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Development and Application of the Everglades Landscape Model

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Abstract

Water management infrastructure and operations have fragmented the greater Everglades into separate, impounded basins, altering flows and hydropatterns in these internationally recognized wetlands. A significant area of this managed system has experienced anthropogenic eutrophication. This combination of altered hydrology and water quality has interacted to degrade vegetative habitats and other ecological characteristics of the Everglades. As part of a massive plan to “restore” the Everglades, simulation models are being applied to better understand the system’s hydrologic and ecological dynamics, evaluating options for restoration plans. One such tool is the Everglades Landscape Model (ELM), a process-based, spatially explicit simulation of ecosystem dynamics across a heterogeneous, 10,000 km^2 region. The model development has proceeded in tandem with advances in Everglades research, improving its algorithms and calibration to best capture dynamics of key landscape attributes. The first spatial application of the model was in an intensively studied subregion along an anthropogenic nutrient gradient. The model captured the spatio- temporal dynamics of hydrology, surface and ground water phosphorus, periphyton biomass and community type, macrophyte biomass and habitat type, and peat accumulation. Refinements to the model have improved its hydrologic and ecological performance, with good calibrations of long term hydrologic and surface water quality dynamics across most of the Everglades landscape. Using this updated version, we evaluated phosphorus loading throughout the Everglades system under two base scenarios. The 1995 base case assumed current management operations, with phosphorus inflow concentrations fixed at their long term, historical average. The 2050 base case assumed future modifications in water management, with all managed inflows to the Everglades having reduced phosphorus concentrations (due to filtering by constructed wetlands). In an example “indicator” subregion that currently is highly eutrophic, the 31-yr simulations predicted that desirable periphyton and macrophyte communities were maintained under the 2050 base case, whereas in the 1995 base case, periphyton biomass and production decreased to negligible levels and macrophytes became extremely dense. The negative periphyton response in the 1995 base case was due to high phosphorus loads and rapid macrophyte growth that shaded this algal community. Along an existing 11 km eutrophication gradient, the model indicated that the 2050 base case had ecologically significant reductions in phosphorus accumulation compared to the 1995 base case. Indicator regions (in Everglades National Park) distant from phosphorus inflow points also exhibited reductions in phosphorus accumulation under the 2050 base case, albeit to a lesser extent due to its distance from phosphorus inflows. The ELM fills a critical information need in Everglades management, and has become an accepted tool in evaluating scenarios of potential restoration of the natural system. Refinements to the model will enable us to evaluate the full suite of ecological responses to management scenarios throughout the greater Everglades.

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Introduction

The Everglades region of south Florida, USA, is currently a vast system of neo-tropical estuaries, wetlands, and uplands interspersed among agricultural and urban land uses. Starting in the early part of the 20'th century, long stretches of canals were dug in attempts to drain the relatively pristine Everglades for agriculture. However, after severe flooding in 1947, the Central and South Florida (C&SF) Project was initiated. In this massive engineering feat, the U.S. Army Corps of Engineers developed an elaborate network of canals, levees, and water control structures to improve regional flood control and water supply (Light and Dineen 1994). It was ultimately very effective in managing water for those purposes, enhancing the development of urban and agricultural sectors of the region. Dramatic increases in such land uses were seen during that century, significantly reducing the spatial extent of the "natural" Everglades system by the mid 1970's. Agricultural and urban development has generally continued through the present day, particularly along the corridors east and north of the Everglades. While the C&SF Project led to a reduction in spatial extent of the Everglades, it also fragmented the once-continuous Everglades wetlands into a series of large impoundments.

Water historically flowed from the northern parts of the region into and through the Everglades largely as overland sheet flow. This flow regime changed to point releases at the pumps and weirs of water control structures. Operational criteria for these managed flows dictated the timing and magnitude of water distribution into and within the Everglades, further modifying its hydrology. Many of these inflows also carried higher loads of nutrients into the historically oligotrophic Everglades, as a result of agricultural and urban development. The altered distribution and timing of flows in a fragmented watershed, combined with increased nutrient loads into the Everglades, changed this mosaic of habitats. Increasingly, the public and scientific communities were concerned that ecological structure and function would continue to decline within this nationally and internationally protected landscape. In the late 20th century, it became apparent that revisions in the infrastructure and operations of the C&SF Project were necessary in order to halt further ecological degradation, and a plan to restore the Everglades was developed by federal and state agencies (USACE and SFWMD 1998). After years of effort, under a schedule accelerated by approximately two years, the Comprehensive Everglades Restoration Plan (CERP) was developed, and it is starting to be implemented as a thirty year project to address the future of south Florida's ecology – while also enhancing urban and agricultural water supply for what is anticipated to be a doubling of the regional population by 2050.

In the Everglades, the existing management infrastructure bisects the area into a series of impoundments, or Water Conservation Areas (WCAs). Everglades National Park is south of these WCAs, while Big Cypress National Preserve is to the west (Figure 1). Agricultural land uses dominate the area just north of the Everglades, while extensive urban land uses predominate along the eastern boundary of the Everglades. Lake Okeechobee, historically bounding the northern Everglades marshes, is now connected to those marshes via canal routing.

Anthropogenic nutrient enrichment was introduced into the Everglades from management of agricultural, and to a lesser extent, urban runoff. Because of the significant, negative, impacts of this nutrient loading on the naturally oligotrophic system, a series of wetlands is being created along the northern periphery of the Everglades. These Stormwater Treatment Areas (STAs) are intended to serve as natural nutrient filters to remove nutrients (primarily phosphorus) from waters flowing into the Everglades. The first constructed wetlands to be in operation appear to be effective in reducing phosphorus concentrations well below the interim target of 50 $ug \cdot L^{-1}$ (Chimney et al. 2000, Nungesser et al. 2001), and will be supplemented with other phosphorus removal mechanisms to reduce inflow concentrations to the threshold target, anticipated to be 10 $ug \cdot L^{-1}$.

While water historically flowed from the northern Kissimmee River and Lake Okeechobee to the south and somewhat to the east, the managed system enables a variety of flow distributions. Operation of the entire system for flood control, water supply, and the environment is governed by a complex set of rules adopted and modified over time by the South Florida Water Management District and the U.S. Army Corps of Engineers. Control over this system is managed by operating a large number of pumps, weirs, and culverts to pass water into the canals and wetlands, distributing it as needed in various parts of the regional system. Thus, different regions of the Everglades experienced different hydrologic regimes, often to the detriment of the wetland ecosystems. Under the CERP, there will be significant decompartmentalization of the levees impounding parts of the Everglades, increased storage above and below ground, and modified flows throughout the south Florida landscape (USACE and SFWMD 1998).

Changes to the hydrologic and nutrient management under the CERP is anticipated to provide some level of restoration of the Everglades system. However, there is significant uncertainty in the potential ecological response. In order to try to reduce some of this uncertainty, 1) predictive simulation models are being used to refine the plan, and 2) an extensive monitoring and adaptive assessment procedure (CERP_Team 2001) is being implemented. The primary simulation tool used to date is the South Florida Water Management Model (SFWMM), a model with rule based management of water flows and resultant water levels in the entire south Florida region, from Lake Okeechobee to the southern Everglades (Figure 1) (HSM 1999). Most of the Everglades restoration targets were derived from the Natural System Model. This hydrologic companion to the SFWMM is basically the SFWMM with the water management infrastructure removed, adjusting various data to attempt to simulate the regional hydrology prior to any drainage efforts (SFWMD 1998). The Everglades Landscape Model (ELM) is a regional scale, process-oriented simulation tool designed to develop an understanding of the ecological interactions in the greater Everglades landscape. The ELM integrates modules describing the hydrology, biogeochemistry, and biology of ecosystems in a heterogeneous mosaic of habitats that comprise the Everglades.

The ELM has been used as a research tool to better understand the dynamics of the Everglades, enabling hypothesis formulation and testing. This is a critical, ongoing application of the model. However, one of the primary objectives of this simulation project is to evaluate relative ecological performance of alternative management scenarios. The objectives of this chapter are to review the iterative sequence in model development, demonstrate some aspects of its current level of performance through calibration and scenario evaluations, and discuss its current and anticipated application to Everglades restoration plans.

Model Development

Central to the ELM structure is division of the landscape into square grid cells to represent the landscape in digital form. Currently, all of the attributes of a model grid cell are assumed homogeneous in the ELM. Superimposed on this grid are canal/levee vectors that define the hydrologic basins and provide for rapid flow of water through the managed system. Covering the existing Everglades from the Water Conservation Areas (WCAs) to Big Cypress and Everglades National Park (Figure 1), the ELM uses a 1.0 km^2 grid cell resolution over a 10,394 km^2 domain. This model was designed to be explicitly scalable, and has been applied at finer resolution for particular objectives. For the current serial version encompassing the full ELM domain, computational complexity in the hydrologic modules generally constrains us to the 1.0 km^2 grid cell resolution.

In order to capture the general ecosystem dynamics, we explicitly incorporated the processes and feedback interactions among the physical, chemical, and biological dynamics of the system (Fitz et al. 1996). Applying this in a spatial framework, we have been able to make useful predictions on a wide spectrum of ecological dynamics that describe ecosystem function in various habitat types across the landscape. Two critical landscape drivers in the Everglades are hydrology and nutrient dynamics. With appropriate simulation of the physical and biogeochemical dynamics of the Everglades, we have simulated the response by macrophytes and periphyton, including their feedback on the system physics and chemistry. Evolving the landscape through vegetative succession in a simulation depends strongly on these dynamics.

The vertical solution modules of the ecological processes are the most basic building blocks of the model, simulating the temporal dynamics of important biological, chemical, and physical processes within a grid-cell (Fitz et al. 1996). Growth of macrophyte and periphyton communities responded to available nutrients, water, sunlight and temperature. Hydrology in the model responded directly in turn to the vegetation via linkages such as Manning's roughness coefficient and transpiration losses (Fitz and Sklar 1999). Phosphorus cycles included uptake, remineralization, sorption, diffusion, and organic soil loss/gain. Different vegetative habitats have unique parameter values, but all habitats solved the same set of ecological vertical dynamics.

Model structure modifications

We have been continually evaluating and enhancing the ELM since its initial conceptualization and development in the early 1990's (Costanza et al. 1992, Fitz et al. 1993). The original suite of ecological modules have been significantly modified in several major iterations, starting with the spatial implementation in Water Conservation Area 2A (Fitz and Sklar 1999). After evaluation of that model version, we found it necessary to enhance the phosphorus biogeochemical dynamics in order to capture the wide range of behaviors in some of the storages and rates of change. Primary modifications to the codes from version 1.0 to 2.1 involved 1) variable carbon:phosphorus stoichiometry in all modules that track organic matter; 2) the incorporation of a dynamic, highly labile flocculent soil layer; 3) numerous enhancements to increase the efficiency of the program execution. Figure 2 shows these changes in an updated version of the conceptual basis of the General Ecosystem Model (Fitz et al. 1996) within the ELM, indicating the major interactions among the model state variables.

Raster cell surface and groundwater flows were solved using a finite difference, Alternating Direction Explicit (ADE) technique, providing for propagation of water and water-borne constituents (e.g., salt and nutrients) across space. Although another technique is available for propagation of surface water across multiple cells within larger time steps (Voinov et al. 1998), the standard ADE technique was preferable regarding our needs in the incorporation of canal/levee vectors and explicit surface-ground water interactions. Subsurface groundwater (horizontal) flows are critical in particular subregions where hydraulic conductivity values are significantly greater than 10,000 $m \cdot d^{-1}$. In version 2.1, surface and groundwater interactions were calculated within the groundwater module, using an enhanced mass balance approach that evaluated capacities following overland and groundwater flow calculations.

Canals and associated levees were represented by a set of vector objects (Figure 3a) that interact with a specific set of raster landscape cells. This allowed for flux of water and dissolved constituents over long distances (along multiple grid cells) within a time step. Flows through water control structures were driven by daily flow data, using either historical observations (for calibration runs), or output from the SFWMM for management scenarios. Within each canal reach, water and dissolved constituents were distributed homogeneously along the entire reach, with an iterative routine allowing exchange among the grid cells along the canal such that an equilibrium is achieved between rates of exchanges from the grid cells and from the canal reach. For some very long canal reaches, the reach was bisected by "virtual" structures that partition the subreaches, equilibrating their hydraulic heads within one time step. These virtual structures effectively allowed dissolved constituents to exchange with grid cells in the upstream portion of the canals, preventing the instantaneous equilibration of concentration of newly input nutrients or other dissolved constituents along the full length of the canal that would otherwise occur in the absence of such partitioning.

The Spatial Modeling Environment (SME) (Maxwell and Costanza 1995) integrated all of the spatial and non-spatial solutions, and coordinated input/output in the ELM. The SME that we employ is a modification of the earlier (C language) SME v. 2 codes, with the primary changes involving a variety of new input and output routines, the sequencing and integration of the vertical solution modules, user- input options, and other customizations desired for implementation of the ELM. One such modification added to version 2.1 calculated water and phosphorus mass budgets for user-defined regions within the model domain. These modules determined all inputs and outputs for each region, also verifying that no mass balance errors accumulate in these variables.

Spatially explicit data such as habitat type, elevation, and canal vectors are maintained in GIS layers. Other relational databases store time series inputs (e.g., rainfall) and parameters that vary with habitat (e.g., growth rates). The data structure organizes the information and alleviates the need to recompile the model code when evaluating the effects of different management scenarios. This becomes an important characteristic when the model is used across multiple projects at varying scales, and testing a large number of alternatives with short turn-around time for results.

Model inputs

The ELM used SFWMM initialization input data wherever appropriate: 1) the elevation map was interpolated from SFWMM grid cell midpoint data; 2) rainfall was directly input (without rescaling) from the historical daily spatial time series data generated for the SFWMM; 3) saturated hydraulic conductivity was calculated from spatial data on transmissivity and aquifer depth used in the SFWMM, again using an interpolation routine to scale the data to the ELM grid resolution.

Calibration input assumptions

The initial (1979) soil phosphorus (P) concentration, bulk density, and percent organic matter were assumed to be similar in pattern (but not in magnitude) to those observed in the Everglades during the early to mid 1990's (DeBusk et al. 1994, Newman et al. 1997, Stober et al. 1998). The highest soil P concentrations in those studies were found in northeast WCA-2A. Point locations in this area had previously been sampled in 1975, resulting in values of 420-440 mg $P \cdot kg^{-1}$ (Davis 1989). Based on these historical data, we proportionately reduced the mid-1990's soil P data to values between the lowest background concentration and a maximum of 450 mg $P \cdot kg^{-1}$.

Phosphorus concentrations in daily inflows to the ELM domain were available at a frequency on the order of bi-weekly to monthly. To fill in missing data for the required daily concentrations, a linear interpolation method was used (Walker *pers. comm.*). Concentrations in flows internal to the ELM domain were calculated by the model. We assigned rainfall to have a concentration of 20 mg/L, resulting in total annual atmospheric deposition that was generally on the order of 27 mg $P \cdot m^{-2} \cdot yr^{-1}$.

Scenario input assumptions

There are two basic scenario conditions that we evaluated. The “1995 base”, (or current base), represents water management infrastructure and operations that are currently used. The “2050 base” (or future base), simulates water management that is planned to be operational in the future. These base case scenarios were designed to predict how the regional system would have responded, under the observed 1965-95 climate, to the proposed management operations. The base simulations incorporated numerous hydrologic assumptions on the structures and operations of the managed system (USACE and SFWMD 1998). All managed flows through water control structures in the ELM were driven by daily output data from these SFWMM (v.3.5) 1995 base and 2050 base runs (USACE and SFWMD 1998).

The Stormwater Treatment Areas (STAs) that are being constructed in the northern part of the Everglades were designed to improve water quality of the inflows into the Everglades. Figure 3b shows the location of the STAs, and a generalized schematic of the nature of the flows within the managed system. The objective of the scenario simulations was to compare how the system would have potentially responded with and without STAs starting in 1965, initializing the model with relatively oligotrophic soils and vegetative biomass.

In simulating the long term response of the landscape to reduced phosphorus inflows from STAs, we made a variety of ecological assumptions. In our 1995 base, water flows through boundary inflow structures were assigned P concentrations at the fixed, long term observed (1979-95) mean, which varied among the different structures from 10.8 to 170 $ug \cdot L^{-1}$. For the 2050 base, the STAs were assumed to remove phosphorus at varying efficiencies. A fixed concentration of 50 $ug \cdot L^{-1}$ was applied to all boundary inflows in the 2050 base, 50 $ug \cdot L^{-1}$ scenario. Similarly, a concentration of 10 $ug \cdot L^{-1}$ was applied to all boundary inflows in 2050 base, 10 $ug \cdot L^{-1}$ scenario.

Model Calibration

Development and refinement of a landscape model at this level of complexity is far from a one-step procedure. Some of the first steps in ELM development and refinement involved the unit, or non-spatial, model component of the simulation system. Significant efforts were made to determine the appropriate levels of algorithm aggregation, including and omitting particular ecological modules or algorithms as development proceeded. A large concern was, and continues to be, the optimization of the model algorithms to a) capture the targeted, fundamental ecosystem responses, while b) avoiding algorithm extension (too far) beyond existing ecological knowledge (i.e., data). The resulting General Ecosystem Model (Fitz et al. 1996) may be applied to a variety of ecosystem types. As this fundamental building block became better refined and demonstrated appropriate ecosystem dynamics for varying habitat types, we focused on integration of the non-spatial and the spatial modules. While it is generally necessary to work within a spatial framework to fully evaluate and calibrate the ELM, we continue to maintain an independent unit model for algorithm development/testing and parameter optimization.

In the early implementations of the ELM, we were able to approximate some of the fundamental ecosystem dynamics across the Everglades landscape. The model simulated short term (several year) water depths and surface water phosphorus concentrations, showing that the spatial pattern was reasonable compared to general observations (Fitz et al. 1995a). Moreover, dynamics of other modules, such as live macrophytes, responded appropriately to changing conditions and stayed within reasonable dynamic ranges. This “ballpark”, or “Level 1”, calibration was primarily useful in demonstrating the potential utility of the model – and in defining avenues for model enhancement.

In parallel with the full ELM testing, we implemented the ELM code in a smaller subregion of the Everglades, primarily as a tool for facilitating model understanding. This Conservation Area Landscape Model (CALM) had less complexity in habitat distributions and simpler water management infrastructure relative to the full ELM, and we were better able to discern the spatially explicit ecological interactions. At this point, we performed rigorous sensitivity analysis on the modeling system, employing three levels of spatial complexity: 1) the unit model; 2) the CALM, with two encoded habitat types and little internal water management infrastructure; and 3) the ELM, with (at that time) eleven habitat types and a complex water management infrastructure. That analysis (Fitz et al. 1995b) allowed us to investigate a large number of parameter sensitivities at the ecosystem level, then progressively evaluate their influence in the landscape(s) as spatial complexity increased. There were a number of parameters, such as plant phosphorus uptake rates and antecedent soil nutrient concentrations, that had relatively high uncertainty but significant effects on results at the unit model and landscape scales. With an improved understanding of the weaknesses of the model and supporting data, the next steps were to utilize more data observations and enhance the model algorithms to improve model performance.

During this development, field and mesocosm research had been progressing to the point where significantly more information was accumulating on Everglades system dynamics. In particular, the Phosphorus Threshold Program, incorporating ecosystem process experiments and synoptic measurements along an existing phosphorus gradient in Water Conservation Area 2A (WCA-2A), lead to improved simulations of phosphorus cycling in the ELM. Model development at this point centered on enhancements to better simulate the ecological responses to the observed nutrient gradient in WCA-2A (Figure 4). Though this is one “small” (433 km^2) subregion of the Everglades, many ecological processes can be generalized across much of the Everglades. This is an important assumption that we are evaluating as data from other Everglades subregions are becoming available. While we fully recognize distinctions within the Everglades, the CALM has proved to be applicable, with some limitations, to other areas. WCA-2A may be considered representative of many Everglades habitats in some critical respects. For example, sawgrass will respond similarly to environmental changes in water depths or nutrient loads in WCA-2A compared to other areas with similar antecedent conditions. Similarly, soils in WCA-2A will respond to drying in the same way in other regions with similar antecedent conditions. Of particular value is the distinct gradient in eutrophication within WCA-2A, allowing us to refine the model to capture changes in ecological responses along this gradient.

Version 1.0

We evaluated the performance of the WCA-2A model implementation (i.e., CALM) with respect to water stage, surface- and pore- water phosphorus (P), peat accumulation, macrophyte & periphyton biomass, and macrophyte and periphyton succession. In general, the model was able to capture the critical changes in these variables when compared to available observations (Fitz and Sklar 1999). Captured by the relatively fine-scale (0.25 km^2) grid of this model is the ridge and slough heterogeneity along the general north-south elevation gradient. Deeper sloughs are interspersed with elevated ridges, while elevation slowly decreases about 1.5 m across the landscape. Figure 5a shows the hydrologic model response to these features, with ponded surface water depth and hydroperiod (or days per year having positive ponding depth) following the ridge and slough topography and increasing down the north-south topographic gradient.

The WCA-2A eutrophication gradient downstream of the S-10 structures (Figure 4) was very evident in the simulation results. There were high levels of surface water phosphorus, porewater phosphorus, and microbial activity (soil decomposition) near the inflow region, decreasing significantly toward the interior of WCA-2A (Figure 5b). Soil decomposition from microbial activity responded positively to the downstream P transport (and thus increased soil P availability) from the S-10 inflows. Also evident was the increased soil mineralization in areas of shorter hydroperiods along some of the higher elevation ridges and in the northern section of the impoundment.

Macrophytes increased dramatically in response to elevated porewater soil P in the upper portion of the eutrophication gradient (Figure 5c). The model also simulated increased macrophyte biomass as a result of elevated soil P along some of the ridges (as a result of increased mineralization of organic P). The oligotrophic periphyton community in the model was, as observed in nature, generally distributed throughout much of the region, but at lower densities in upper elevations and ridges as a result of shorter hydroperiods compared to areas of lower local elevation. In a contrary response relative to macrophytes, this periphyton community decreased in biomass in the upper zone of the nutrient gradient. As observed in the field (McCormick and O'Dell 1996), the simulated periphyton community responded negatively to higher surface water P, while macrophyte shading reduced light availability and also significantly constrained its growth.

Using a 17 yr period of record of water stages at one gauge in central WCA-2A, we were able to closely approximate the observed water levels that varied dramatically across a time period of extreme drought and extreme rainfall (Fitz and Sklar 1999). Ecologically, the changes along the nutrient gradient were comparable to the observed data that were available for the later part of the simulation period (1995-96). Although there was substantial variation in observed data, the model and observed data indicated a similar decrease in surface water P concentration with increasing distance from the canal with the S-10 inflow structures (Figure 6a). A steep decline in porewater P was similar in magnitude to that which was observed (Newman *pers. comm.*), declining to near-background concentrations after more than 6 km downstream (Figure 6b). The simulated decline in the rate of peat accretion (Figure 6c) along the gradient was similar to the long term, Cesium-137 accretion data of Reddy et al. (1993) and Craft and Richardson (1993). Finally, biomass of sawgrass and cattail macrophyte communities decreased as distance from the canal increased (Figure 6d), with the magnitude of the changes similar to observed data (Miao and Sklar 1998).

Succession of macrophytic vegetation is another critical landscape dynamic that we desire to capture with adequate realism. While there are a variety of processes that drive succession, a primary driver of transitions of sawgrass to cattail is that of elevated soil nutrients. The model was able to match the observed (Reddy et al. 1991) pattern and magnitude of porewater P in WCA-2A, showing a pattern of high concentration adjacent to the S-10 inflow structures, in addition to an elevated mineralization response to shorter hydroperiods and higher concentrations in the ridge habitats further downstream (Figure 7a). Largely responding to this increased available phosphorus, macrophyte communities shifted from sawgrass to cattail during the 17 yr simulation (Figure 7b and c). Simulated cattail cover increased from 44 km^2 in 1991 to 117 km^2 in 1995, compared to observations of 53 and 95 km^2, respectively (Rutchey and Vilchek 1999).

Version 2.1

While the version 1.0 model dynamics captured many of the patterns and general magnitudes of the critical ecosystem dynamics, it was desirable to enhance some of the model capabilities. While we have not fully evaluated and calibrated all of the ecological dynamics across the entire region, their dynamics were improved over the previous version, and we have sufficiently calibrated the hydrology and surface water quality (with respect to total phosphorus) for useful model application throughout the ELM domain. In this section, we review a subset of the calibration analyses for hydrology and surface water quality. Other data on this current (v. 2.1, May 2001) calibration are archived in the Model Results section at the ELM web site (Fitz 2001).

Hydrology

It was necessary to ensure that the ELM hydrology was comparable to field observations and SFWMM output. Thus, we compared the ELM simulated stages to those observed in the field and to those simulated by the SFWMM. We used over 40 stage monitoring gages located throughout the Everglades landscape for the ELM calibration run (Figure 8a), comparing model to observed daily stage data every 7 days. The 17 yr period of record for this simulation spanned periods of extreme rainfall (1994-95) and extreme drought (1989-90). A regression analysis of goodness of fit of the ELM output to observed stage data for each gage had an R^2 value that averaged 0.65 for all stations, with an average Root Mean Square Error of 15 cm. Two stage hydrographs with statistically low correlations (R^2 approximately 0.5) are shown in Figure 9. The NP-206 gage is in the short hydroperiod, marl prairie habitat of Everglades National Park, while the NP-36 gage is a dozen miles to the west in Shark River Slough, a long hydroperiod slough habitat. Despite the relatively low R^2 in these examples, observed and simulated water stages fluctuated very similarly. Since a very substantial proportion of the time series was well-matched by the models, it appeared that the ELM and the SFWMM performed effectively in both of these different hydrologic regimes. Both models had a generally similar pattern when they mis-predicted several of the extreme drydown events recorded at the gaging stations, even though other drydown events of similar magnitude were well- predicted by the models.

We compared ELM and SFWMM hydrologic budgets for major basins, evaluating the degree to which surface and subsurface inputs and outputs were consistent between the models. The hydrologic budgets that quantify all of the inflows and outflows associated with major hydrologic basins (such as impounded Water Conservation Areas) provided a useful hydrologic check. Because of significant scale differences between the models, (with the ELM being 10x finer in grid resolution), there were basin- surface area differences between the models when partitioning the irregular basins. To better normalize some of these scale differences, the flows were expressed as a height across each model's basin. The 30-day mean flows, on an annual basis, for WCA-3A were generally on the order of less than 1 cm different between models (Figure 10), representing a reasonable degree of concordance. Note that even though the two models used the same rainfall inputs, there were some differences in the rainfall budgets (as much as 0.84 cm), which are due to the somewhat different surface coverages of the models' basin definitions. The discrepancy in surface water outflow (through the gap in the western levee of WCA-3A) was indicative that ELM calculated somewhat higher flows in 1994 and 1995. Budget comparisons for five other major basins were archived at the ELM web site.

Water Quality

Surface water transport and fate of phosphorus is driven, in the model and in the Everglades, by both hydrologic flows and ecological responses. While we have not fully evaluated and calibrated all ecological variables in the range of soils and habitats throughout the Everglades, their responses have shown improvement over those of ELM version 1.0. We used over 40 monitoring locations located throughout the Everglades landscape for the ELM surface water quality calibration (Figure 8b), comparing model 30-day means to observed monthly mean observations where available, (although there were generally no more than 2 observations per month). The model captured the general trends of decreasing concentrations from the northern to the southern Everglades (Figure 11). Surface water total phosphorus observations averaged 40 ± 38 (SD) $ug \cdot L^{-1}$ at the S-11 structures in the northern part of the system, with a lower mean of 17 ± 20 $ug \cdot L^{-1}$ at the S-12 structures flowing into Everglades National Park. The model predicted 30 ± 29 ug·L^{-1} at the S-11 sites, with a mean of 13 ± 13 ug·L^{-1} at the S-12 sites. The model was generally able to capture short term increases and decreases in P concentration, staying within appropriate ranges of concentrations as the P concentration fluctuated dynamically. For example, at the S-11 site, concentrations were on the order of 100 ug·L^{-1} in mid- 1985, decreasing to less than 25 ug·L^{-1} in the latter part of the year. This dynamic was captured in the simulation. Likewise, an observed spike to approximately 200 ug·L^{-1} in mid 1986 was predicted by the model at that site. Concentrations at the S-12 sites had few excursions above the 10-20 ug·L^{-1} range, but the large peak to >100 ug·L^{-1} in mid 1985, and prolonged excursions up to 40-50 ug·L^{-1} in 1989 and 1990, were captured reasonably well by the model. As with the hydrologic calibration, other comparisons of model to observations are archived in the ELM web site.

The distribution of simulated surface water quality across the landscape is shown in Figure 12, highlighting the major zones of P input in the northern Everglades. Relatively high concentrations of phosphorus were distributed along the canal system, with overland flow across the marsh attenuating the concentration as the soils and vegetation sequestered the nutrients. While the region south of the Water Conservation Areas in Everglades National Park was relatively low in concentration compared to many of the regions in the north, there were relatively broad regions with somewhat high P levels. This may be explained by the fact that these areas (alongside the Shark River Slough which runs northeast to southwest) are comparatively high in land elevation, and their shorter hydroperiods resulted in increased soil mineralization. Because of the lack of adequate topography and hydrography in the southwest mangrove region (outside of the domain of the SFWMM, Figure 1), it is not adequately captured in current model dynamics.

Model Application

In this application of ELM, we evaluated landscape phosphorus dynamics with and without the STAs. The scenario simulations reflected the system responses had it been managed differently during the 1965-1995 climate years. The 1995 base, assuming "current" operations, without treatment of inflow waters by STAs, demonstrated eutrophication in the Everglades that would have occurred in the absence of these biological filters for the inflow waters. The 2050 (future) base was driven by altered water management, with the STA's in place in order to remove significant phosphorus mass from surface inflows to the Everglades. In an indicator region immediately (0-2 km) south of the S-10 inflow structures of WCA-2A, the ELM showed macrophyte biomass increasing from 1965 through the end of the simulation in 1995. Accelerated P uptake was indicative of this growth, which became much greater than that of the 2050 base in the 1980's and 1990's (Figure 13a). Due to the deleterious combined effects of high surface water P concentrations and increased macrophyte shading, oligotrophic periphyton productivity was lower in the 1995 base compared to the 2050 base with 10 ug·L^{-1} phosphorus concentrations in inflow waters (Figure 13b). Early in the simulation, this periphyton community existed in this region under 1995 base conditions, but at lower productivity levels than those of the 2050 base. As macrophyte productivity and biomass increased in the 1995 base, the periphyton was increasingly shaded and effectively disappeared. Productivity continued to respond dynamically to changes in low level nutrient inputs and water levels in the 2050 base.

The response of the biological communities varied along nutrient gradients, depending on the nutrient loads in the simulations and on the proximity of the areas to the phosphorus inflows. We compared the 1995 base with two implementations of the 2050 base: one with 10 ug P·L^{-1} and one with 50 ug P·L^{-1} in the inflow waters. We analyzed two example gradient regions, circled in Figure 8. The indicator regions in WCA-2A south of the S-10 structures are in relatively close proximity to anthropogenic nutrient loading, while the indicator regions in Everglades National Park (ENP) south of the S-12 structures are more indirectly affected by P loading in the northern part of the system. The 31-yr mean and maximum P concentrations in the surface water declined steeply with distance from the inflows in the 1995 base simulation in the WCA-2A region, while there was less change down-gradient in ENP (Figure 14a). Neither 2050 base case demonstrated a significant change in mean concentrations along either spatial gradient, although the maximum monthly mean concentrations declined along the gradient in the 2050, 50 $ug \cdot L^{-1}$ case in WCA-2A. The magnitude of that difference was relatively small. In all of the cases, the 1995 base showed substantially higher P concentrations relative to the 2050 base cases. In these particular indicator regions, both 2050 base cases resulted in approximately background, oligotrophic, surface water concentrations on the order of 5 $ug\ P \cdot L^{-1}$.

Phosphorus accumulation in the soils and biota within the indicator regions generally reflected the pattern of surface water concentrations, showing similar trends along spatial gradients in the scenarios (Figure 14b). However, the phosphorus accumulation (and loads) provided indications of eutrophication that were somewhat obscured in the long term mean surface water concentrations. The furthest downstream (U3) region in WCA-2A, considered by some to be relatively unimpacted from significant anthropogenic nutrients, accumulated more P than the gradient regions to the south in the ENP. Relative to the ~27 $mg\ P \cdot m^{-2} \cdot y^{-1}$ being input to the system from atmospheric sources, all of the indicator regions were impacted by overland P loads in the 1995 base. Only when inflow concentrations were reduced to 10 $ug\ P \cdot L^{-1}$ (2050 base, 10 $ug\ P \cdot L^{-1}$) did the total net accumulation in all indicator regions approximate that from atmospheric inputs alone.

Discussion

The development of the ELM involved an iterative procedure of evaluating the model's performance at various scales and for different submodule objectives. Some of the earliest applications demonstrated that the model simulated general spatial patterns of ecological processes in a reasonable manner, demonstrating the applicability of the general concept of the model algorithms. The fundamental structure of the ELM remains very similar to that in its early development. However, some simplifications were made to some modules, while complexity was increased in other parts of the model. In balance, the model has increased slightly in complexity, but also has undergone a significant increase in computational efficiency (with ~12 hr runtimes for 31 yr simulations on a high end unix workstation). We are designing a variety of further enhancements which will somewhat increase model complexity, but are being considered in order to increase our ability to address research and management questions with better realism. These anticipated modifications include multiple grid resolutions and enhanced vegetative succession algorithms in order to best capture changing habitat distributions within the Everglades.

A simpler model has been developed that simulates the surface water phosphorus concentrations in response to changing flows in the Everglades (Raghunathan et al. 2001). This model used hydrologic flows and depths from the SFWMM, with phosphorus being introduced to the system at the boundaries, and lost from the simulated system by a net phosphorus settling equation and by surface flows out of the domain. The net settling rate was considered homogenous within hydrologic basins (e.g., WCAs), and used a single parameter that is a calibrated, statistical representation of the physical settling, plant uptake, and all of the other ecological processes affecting phosphorus in surface water. No release from the soils was explicitly considered, such as increased soil oxidation under reduced hydroperiods. The model was calibrated at a basin-level scale for some areas, but was unable to be adequately calibrated for some large basins such as WCA-3A (Raghunathan et al. 2001). Nevertheless, it provided a means to provide some estimate of phosphorus flows using the calibrated SFWMM hydrology.

Another relatively simple landscape model of the Everglades employed a transition probability approach to estimating the spread of cattail in WCA-2A (Wu et al. 1997). Dynamic hydrologic changes were not considered, but the model proved effective in simulating the cattail spatial distributions in response to changing soil phosphorus from 1973 to 1991. With phosphorus loads and accretion assumed constant in time, the mechanisms of phosphorus transport and plant/soil interactions were not considered, and it has subsequently been found to have overestimated cattail spread by 2000. A primary value of the model was its suggestion of a numeric value for soil phosphorus that was correlated to the transition from sawgrass to cattail habitats, and in particular the analysis of the subsequent patterns of habitat fragmentation.

With its focus on ecosystem dynamics within the greater Everglades, the ELM explicitly incorporated feedbacks among hydrology and the other ecological processes that define the landscape. The ELM assumed that there are important ecosystem interactions that affect the system dynamics, using simple process-based algorithms that described soil and vegetation responses to dynamic environmental conditions. The power of this process-based approach should be apparent when one considers that Everglades restoration initiatives embark upon entirely new suites of environmental regimes in particular regions, which more statistically-based models would be unable to accommodate as they rely upon the continuity of historically observed conditions.

In the ELM's first application (Fitz and Sklar 1999), we demonstrated realistic calibration of the model's dynamics across the landscape over decadal time scales. One of the strengths of this model has been the ability to evaluate interactions among the ecological processes. While Figure 5 is a static indicator of some of these interactions, it provides evidence of the cumulative and integrated effects of hydrology and nutrient loading on soil and plant attributes. Also important were the interaction among biological communities such as periphyton and macrophytes. The oligotrophic, or calcareous, periphyton community type responds negatively (in the model and in nature) to elevated phosphorus concentrations (McCormick and O'Dell 1996). Periphyton serve to sequester phosphorus at short time scales, while the macrophyte community takes up phosphorus (primarily from soil pore water) and was observed to increase in biomass in zones of general eutrophication. One aspect of lowered periphyton biomass was the shading of light by macrophytes, accentuating the local reduction of periphyton biomass. While many of the landscape variables in version 1.0 were found to be calibrated reasonably well, version 2.1 enhanced the model capabilities through a wider range of behaviors.

Using ELM v. 2.1, we evaluated the calibration of two of the most important landscape drivers in this managed wetland system - hydrology and water quality. As determined from correlations between model and observed data at more than 40 locations, the model's hydrologic performance appeared to be suitable for applications throughout the greater Everglades. Surface water quality output likewise demonstrated good matches to observed data over decadal time scales and widely varying environmental inputs, such that we could apply the ELM to evaluate scenarios of changes in surface water quality in response to management changes.

The ELM v.2.1 demonstrated that reduced nutrient concentrations entering the Everglades will be manifested in generally lower P accumulation and ecological responses in a spatially varying manner. The area of currently-impacted regions may (arguably) be considered to be comparatively small relative to the entire regional extent: Figure 12 shows the simulated long term historical mean distribution of phosphorus in surface water throughout the region, with the highest nutrient concentrations distributed along canals and discharge points in the managed system. Areas with reduced hydroperiods also had slightly higher concentrations than those of background or oligotrophic areas, but some of that signal is actually a concentration effect of very shallow water depths. Because of the potential for rapid sequestering (and recycling) of phosphorus introduced into surface waters, analysis of concentration changes over time is not wholly definitive of an area's nutrient status. Beyond merely concentration, phosphorus loading or net phosphorus accumulation are informative metrics to evaluate the trophic status of any area (indicator region) within the system.

When we evaluated the P accumulation along existing (or potential) gradients of eutrophication in the model scenarios, we were able to discern the subtle, but critical, aspects of the altered phosphorus dynamics when loading to the Everglades was reduced via STA treatment. However, managers have not yet conclusively developed methodologies (Chimney et al. 2000, Nungesser et al. 2001) to reduce phosphorus down to 10 ug $\cdot L^{-1}$ concentrations at the outflow points in these constructed wetlands. Several scenarios of varying phosphorus load reductions were evaluated, with simulations that demonstrated the (expected) decreases in phosphorus concentrations as distance from inflow points increased. While concentrations in the surface water were indicative of the phosphorus loading, they were not necessarily a reflection of the magnitude of the eutrophic status of a region. Of interest in this regard was the U3 station in the middle of WCA-2A, which had low long-term mean P concentration, but exhibited indications of slight eutrophication under the 1995 base scenario (Figure 14a and 14b). This area has generally been considered to be an oligotrophic "reference" site (McCormick and O'Dell 1996) due to low background P concentrations. However, compared to areas much further removed from the canal discharges and elevated nutrient loads, P accumulation at the U3 site was high enough (>60 mg $P\cdot m^{-2}\cdot y^{-1}$) in the 1995 base scenario to potentially cause some level of ecological change. Daoust (1998) found responses by macrophyte communities to loading rates as low as 40 mg $P\cdot m^{-2}\cdot y^{-1}$. Only the model scenario with 10 ug $P\cdot L^{-1}$ STA outflow concentrations (2050 base case) resulted in P accumulation rates that were indicative of near-background conditions in all of the selected indicator regions.

The ELM provides a tool to help determine the spatial extent of impacts from altered inflows to the Everglades. While the regions analyzed for this discussion are just a few examples within the model domain, management implications of these results are significant. As restoration plans are formulated, we will be evaluating the spatial distribution and magnitude of the reductions in phosphorus flow and loads throughout the system, and providing the results in a readily available format on our web site. This will enable us to inform managers of areas with higher probabilities of phosphorus impacts under various scenarios of altered phosphorus inflow concentrations and flow distributions through the landscape. While reductions in inflow phosphorus concentrations to ca. 50 ug $P\cdot L^{-1}$ will reduce the levels of eutrophication in large areas of the system, it was evident from the simulations that further reductions will be necessary to achieve the goal of halting further ecological impacts from continued phosphorus pollution.

The current level of refinement and calibration of the ELM is such that we have focused primarily on the important water quality and hydrology landscape drivers. However, as in the earlier implementation of the model (in WCA-2A), our overall objectives involve understanding the full spectrum of ecosystem dynamics as management and environmental inputs change. Currently, many of the ecological dynamics are well-simulated within most of the system, but some of the uncertainties associated with soil and habitat responses to these drivers need better characterization and analysis. The existing model algorithms and the data structure used in the ELM appear adequate to capture most of these dynamics, and we are working with recently obtained data on landscape attributes in order to develop a final calibration for this version of ELM. As CERP projects proceed in the coming years, results posted on the ELM web site (Fitz 2001) should assist in evaluating the ecological responses of the Everglades to revised restoration alternatives.

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Figures

Figure 1. Major regions in South Florida and the domains of the Everglades Landscape Model (ELM) and the South Florida Water Management Model (SFWMM).

Figure 2. The conceptual model of the Everglades Landscape Model. State variables are in oval boxes, linked by the major flow pathways among those variables. Abbreviations: P = Phosphorus; C = Carbon; OM = Organic Matter; Photo-Bio = Photosynthetic Biomass of macrophytes; NonPhoto-Bio = NonPhotosynthetic Biomass of macrophytes; Standing Detr. = Standing dead Detritus; Floc = Flocculent layer on/above soil.

Figure 3. a. Water control structure locations and canal reach segments in the ELM, with the latter coded numerically for model implementation. b. Generalized schematic of the major flow directions associated with the infrastructure of the managed system. Stormwater Treatment Areas (STAs) are indicated in shaded polygons.

Figure 4. Observed soil phosphorus gradients in 1991 (DeBusk et al. 1994), sampling sites along one gradient, and water control structure flows in Water Conservation Area 2A (WCA-2A).

Figure 5. Spatial relationships of model responses in WCA-2A (calibration run, version 1.0). Model outputs are snapshots of 1-month mean attributes after 10 years of simulation.

Figure 6. Model (version 1.0) calibration results along the WCA-2A eutrophication gradient downstream of the canal and S-10 structures (shown in Figure 4): a) surface water phosphorus concentration; b) porewater phosphorus concentration; c) peat soil accretion; d) macrophyte biomass. Observed and model data encompass the 1994-1996 period.

Figure 7. Model (version 1.0) calibration results of a) porewater phosphorus in 1991; b) sawgrass & cattail distribution in 1991; c) sawgrass & cattail distribution in 1995.

Figure 8. Shaded polygons of indicator regions, and point locations in the Everglades for monitoring a) stage; b) water quality. Circled indicator regions are used in example analyses of model scenario runs.

Figure 9. Model (version 2.1) calibration results for hydrology, showing simulated ELM, simulated SFWMM, and observed stage heights at the a) NP-206 gage, and b) NP-36 gage. Calibration results for other locations (and other ecological variables) are archived at http://www.sfwmd.gov/org/erd/esr/elm.html

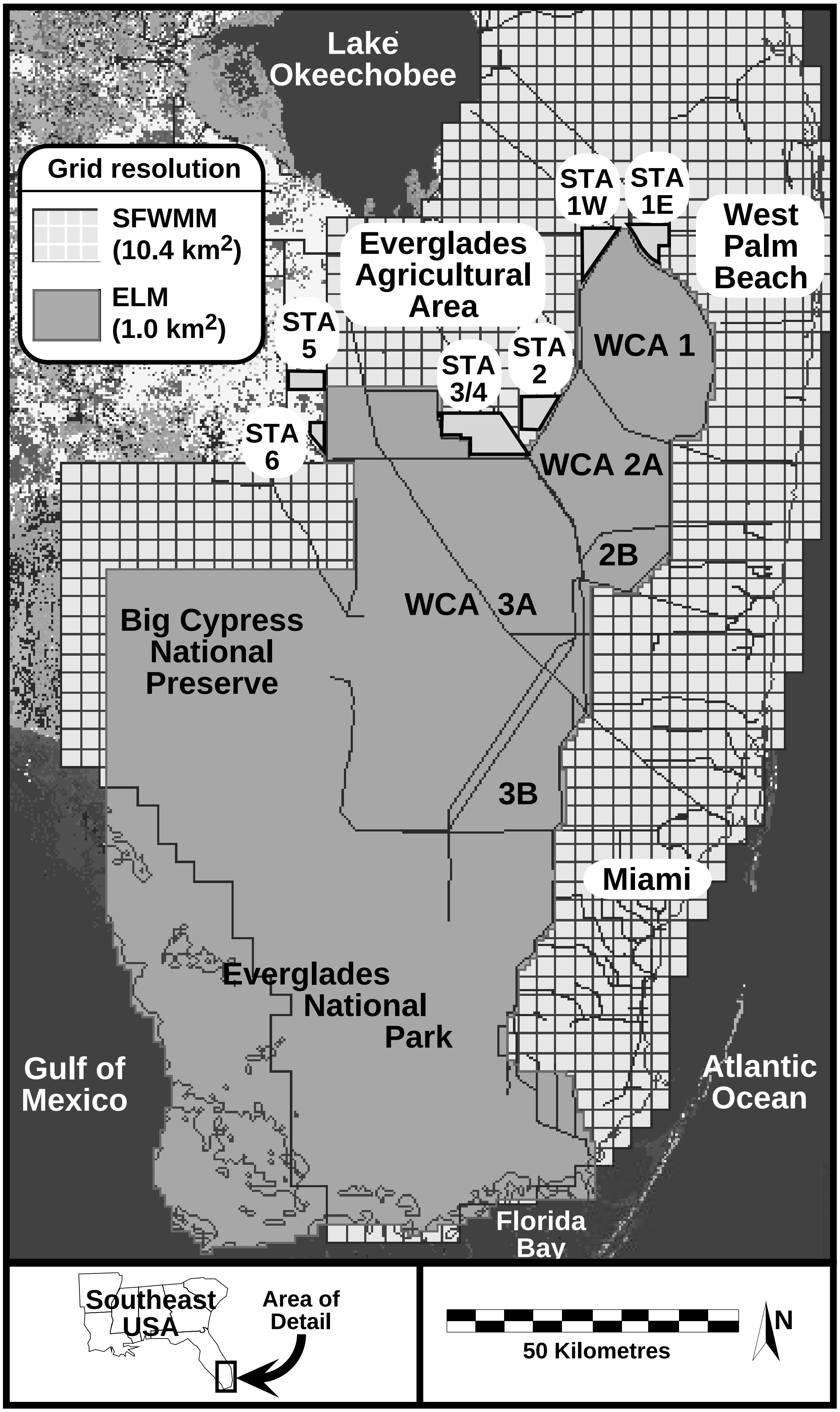
Figure 10. Model (version 2.1) calibration results for hydrology, showing the flow differences between the ELM and SFWMM simulations in the WCA-3A basin (1979-1995).

Figure 11. Model (version 2.1) calibration results for Total Phosphorus (TP) concentration in surface water, showing simulated and observed monthly mean concentrations at the a) S-11 structures, and b) S-12 structures (Figure 8b).

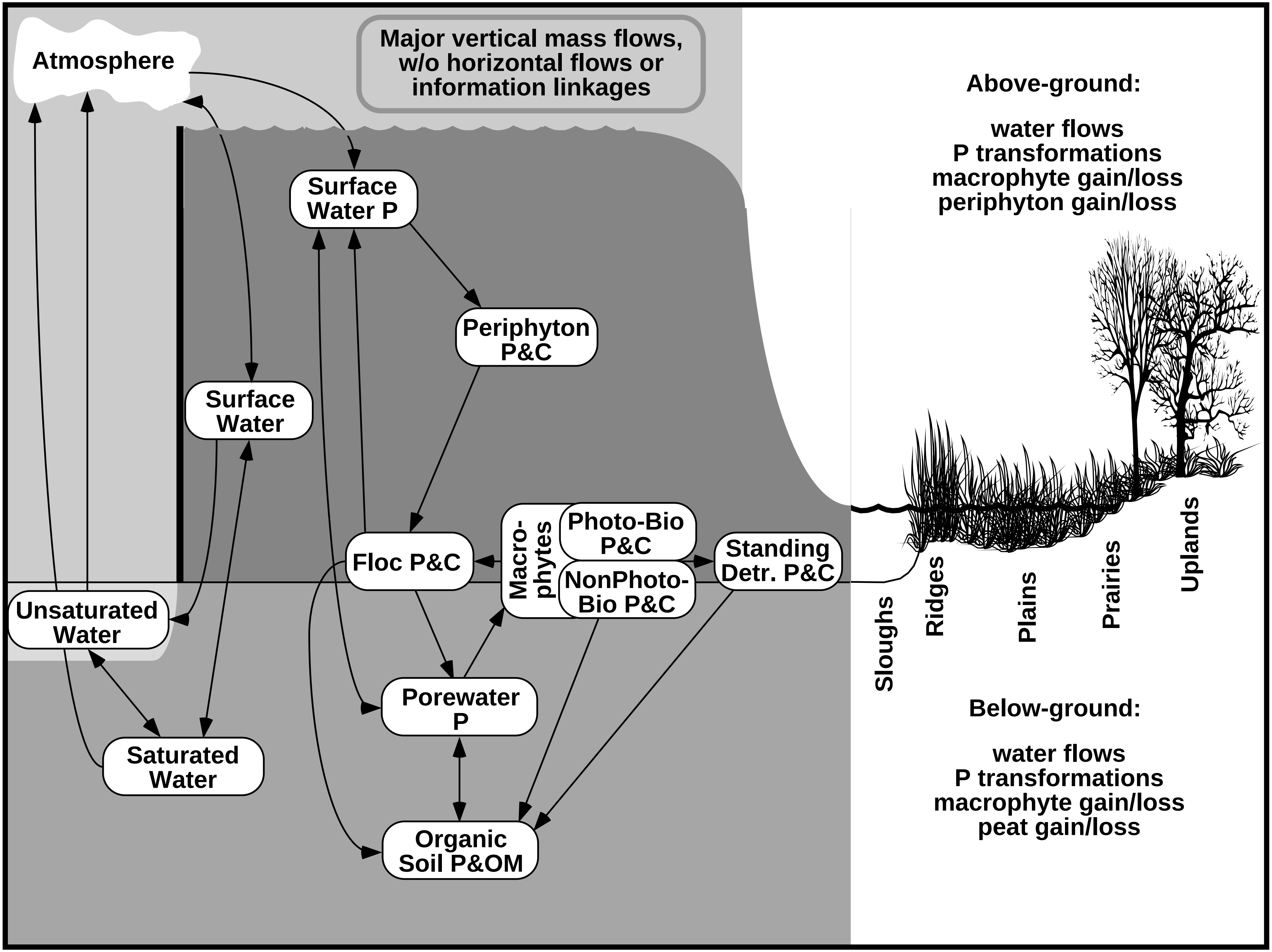
Figure 12. Model (version 2.1) calibration results for Total Phosphorus (TP) concentration in surface water, showing the 17-yr means distributed across the landscape.

Figure 13. Model (version 2.1) scenario results in the indicator region immediately downstream of the S-10 structures in WCA-2A: a) monthly mean phosphorus uptake rate by the oligotrophic periphyton community; b) monthly mean phosphorus uptake rate by all macrophytes in the indicator region.

Figure 14. Model (version 2.1) scenario results in the gradients of indicator regions in WCA-2A and in ENP: a) 31-yr mean and maximum concentration of Total Phosphorus (TP) in surface water; and b) 31-yr accumulation of TP in soils and biota (with atmospheric phosphorus loading indicated for comparison).



Lake Okeechobee
Grid resolution
SFWMM (10.4 km2)
ELM (1.0 km2)
STA 1W
STA 1E
West Palm Beach
Everglades Agricultural Area
STA 5
STA 3/4
STA 2
WCA 1
STA 6
WCA 2A
2B
WCA 3A
Big Cypress National Preserve
3B
Miami
Everglades National Park
Gulf of Mexico
Atlantic Ocean
Florida Bay
Southeast USA
Area of Detail
50 Kilometres
N



Major vertical mass flows, w/o horizontal flows or information linkages
Atmosphere
Surface Water P
Periphyton P&C
Surface Water
Floc P&C
Macro-phytes
Photo-Bio P&C
NonPhoto-Bio P&C
Standing Detr. P&C
Unsaturated Water
Saturated Water
Porewater P
Organic Soil P&OM
Above-ground:
water flows
P transformations
macrophyte gain/loss
periphyton gain/loss
Sloughs
Ridges
Plains
Prairies
Uplands
Below-ground:
water flows
P transformations
macrophyte gain/loss
peat gain/loss

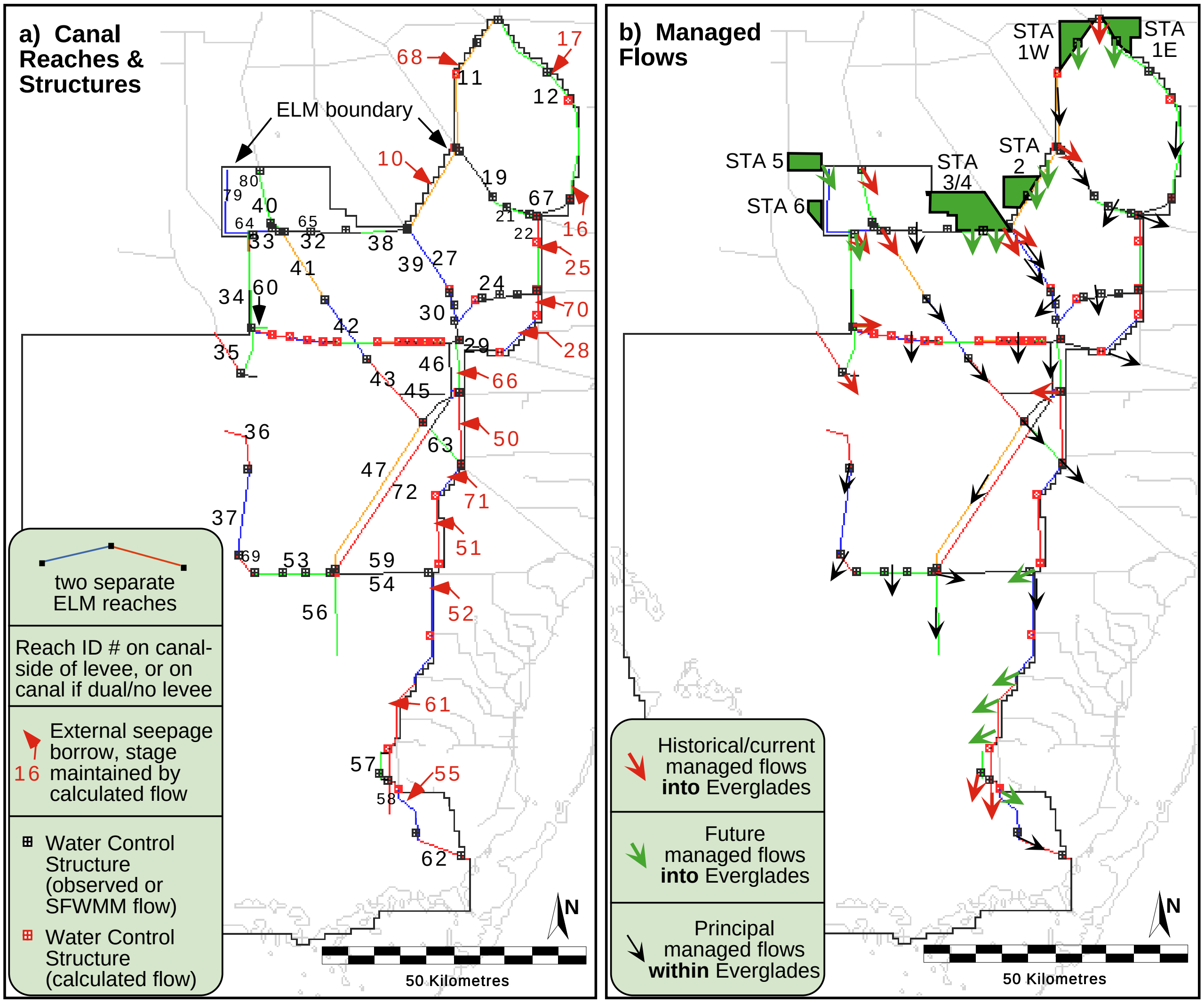

a) Canal Reaches & Structures
ELM boundary
two separate ELM reaches
Reach ID # on canal-side of levee, or on canal if dual/no levee
External seepage borrow, stage maintained by calculated flow
Water Control Structure (observed or SFWMM flow)
Water Control Structure (calculated flow)
50 Kilometres
N
b) Managed Flows
STA 1W
STA 1E
STA 2
STA 3/4
STA 5
STA 6
Historical/current managed flows **into** Everglades
Future managed flows **into** Everglades
Principal managed flows **within** Everglades
50 Kilometres
N

Fig. 3

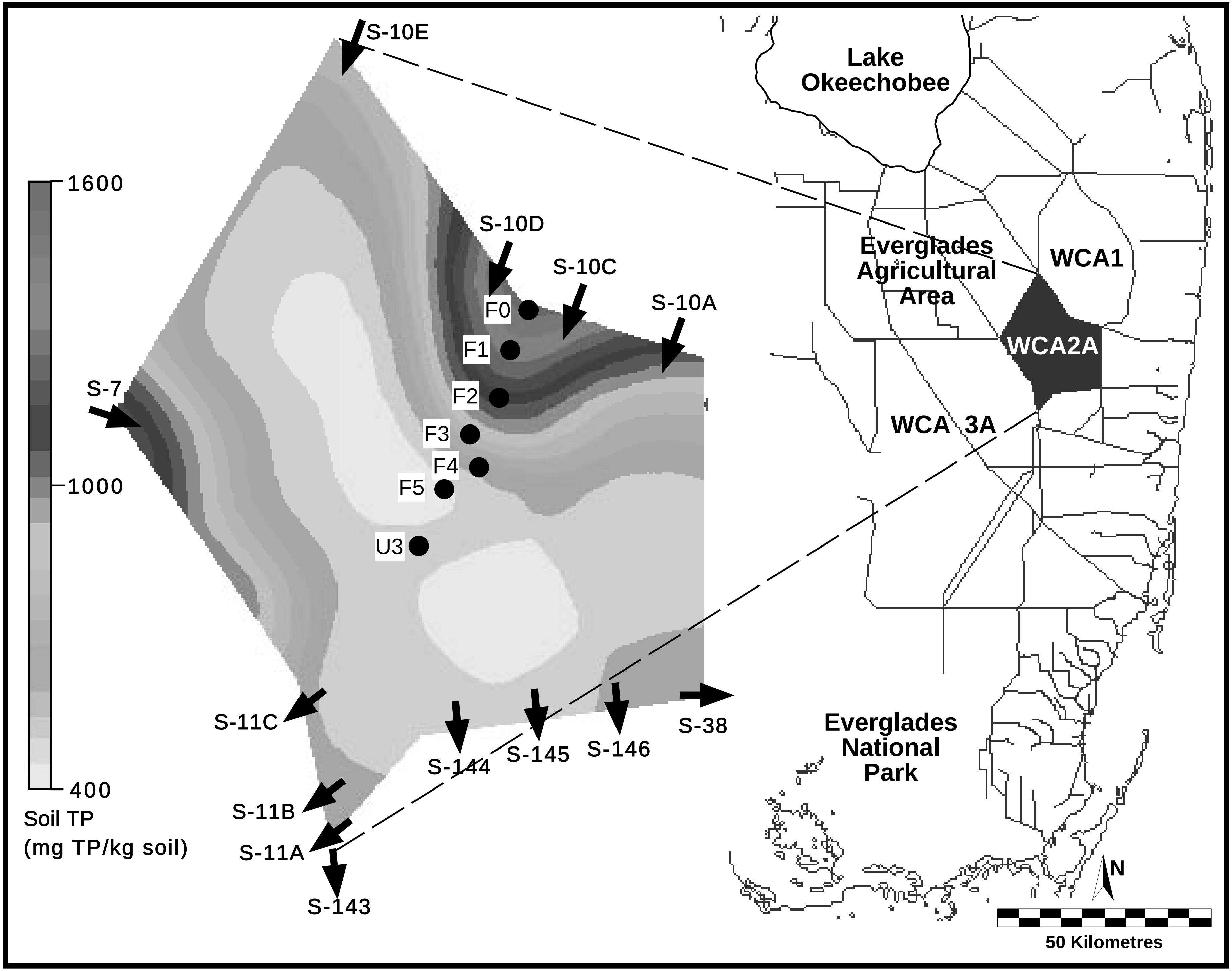
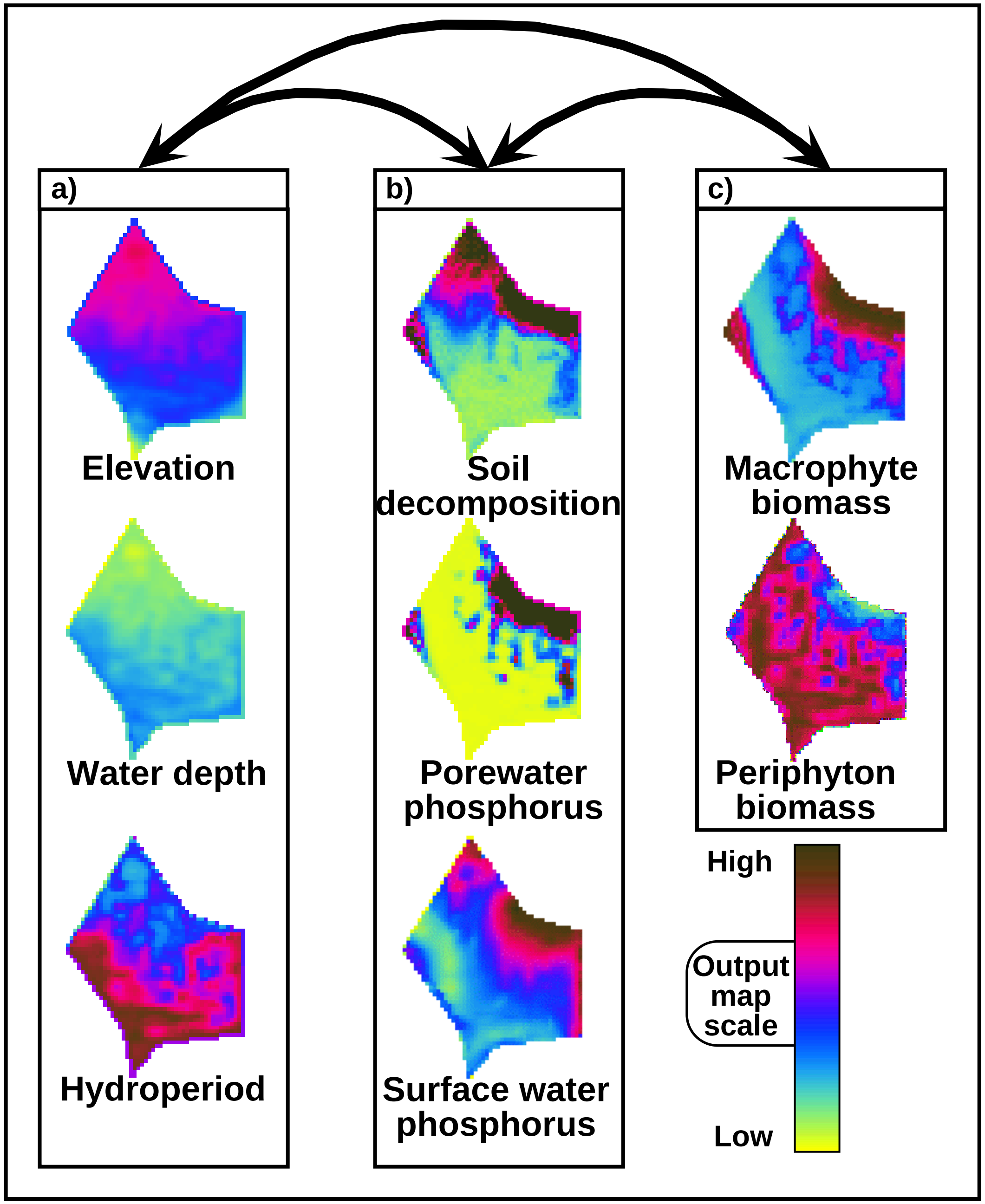
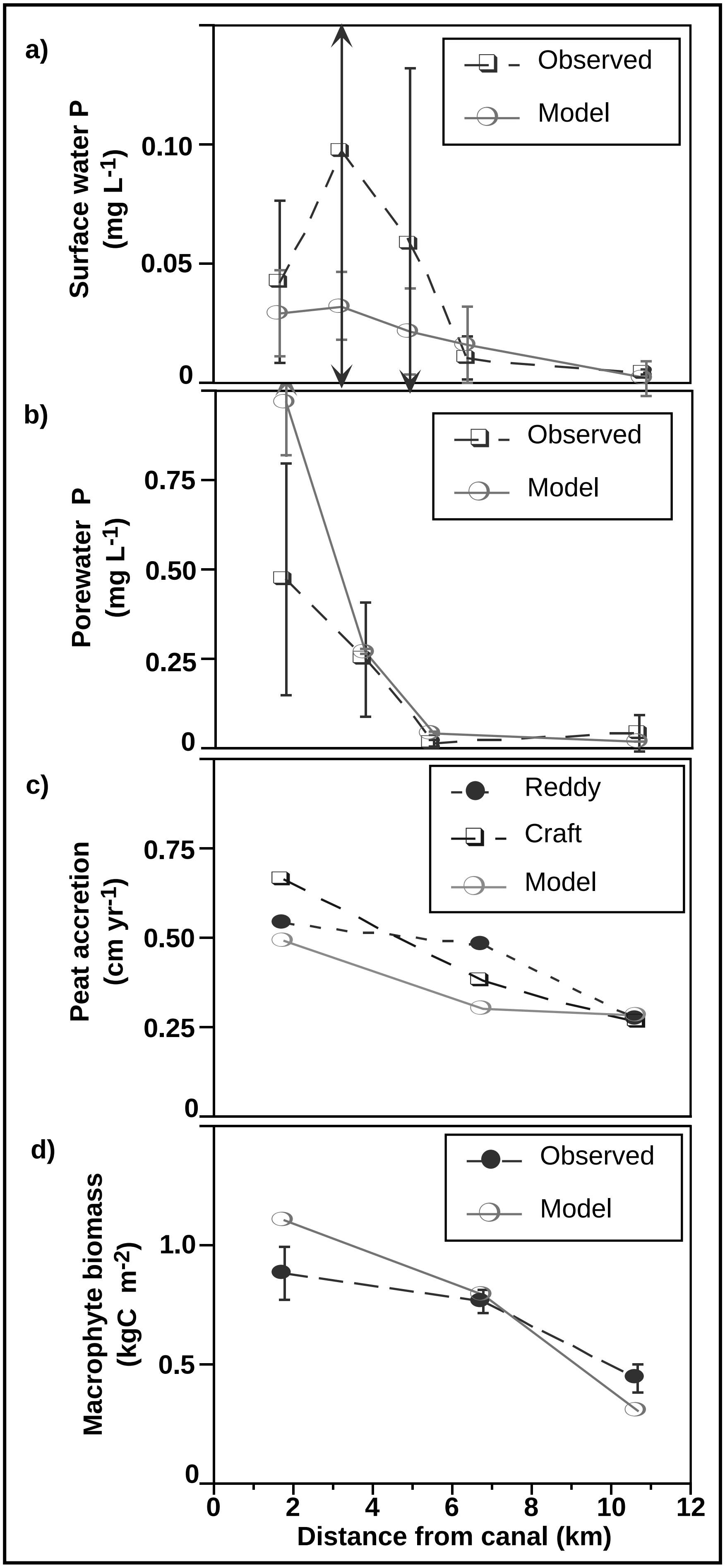

S-10E
S-10D
S-10C
S-10A
S-7
F0
F1
F2
F3
F4
F5
U3
S-11C
S-11B
S-11A
S-143
S-144
S-145
S-146
S-38
1600
1000
400
Soil TP
(mg TP/kg soil)
Lake Okeechobee
Everglades Agricultural Area
WCA1
WCA2A
WCA 3A
Everglades National Park
N
50 Kilometres

Fig. 4



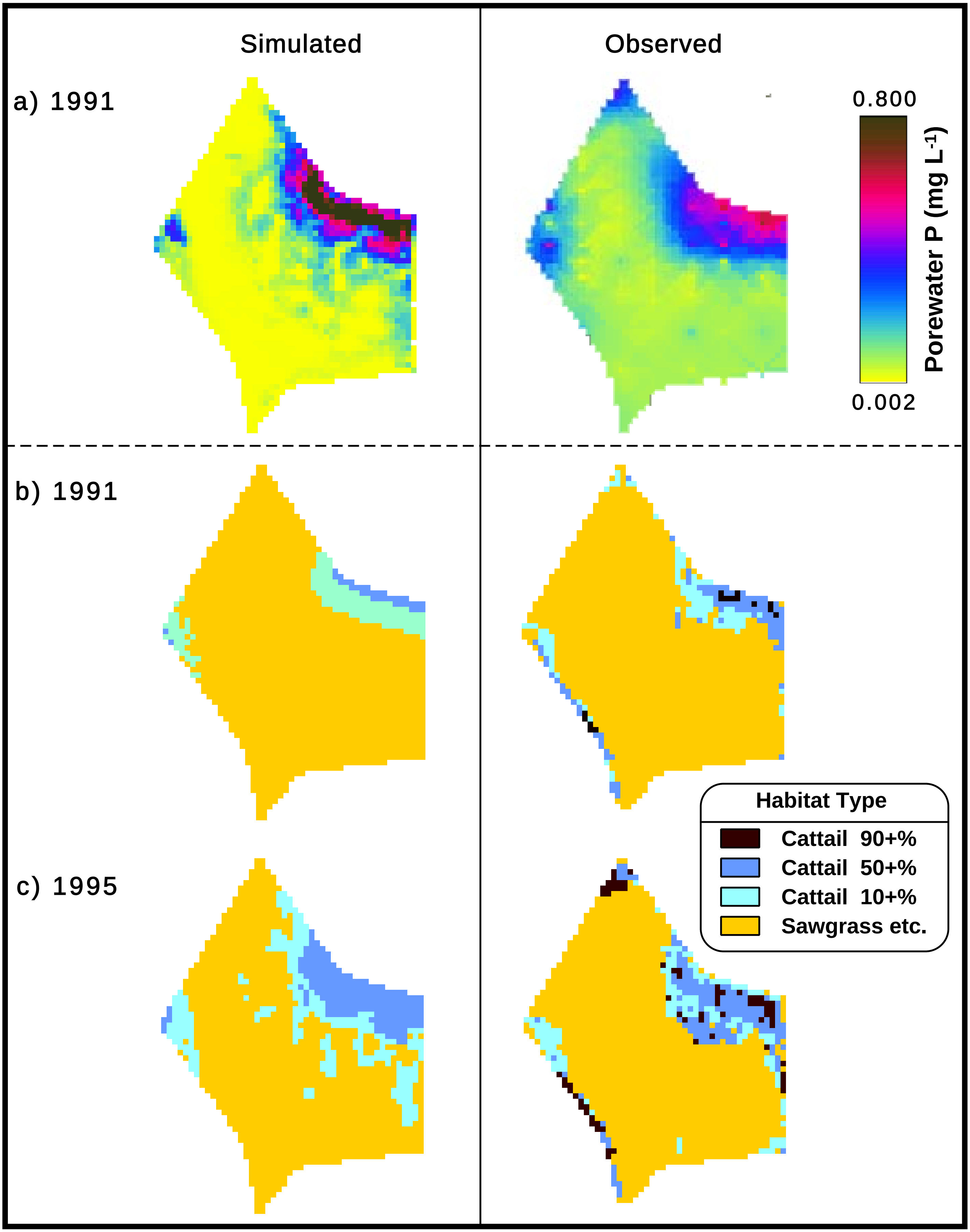
a)
Elevation
Water depth
Hydroperiod
b)
Soil decomposition
Porewater phosphorus
Surface water phosphorus
c)
Macrophyte biomass
Periphyton biomass
High
Output map scale
Low

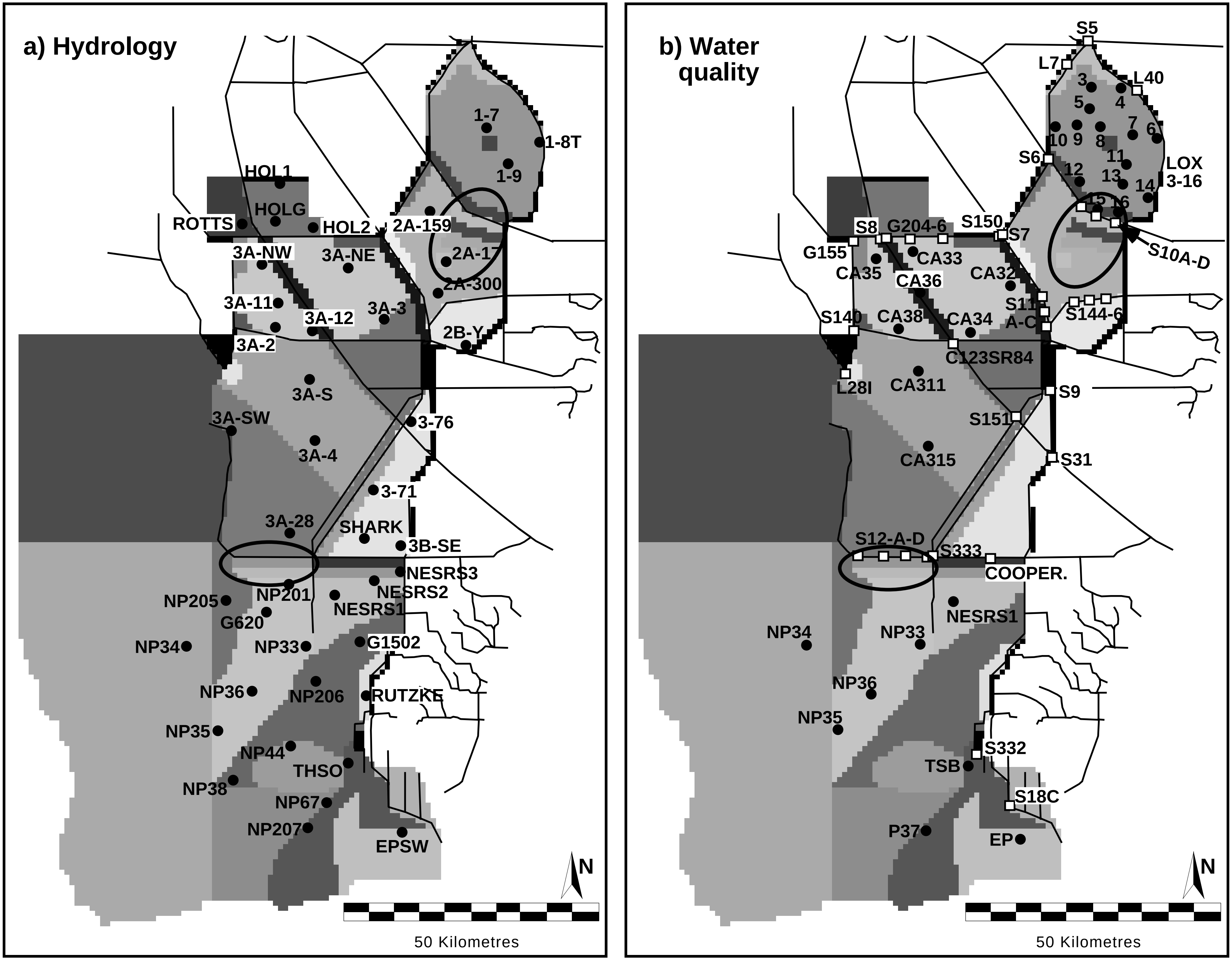
Fig. 5



a)
Observed
Model
Surface water P
(mg L-1)
0.10
0.05
0
b)
Observed
Model
Porewater P
(mg L-1)
0.75
0.50
0.25
0
c)
Reddy
Craft
Model
Peat accretion
(cm yr-1)
0.75
0.50
0.25
0
d)
Observed
Model
Macrophyte biomass
(kgC m-2)
1.0
0.5
0
0
2
4
6
8
10
12
Distance from canal (km)

Fig. 6


Simulated
Observed
a) 1991
b) 1991
c) 1995
0.800
0.002
Porewater P (mg L-1)
Habitat Type
Cattail 90+%
Cattail 50+%
Cattail 10+%
Sawgrass etc.



a) Hydrology
1-7
1-8T
1-9
HOL1
HOLG
ROTTS
HOL2
2A-159
2A-17
2A-300
2B-Y
3A-NW
3A-NE
3A-11
3A-12
3A-3
3A-2
3A-S
3A-SW
3-76
3A-4
3-71
3A-28
SHARK
3B-SE
NESRS3
NP201
NESRS2
NP205
G620
NESRS1
NP34
NP33
G1502
NP36
NP206
RUTZKE
NP35
NP44
THSO
NP38
NP67
NP207
EPSW
N
50 Kilometres
b) Water quality
S5
L7
3
L40
5
4
10
9
8
7
6
S6
11
LOX
3-16
12
13
14
15
16
S150
S8
G204-6
S7
G155
CA35
CA33
S10A-D
CA36
CA32
S11
A-C
S144-6
S140
CA38
CA34
C123SR84
L28I
CA311
S9
S151
S31
CA315
S12-A-D
S333
COOPER.
NESRS1
NP34
NP33
NP36
NP35
S332
TSB
S18C
P37
EP
N
50 Kilometres

Fig. 8

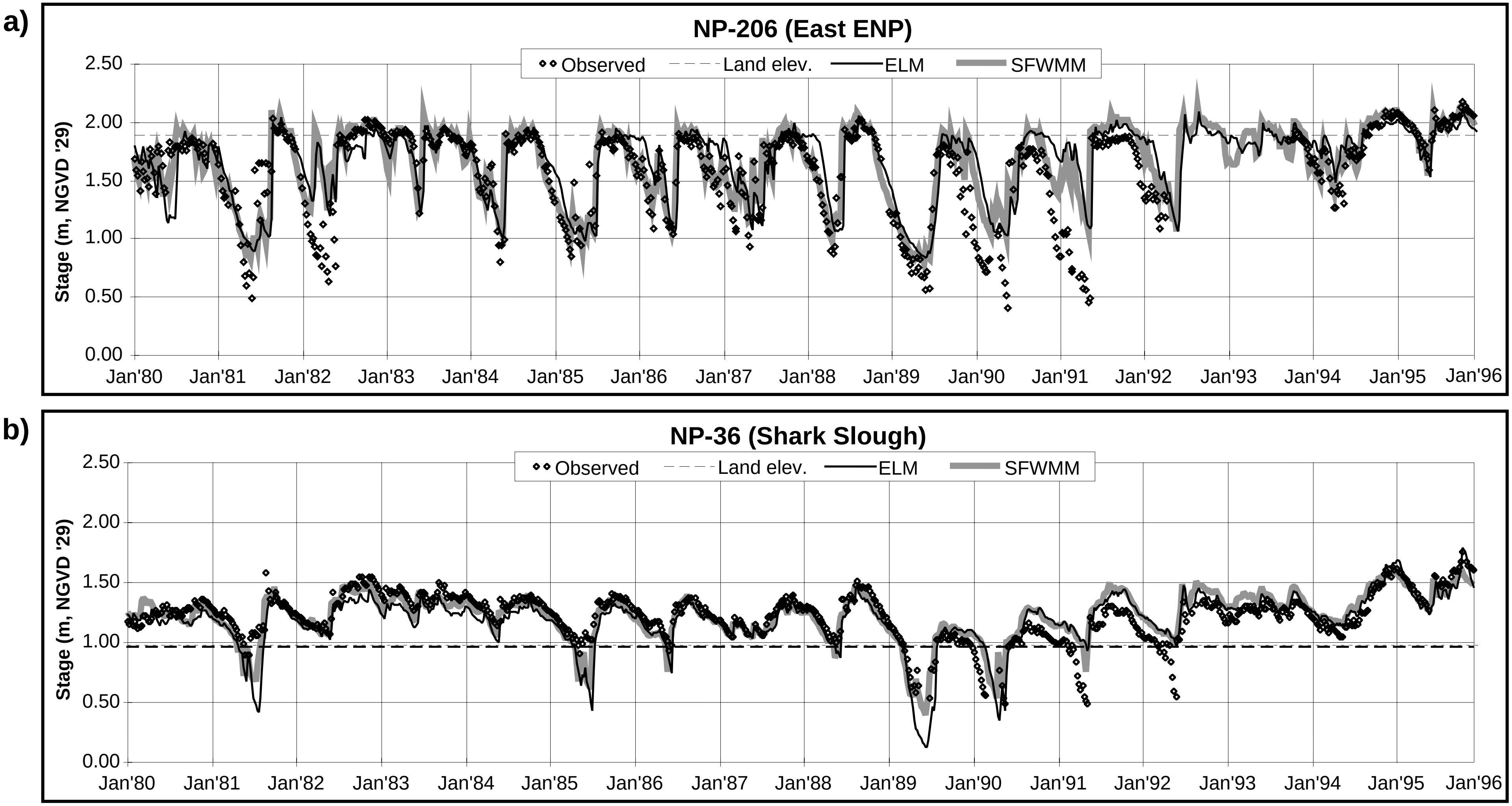
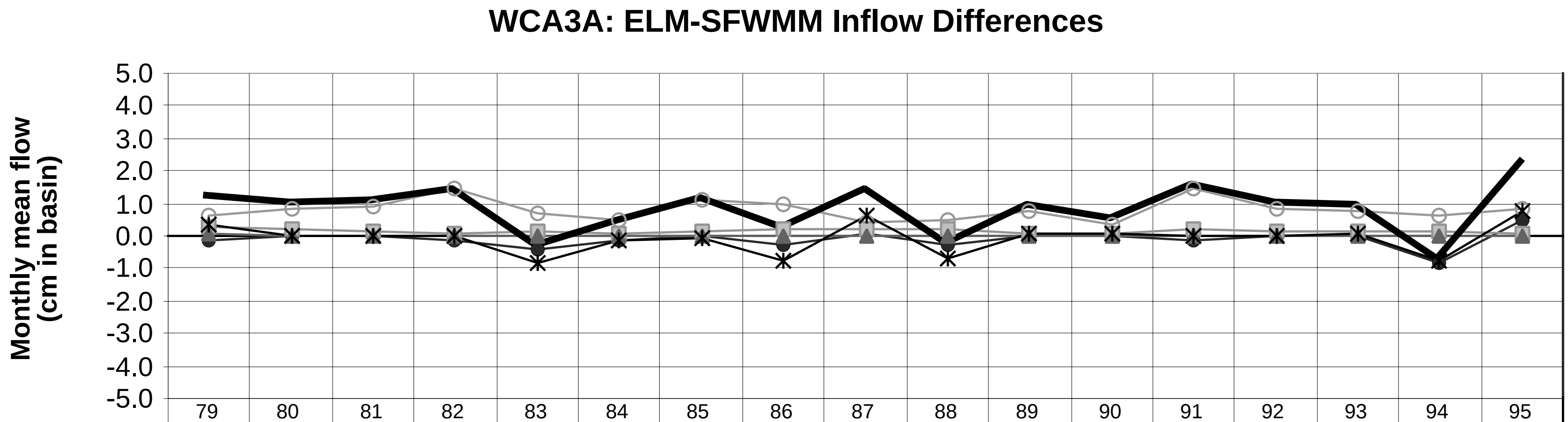

a)
NP-206 (East ENP)
Observed
Land elev.
ELM
SFWMM
Stage (m, NGVD '29)
2.50
2.00
1.50
1.00
0.50
0.00
Jan'80
Jan'81
Jan'82
Jan'83
Jan'84
Jan'85
Jan'86
Jan'87
Jan'88
Jan'89
Jan'90
Jan'91
Jan'92
Jan'93
Jan'94
Jan'95
Jan'96
b)
NP-36 (Shark Slough)
Observed
Land elev.
ELM
SFWMM
Stage (m, NGVD '29)
2.50
2.00
1.50
1.00
0.50
0.00
Jan'80
Jan'81
Jan'82
Jan'83
Jan'84
Jan'85
Jan'86
Jan'87
Jan'88
Jan'89
Jan'90
Jan'91
Jan'92
Jan'93
Jan'94
Jan'95
Jan'96

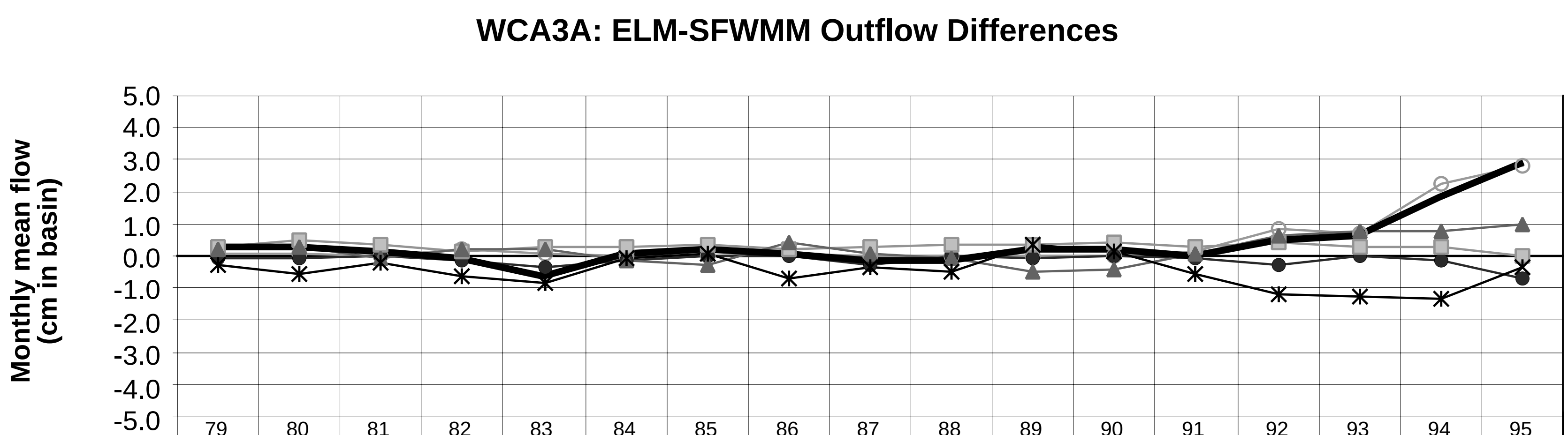
Fig. 9

a)



	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
Overland In	0.66	0.86	0.92	1.46	0.72	0.52	1.09	0.99	0.45	0.47	0.77	0.34	1.44	0.83	0.75	0.65	0.82
Structure In	-0.17	-0.02	0.00	-0.13	-0.40	-0.11	-0.03	-0.24	0.08	-0.28	-0.02	-0.01	-0.11	0.01	0.03	-0.81	0.51
Groundwater In	0.29	0.18	0.12	0.09	0.17	0.10	0.15	0.21	0.19	0.20	0.08	0.08	0.18	0.13	0.11	0.15	0.10
Seepage In	0.04	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rain	0.38	-0.03	0.01	-0.03	-0.84	-0.12	-0.09	-0.77	0.65	-0.68	0.08	0.04	0.00	0.00	0.04	-0.75	0.77
Sum inflows	1.20	1.00	1.06	1.39	-0.34	0.39	1.14	0.18	1.38	-0.28	0.90	0.45	1.53	0.97	0.93	-0.76	2.19

b)



	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
Overland Out	0.06	0.04	0.03	0.25	0.07	0.01	0.03	0.07	0.02	0.01	0.00	0.00	0.15	0.87	0.72	2.23	2.84
Structure Out	-0.08	-0.05	-0.02	-0.12	-0.35	-0.11	-0.01	0.00	-0.27	-0.01	-0.05	-0.02	-0.05	-0.25	0.02	-0.16	-0.67
Groundwater Out	0.28	0.51	0.38	0.13	0.28	0.28	0.33	0.20	0.30	0.35	0.37	0.42	0.31	0.40	0.31	0.30	-0.01
Seepage Out	0.21	0.30	-0.06	0.23	0.19	-0.12	-0.29	0.41	0.09	-0.06	-0.46	-0.44	0.08	0.61	0.80	0.79	1.01
Evapotranspiration	-0.26	-0.59	-0.22	-0.62	-0.87	-0.04	0.10	-0.70	-0.38	-0.50	0.32	0.15	-0.58	-1.18	-1.26	-1.37	-0.34
Sum outflows	0.22	0.21	0.11	-0.14	-0.68	0.01	0.16	-0.02	-0.23	-0.20	0.17	0.11	-0.09	0.45	0.60	1.79	2.84

Fig. 10

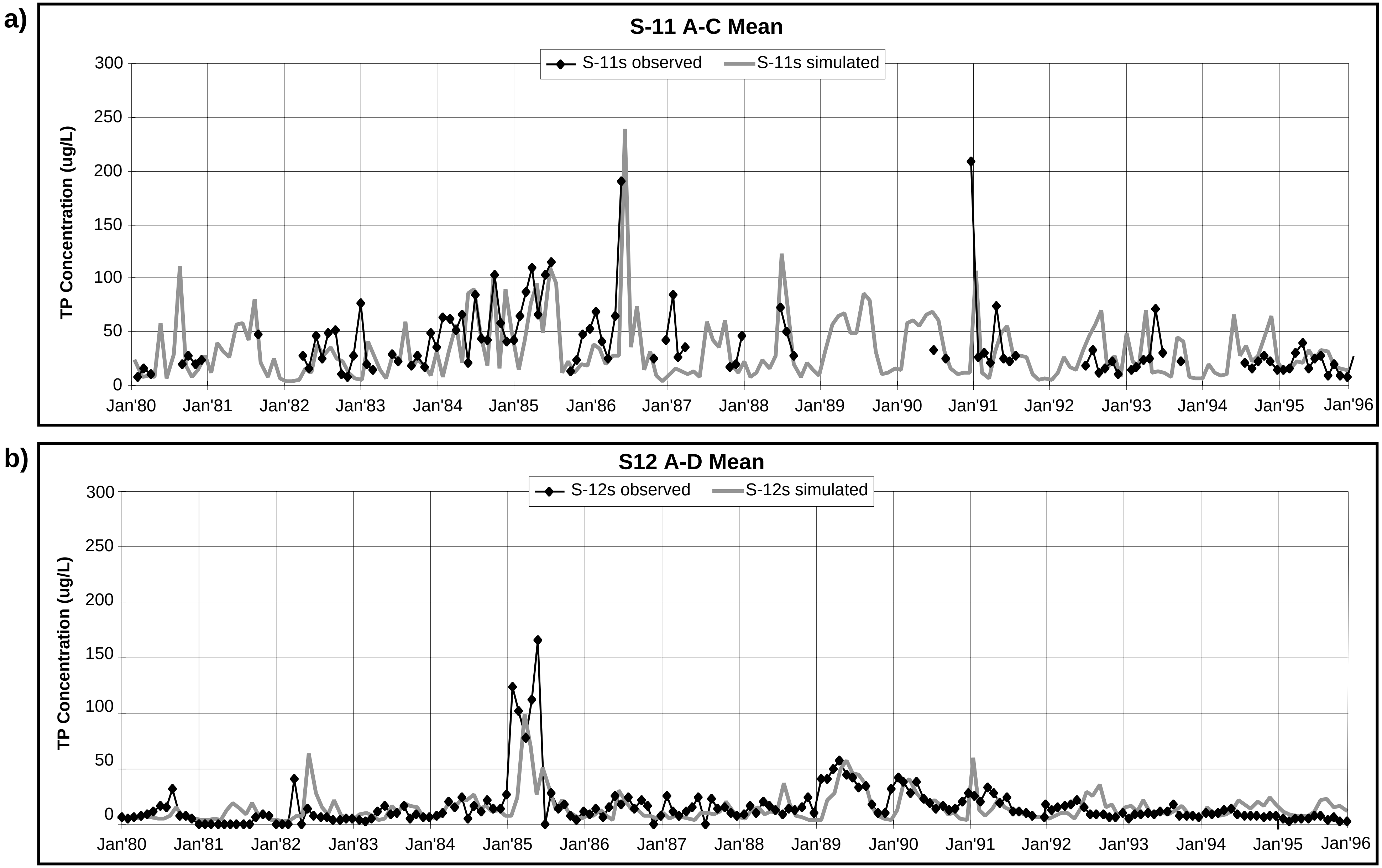

a)
S-11 A-C Mean
S-11s observed
S-11s simulated
TP Concentration (ug/L)
300
250
200
150
100
50
0
Jan'80
Jan'81
Jan'82
Jan'83
Jan'84
Jan'85
Jan'86
Jan'87
Jan'88
Jan'89
Jan'90
Jan'91
Jan'92
Jan'93
Jan'94
Jan'95
Jan'96
b)
S12 A-D Mean
S-12s observed
S-12s simulated
TP Concentration (ug/L)
300
250
200
150
100
50
0
Jan'80
Jan'81
Jan'82
Jan'83
Jan'84
Jan'85
Jan'86
Jan'87
Jan'88
Jan'89
Jan'90
Jan'91
Jan'92
Jan'93
Jan'94
Jan'95
Jan'96

Fig. 11

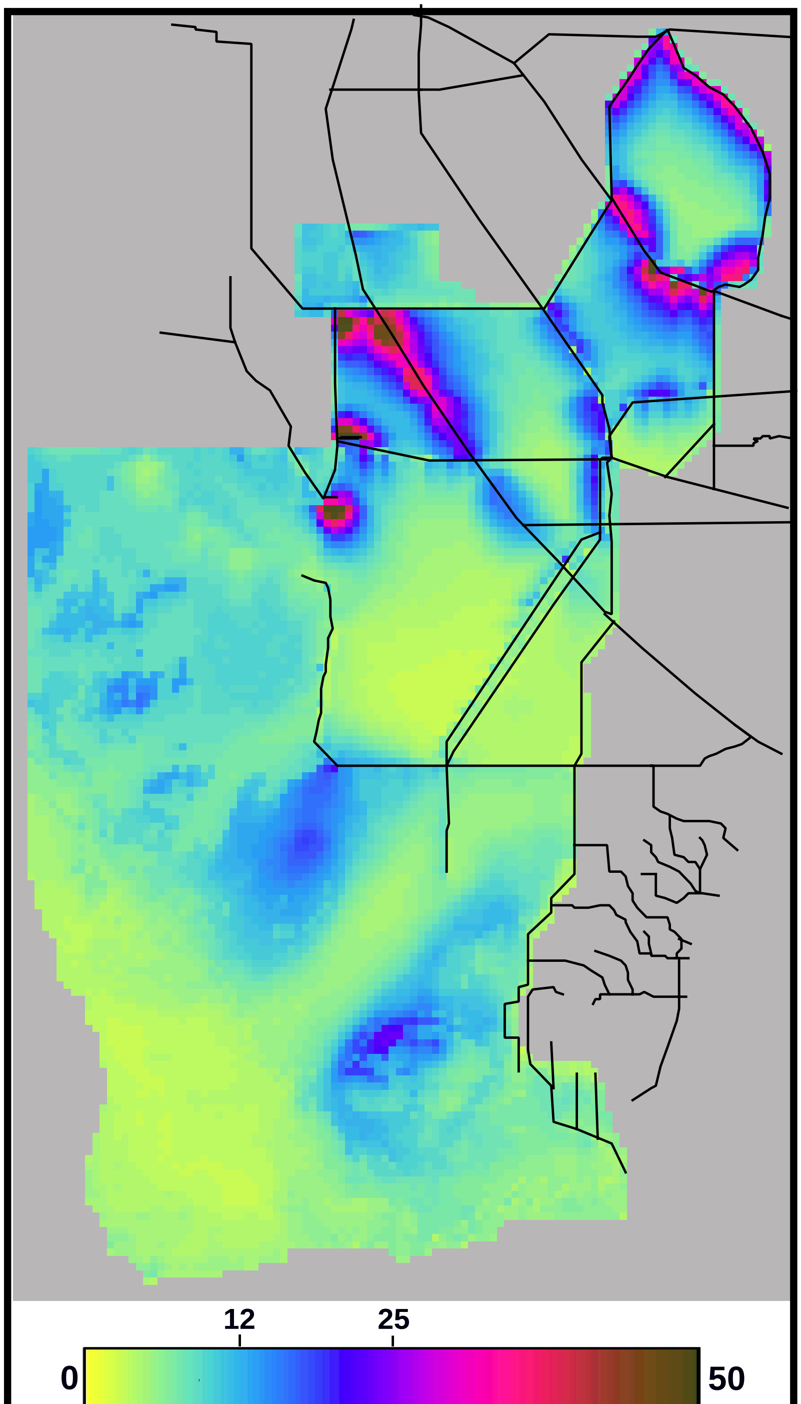
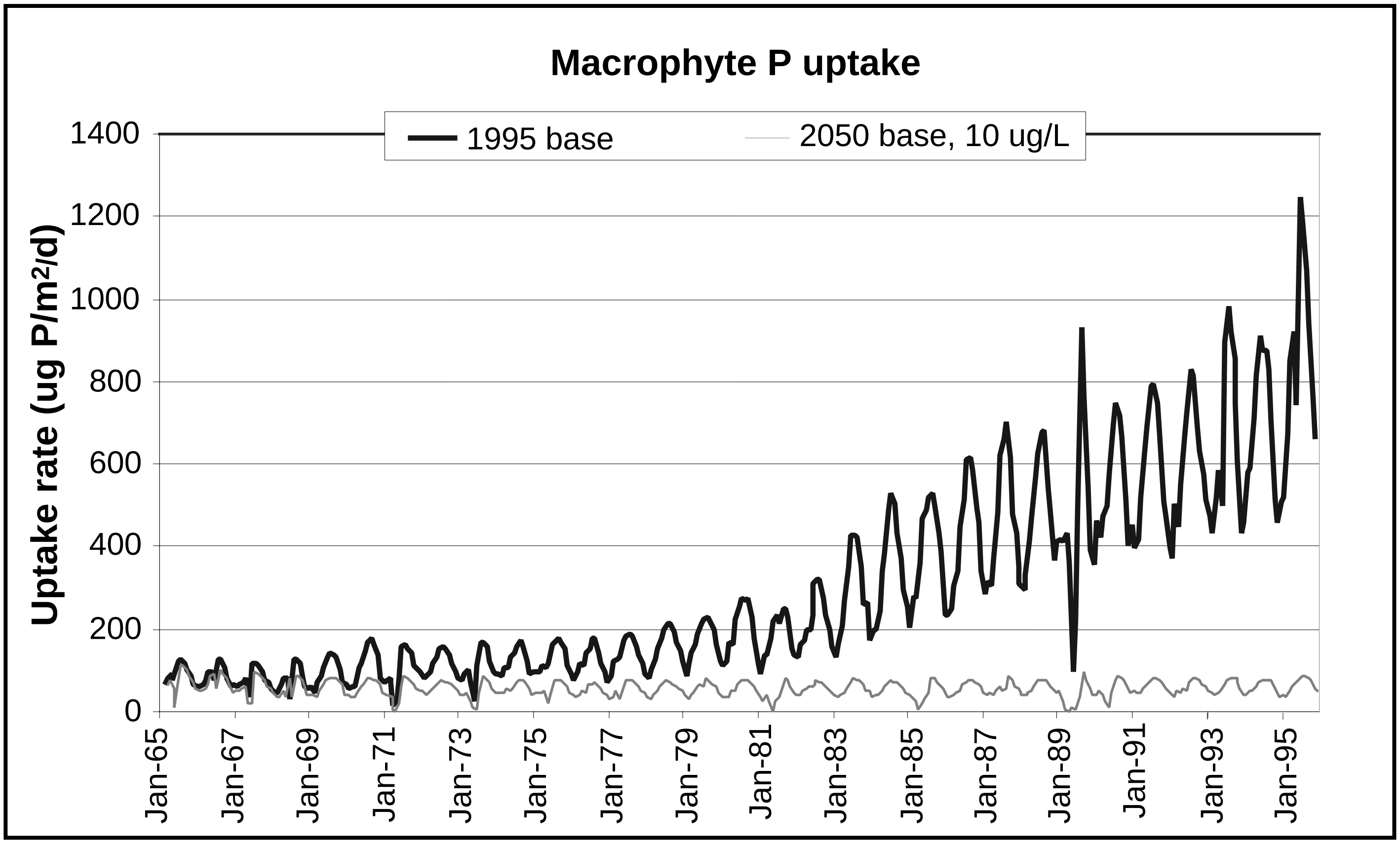


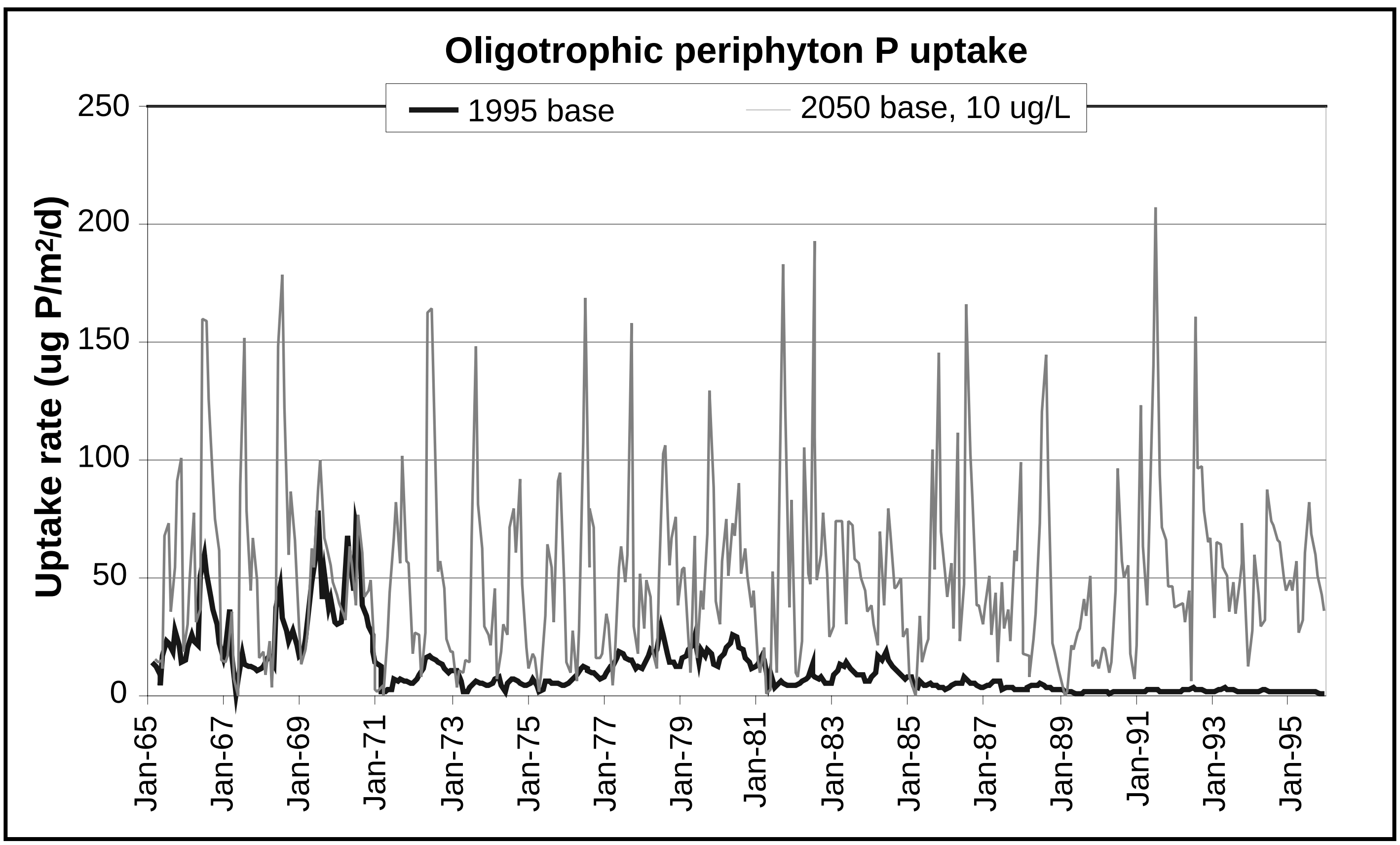
Fig. 12

a)



Macrophyte P uptake
1995 base
2050 base, 10 ug/L
Uptake rate (ug P/m²/d)
0
200
400
600
800
1000
1200
1400
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95

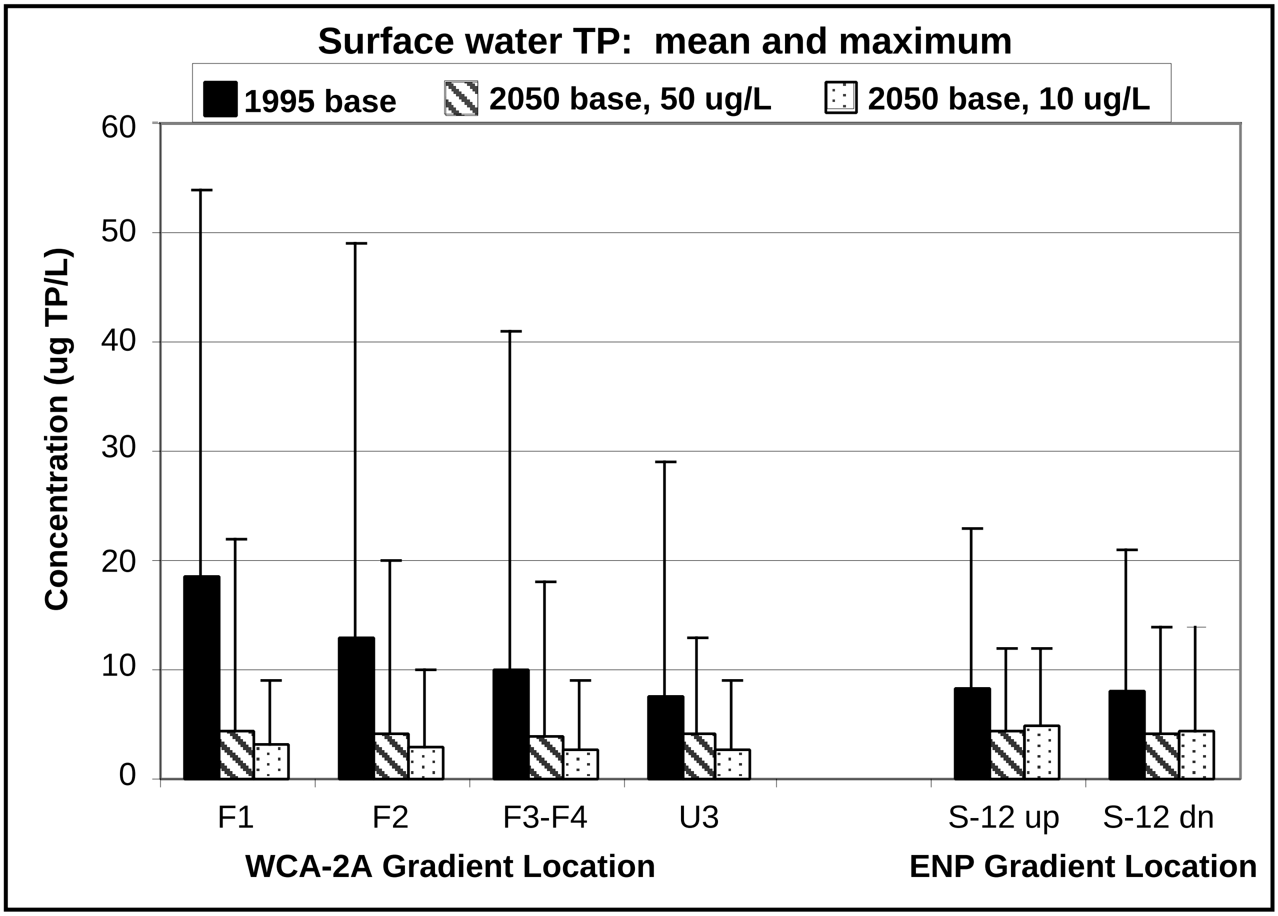
b)



Oligotrophic periphyton P uptake
1995 base
2050 base, 10 ug/L
Uptake rate (ug P/m²/d)
0
50
100
150
200
250
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95

Fig. 13

a)


Surface water TP: mean and maximum
1995 base
2050 base, 50 ug/L
2050 base, 10 ug/L
Concentration (ug TP/L)
0
10
20
30
40
50
60
F1
F2
F3-F4
U3
S-12 up
S-12 dn
WCA-2A Gradient Location
ENP Gradient Location

b)

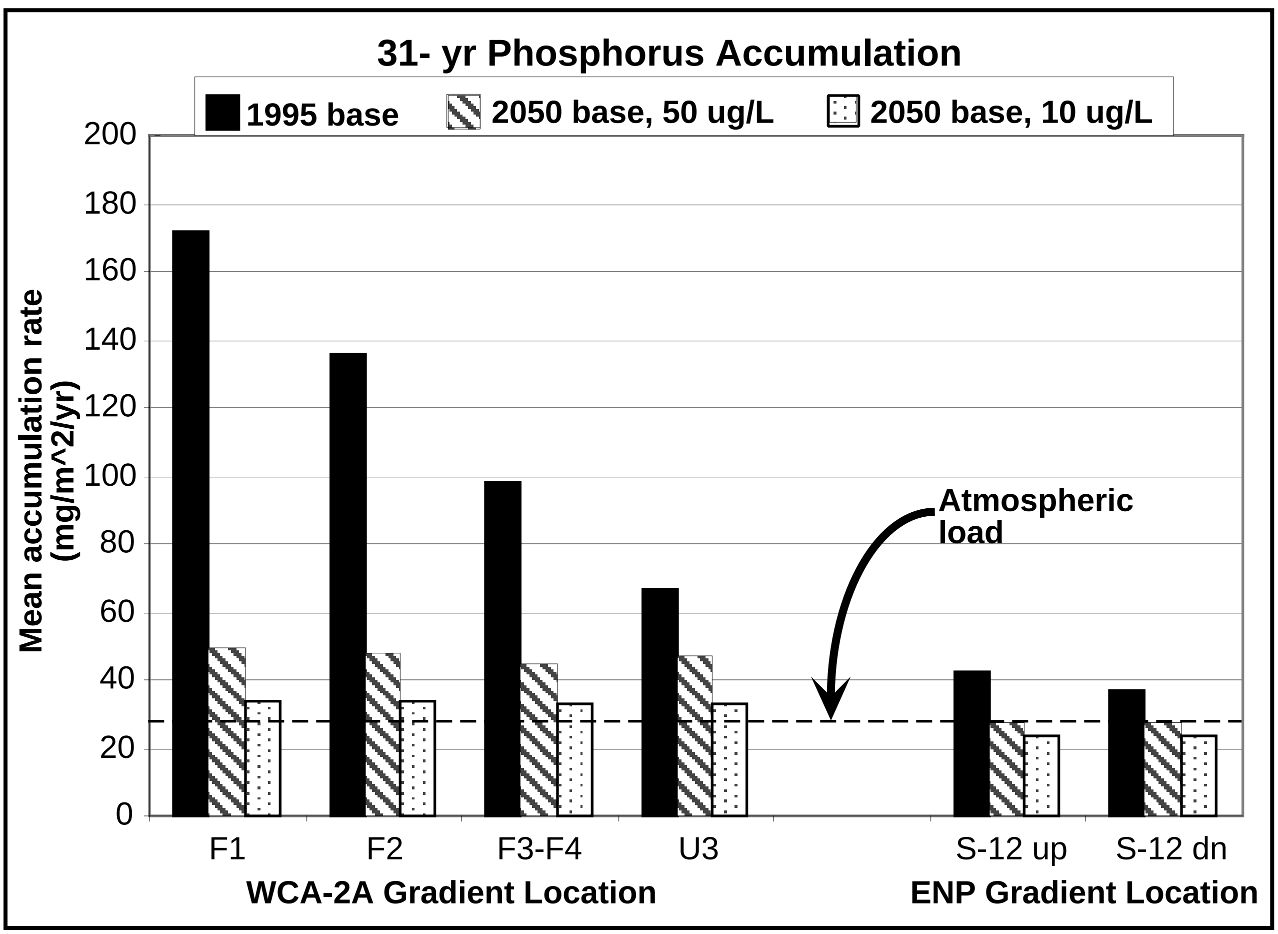

31- yr Phosphorus Accumulation
1995 base
2050 base, 50 ug/L
2050 base, 10 ug/L
Mean accumulation rate (mg/m^2/yr)
0
20
40
60
80
100
120
140
160
180
200
Atmospheric load
F1
F2
F3-F4
U3
S-12 up
S-12 dn
WCA-2A Gradient Location
ENP Gradient Location

Fig. 14