm approach are the ability to replicate sufficiently at each experimental site, moderate control over P dosing, relatively realistic hydrologic conditions (water exchange is facilitated by holes in the sides of the cylindrical mesocosms), and ability to conduct identical experiments at several different sites. There may be some need to compare timing and duration of experimental nutrient pulsing with actual pulses of nutrient inputs in the Everglades. There is also a need for careful evaluation of the relation between ecosystem responses and P concentrations in water. The mesocosm approach is being used by SFWMD in conjunction with their P gradient studies in WCA-2A. The combination of these two approaches should allow P dose-response relationships determined from the mesocosm work to be translated into P concentration-response relationships determined from the P gradient studies. Additional mesocosm experiments have been proposed by SFWMD (Table 1) and these would be of considerable value in WCA-3A.

The flow-through flume studies using continuous additions of P are being conducted by the Duke group in WCA-2A and soon will be initiated by the FIU group in WCA-1 and the ENP (Table 1). As with the mesocosm studies, a large set of structural and functional characteristics of the ecosystem are being monitored to determine response to P addition. The strengths of this approach are good control over P dosing and the creation of P concentration gradients at small scales, minimization of enclosure artifacts, and the maintenance of relatively natural hydrology, including advective flows. Limitations include the high cost of construction and operation, precluding replication within sites and their use at many sites, plus inability to detect long-term (decade-scale) responses to low levels of P addition. The Duke study in WCA-2A has been under way for several years and data analysis has lagged data collection, as often happens with this type of large-scale field experiment. Future emphasis needs to be placed on data analysis. In addition, previous data analysis has primarily used ANOVA. However, given the inherent low degree of power of ANOVA with only two replicates per treatment, and given the gradients in P concentration that have been established in each channel (and data have been collected along these gradients in each channel), regression-type analyses may be a more powerful approach for determining P concentration-response relationships and thresholds (e. g. relating measured average P concentrations and ecological responses at different locations in the experimental flumes). It is suggested that structural (e.g., biomass, species composition, sediment characteristics) and functional (e.g., areal productivity, dissolved oxygen dynamics, P cycling) characteristics be analyzed in this manner.

The FIU flume studies appear to be well formulated, although some issues relating to flume hydrodynamics should be carefully evaluated and perhaps modified to provide the intended flow and dosing regimes (see panel comments on the February 22 site visit). Strengths of the FIU flume-study design are their replication in ENP (separate flume networks at three different locations) and an additional flume network in WCA-1, and the close interaction between the empirical studies and simulation modeling that appears to be planned (Table 1). Because of the similarities in design of the Duke and FIU flume experiments, close interaction during data analysis and evaluation to compare P concentration-and-response relationships between groups should be a high priority. One possibility would be for FIU to have one flume at each site set up by the load-based approach that Duke is using. Also, extension of the FIU simulation modeling to the Duke studies would be a valuable exercise for validating the model and/or identifying the mechanisms responsible for any observed differences in P concentration-response relationships between WCA-2A and the other sites.

Simulation modeling in support of P threshold research is currently being conducted primarily by SFWMD, although efforts by the USGS (ATLSS model) may also have some application. The SFWMD effort appeared to be driven originally by a need to determine hydrologic and P budgets for the Everglades. It has been expanded to include simulation of ecosystem properties, particularly plant communities, and the effects of hydrology and nutrients on changes in vegetation types, particularly from sawgrass to cattail. The strengths of this approach for P threshold research are that it allows an evaluation of interactive effects of hydrology and P on the ecosystem, an evaluation of ecological interactions in response to P (especially food web effects), and predictions of effects across a much broader range of P and hydrologic conditions than can be empirically evaluated. The value of simulation modeling is enhanced when used in close interaction with empirical research that can provide the data needed to parameterize and validate the models, as appears to be the case here. Its limitations are that it represents a simplification of reality, and potential mismatches may exist between available data and that required by the model. There may be weaknesses with some of the simulation models now being used, particularly the lack of sufficient biogeochemical reality in treating P dynamics, lack of rigorous validation and insufficient attention or linkage to higher trophic levels (consumer animals). It is suggested that future efforts be focused on these areas.

3. Research issues

3.1. A phosphorus budget for the Everglades

The panel has repeatedly called for the assembly of a statistically rigorous budget quantifying all standing stocks of phosphorus, residence times of those stocks, and rates of fluxes between the stocks. This fundamental exercise in ecology has been bypassed by modeling. While it may seem that this is “just another model,” or that it has been accomplished already through modeling, we argue that it has not. The models condense and average in ways that can lead us to overlook significant stocks and processes, for example, by the use of “settling rates” of P from water to sediment. Such a budget should, of course, include data from all three research groups and potentially from other reliable sources. The immediate value of a quantitative assessment of the Everglades phosphorus budget would be to identify significant standing stocks or fluxes of P that have not received sufficient attention.

3.2. Phosphorus sources, current and historical

Current inputs of phosphorus to the Everglades are being monitored through the combined efforts of the South Florida Water Management District and the Florida Department of Environmental Protection. Monitoring of current inputs of phosphorus to the Everglades is conducted by SFWMD at control structures and other locations. These in-house analyses have minimum detection limits (MDL) of 4 µg/L for both total P and reactive inorganic P. However, the DEP laboratory is providing analyses of samples for gradient and mesocosm research for SFWMD. Duke and FIU do their own analytical work. We were informed during review of this report that the FIU group has detection limits of 0.6 and 0.3 µg/L for total P and reactive inorganic P respectively, the DEP laboratory (which is providing analytical services to SFWMD for nutrient threshold studies) currently has detection limits of 2.0 and 1.0 µgP/L for total P and dissolved reactive P respectively, and the Duke laboratory has a detection limit of 2.0 µgP/L for both total and dissolved reactive P. Other contract laboraories being used for phosphorus analysis for nutrient threshold research by SFWMD have MDLs in the 1-5 µg/L for total P and in the 1-2 µg/L range for dissolved reactive P.

While this report was under final review, the panel received copies of reports on a quality assurance/quality control study of all research groups, the FDEP laboratory, and several contract analytical laboratories that was performed by the FDEP Quality Assurance Section. Most of the improvements recommended by the QA Section were concerned with record-keeping and record storage, which do not affect the precision or accuracy of analytical results. A need for FIU and SFWMD to use standard solutions having concentrations nearer to the minimum level of detection (MDL) was expressed. It was also suggested by the QA Section that FDEP run more frequent blanks. Panel believes that a total phosphorus procedure with a MDL ≤1 µg/L should be implemented for all nutrient-threshold-related research. Having said this, we have no serious concerns about the rigor of the measurements of total phosphorus in surface waters, but there is some question about the quality and quantity of rainfall and dryfall phosphorus data. Collecting samples not contaminated by birds, insects, and fine detritus recirculated by wind is difficult. Because atmospheric sources of phosphorus are believed to be a major natural input, we consider data on atmospheric inputs to be important. We have been told during final review of this report that atmospheric P is receiving attention from all research groups, but Panel has had no opportunity to review the plans or work in progress.

Discussions of the measurement of dissolved reactive phosphorus at two panel meetings left the panel confused. While data on dissolved reactive phosphorus likely will not become the focus of future regulation, the panel views knowledge of dissolved reactive phosphorus concentrations, especially at experimental or reference sites, as an essential component of a basic phosphorus budget for the Everglades. The Panel has doubts that a MDL greater than 1 µg/L for dissolved reactive phosphorus is sufficiently low to characterize the variation of dissolved reactive P in relatively unimpacted areas of the Everglades. A MDL of 2-4 is likely sufficient, however, for the experimental studies to identify significant increases over ambient concentrations, even in relatively unimpacted areas. Because of the central importance of measurements of phosphorus in water, the panel recommends that intercomparisons between laboratories continue and include soluble reactive phosphate. It should be possible to do this by exchanging frozen samples.

Estimates of historical phosphorus inputs to the Everglades are important, since evidence suggests that atmospheric inputs have increased. A systematic effort to do this on the part of one or more of the research groups is needed. Historically, the sources of P input to the central Everglades were the atmosphere and Lake Okeechobee. Atmospheric deposition of nitrogen has increased worldwide, so it is likely that phosphorus has also. The range of previous estimates of total P in rainfall in South Florida is 13-96 mg P m^{-2} y^{-1} (Hendry et al. cited by Walker 1995, Kushlan cited by Rader and Richardson 1992, Schnieder and Little, cited by Bayley an Odum 1976, Richardson and Vaithiyanathan 1995). Inputs of phosphorus from Lake Okeechobee actually may have decreased in the past century, based on paleostratigraphic data (Richardson, in periphyton workshop). The best indices of historic phosphorus concentrations may be derived from analyses of diatom communities in the sediment record (S. Cooper, oral report 4-22-97). This research is discussed further in the section below on periphyton.

3.3. The phosphorus cycle in the Everglades

It is characteristic of phosphorus-limited aquatic and marine systems that concentrations of total phosphorus in the water are very low (Pomeroy et al. 1995a and references therein), and that a small pool of dissolved phosphorus turns over very rapidly (Pomeroy 1960). Added phosphorus is assimilated rapidly into biomass or adsorbed by particulate matter. Phosphorus concentrations in the water will begin to increase only when a number of other living and non-living pools begin to saturate with excess P. For this reason, measurements of the standing stocks of total P in Everglades water are a relatively insensitive measure of significant changes of the system. By the time the concentration of total P in water has increased significantly, the system has already begun to approach P saturation in other components of the system (periphyton, macrophytes, sediments) and species succession may be well underway. In terms of time, the microbial components will be first to change, followed much later by changes in macroorganisms, such as sawgrass to cattails. The stages in this succession can be seen in the present-day Everglades.

We might assume that in the past, when P inputs were low and water levels high, burial of P in peat equaled input from all sources, minus some output to estuarine receiving waters. Some long-term recycling by peat fires occurs in dry years, but this would be re-assimilated into peat. Current rates of peat accumulation may be reduced as compared with pre-drainage rates. Soil subsidence in the Everglades is >2.5 cm y^{-1}, primarily as a result of microbial mineralization (Brown et al. 1990 in Meyers and Ewel, cited by Amador and Jones 1995). Net peat accumulation in WCA-3A and net P accumulation were measured, based on the ^{137}Cs horizon and assumption of linear accumulation rates (Craft and Richardson 1993). At minimally enriched sites in WCA-2A, P accumulation was 0.08-0.23 g m^{-2} y^{-1}. At an enriched site in WCA-2A, P accumulation was 0.46 ± 0.12 g m^{-2} y^{-1}. Craft and Richardson (1993) state that removal of P is reduced to 75% in P-impacted marshes: "...the long-term P storage potential of the Everglades [is] poorly understood (Ibid.)." Reddy et al (1993), who estimated somewhat lower P accumulation rates in unenriched sites in WCA-2A (0.11-0.18 g m^{-2} y^{-1}) found a high correlation between P and Ca in sediments, suggesting co-precipitation. Because of the significance of P removal, soil processes are a potential subject of a future research workshop. This is one of several areas in which hydrological events influence the cycle of phosphorus.

3.4. Photosynthesis and Respiration in relation to inputs of phosphorus

Photosynthesis and respiration are two complementary and sensitive functional ecosystem-level processes that tell us much about trophic conditions, especially when they are related to other system characteristics. Photosynthesis is one of two biological routes by which soluble phosphate is converted into organic biomass (the other being immobilization by microbes during decomposition of P-deficient substrates). Therefore, knowledge of rates of photosynthesis helps us develop a model of phosphorus flux through Everglades communities of organisms. Measurement of community respiration rates is at least equally useful, and the two together give the very useful P/R ratio. These rates can be deduced in various ways from data being collected by the research groups. However, information available to the Panel does not suggest much direct focus on these basic processes, although we were told during review of this report that measurements of P/R are being made.

Blue-green autotrophic bacteria ("blue-green algae") are said to dominate biovolume of the periphyton 'algal' mats. Estimates of photosynthesis in unenriched open water of the Everglades are -0.065 to 2.01 gC m^{-2} d^{-1}, with a mean of 0.9 (Rader and Richardson 1992). It is not clear if this includes macrophytes, but it is a very respectable rate, and it needs verification at sites being studied by SFWMD and FIU as well as at other locations in the Everglades. Concentrations of CO_2 in water and surface sediment decline to zero around noon (and concentrations of O_2 rise above 150% saturation), indicating that for part of each day carbon may be limiting. This tends to support the estimates of ~1g m^{-2} carbon fixed by the periphyton community (but these are very approximate estimates). Phosphorus is the limiting factor during those hours when CO_2 is available for photosynthesis and/or chemosynthesis. The literature, and current research, seems to be rather weak on description of those parts of the food web that are based on periphyton. That is a question that may be addressed in a future workshop on invertebrates.

Rader and Richardson (1992) and Browder et al. (1994) suggest that P is precipitated by periphyton as calcium phosphates, but they present no data to support that. More recent publications by the Duke group indicate that most of the soil P is in organic form. It is not clear what role Ca plays in phosphorus incorporation into sediments. Rates of calcium phosphate precipitation, and the conditions that promote it are an important consideration, since this form of phosphorus removal may be more effective and lasting than incorporation into plant biomass. Autotrophic microorganisms may play a direct part in the precipitation or may cause it incidentally by drawing down the CO_2 with a resulting rise in the pH of the water to 9 or more (cf Reddy et al. 1993). In apparent contrast, research by SFWMD suggests that periphyton may reduce the rate of sediment accrual of P. The issue of effect of periphyton on sediment P accrual and the fate of P needs more study.

4. Modeling Workshop, West Palm Beach, February 24-26, 1997

Modeling is a research tool that can be used as a predictive management device or simply as a means to improve and simplify experimental and observational work. The immediate utility of modeling in the nutrient-threshold research program is the latter. Modeling is means for refining experiments and gradient studies by helping investigators understand which processes are most sensitive to changes in concentrations of phosphorus and which are least sensitive. Modeling, by itself, is not likely to be an appropriate way to define threshold concentrations of nutrients, but it can greatly expedite other phases of the research and improve our assurance from other kinds of experiments. Lean et al. (1992) recommended the development of a decision-support system to complement research elements consisting of both monitoring and experimental science. Modeling would be used for quantitative guidance in the design of monitoring and experiments, testing hypotheses, and integration of results. The decision-support system would be focused around an integrated modeling program, including statistical, empirical, and mechanistic process-based models as a basis for decisions on biological balance and a phosphorus threshold. This recommendation is being followed, and it is the best current scientific practice (cf. Hilborn and Mangel 1997). Ongoing and planned modeling include both empirical-statistical models (e. g. regression) and simulation modeling. While all the principal groups are involved in empirical-statistical modeling, it is primarily the SFWMD that currently is doing simulation modeling. Their work is solid, and is well along toward evaluating the effects of various P-loading scenarios. FIU has simulation modeling planned, but there was not a great deal of detail in their presentation of it at the February, 1997 workshop. The USGS also plans simulation modeling (ATLSS), but this effort is focused primarily on the effects of hydrology on upper trophic levels. Models of stormwater treatment areas (STA's) by Walker and Kadlec (PGM model) are mass balance calculations of P input and loss based on P sedimentation rates. Tetra Tech also is doing simulation modeling driven by P loading, and this work also appears to be in a beginning stage.

4.1. Use of modeling by the research groups

The Duke Wetlands Center employs statistical, regression-type models to analyze monitoring and experiments designed to determine "how the system works" (Richardson et al. in press). This approach has been extremely useful in identifying possible relationships between drivers and variables (e. g. cattail/sawgrass abundance vs soil P content, periphyton type vs water P). These efforts should be continued. Future challenges include incorporation of interaction effects of other factors, such as hydroperiod and disturbance, perhaps by multiple regression, ANCOVA, or other such techniques. The Duke group is beginning to develop simulation models for testing their conceptual and statistical models, but Panel has had no opportunity to review the plans or work in progress. It is not clear that, under the timeframes necessary for criterion development under the EFA, these modeling efforts will be of use in establishing phosphorus criteria. The strength of their program to date has been the extensive monitoring and experimental data base that has been developed using statistically appropriate experimental procedures. The modeling efforts of all the research groups can benefit from the Duke data. Interactions that include active data sharing among groups should be encouraged.

FIU is beginning new research efforts at sites in Everglades National Park and Loxahatchee National Wildlife Refuge. At the time of the workshop, FIU scientists presented box-and-arrow diagrams of proposed simulation models, although no actual simulation had been done, and indeed an additional modeler was yet to be hired. However, the overview that was presented identified key state variables (with provisional phosphorus concentrations) and fluxes of nutrients, indicating where experimental research would be focused. Two important working hypotheses are to be evaluated through their combined experimental and modeling approaches.

The first hypothesis is that over time any given addition of phosphorus will lead to the same end condition, independent of the concentration of phosphorus in influent water; only phosphorus inputs influence the rate at which changes will occur. In other words a small excess of inputs of phosphorus over a long time will have the same end result as a larger excess of inputs over a short time. This implies that the effects of a small input of nutrients may not be fully seen as biological change until many years after the inputs occur. There may be a slow buildup of soil phosphorus while visible biotic changes may occur only after phosphorus has accumulated sufficiently to overcome the resilience of the natural community. If not falsified, this hypothesis has important implications for related research and modeling. This is an issue that needs further discussion. This issue, obviously, is what amount of input of phosphorus to the Everglades will result in system change after several decades or a century (Everglades Forever). Richardson of thge Duke group, in review of this report, argues that the Everglades has a finite, albeit relatively small, assimilative capacity, which needs to be better quantified.

The second hypothesis to be tested in the FIU research and modeling is that, after its initial incorporation in the system, transport of P from one part of the Everglades to another is mainly in the form of motile organisms, such as fishes, rather than passive transport in solution in slowly flowing water. There is some precedent for this in the wetlands literature (Wiegert 1986). In a P-limited system such as the Everglades, new introductions of available inorganic P are assimilated by microorganisms or adsorbed onto particulate matter on a time scale of minutes, and subsequent transport of that P is likely to be in an organic form. This has implications for P turnover times and spiraling distances that can be addressed in part by the proposed simulation modeling. Information will be required on the rate of P assimilation into secondary consumers and the fate of P that is moved from enriched to unenriched areas. Long-term experiments in P-limited mangrove ecosystems in Belize, however, support the hypothesis that P does not move readily from an area where it has been assimilated (Feller 1995). Dwarf mangroves probably more than 50 years old were converted to taller trees by the addition of P, as inorganic superphosphate, to the rooting zone of the soil. The dwarf trees responded very readily to P additions, but after almost a decade, only the fertilized trees and a few neighboring ones responded. In contrast, most transport in streams involves remineralization and loss of P into water, while consumers tend to remain in place (Newbold et al. 1981). Rates and mechanisms of phosphorus transport within the Everglades need to be defined in order to sort out these possibilities.

Here, again, we see a need for a more complete phosphorus budget as underpinning for models. Instead of simply concerning ourselves with ‘phosphorus,’ we should consider each chemical form (or classes of chemical forms) of phosphorus, its instantaneous concentration, its turnover time, where it comes from and where it goes. At minimum this should include reactive inorganic phosphorus, sorbed phosphate on soil particles, particulate calcium phosphate, particulate organic P, dissolved organic P, with an agreed, uniform definition of size separation of particulate P (i. e. filter type, pore size). Each of the latter can be further subdivided. This is analogous to carrying the systematics of the Everglades organisms down to the genus or species level.

The South Florida Water Management District has an extensive Everglades modeling program. It has been using modeling for water management and is now extending modeling to nutrients. Modeling is but one component of an overall research program of the District that also includes experimentation and monitoring. The District is the only research group with an active simulation modeling program underway. The major models developed by the District are the everglades Water Quality Model (EWQM) and the Everglades Landscape Model (ELM). Additional models include CALM (spatially detailed version of ELM) and SAWCAT. Calibration efforts for these models were presented at the modeling workshop and are available on their website. Panel recommends validation with data independent of those used during calibration.

The transition probability model, SAWCAT, simulates the transition from sawgrass to cattail marsh, based empirically on nutrients and hydrology. As presented, the model has been applied to WCA-2A and shows which of the two species is dominant. The model shows a switch from one species to the other based on which is dominant. Any segment of the model that has developed 49% cattail is shown as sawgrass. So this is an approximation of the rate of progression of cattail dominance, as phosphorus is added to WCA-2A. For the model to more realistically evaluate conversion of areas from sawgrass to cattail, additional information will be required on the interactions between hydrology and P as they relate to the establishment of cattail seedlings in existing stands of sawgrass. Ongoing and proposed macrophyte research by SFWMD should provide important inputs to the SAWCAT model.

The most ambitious modeling effort of the district is a spatially explicit model of Everglades macrophytic communities and biogeochemistry. This model, the Everglades Landscape Model (ELM), has been in development for five years. The model covers the entire Everglades Protection Area, breaking up the region into 10,264 separate 1 km by 1 km cells. ELM uses a simplified, mechanistic approach to P dynamics. For instance, nutrient limitation of primary production is based on the standard Michaelis-Menton relations for P and N. Adsorption and desorption of phosphorus to soil particles in the sediment assumes equilibrium conditions over daily periods and uses an empirically defined sorption coefficient. It is not clear whether the coefficient was actually defined for Everglades soils. Like most biogeochemical models, ELM lacks explicit microbial and higher trophic level compartments. Rather, all trophic processing of organic matter is lumped into a single "decomposition" term. Microbes and higher trophic levels are not explicitly modeled. Like settling rates, decomposition rates are empirical mean estimates. One concern Panel has with the model is the use of fixed C:N:P ratios in live and dead organic matter state variables. While the ratios generally differ between habitats (e.g., sawgrass vs cattail) as along a successional gradient, they are not temporally dynamic. The use of fixed ratios could be a serious problem, as the model will underestimate incorporation of excess P in living organisms, a change that undoubtedly will occur following P additions (Feller 1995). Based on empirical Everglades stoichiometry, ELM could under-estimate P flux by an order of magnitude. We are also concerned about the adequacy of available data on P inputs. The model shows that rainfall is the major source of new P for interior portions of the system, away from canals. However, current assumptions about the P content of rainfall over the Everglades may suffer from contaminated rain samples. The modelers are, of course, aware of these limitations of ELM, having pointed out most of them. Panel agrees with the comment by SFWMD on a draft of this report that ELM should be useful in identifying areas of the Everglades where change will occur, but this and other models will not provide final criteria of 'normal' flora and fauna. Rather, the model(s) enhance experimental and observational research.

The EWQM is designed to capture the aggregated dynamics of fate and transport of P using simple first order equations, such as a net settling rate. The net settling rate approach is not mechanistic but this approach has been demonstrated to be an entirely appropriate formulation for certain uses such as design of Stormwater Treatment Areas, basin-wide responses of the Great Lakes to nutrient enrichment, and for performing screening-level calculations of nutrient fate and transport in the Everglades. The model has been useful for identifying processes in need of additional research, such as scouring, resuspension and deposition of sediments and P in the numerous canals of the Everglades.

District scientists state that they do not intend to use any of their models to identify nutrient threshold levels. In the context of setting nutrient thresholds, they view simulation models as useful for estimating permissible loads that will achieve the experimentally-defined nutrient threshold concentrations in the Everglades system. The District feels that one of the greatest strengths of the models, once they are validated, is to conduct "what if" experiments that cannot possibly be conducted, let alone replicated, at the scale of the entire system. Without such quantitative modeling tools, the alternative decision making approach is probably of equal or greater risk: regional decisions will be made using mental models that may be neither synthesis oriented nor peer reviewed. The District believes that if rule making were to be amended to include setting of permissible loads, then their simulation models will be useful. However, none of the models will be adequately validated within the timeframe of criterion development under EFA.

The panel's major concerns with the SFWMD modeling efforts are 1) lack of adequate mechanistic detail in modeling P dynamics including uptake, sorption, precipitation, organic-inorganic transformations, dissolved-particulate transformations, and solid-aqueous equilibria, and 2) lack of rigorous validation of model results. The value of simulation predictions will depend on the rigor of model validation based on accurate ground truth data in several remote areas of the Everglades (cf. 6. Reference Sites).

USGS is coordinating the development of another landscape-level model of the Everglades (ATLSS). The model as presently conceived focuses primarily on higher-trophic-level endangered species, such as water birds and the Florida panther. The utility of this model in research related to nutrient threshold research appears to be limited, at least for the near future, because it focuses on populations furthest removed from the dynamics of phosphorus. There is no evidence that data will be available for linking information on macroorganisms and biogeochemistry with the endangered species models.

Tetra Tech has produced an extremely simplified simulation model of P loading (the EPH model), from which predictions were offered about recovery of the Everglades from P loading under various mitigation scenarios. Commentators at the workshop pointed out that empirical data on recovery of a previously enriched wetland are not available, so one must consider release of P from previously enriched soils, and not simply set the model at a new settling rate. This served to raise as an important issue the need for empirical research on P dynamics during recovery from eutrophication. In review of this report the question was raised about inclusion, or not, of the L-67 canal in the model. Because of its length and position in the system, and because it is modeled as a unit, inclusion might bias the results with reference to P transport to the ENP.

The Walker-Kadlec PGM model (Walker 1995) simulates stormwater treatment areas (STAs) with three elements, water, soil, and biological response. The location and size of the STAs is designed to provide primary treatment of water from the Everglades Agricultural Area (EAA), with effluent P <50 PPB. It was pointed out that this model works only in a forward direction and cannot be used as written to simulate a recovery mode. The PGM model uses an empirical mean settling rate of 10.2 m/y to predict phosphorus retention in the STAs. Thus this model is simplified with respect to P dynamics, as was the SFWMD model. According to Walker (pers. comm.), the rate was based on peat accretion data from the region 0-10 km south of the S-10 structures, a region now dominated by cattails. He further states that settling rates in that region are uniform, but they are sensitive to drought, while rates in sawgrass are less sensitive to drought.

Because of data limitations, computing power constraints, and time constraints, aggregation of state variables and processes is essential for models of complex systems. None of the models being used in synthesizing Everglades research addresses in detail the specific chemical or biochemical mechanisms of P dynamics. That is acceptable modeling procedure, but it is important to remember that many of the models are empirical, and significant features may have been omitted as a result of aggregation. For example, Walker (1995) points out that a qualitative difference in settling of phosphorus may exist between a cattail marsh and a sawgrass marsh with periphyton. In the latter, a significant portion of phosphorus settling may be in the form of carbonates, rather than organic matter, because of the effect of periphyton on pH of the water. Settling rates appear to be higher in the sawgrass-periphyton community, and the carbonates may be more resistant to regeneration by drying or even fire. Although this distinction is not incorporated into any model, it could be an important factor in predicting the long-term retention of phosphorus in accreting sediments. Moreover, since the STAs will be largely cattail marsh, they may have less effective long-term retention of phosphorus than a sawgrass marsh. Moreover, it is recognized that they will need to be kept inundated permanently in order to be effective (Walker 1995).

4.2. Modeling issues

4.2.1. Better coordination between modelers and those collecting empirical data and doing experiments could improve model development and the utilization of available information for calibration and validation. The Panel learned during review of this report that about 45% of the data used by SFWMD for model implementation and validation are from Duke research. This is a step in the right direction, but since the SFWMD is currently doing most of the simulation modeling, it would be beneficial for the District to have access to all data sets of the other research groups. If impediments exist for data sharing, efforts to resolve this should be made. NSF has faced this problem with its JGOFS, LTER and LMER programs, and some major polar research projects. No single set of procedures has been accepted by all these research groups. Usually, as soon as data and experimental results are processed and verified by the NSF-funded researchers, they are put on a web page that other researchers in the project can access by password. Within the project, it is understood that the originators of data sets have publication rights for two years. After that, the password is dropped and the general public can access, use, and publish the data. The web pages are to be maintained indefinitely (but data may ultimately be archived). Some researchers object to the two-year limit on exclusive rights to data, demanding as much as seven, while some other federal agencies appear to be demanding immediate release of data as soon as they are processed. A detailed and interesting set of data access criteria can be accessed at the GLOBEC web page (http://www.usglobec.berkeley.edu/usglobec/reports/datapol/datapol.contents.html). For the Everglades the criteria may need to be developed with the rule-making deadline as a paramount consideration. Most large NSF projects have data managers who collect and post processed data sets. Possibly the Everglades research needs an overarching data coordinator to serve as referee and facilitator of data access.

4.2.2. The panel was unanimous in its concern that insufficient chemical and biological reality is going into the various simulation models. At present, no model is simulating inorganic carbon chemistry, variable stoichiometry of P, or microbial-based and periphyton-based, food webs. These processes are presently being modeled using questionable or poorly quantified empirical constants.

4.2.3. A number of additional submodels could help to define critical shortages of data and to integrate recent research on periphyton, macroinvertebrates, macrofauna, and soil-sediment P biogeochemistry. Parameterization of some of these may be difficult but should help focus on immediate data needs and in the long run help the ATLSS modeling effort. In general, a need exists to evaluate the degree of aggregation in models and its effect on model output. As would be expected, there is much variation in the aggregation of state variables in the current models. Few state variables deal with demographic properties of ecosystems to specifically define ecosystem state change.

4.2.4. Modeling could be a valuable tool to translate the temporal and spatial responses of soil total P to loading rates and soil conditions. Total P concentration in soil is the metric most often cited as having a threshold value for macrophyte change. With the addition of other demographic or functional metrics of change, soil total P may not be the key parameter on which to focus, since it is a balance between input and loss and is thus difficult to translate to a discrete concentration of phosphorus in overlying water.

4.2.5. There is a need to better incorporate interactive effects of P loading (increased and decreased) and hydroperiod on biogeochemistry and biota in the simulation modeling. The SFWMD has designed the ELM to understand the interactive effects of phosphorus and hydroperiod on biogeochemistry, but to date there is limited information upon which to adequately parameterize the models. The proposed greenhouse studies should provide much needed information to enable significant progress along these lines in the future.

4.2.6. An ecologically significant and standardized metric for quantifying macrophyte communities and periphyton communities is needed. This metric must be measurable in experimental studies as well as in the gradient studies of P effects. It must also be incorporated easily into ecosystem models. For periphyton, the metric might be total chlorophyll *a* per unit area, separated into floating mats, benthic, and attached to stems. Other possibilities include total organic mass (loss on ignition) per unit area of the floating community, or total biomass (cell volume) of the dominant forms (comprising >90% of the community). More functional metrics would be diel dissolved oxygen profiles (free water) and P/R ratios determined by chamber studies. For the dominant macrophytes, stem density, stem height or some index that incorporates both may be useful.

4.2.7. Defining the relative utility of functional groups vs. bioindicator species is an important issue in both modeling and research agendas. ELM uses state variables that are not specifically linked to demographic analysis of change. Functional groups may be better indicators, and at the modeling workshop macrophytes were used as indicators of state change. Both panelists and research participants agreed that other biological and biogeochemical indicators could be used to indicate system changes, and some of them might be better early warning devices. Invertebrates with short life cycles, which happen to fall readily into functional groups, offer one potential approach (Merritt et al, 1996). There is a clear need to use modeling to evaluate early indicators of change, followed by experimental validation.

4.2.8. Field work to more completely define the temporal (seasonal) and spatial variation in macrophyte and periphyton communities in areas as yet minimally impacted by increased P may be needed to define the baseline(s) for which models of P effects are calibrated and tested (see 6, discussion on reference sites).

4.2.9. Higher order food web models (or components of larger simulation models) may be needed to address the effects of P loading (soil or water) and the interactive effects of P and hydroperiod on upper trophic levels. While this may be impractical for the highest trophic levels (alligators, wading birds), it is needed for macroinvertebrates. Because the number of dominant species in some invertebrate groups is probably small (cf. Merritt et al. 1996), changes in the populations of dominant invertebrates may be indicative of subtle phosphorus loading. However, detailed knowledge of periphyton and invertebrate population dynamics is necessary for such an approach. The dosing studies and gradient studies could provide data to calibrate and test such models. SFWMD notes in final review of this report that Joel Trexler of FIU found that fish biomass differences between P-enriched and unenriched sites are greater and more consistent than those of invertebrate biomass. Panel agrees that it may be advisable to study fishes as well as invertebrates, and that this may create a data link to fish-eating higher trophic levels. Moreover, as FIU points out, fishes represent a potentially motile pool of phosphorus.

4.2.10 The panel was concerned about rigorous model validation. While the details of sensitivity analysis are clearly presented in the SFWMD web pages and refereed articles, it was not clear what work is being conducted to better understand the several parameters to which the sensitivity analysis showed the model to be particularly sensitive but which are poorly known. The value of simulation predictions will depend on the rigor of model validation based on accurate ground truth data in several remote areas of the Everglades (cf. 6, Reference Sites).

5. Workshop on periphyton, West Palm Beach, April 21, 1997

Periphyton is the algal-bacterial community attached to submerged macrophytes, other objects, or the soil surface. The periphyton community is a particularly important component of sloughs in the Everglades, and often is associated closely with floating macrophytes (e.g., *Utricularia* spp.) which serve as physical substrata for growth. Periphyton contributes a substantial fraction of the primary production in the Everglades and appears to be the primary food resource for many macroinvertebrates. Periphyton may be of greater importance in Everglades food webs than macrophytes because of its high rate of production and turnover. While organic matter derived from sawgrass and other macrophytes is consumed primarily after it dies and becomes the basis of a relatively inefficient detritus-based food web, periphyton is consumed while living, providing a richer, more direct, and probably more efficient, transfer of organic matter and energy to invertebrate and vertebrate consumers. Loss of periphyton or shifts in species composition toward forms that are less palatable to consumers are likely to create a significant change in Everglades food webs.

Currently, both the Duke and SFWMD groups are conducting studies to identify effects of P enrichment on periphyton communities. These studies are of two types: (1) observations along

P gradients produced by historical and current P loading from water control structures, and (2) experimental P additions (dosing) in flumes or in semi-enclosed mesocosms. Routine measurements being performed include taxonomic composition (cell counts), biomass (ash-free dry mass), biovolume computed from cell count data, and chlorophyll a), and chemical composition (carbon, nitrogen, phosphorus). Other measurements include productivity (oxygen evolution, ^{14}C uptake), alkaline phosphatase activity, and algal growth assays to determine limiting nutrients. Together, these measures appear to provide the appropriate information for identifying the effects of phosphorus on periphyton. In the gradient studies these measurements have been made on ambient periphyton collected from both natural and artificial substrata (e. g. periphytometers and dowels), whereas in the flume and mesocosm studies periphyton are collected mostly from introduced artificial substrata owing to constraints stemming from repeated sampling of a limited area. The experimental approaches and measurement techniques used by the Duke and SFWMD are quite similar, thus maximizing potential for comparing results. The Duke group has focused their efforts primarily in WCA-2A, whereas the SFWMD is conducting studies in WCA-1 and WCA-2A. Because of the apparent importance of periphyton to the food web in the Everglades and its sensitivity to changes in ambient concentrations of phosphorus, the multiple studies by more than one research group are viewed by the Panel as needed and important.

The Duke group has also initiated paleoecological studies of historical changes in periphyton communities in response to changes in P loading. Results from this work will complement results from current measurements of periphyton along the existing P gradients in WCA-2A. This work will provide important information on the timing of species changes relative to changes in P loading as well as how other factors such as water level variations influence periphyton composition. During review of this report, the Panel has been advised that additional paleoecological work is being conducted by USGS with logistical support from SFWMD.

The FIU group has proposed periphyton studies in conjunction with their P additions in experimental flumes in WCA-1 and in the Everglades National Park. Many of their proposed periphyton measurements involve remote, non-destructive techniques (digitized aerial photos, visual estimates of percent cover) and will only permit detection of gross changes in periphyton communities. Community structure and species composition will be sampled by collecting small cores of periphyton from four plots in each flume channel to determine chlorophyll a content, ash-free dry weight, C, N. P, ad species abundance. Periphytometers and hardwood dowels will also be used for measurements requiring destructive analysis. These, and in-situ measurements of natural periphyton, will provide the most sensitive measures of periphyton community response to added P as well as data comparable to that of the Duke and SFWMD groups and should be emphasized in the study. Community metabolism measurements made in chambers would also be useful in identifying changes in primary productivity and community respiration that can be related to other observed changes in periphyton. We suggest that these be added.

Results of the Duke and SFWMD periphyton studies have been published in the open literature (Duke: Craft et al. 1995; Rader and Richardson 1992; Vymazal et al. 1994; Vymazal and Richardson 1995; SFWMD: McCormick and O'Dell 1996; McCormick et al. 1996). These studies have built on earlier work summarized by Browder et al. (1994). Based on the Duke and SFWMD work to date, several conclusions emerge. First, the periphyton community is P limited, with additions of P resulting in rapid increases in the rate of biomass accumulation. Second, substantial changes in the periphyton community appear to occur at total phosphorus (TP) concentrations within the range 10-30 μg/L, or roughly twice the natural background TP concentration in the northern Everglades. This result is consistent with studies in other P-limited aquatic ecosystems showing species composition shifts at relatively low levels of P enrichment. The taxonomic changes include shifts in the diatom assemblage and replacement of diatoms and calcareous periphyton mats composed of several species of cyanobacteria (*Scytonema hofmanii* and *Shizothrix calcicola*) by filamentous green algae and in some cases by non-calcareous forms of cyanobacteria (e.g., *Microcoleus*). Third, at somewhat higher TP concentrations, loss of the periphyton community occurs. However, it is unclear as to whether the lower levels of enrichment at which species shifts have been observed would eventually lead to loss of the periphyton community. Continued operation of the flume and mesocosm dosing studies may be able to answer this question. Fourth, alkaline phosphatase activity associated with periphyton communities is significantly reduced with increases in TP concentration, indicating a significant reduction in P limitation of the periphyton community. Fifth, shifts from single-cell or colony to large filamentous species will have major impacts in invertebrate consumers, since the latter are less readily consumed. Finally, the P content of periphyton increases with increasing concentrations of P in water. As a result, periphyton serve as a partial sink for P additions, potentially contributing to the transfer of P from water to sediments as organic P associated with detritus. Exactly how quantitative and qualitative changes in periphyton effect accumulation of soil phosphorus is not yet fully understood. This deserves additional study.

The strength of the periphyton work to date is the taxonomic characterization and identification of effects of P enrichment on species composition by both the Duke and SFWMD groups. This work has been outstanding and forms an important component of the evaluation of effects of P enrichment on the Everglades ecosystem. The value of these studies is enhanced by the scientific rigor with which they have been conducted and the similarity in the approaches and techniques used. The work has demonstrated that periphyton species composition is among the most sensitive of ecosystem characteristics to P enrichment. Total biomass and primary productivity appear to be somewhat less sensitive as indicators of change in the periphyton community. It appears that biomass and productivity increase with low levels of P enrichment, then decline at higher levels of P enrichment with eventual loss of the entire community. However, this pattern is not clear-cut. Furthermore, it is not known if the community is able to re-establish following long-term reduction of P inputs, and this question is not being addressed. Further, it might prove very informative to tie in the species-level changes with system-level changes, such as the photosynthesis/respiration ratio.

5.1 Periphyton issues

Several unresolved issues are likely to be important for determining the level of P enrichment producing changes in the periphyton community within the Everglades ecosystem.

5.1.1 Are the changes in the periphyton communities with P enrichment observed in WCA-1 and WCA-2A generally applicable for other areas of the Everglades with different periphyton

communities and with different hydrological and chemical characteristics (e.g., WCA-3A, Everglades National Park)? Consideration should be given to identifying reference sites as suggested in Section 6.

5.1.2 Do the changes in periphyton species composition represent an ecological change, or is ecosystem function (primary and secondary productivity, biogeochemical cycling, food web structure, and physical/chemical habitat) little affected by species shifts as long as the periphyton community, or its macrophyte substratum, is not eliminated? To address this issue, detailed studies on effects of periphyton species shifts and community deterioration on macroinvertebrates, primary and secondary productivity, P uptake and retention, and water column dissolved oxygen patterns (particularly minimum D.O. levels, length of anoxia) are needed. The current and planned P gradient and dosing studies appear to include these types of analyses to some extent, but the panel is concerned that the ongoing and planned efforts may not be sufficient on several hierarchical levels. Additional studies are needed on at least the following: (1)Effects of changes in periphyton community composition on invertebrate food webs; (2) effects of changes in periphyton community composition on water pH and dissolved oxygen concentrations (diel profiles); and (3) effects of changes in periphyton community composition on chemical forms and concentrations of phosphorus in water and sediments and the rate of P incorporation into sediments. The use of both indicator species and functional groups of species should be evaluated. The panel has been advised during review of this report that SFWMD has initiated some of these additional studies.

5.1.3 The periphyton community is considerably more diverse than the 'algal' component alone. Deterioration of the periphyton with P enrichment is likely the result of a complex set of interactions among algae, bacteria, protozoa, meiofauna, free-floating macrophytes, and the biogeochemistry of the assemblage (particularly Ca precipitation and P uptake and retention). Because periphyton appear to be among the components of the Everglades ecosystem most sensitive to P enrichment, studies aimed at how low levels of P enrichment alter ecological and biogeochemical processes within periphyton communities should be a high priority.

5.1.4 Research results of the periphyton field program need to be integrated with existing models. As described above for the modeling workshop, most of the modeling efforts have been focused on changes in macrophyte communities, while little emphasis has been placed on periphyton-microbial communities. This is not the result of a lack of information to parameterize such models, because both the SFWMD and Duke groups have extensive data. It was not evident at the workshop whether field results of either program are being integrated into modeling efforts. Specific plans for modeling the periphyton responses in the FIU flume studies also were not clearly identified.

5.1.5 During the workshop it was suggested that the three research groups establish reference collections of the microorganisms characteristic of Everglades periphyton. This would serve both as a means of current intercomparisons between investigators and as an archive for future reference. Consideration should be given to preserving specimens in such a way that they can be examined in the future with RNA-DNA probes as well as by microscopy.

6. Workshop on reference sites, West Palm Beach, April 22, 1997

The scientific merit of the research conducted by SFWMD, Duke and FIU will be evaluated through the normal scientific procedures associated with publication in peer-reviewed journals, peer-reviewed symposium proceedings, etc. The research conducted by the three groups will also be used, however, in a broader context associated with management of the Everglades. It is desirable, therefore, that the research results from small-scale and site-specific studies be applicable to as much of the Everglades system as possible. The Panel has been concerned that the three research groups may be limited in their ability to compare and extrapolate their results because of possible dissimilarities between their study sites and because their sites may not be representative of the natural variation in hydrology, biogeochemistry, and biology that exists within the Everglades system. Three members of the Review Panel expressed this concern in their report from the February, 1995 Nutrient Threshold Research Workshop (Pomeroy et al. 1995b). At the time the current panel began its work, no progress had been made with respect to the questions and concerns that the Panel raised in 1995. Accordingly, the Panel recommended that a discussion on Reference Wetlands be included in the agenda for the April, 1997 workshop.

Dennis Whigham initiated the discussion on Reference Wetlands by presenting an overview of the hydrogeomorphic (HGM) approach that is being developed to perform functional assessment of wetlands. One of the essential components of HGM is the use of Reference Wetlands, defined as sites that encompass the known variation within a class of wetlands, and thus should encompass the range of ecological functioning within the class (Brinson et al. 1995). Whigham's objective was to present a case study and demonstrate the importance of collecting data from a series of Reference Wetland sites that represent the range of conditions that are found in nature for each class of wetlands. In the case of the Everglades, it would be similar to having a set of study sites in Wet Prairie habitats and the sites would be chosen to cover as much of the geographic range of the vegetation type as possible as well as sites that represent the range of conditions from as pristine as possible to sites that have been modified through human activities (e. g. hydrologic modifications, addition of nutrients, etc.). A positive discussion about the utility and suitability of using reference wetlands followed Whigham's presentation but, overall, no consensus was reached on whether or not the concept should become an integral part of the current nutrient threshold research efforts.

One concern expressed by all research groups was that they did not have the time, manpower, and monetary resources, either singly or in combination, to establish and monitor a set of reference wetland sites. One investigator suggested that it was not important to establish reference wetlands because the three research groups were primarily using an experimental approach and that it would be too costly and time consuming to obtain similar information, or conduct similar experiments, over a range of reference sites. The panel, however, remains concerned that results from flume studies, mesocosm studies, and transect studies will have limited value unless it is possible to extrapolate results from one study area to other research areas as well as other areas within the region. While the panel agrees with those comments, it suggests that much valuable information could be obtained from Reference Wetlands without measuring every parameter and process that has been or is now being measured at the sites being used by the three research groups. Comments from SFWMD, DUKE and DEP on earlier drafts of this report indicated with there remain differences in how Reference Wetlands are viewed. Comments from the research groups also suggest that the U. S. Environmental Protection Agency's EMAP program may serve as a basis for establishing and sampling Reference Wetlands in the context of the ongoing nutrient threshold research effort.

Before describing how a Reference Wetland study might be conducted, it is necessary for the Panel to describe further the concept of Reference Wetlands, because comments from one research group suggest that they interpret Reference Wetlands to be only pristine sites, or sites which have not been modified by human activities. In the HGM approach to wetland assessment, some of the Reference Wetlands would indeed be sites that are as pristine as it would be possible to find. These are called Reference Standard sites in HGM terminology. The collection of sites chosen for the set of Reference Wetlands would, however, also include sites that have been modified to varying degrees, including sites that have been so modified that it might not be possible to restore them to conditions that would be characterized by the Reference Standard sites. Reference Wetlands, therefore, include sites that represent the range of ecological conditions found for a class of wetlands.

What is the relationship between Reference Wetlands and ongoing nutrient threshold research? The example of HGM was given because the same approach would allow two types of comparisons. First, the sites that the three groups are currently studying represent a set of Reference Wetland sites because they occur in different locations and they represent a range of ecological conditions. Analysis of existing data from each of the types (e. g. classes) of Everglades habitats being studied by the three research groups (Table 1) would allow for a better understanding of the spatial variability that exists in the structure, chemistry, and biodiversity of similar types of habitats located in different areas (e. g. slough communities in WCA-1 compared to the same communities in WCA-2A, etc.). Second, a comparison of differences and similarities between the current research study sites could serve as a basis for comparison with sites that might be sampled as part of other larger-scale ongoing activities throughout the Everglades (e. g. EMAP).

The Panel suggests that the issue of comparability among current research sites could be addressed efficiently and relatively fast (e.g., within 6 months) by an independent contractor who would work closely with the three research groups. The contractor and research groups would first identify the classes of wetlands for which they have enough data for a comparative study (e.g., Table 1). For each wetland class chosen, the three groups would develop a listing of the sites, experiments, and variables measured. The research groups and contractor would then select a subset of variables and sites, for each class, for which there are enough data to conduct an ordination analysis. Multivariate analyses such as ordination allow comparisons of sites and identification of important underlying environmental factors that characterize the sites. If, for example, the analysis shows that the slough communities the three groups are studying are similar, then we can assume that the groups are all working in areas that are similar enough for one to conclude that results from one study will be relevant and applicable to all sites within that same wetland class. If, however, the analysis shows that the research sites are dissimilar, this would be a good indication that there is a large degree of variability among sites and that results from one location may not be applicable to other locations. The Panel suggests that the most relevant data for this type of analysis would be species composition of the macrophyte and periphyton communities as well as data such as plant biomass at peak standing crop, standing crops of nutrients, soil nutrients, water quality data, density of soils, etc.

If time and resources were available, it would also be desirable to include process data (e.g., P/R data) in the analysis to attempt to relate structure with function. It is unlikely, however, that much process data would be available for enough sites to be included in the analysis without additional field work. The Panel recommends that, if time and resources are available for additional field work, the three research groups identify a few process variables (2-3) that they believe are important. The three groups could agree on a standard sampling protocol and analytical procedure for each variable identified. The contractor would sample all of the sites that would be included in the analyses under their supervision of the three research groups. The process data would then be included with the other data and become part of the analysis. The compilation of process data in conjunction with structural data at the sites using standard procedures would provide a more powerful tool in obtaining a better understanding of the correlations between structure and function that the three groups are now evaluating separately.

This analysis would also provide a basis for conducting a larger-scale reference study across a broader range of sites within the Everglades. The study would provide an assessment of critical data that would be needed to be collected at all sites that would be included in a comparative study using, for example, EMAP sites. It is more likely that development of a set of Reference Wetlands for each class would entail inclusion of EMAP sites with additional sites, including some that are currently being studied by the three groups. A larger-scale study of Reference Wetlands could also be accomplished by a contractor working with the research groups but, given the range of comments from DEP and the three research groups, the Panel believes that a larger-scale Reference Wetlands study would be less important to accomplish than a comparative study of existing research sites.

7. Field trip to WCA-1 (Loxahatchee N. W. R.), Feb. 25, 1997

While the margins of the Loxahatchee Wildlife Refuge show cattail stands that appear to indicate P-enrichment, the central portion of the refuge appears to be phosphorus-limited at present. The research sites in the central Loxahatchee Wildlife Refuge appear to be in a part of the Everglades with relatively low impact from nutrient enrichment, with sawgrass stands and sloughs, the latter having the natural *Utricularia*-periphyton community. The SFWMD research site in central WCA-1 provides a set of semi-enclosed mesocosms for experimental work with indigenous species and communities. Everything appeared to be in good condition and in very active use by several investigators. The FIU flume in WCA-1 is discussed in section 10.

8. Field trip to Water Conservation Area-2A, October 1, 1997

The visit to research sites in WCA-2A included several stops along the nutrient enrichment gradient. This was helpful in getting a clearer understanding of the types of changes in vegetation that have occurred as a result of the long history of phosphorus enrichment in WCA-2A. It appears that it is not only the replacement of sawgrass by cattail that is occurring in response to P enrichment, but also a change in the relative distribution of emergent vegetation and open-water sloughs, with a reduction in open water. This has not been emphasized in previous visits and workshops, and it may need additional study, because the food webs and phosphorus dynamics differ between sloughs and dense stands of macrophytes. Such a study requires. a landscape-scale approach, probably involving aerial photographs or other remote sensing technique. It also appears that there is a strong hydrology-nutrient enrichment interaction such that nutrient enrichment results in very different responses under different hydrologic regimes. This interaction does not appear to be a focus of any major research effort by the three research groups, although the Duke group apparently has conducted some small-scale experiments to begin to address some aspects of it with regard to the sawgrass-cattail transition. Perhaps some additional analyses could be conducted using the nutrient enrichment gradients in WCA-2A and recreating hydrologic histories. However, it is not clear whether sufficient historical data exist for such an effort.

The confounding effects of fire and water level in controlling successional stages was discussed as it pertains to the effects of P addition. While it might appear from following the P gradient that decreased vigor of sawgrass and increased areal extent of slough communities is related to decreasing P loads, we learned that during succession in the Everglades these patterns can be reversed by fire, thus mimicking P addition. Shifts in some of the properties we saw along the gradient could be induced naturally during succession. It will therefore be difficult to attribute future changes to a single cause without detailed knowledge of the successional history of a specific region. This is an important issue that needs to be addressed prior to establishment of metrics that document the effects of P loading. During review of this report, recent work on fire effects was pointed out to the Panel (Wu et al. 1996; Newman et al. in press). This issue again relates to the need for knowledge about reference conditions that included data from reference sites.

The visit to WCA-2A also included a tour of the Duke experimental flume study site. This is discussed in section 10.

9. Field Trip to Shark River Slough, Everglades National Park, Oct. 2, 1997

Lower Shark River Slough in Everglades National Park is one of the least impacted parts of the Everglades. It has changed little over the past 50 years (cf. Davis 1943, Fig. 62 and LRP pers. comm.), and is characterized by sparse tree islands, low sawgrass, and extensive sloughs. The purpose of this trip was to observe the newly established FIU flume, which we discuss in Section 10.

10. Flume Experiments

Flume experiments are a regularly used technique in wetland research. They are probably the nearest approach to "natural" conditions and are therefore worth the considerable costs involved in doing them properly. They are a significant contribution to the Everglades nutrient threshold research.

10.1 Original demonstration flume.

To the best of our knowledge, the first flume experiment in the Everglades was conducted in Shark river Slough during 1983 and 1984 (Flora et al. 1988; Walker et al. 1988). The panel spent some time examining this site, which still showed the effects of enrichment, including a stand of cattails. Lessons learned at this site apply to the ongoing flume experiments, as we note below.

10.2 Duke flume study

The Duke group is now completing a five-year flume experiment in WCA-2A. They clearly made an effort to keep the design as uncomplicated as possible, which is a virtue in any experiment but especially one in a remote location. Rigid, fixed walls were placed between flumes and shading effects were minimized by taking samples only near the center of each flume. Rather than depend on the natural flow regime, the Duke group closed the ends of the flumes and allowed water with added nutrients to flow from header tanks into and through the flumes. In retrospect, the flumes might have been made longer. If dosing of the Duke flumes is soon terminated, as planned, this presents an opportunity to study recovery, which is an important and generally neglected aspect of the nutrient studies. The present condition of the flume experiment in Shark River Slough that was terminated in 1984 tells us that return of vegetation to pre-dosing conditions is a very long-term process. However, processes involving other components, especially microbial ones, should move much more quickly, and it is hoped that these changes can be followed. Changes in the water column, including periphyton, should change especially quickly, followed by the benthic periphyton mat, and much later the upper peat layer.

A minority opinion in the panel is that the Duke flume study should continue, that results of long-term dosing would be of more value than a study of recovery following dosing. At the same time, the panel recognizes that neither of these may happen, because they require a continuing commitment of significant funds. Certainly, as the deadline for rule-making approaches, the first priority should be processing and interpretation of the data and their utilization by modelers. Plans to analyze the data using regression and measurements of loading and concentration versus ecological response at different locations in each flume should greatly enhance their value over and above the whole-flume analysis of effects of the three P input concentrations. Use of the Duke data in simulation models is, as we have noted elsewhere, important. This study is generating information that could be extremely useful in developing and calibrating models for slough environments experiencing minimal P additions.

10.3 Florida International University flume studies

The panel visited one of three flume sites in Shark River Slough. The FIU flume studies are more elaborate and technically sophisticated than those of Duke, as expected, because they were designed recently and benefited from previous experience. The FIU group is using P concentration as the treatment variable and targeting somewhat lower increases in concentration (5-30 µg P l^{-1}). They also chose to utilize natural flow regimes through open-ended flumes rather than force water through an essentially closed system. That is more natural but also technically more difficult. FIU also opted to minimize shading by using "window-shade" side walls of polyethylene. Previous experience with retractable side walls suggests that they do not retract properly during declining water level and must be rolled by hand at such times. However, during review of this report, FIU investigators assure us that the moving walls work well and that changes in water level are so gradual it is easy to monitor the walls. Use of natural flow regimes requires that flow be measured. FIU has installed a Doppler system that is state-of-art but previously untried in such shallow water. The panel was assured that it is working, and that it gives net flow rates. We were also assured that on the day of our visit to the Shark River Slough flumes, significant flow was occurring, although that could not be verified by observation of the movement of natural suspended materials. Although the Doppler system is in theory more sensitive and precise than others, we urge early and regular comparisons with tracer techniques such as rhodamine or bromide. We have been informed during final review of this report that a bromide tracer is being used. The high intensity of phosphorus sampling along the flume will provide a further check on water movement. Even though the researchers may not feel the need for it, it will help to assure others that the open system is working.

In the FIU flumes in ENP, PO_4^{3-} will be added apparently only when water flow is moving downstream. It will be added approximately 5 m before entering the vegetated portion of the flume. While traversing this short distance, the PO_4^{3-} presumably will mix thoroughly in the flume cross section. Loading will be calculated as measured water flow and measured total P concentration at the unvegetated portion of the flume, immediately upstream of the vegetated portion. If this interpretation of procedures is correct, probably the design will work. Another possible shortcoming of the FIU flume design is the lack of an undisturbed control. While there is a disturbed control (flume with no added P), it is equally important to have data on undisturbed environments. Sampling could be done immediately adjacent to the outer flume with no additional construction involved.

The Loxahatchee FIU flumes present an even greater problem of water flow than the Shark River flumes. Several panel members and two ETAC members have raised questions about the design of the flumes that may merit consideration. The fundamental question is whether a fixed orientation flume design that utilizes natural water movement will function predictably, given the very low rate of water movement (<1 cm/sec) and the influence of prevailing wind on the direction of water movement. Kadlec (memo. to DEP) notes that at the time of our visit water flow was approximately 45° to the channel axis, and this will influence flow speed through the channels. Since the flow measurement device in the channels integrates water velocities over the entire depth, the reading is the mean rate. When wind is accelerating surface flow, it is possible for a return flow to be set up along the bottoms of the channels. This might result in a near-zero flow reading and would not reflect what was happening. The actual dosing during such a scenario may depend on the vertical placement of the drip tube.

Kadlec further notes that the drip tubes are located exactly at the channel inlets (in review of this report, we learned that FIU has since modified the design to provide a mixing channel). The possible scenarios discussed above of currents at an angle or winds forcing a circulation pattern in the channels will tend to cause back-mixing that will introduce dosing into inappropriate channels or exclude some of it from channels. Further, the stated intent is to restrict flow at the incurrent ends of the flumes so as to increase flow rate sufficiently to achieve turbulent mixing of nutrients that are added through a diffuser. Flow rates will have to be increased more than one order of magnitude (i. e. >>10 cm/sec). Walker (memo to ENP) suggests that the flumes be operated initially with a conservative tracer to verify that the channels are independent and do not cross-contaminate. The Panel concurs.

10.4 Potential early bioindicators

The site visits, together with seeing the flume experiments, made the Panel speculate on the effects of nutrients on the water lilies and their potential as an indicator of phosphorus loading. They appear to respond rapidly to phosphorus by increasing leaf size. This was seen in the Duke flumes. We also noted that in the Shark River Slough the lily pads were not much larger than a silver dollar. One panel member suggests that FIU consider placing water lilies planted in pots in the Shark River Slough flumes. In review of this report, however, Jenny Richards of FIU remarked that the Panel may be confusing two species of water lilies, or two life history stages, but she went on to suggest that better, even faster-growing potential bioindicator species are *Utricularia foliosa* and *Sagittaria lancifolia*. Both are said to show “striking morphological changes in response to nutrients.” Both grow rapidly and are said to be present in the flumes. If morphological changes in a conspicuous, widely distributed plant do indeed occur over a much shorter time than cattail incursion, this might offer a simple, easily observed change that correlates with phosphorus loading. Moreover, during review, SFWMD say they are already using water lily size differences in transect monitoring and have correlated them with changes in tissue phosphorus. Considering the effort that has been put into *Typha* (cattail) incursion, some attention to earlier successional changes in macrophytes seems a worthwhile project of small additional cost that could still be built into ongoing and projected flume and transect observations.

11. Summary of recommendations

11.1 General recommendations

11.1.1. Future work should emphasize both demographic (e. g. species dominants, especially those responding rapidly to increased P loading) and functional ecosystem characteristics along P gradients (e.g., areal gross primary production, community respiration, dissolved oxygen dynamics, P cycling, ATP, and adenylate ratios), with a view to ultimately identifying a few key parameters of state change.

11.1.2. Atmospheric fallout and surface water input probably are the two principal routes by which phosphorus enters the Everglades. Accuracy of estimating the latter is currently much better than accuracy of estimating the former, so far as we can tell. More attention to atmospheric inputs seems needed, particularly since there is strong evidence that atmospheric inputs were the principal historic source of P.

11.1.3. Research on all historic inputs of phosphorus to the Everglades is needed, and this may be best done by a comparison of the response of extant diatom communities to phosphorus with the diatom communities in the stratigraphic record.

11.1.4. Periphyton appears to be a major primary source of energy and elements such as phosphorus for food webs involving invertebrates and fishes in the Everglades. In addition to understanding the effects of P inputs on periphyton, it is important to have a good description of the food web the periphyton supports, and changes in the food web that result from a shift from a single-cell to a filamentous periphyton community.

11.1.5. The role of calcium carbonate precipitation in sequestering and immobilizing phosphorus needs better quantification. Is this a significant process in the central and southern Everglades?

11.1.6. The first community to respond to changes in phosphorus concentration is the microbial community. Its response to available phosphorus is to cease producing the enzyme alkaline phosphatase. Since alkaline phosphatase activity varies with season and location, it should be evaluated in that context and compared with other microbial activity parameters.

11.1.7. Experimental research on, and modeling of, the fate of accumulated excess phosphorus in both soils and biomass upon the cessation of inputs of high concentrations of phosphorus are needed. In which compartments does the P remain in place and in which does it recycle and move through the system as the system undergoes recovery? Are motile organisms involved in transfers of phosphorus?

11.1.8. Experimental research on the details of P cycling should include uptake, sorption, precipitation, organic-inorganic transformations, dissolved-particulate organic transformations, and solid-aqueous equilibria. Incorporation of these dynamics into simulation models would enable recovery to be examined and would add some biological and chemical reality to the simplistic approaches currently being taken.

11.1.9. Future work should continue to emphasize important interactive effects between P loading, hydroperiod, and water movement. Semi-open mesocosms are an appropriate way to incorporate the first two variables, and flumes are appropriate for studying all three when there is strong, unidirectional water flow. Flume design may have to be modified to examine dosing response when water flow is sluggish and variable in direction.

11.1.10 The confounding effects of fire and water level in controlling successional stages need to be addressed as they pertain to the effects of P addition. While it might appear from following the P gradient that decreased vigor of sawgrass and increased areal extent of slough communities is related to decreasing P loads, these patterns can be reversed by fire, thus mimicking P addition. Shifts in some of the biological properties that occur along a P gradient can be induced naturally during succession. It will therefore be difficult to attribute future changes to a single cause without detailed knowledge of the successional history of a specific region. This is an important issue that needs to be addressed prior to establishment of metrics that document the effects of P loading.

11.1.11 One of the major remaining omissions in the matrix of the nutrient threshold research appears to be wet-prairie marl soils (Table 1). Since research is said to be underway by projects not a part of the nutrient-threshold research effort, future discussions should determine the implications of this knowledge in understanding ecological changes in the Everglades.

11.2 Modeling

11.2.1. Regression-type models have proven useful to identify possible relationships. These efforts should be continued and also should incorporate interaction effects of additional factors, such as hydroperiod and disturbance, perhaps using multiple regression or ANCOVA methods.

11.2.2. Interactive effects of phosphorus loading and hydroperiod on biota should be strengthened in the various simulation models. The SFWMD experimental greenhouse studies will hopefully provide much needed information for strengthening these interactions in existing models, especially ELM

11.2.3. An ecologically-significant standardized metric for quantifying macrophyte communities and periphyton communities is badly needed, as noted in 4.2.6. This metric must be measurable in manipulative experimental studies as well as in gradient studies of phosphorus effects, and it must be easily incorporated into ecosystem models. If a set of agreed-upon reference wetlands becomes part of the nutrient threshold research program, data from the reference sites will be invaluable in developing standardized metrics.

11.2.4. There is a need for defining the temporal (seasonal) and spatial variation in macrophyte and periphyton communities in areas as yet unimpacted, or least impacted, by increased phosphorus (e. g. reference wetland sites). Empirical data are needed to define the baseline(s) from which models of phosphorus effects are calibrated and tested.

11.2.5. All modeling efforts should incorporate the dimension of time more explicitly, to define both the steady state response and the rate of change or length of time required to reach a new steady state after changes in phosphorus loading or hydrology. Simulation models do, of course, explicitly incorporate the time dimension, but, like other model attributes, time requires calibration.

11.2.6. Once the models now under development are running and calibrated, there is a need to validate them rigorously using separate and independent data sets, perhaps from remote areas. Ultimately, it will be necessary also to address the impacts of large-scale, rare events, such as drought and fire. During review of this report we were informed of work on fire effects (Wu et al. 1996 Newman et al. in press). Drought is a more difficult issue that needs consideration.

11.2.7. There is a need to address through simulation models impacts of phosphorus loading (and interactions with hydroperiod) on higher trophic levels, at least up to the level of macro-invertebrates and perhaps fishes. Dosing studies and gradient studies will provide data to calibrate and test such models.

11.2.8. Modeling, as well as empirical research, on changes in phosphorus cycling after their eutrophication has ceased, or is reduced, is needed. The fate and effects of the excess phosphorus already in the system needs to be predicted. Incorporation of more chemical reality into existing simulation models would facilitate this focus.

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Appendix A.

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Appendix B.

List of Research Projects Relevant to Everglades Nutrient Threshold Studies.

Note: This information was provided after completion of the above report. The External Peer-review Panel did not have this information during report preparation and has not commented on it in the report. Each research group provided the information in a different format, and to preserve as much information as possible the original formats are retained.

1. Duke Wetland Center projects, Time line for 1997-2001.
(Sampling periods shown by Ö, reports in progress are projected for each project phase)

I. *What is the threshold P concentration that results in alterations of ecosystem structure and function in the Everglades?*

A. Slough communities: WCA-2A dosing study.

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. P addition phase	√	√			
2. Recovery phase (potential 1998-2000)		√ (Sept)	√	√	
3. Periphyton sampling	√	√	√		
4. Macrophyte sampling	√	√	√	√	
5. Invertebrates and fish sampling	√	√	√	√	
6. Effect of P on macrophytes decomposition	√	note 2			
•Effect of P on algal mat	√	note 2			
•Effect of P on peat decomposition	√	note 2			
7. Phosphatase studies					
•Monitoring	√	note 2			
•Algae, bacteria, macrophytes	√	√	√	√	note 2
8. Mechanisms of algal mat decline (experiment)	√	note 2			
9. soil sampling (microbial P, diffusion into soil, P accumulation)	√	note 2	√	√	note 2
10. Data analysis and interpretation	√	√	√	√	note 2
11. Final report	note 2	complet e dosing	√	complete recovery	note 2

B. Sawgrass/cattail communities: fertilizer study

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Apply N and P	√	√	√	√	
2. Monitor water chemistry	√	√	√		

3. Biomass and soil response	√		√		
4. Data analysis and interpretation	√	√	√		
5. Final report	√ note 2		√ note 2	Finish	note 2

C. Gradient study

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Paleoecological analysis					
• Pb-210 analysis	√	√	√	note 2	
• Pollen, diatom, charcoal analysis	√	√	√	finish	
• Data analysis and interpretation	√	√	√	√	
• Final report	√	√	note 2	finish	
2. Changes in macrophyte species along gradient in WCA-2a					
• Vegetation sampling		note 2		√	note 2
• Final report	note 2		√	finish	
3. Nutrient analysis along the S-10 gradient					
• Development of P availability for soil	√	√	finish		
• Diffusion, mineralization modeling	√	√ finish			
• SRP/TP studies along gradients (particle size, bioavailability)	√	√	finish		
4. Gradient studies along WCA-2A and western WCA-3A (new study, 1997-98)					
• Establish plots along gradient	√	√			
• Monitor plants, soil, water	√	√	√ report	√	√ finish

D. Phosphorus dosing in sawgrass (Proposed 1998-1999)

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Establish dosing site		√			
2. Monitor plant and biotic response		√	√	√	
3. Analyze water chemistry		√	√	√	√
4. Data analyses		√	√	√	√
5. Final report			√	Report	finish note 2

II. *What are the effects of altered hydrology and distrubance on the Everglades?*

A. Water level/disturbance study

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Plot sampling	√	√	√	finish	
2. Plant analysis	√	√	√		
3. Data analysis/interpretation	√	√	√		
4. Final report	√	√ note 2	√	finish	note 2

B. Proposed water pulsing and water level study (New study, 1998-1999)

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Build microcosm		√			
• Monitor water levels		√	√	√	√
• Monitor nutrients		√	√	√	√
• Measure plant community structure		√	√	√	√
2. Community transect analyses (WCA-2A and WCA-3A (See I.C.4)		√	√	√	√
3. Data analysis and interpretation		√	√	√	√
4. Final report		√	√	√ note 2	√ finish

III. *Low level chemical dosing*.

A. Phase I.

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Microcosm experiments	√	finish	note 2		
2. Mesocosm experiments					
• Construct chambers	√	√			
• Fe and Al addition, monitor water, soil		√	note 2 √	note 2	
3. Data analysis and interpretation	√	√	√	√	
4. Final report	√	√	√	finish	

B. Phase II. Macrocosm (contingent on Phase I data).

Project	*1997*	*1998*	*1999*	*2000*	*2001*
1. Design and build (flow ways, set up test cells)		√	√		
2. Chemical addition, monitor water, soil			√	√	√
3. Data analysis and interpretation			√	√	√
4. Final report		√	√	note 2	finish note 2

Note 1. Quarterly reports will be submitted.
Note 2. Manuscripts are prepared each year on various phases of the projects as they are completed.

2. Everglades National Park

A. Projects designed specifically to correlate phosphorus loads with changes in flora and fauna.

- Numerical interpretation of Class III narrative nutrient water criteria for Everglades wetlands. R. Jones/SERP (dosing study).

- Transect sampling in Everglades National Park marshes - 1989 and future. Doren (ENP) and Childers (SERP).

B. Other studies examining various aspects of Everglades ecosystems.

- Mercury and phosphorus distributions: R-EMAP - Stober (EPA)/R. Jones (FIU).

- Mercury food web cycling - Loftis (BRD/USGS)

- Fish and invertebrate studies - Perry (ENP) / Loftis (BRD/USGS)

- Population structure of Everglades fish and invertebrates - Trexler (FIU)

- Freshwater and upland vegetation projects.
  a. Hydrologic changes and plant community shifts (Taylor Slough)- Armentano and D. Jones (ENP.
  b. Hydrologic changes and solution holes (Rocky Glades) - Armentano and D. Jones (ENP)
  c. Exotic plant invasions - D. Jones (ENP)/ USDA
  d. Fire (mis)management on pine rocklands (Long Pine Key) - ENP Fire Cache
  e. High water event impacts on tree island hammocks (Shark River Slough) - Armentano and D. Jones (ENP)
  f. Sea level rise effect on coastal plant communities in coastal areas and keys - Armentano and D. Jones (ENP)
  g. Mangrove die-back in Florida BayKeys - Tom Smith (BRD/USGS)
  h. Vegetation assessment/baseline study of tree island hammocks (shark River Slough) - Armentano and D. Jones (ENP)
  i. Vegetation mapping - D. Jones (ENP)/Welch (UGA)
  j. Cape Sable seaside sparrow habitat - Pimm (UT)
  k. Shark River Slough marsh vegetation - Ross (SERP/FIU)
  l. Vegetation:community characterization and disturbance effects - Platt (LSU)
  m. Water relationships of pines and hardwoods - Sternberg (UM)
  n. Exotic grass invasion - Gottschalk (LSU)

- Estuarine water quality monitoring netword (Florida Bay, Whitewater Bay, Ten Thousand Islands, Biscayne Bay, and the SW Florida shelf) - Smith (ENP)/ Jones (SERP) -SFWMD

- Nutrient inputs to florida Bay - Rudnick (SFWMD)

- Geochemical studies in Taylor Slough and Eastern Florida bay. - Orem (USGS)

3. Studies at Loxahatchee National Wildlife Refuge

1) Atmospheric deposition collectors (Refuge staff) To compare bulk densities of total phosphorus from rainfall and dryfall and determine the magnitude of P deposition from natural atmospheric sources. 1993-ongoing.

2) 16-station monitoring (Refuge staff). Determine trends of mean total P throughout WCA-1 and monitor compliance with terms of settlement agreement under U.S.A. vs SFWMD et al. 1992-ongoing.

3) Everglades Nutrient Removal (ENR) Project sampling (Refuge staff) Compare mean total P at selected sites, especially near inflow and outflow locations. 1994-ongoing.

4) FIU dosing study (FIU) Determine numerical mean water column concentration of total P which causes an imbalance in the flora and fauna of Lox. Nat. Wildlife refuge. Initiated.

5) Water Quality criterion for P in the Loxahatchee National Wildlife Refuge. (Paul McCormick, SFWMD). Characterize spatial variation in ecosystem sensitivity to P enrichment. 1996-0ngoing.

6) Sampling for Eustrongylides in fish. (Marilyn Spalding, U. Fla.) Detemine prevelance of *Eustrongylides ignotus* in fish community of the Everglades Nutrient Removal Project. 1995-ongoing.

7) Mercury concentration in largemouth bass in Loxahatchee National Wildlife Refuge. (Ted Lange, Fla. Game & Freshw. Fish. Comm.). I. Determine current concentrations of Hg in bass in WCA-1. II. Determine relationships between Hg and other factors and compare with other locations. 1996-ongoing

8) Mercury contamination throughout the Everglades and Big Cypress region. (Dan Scheidt, USEPA). I. Define extent of Hg contamination in canal and marsh water, soil, air, biota. II. Determine Hg sources. III. Determine environmental conditions that regulate formation of methylmercury and its bioaccumulation. IV. Assess environmental and human health risks. 1993-ongoing.

9) Spatial and temporal changes in tree islands of Loxahatchee National Wildlife Refuge. (Laura Brandt, U. Fla) Identify ahnd quantify patterns of tree islands and relate to hydrology. 1996-7.

10) Palynological census data from surface samples in South florida. (Debra Willard, USGS) Understand distribution and abundance of pollen of various plants in modern sediments and their relationship to source plant distribution and abundance. 1997

11) Marl, rocky, and organic flat wetlands of the Florida Everglades.(Katheryn Trott, U. S. Army Corps of Engineers) Develop hydrogeomorphic model to assess wetland functions; assess

impact of dredge and fill projects on wetlands; measure capacity of a wetland to perform functions. May be usef for Central and South Florida Restudy. 1997-ongoing.

12) Nutrient levels in Ibis rookery (Edward Maltby, Univ. London). Determine correlatins between decomposition rates of plant fibers and concentrations of P in sediment and the rate of spread of P from an ibis colony. 1993-ongoing.

Project title	**Key Deliverables through 2001**	**Anticipated Completion Date***
WCA-2A nutrient threshold gradient study	Water quality changes 1994-1995	Dec-96
	Water quality changes 1994-1997	Dec-98
	Water quality changes 1994-1999	Dec-00
	Long-term changes in surface water TP (1976-1997)	Jun-98
	Soil/porewater 1996-1997	Dec-98
	Soil/porewater 1996-1999	Dec-00
	Periphyton changes 1994-1995	Dec-96
	Periphyton changes 1994-1997	Dec-98
	Periphyton changes 1994-1999	Dec-00
	Macrophyte decomposition rates	Sep-97
	Macrophyte biomass and nutrient content	Dec-97
	Macrophyte species composition and density	Dec-98
	Temporal changes in macrophytes	Dec-01
	Invertebrate changes 1994-1995	Jun-98
	Invertebrate changes 1994-1997	Jun-99
	Invertebrate changes 1994-1999	Dec-01
WCA-2A phosphorus threshold dosing study	Terminate dosing/begin monitoring recovery	Dec-98
	First-year soil/porewater responses	Jun-98
	First-year periphyton responses	Jun-98
	First-year macrophyte responses	Jun-98
	Four-year soil/porewater responses	Jun-00
	Four-year periphyton responses	Jun-00
	Four-year macrophyte responses	Jun-00
	Four-year invertebrate responses	Jun-00
	First year recovery - all compartments	Dec-00
	Second year recovery - all compartments	Dec-01
LNWR nutrient threshold gradient study	Water quality changes 1996-1997	Dec-98

	Water quality changes 1996-1999	Dec-00
	Water quality changes 1996-2000	Dec-01
	Soil/porewater 1996-1997	Dec-98
	Soil/porewater 1996-1999	Dec-00
	Periphyton changes 1996-1997	Dec-98
	Periphyton changes 1996-1999	Dec-00
	Periphyton changes 1996-2000	Dec-01
	Macrophyte biomass and nutrient content	Dec-98
	Invertebrate changes	Jun-99
LNWR phosphorus threshold dosing study	Terminate dosing/begin monitoring recovery	Dec-99
	First-year soil/porewater responses	Dec-98
	First-year periphyton responses	Dec-98
	First-year macrophyte responses	Dec-98
	Macrophyte germination study	Dec-97
	Four-year soil/porewater responses	Jun-01
	Four-year periphyton responses	Jun-01
	Four-year macrophyte responses	Jun-01
	Four-year invertebrate responses	Jun-01
	First year recovery - all compartments	Dec-01
Soil P accretion rates	Cs dating of WCA1 and WCA3 soil cores	Feb-95
	Development of Cs vertical transport model	Jun-96
	Cs and Pb dating of WCA 2 soil cores	Jun-98
	Sorption of Cs to Everglades soils	Jun-98
Biogeochemical indicators of imbalance	Microbial respiration and extracellular enzyme activity in WCA 2	Dec-98
	Phosphorus cycling and retention in WCA 2	Dec-98
	Nitrogen cycling and retention in WCA 2	Dec-98
	Biogeochemical indicators in 1998 dry season in WCA1 and 2	Dec-98
	Biogeochemical indicators in 1998 wet season in WCA1 and 2	Sep-99
Macrophyte responses to phosphorus and hydrology in WCA 1 and 2	Nutrient uptake rates and competition between sawgrass and cattail	Sep-97
	Effects of P and oxygenation on growth and nutrient accumulation	Mar-98
	Effects of P and oxygenation on uptake kinetics	Sep-98

	Effects of P and oxygenation on root physiology and morphology	Dec-98
	Interactive effects of P and hydrology on macrophyte physiology	Jun-99
	Macrophyte regrowth in relation to P	May-99
	Macrophyte responses along a (greenhouse) P gradient	Dec-99
	Interactive effects of P and hydrology on macrophytes	Dec-00
Periphyton linkages to Everglades foodwebs in WCA 2	Complete Statement of Work for cooperative agreement	May-98
	Initiate field work	Jun-98
	Completion of field work	Jun-99
	Complete sample processing	Dec-99
	Complete data analysis and report preparation	Jun-00
Everglades Water Quality Model (EWQM)	Complete calibration level 3	Complete
	Complete calibration level 2	Apr-98
	Complete nutrient fate and transport scenario testing for Restudy	Apr-98
	Screening-level simulations for P loads that reach no-imbalance [P]	as needed
Conservation Area Landscape Model (CALM) for WCA-2A	Complete calibration level 2	Complete
	Complete validation level 2	Complete
	Initiate nutrient and hydroperiod scenario testing	Oct-98
Everglades Landscape Model (ELM) #1 (WCA1, WCA-2A, WCA-3A, and WCA-3B)	Complete calibration level 2	Aug-98
	Complete validation level 3	Aug-98
	Initiate nutrient and hydroperiod scenario testing	Oct-98
	Report on scenario testing	Dec-98
Everglades Landscape Vegetation Model (ELVM) for predicting detailed vegetation succession	Complete calibration level 2	Jun-98
	Complete validation level 3	Jun-98

	Initiate nutrient and hydroperiod scenario testing	Aug-98
	Report on scenario testing	Oct-98
Integration of ELM #1 and ELVM	Complete calibration level 2	Mar-99
	Complete validation level 2	Mar-99
	Initiate nutrient and hydroperiod scenario testing	Jun-99
	Report on scenario testing	Sep-99
Everglades Landscape Model (ELM) #2 (Entire Everglades Protection Area)	Complete calibration level 2	Dec-98
	Complete validation level 3	Dec-98
	Initiate nutrient and hydroperiod scenario testing	Mar-99
	Report on scenario testing	Sep-99

Key to Levels of Calibration and Validation:
3 = Model represents "reasonable" spatial or temporal dynamics.
2 = Model represents reasonable and observed spatial or temporal dynamics but observations are incomplete.
1 = Model represents observed spatial and temporal dynamics, and observations are complete.
(Note: For landscape models that span 10-30 years and thousands of "cells", this level of calibration and validation is rare.)

***Anticipated Completion Date =** data analysis and interpretation completed.