Phosphorus Management in the Okeechobee Basin: Current State of Knowledge and Future Research Needs

Submitted to:
Florida Department Agricultural and Consumer Services
Florida Department of Environmental Protection
South Florida Water Management District

UF | UNIVERSITY of FLORIDA

Phosphorus Management in the Okeechobee Basin: Current State of Knowledge and Future Research Needs

Executive Summary

Total phosphorus loading from the drainage basin to Lake Okeechobee is approximately 600 metric tons per year. Intensive phosphorus management strategies are needed to reduce loads from the Lake Okeechobee Basin (LOB) and to meet the current Total Maximum Daily Load (TMDL) target of 140 metric tons by the year 2015. The purpose of this paper is to summarize the current state of knowledge on phosphorus storage, fate, and transport in various components of the watershed, as related to water quality and sustainable agronomic productivity. The following are few highlights of what is known on phosphorus management in the LOB.

- Approximately 80% of the phosphorus imported into the basin has accumulated in soils and sediments. At a site-specific level, we have good estimates of the phosphorus storage in soils under various land uses in the LOB. Stored phosphorus in soils and sediments has been identified as a major source to surface and sub-surface waters.
- Phosphorus loadings from uplands may be decreasing due to implementation of best management practices (BMPs) and decreased intensity of upland land use. However, several phosphorus hot spots exist in the drainage basin. As new research data become available, these BMPs need modification to increase their effectiveness. Development of effective BMPs is an on-going process and requires continuous development and verification.
- Phyto and chemical remediation have been identified as BMPs to reduce phosphorus loads. Phosphorus retention in uplands is related to the availability of metals such as aluminum and iron. Chemical amendments with these metals were found to be effective in stabilizing soil phosphorus. In wetlands, phosphorus retention is regulated by metals and organic matter accumulation.
- Vertical movement of phosphorus through the soil profile would allow phosphorus to be retained by the Bh horizon. However, there is the likelihood of the phosphorus being lost via lateral subsurface drainage before it reaches the spodic horizon. The extent of this loss is yet to be documented.
- Isolated wetlands collect water from uplands via subsurface and overland flow only during and shortly after rain events and then slowly release water both to the atmosphere, groundwater and to ditches.
- Managed constructed wetlands strategically placed in the watershed can be very effective in removing phosphorus.

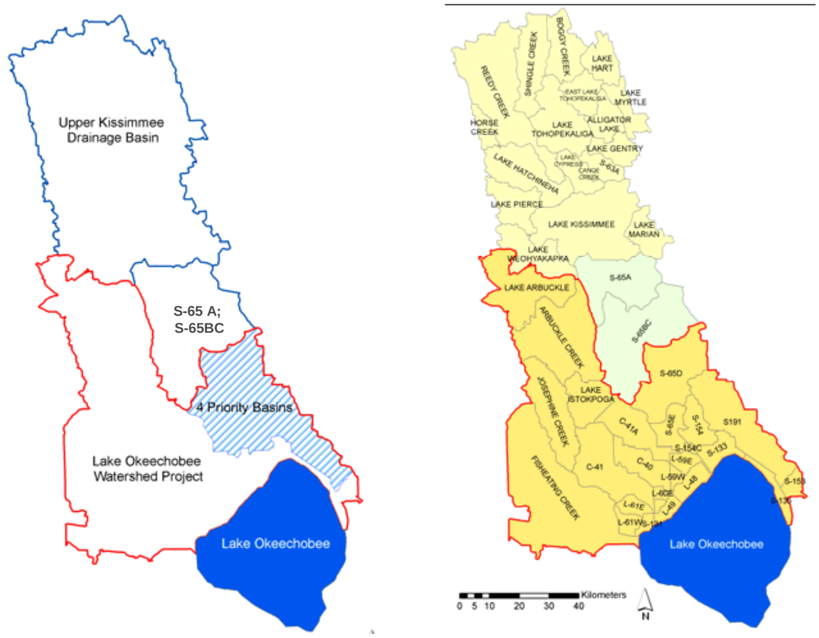
Due to the high phosphorus loadings and generally high phosphorus concentrations in the watershed north of the lake, it is unlikely that strictly ecologically engineered systems alone (e.g, Stormwater Treatment Areas, STAs) will be adequate in reducing loads to the extent needed to meet the TMDL target for Lake Okeechobee. Therefore, additional

remedial measures may be needed to meet this goal (several strategies are described in this paper). The following are some of the key research needs.

- Improved estimates of soil phosphorus storage and the lability of that storage in different landscape units such as uplands, wetlands, streams and ditches and the environmental parameters controlling storage are needed to adequately ascertain the phosphorus dynamics in the system.
- Develop soil test indicators to better estimate threshold concentrations and phosphorus storage/release potential at the landscape level, but also through time.
- Estimate relative contribution of phosphorus loads from uplands, ditches, wetlands, and stream sediments.
- Determine hydrologic flow paths and relative contributions of surface and sub-surface flows.
- Determine the effects of water table management to control phosphorus loss in drainage water from upland soils.
- Develop strategies for use of chemical amendments for in-situ remediation of excess soil phosphorus.
- Assess the spatial distribution and variability of soil phosphorus and interrelated environmental properties such as metals, soil types, land uses, parent material at the basin scale. This is essential to provide baseline data for water quality and ecological simulation models.
- Long-term monitoring of soil and water quality to verify the effectiveness of BMPs. There has been a large investment in monitoring infrastructure at the Buck Island, Palaez, Larson and the Beatty Ranches in the LOB. Monitoring at these ranches should continue in order to build a long-term record of water fluxes and P-loads from cow-calf operations under a wide range of land management and climatic conditions. Maintaining this type of intensive monitoring at a few strategic locations will allow development of improved hydrologic and water quality models which will have the capability to extrapolate these observations into predictions over the entire region.
- Develop management and predictive tools for rapid implementation of practices to reduce phosphorus loads.
- Develop practical tools for assessing phosphorus input-output budgets for different land uses or basins within the watershed and identify opportunities for reducing net phosphorus imports without jeopardizing agronomic productivity.
- Information from the research projects should be disseminated to the clientele, producers, managers, agencies alike, through a range of extension educational programs.

Introduction

Lake Okeechobee has a drainage basin containing approximately 2.8 million acres, or 4,400 square miles. Without the lake, the area is approximately 2.4 million acres, or 3,700 square miles.   Total phosphorus loading to the Lake is approximately 600 metric tons per year. The four priority basins (S-191, S-154, S-65D, and S-65E) comprise approximately 450 square miles of the Lake Okeechobee watershed and contribute the highest phosphorus concentrations and account for 35% of the total phosphorus load to the Lake. Therefore, the majority of current research and management strategies are concentrated in these priority basins. Intensive phosphorus management strategies are needed to reduce loads not only from the priority basins, but also the whole watershed and to meet the current TMDL target of 140 metric tons by the year 2015. Effective phosphorus control strategies can only be implemented by understanding the storage, fate, and transport of phosphorus in uplands, ditches, wetlands, and streams of the watershed. Research conducted by UF-IFAS in the early 1990’s (summarized in Ecological Engineering, vol. 5:1995) and during the last four years provides a sound scientific basis to develop and implement phosphorus management strategies in the Lake Okeechobee Basin (LOB).



Phosphorus dynamics in the watershed are very complex and several gaps remain in our understanding of phosphorus fate and transport in this unique landscape. The purpose of this paper is to summarize the current state of knowledge on phosphorus storage, fate, and transport in various components of the watershed, as related to water quality and sustainable agronomic productivity.

Figure 1: Proposed study areas: (i) phase I: Lake Okeechobee Watershed project area including the 4 priority basins and (ii) phase II: Upper Kissimmee Drainage Basin, S-65A and S65 BC.

Current State of Knowledge

General Observations

Current estimates indicate that more than 80% of the phosphorus imported into the LOB has accumulated in soils and sediments. At a site-specific level, we have good estimates of the phosphorus storage in soils under various land uses in the LOB. For example, we have landscape-scale information on isolated wetland phosphorus storage and the effect of land use. However, we do not have data on the variability of soil phosphorus storage among important landscape components such as ditches, streams, other wetlands (riparian, forested, and constructed), and uplands. These detailed data are needed to accurately quantify phosphorus contributions from soils and sediments to overlying waters at the landscape-scale. The geographic position of environmental landscape properties and their relationship to soil phosphorus are critical to assess accurately the sources, sinks and transport of phosphorus throughout the basin. There is need to upscale site-specific measurements using geostatistical/geospatial methods to better characterize soil phosphorus at different spatial scales (site-specific, farm, sub-basin, and basin scales).

Phosphorus loadings from uplands may be decreasing due to implementation of BMPs and decreased intensity of upland land use (fewer active dairies, several abandoned dairies and decrease in density of cattle per unit area). However, several phosphorus "hot spots" exist in the drainage basin. Additional verification is needed to document potential trends in phosphorus reduction from uplands through time.

Several best management practices (BMPs) are currently under evaluation. As new research data become available, we may want to modify these BMPs to increase their effectiveness. To determine the effect of a given BMP at a given point in time is difficult, as it may take long periods to assess BMP effectiveness. Additionally, a simple cause and effect relationship identified at site-specific scale is likely to be confounded by interrelated properties at landscape scales. Thus, developing linkages between soil-landscape models across multiple spatial scales is needed to develop management strategies at the landscape level.

Wetlands and other landscape units in the LOB are adapted to receive high phosphorus loadings from adjacent uplands due to historical nutrient loading of uplands from agriculture practices. Under these conditions, wetlands and other landscape units such as ditches and streams have functioned as sinks for phosphorus, while maintaining high equilibrium phosphorus concentrations (EPC) in overlying surface waters. However, when systems receive waters with low phosphorus concentrations (lower than EPC values), they can function as sources of phosphorus to surface waters. This situation may occur as: (1) BMPs reduce nutrient loads to uplands; (2) labile soil phosphorus in uplands soils is taken up by pasture grasses; and (3) extreme storm events produce runoff from surrounding landscapes with lower phosphorus concentrations than overlying waters in wetlands, ditches and streams. Thus, land management practices may be required to buffer this effect until a new EPC threshold is established.

In addition to the adoption of BMPs, intense remedial measures are needed to reduce phosphorus loading from the LOB to meet the TMDLs by the year 2015. Some of these measures as they relate to soil/sediment resources are described in this document under a section on “Unknowns and Research Needs”.

Uplands

Upland soils in the drainage basin are predominantly poorly-drained, sandy Spodosols. Approximately 80% of the total phosphorus in the basin is stored in soils in both stable and unstable forms.

Spodosols have little phosphorus retention capacity in the surface A and E horizons, but have high retention capacity in the spodic horizon. Phosphorus retention and release properties of spodic horizons differ from other Florida soil materials due to the prevalence of organically-associated aluminum. Although the organo-aluminum complexes have a high surface area, phosphorus retained in these complexes can be more readily released than phosphorus-bound metal oxides typical of other soils. In general, phosphorus retention capacity of Spodosols is regulated by iron, aluminum, and organic carbon.

Vertical movement of phosphorus through the soil profile would allow phosphorus to be retained by the Bh horizon. However, there is the likelihood of the phosphorus being lost via lateral subsurface drainage before it reaches the spodic horizon. Also, since the spodic horizon is discontinuous in many soils with ‘gaps’ having higher hydraulic conductivity, much of the vertical flow may bypass the spodic when the water table is below the spodic horizon. The extent of this loss is yet to be documented, however current work by UF-IFAS researchers is aimed at quantifying hydrologic flowpaths between uplands, ditches and wetlands in the LOB.

Water soluble phosphorus as well as equilibrium phosphorus concentrations (EPC; calculated from adsorption isotherms) in Spodosols vary with antecedent soil phosphorus storage in the soil profile. Soils with high phosphorus concentration that come in contact with low phosphorus water (such as rain) tend to release more phosphorus and support higher phosphorus concentrations in surface and subsurface waters.

Soils with the same soil test phosphorus (Mehlich 1-P) concentration may pose different environmental risks (impact on water quality) depending on the capability of the soils to retain phosphorus. A soil with a higher P retention capacity would likely lose less P to the environment compared to a soil with a poorer P retention capacity. A threshold P value based on the change-point concept is now available for the surface horizon of some of the Florida soils, but not validated for most soils in the Okeechobee Basin. The method involves calculation of the Phosphorus Saturation Ratio (PSR) as a ratio of Mehlich 1-P to the sum of Mehlich 1 (Fe+Al). The PSR value of 0.15 is the threshold PSR, which, for practical purposes has been identified as that PSR above which Florida soils become an environmental risk.

With respect to minimizing the P load to uplands, dairy nutritionists have focused on minimizing phosphorus concentrations in manure. They have successfully achieved a reduction in the phosphorus excreted by dairy cows by decreasing the phosphorus concentrations and chemical forms in the diet, without negatively impacting animal performance. However, there is an animal health limit to dietary phosphorus reduction. To date, there is no link to the reduction in manure phosphorus concentration with its solubility and subsequent fate in the soil.

Phosphorus Loads from Cow-Calf Operations. One year of intensive monitoring of an 1100 acre ranch in the LOB showed that phosphorus loads from a well-operated cow-calf operation using typical management practices for the area ranged from 1 to 6 lb/acre/year and averaged approximately 2 lb/acre/year over the entire 1100 acre ranch. The sub-area of the ranch with the lowest stocking densities, lowest phosphorus fertilization rates and substantial natural wetland area had the lowest phosphorus loads (1.3lb/acre/year) , while the sub-area with the highest stocking density , highest phosphorus fertilization rates, and substantial improved pasture area had the highest phosphorus loads (5.7 lb/acre/year). Water retention BMPs have been implemented in both these sub-areas and monitoring will continue to determine the impact of this change on phosphorus loads.

Reducing surface runoff by retaining water within drainage ditches has the potential to reduce nutrient runoff from improved pastures on cow-calf operations. However, in an experiment started in 2005 to test the effects of water retention on nutrient loads, there was a 39% increase in total phosphorus load (3.5 versus 2.5 lb/acre/year) where water was retained. This increased phosphorus loading was due to a 38% increase in phosphorus concentration in runoff from pastures with water control structures, and only modest (9%) decrease in total water runoff. The average Mehlich 1-P concentration in soil was nearly two times greater in pasture with water control structures than in pastures without water control structures during the wet season, indicating that higher water levels in the pasture increased phosphorus release from surface soils. Continued monitoring of this project will be necessary to determine whether this phosphorus release is temporary or if it persists through time and, if so, for how long. As discussed below, implementation of pasture water detention/retention practices under a variety of hydrologic and soil conditions will be necessary to determine whether this BMP has the potential to reduce phosphorus loading.

Phytoremediation. It might be possible to remove phosphorus from the spodic horizon via plant uptake. Bahia grass grown on unfertilized Spodosols removes approximately 20 kg P/ha year. Bahia grass can obtain some of its phosphorus from deeper soil layers such as the spodic horizon. It is necessary to evaluate whether phosphorus removal by plants is site-specific and whether the removal depends on the depth to the spodic horizon. Thus, it would be critical to characterize the spatial distribution, depth to, and depth of spodic horizons. Continuous production of bahia grass with no phosphorus may create a deficiency in the plant tissue and ultimately affect forage productivity. The relationship between phosphorus storage in the soil and the tissue concentration must be established to determine phosphorus deficiency of bahia grass for sustainable production. Accordingly, fertilizer recommendations may be modified. There also is the potential to enhance phosphorus removal from deeper layers of the soil profile by planting trees. Water-soluble phosphorus concentrations are high in the surface horizons of pastures compared to that of tree-based pasture systems. Trees also have the potential to lower the water-table and could be an optional BMP in locations of high phosphorus concentrations where raising the water-table has been shown to increase phosphorus in surface waters.

In-situ soil remediation. The phosphorus retention capacity of soils can be improved by application of water treatment residuals (WTRs), which may include aluminum (Al), iron (Fe), and calcium (Ca). Water treatment residuals are very effective in reducing soluble phosphorus. Most Al-WTRs are more effective than Fe-WTRs or Ca-WTRs, especially over short reaction times. Aluminum WTRs are not subject to redox effects on phosphorus retention, whereas Fe-WTR can be. The WTRs tend to buffer soil pH at WTR pH (~5.8); no decrease in soil pH is observed following treatment, as can occur with some metal salts. The WTRs can reduce phosphorus leaching without any detrimental effects on plants. However, to be effective, the soluble phosphorus must flow through or by the zone of WTR application. Reduction in soluble phosphorus is roughly proportional to the soluble phosphorus mass (soil depth) amended with WTR. Surface applications are useful for reducing surface runoff impacts, but incorporation of WTRs into the soil probably is necessary to reduce leaching of P in subsurface flows. At normal WTR application rates and soil pH values, no adverse effects of WTRs on forage yields are expected. There is minimal soluble Al^{3+} in Al-WTR amended soil systems with pH>3.

Initial studies suggest that there appears to be little reason for concern about Al-WTR effects on grazing animal health or growth. For example, no significant effects were observed on performance of sheep fed WTR as 10% of their diet. However, there is insufficient WTR available to treat all the LOB acreage that exhibits elevated phosphorus concentrations at the necessary rate (1 to 2.5%, or 10 to 25 T/A). A useful strategy may be to use WTRs to treat soils in selected “hot spots” and to isolate (e.g., fence out animals) these areas as necessary. Additionally, it may be cost-effective to use “pure” chemicals such as alum, for application in situations where there is inadequate availability of WTRs.

Ditches

Ditch networks are used throughout the basin for drainage and irrigation purposes. This network has effectively modified the hydrologic regime of extensive areas and likely affects the storage volume and detention time of stormwater throughout the basin. Most small ditches in the upper reaches of drainage networks are open (not fenced) to grazing and are within pasture areas. Therefore, cattle have direct contact with these ditches, and they often spend significant amounts of time grazing within ditches. Such animal activity can result in vegetation trampling and direct waste loading to ditch waters at times when ditches are inundated.

In general, ditching intensity tends to increase with intensity of agricultural land. Unimproved pastures have fewer ditches than land uses such as dairy or row crops. Antecedent sediment phosphorus levels in ditches appear to regulate phosphorus retention. Studies by UF-IFAS during 2003 suggested that ditch sediments have lower phosphorus concentrations than isolated wetland soils and that more phosphorus was stored in wetlands with larger ditches. In general, little work has been done specifically within ditches, with respect to either hydrology or nutrient assimilative capacity. In particular, the connectivity of ditches (e.g. inflow and outflow of ditches in wetlands), their morphology and size, input loads, and geographic position within the hydrologic network may have major effects on phosphorus concentrations and loads. Ditches draining individual land parcels may provide an effective intervention point for remedial BMPs, although at present, we have inadequate information to support this management approach.

A mesocosm study by UF-IFAS in 2004-05 indicated that the drainage ditches have the potential to increase P retention (retain soluble phosphorus) by up to 50%. However, the P retention was found to be a function of time as well as sediment characteristics. Actual in-stream studies are needed to better quantify the residence time of water in the ditches as it moves from the upland to the ditches. Knowledge of the residence time together with the sediment characteristics can be used to develop ditch water retention BMPs for reducing the discharge of P from cattle ranches and other agricultural land uses.

Isolated Wetlands

During 2003, a survey of 118 wetlands across dairy, improved pasture and rangeland sites within the Okeechobee Basin indicated that soils in the center of wetlands are higher in phosphorus content than soils at the edge of wetlands, which in turn are higher in phosphorus than soils of adjacent upland areas and ditch sediments. This suggests that a greater phosphorus storage potential can be attained in the watershed by expanding environmental conditions that create soils similar to that of wetland centers. Phosphorus concentrations are also greater in isolated wetlands of dairies relative to wetlands in improved pasture, which had greater phosphorus concentrations than wetlands in unimproved pasture.

On-going studies have shown that in terms of ecosystem phosphorus storage, nearly 90% of phosphorus is stored in isolated wetland soils (0-10 cm) with about 10% stored in above- and below-ground vegetative tissue and litter. Soil phosphorus within isolated wetlands is mostly associated with organic matter, whereas in adjacent upland improved pasture soils it is associated with soil mineral components. A significant proportion of phosphorus associated with organic matter suggests that factors influencing organic matter accretion (carbon production, availability, decomposition) may also influence the phosphorus accretion in wetlands.

Within isolated wetlands, reduced vegetative biomass due to cattle grazing, and trampling of plants and soils, may decrease the nutrient assimilative and storage capacity of wetlands. Increased biomass production and cutting and removal of forage are expected to increase the phosphorus retention capacity associated with organic matter in wetlands.

Antecedent moisture and flooding conditions of soils can also have significant effects on the amount of phosphorus retained and released to the overlying water column. Flooding of previously drained wetland or upland soils, which are high in phosphorus, can result in a release of phosphorus upon flooding. Upland soils appear to have a greater potential to release phosphorus than wetland soils. However, we do not have sufficient information to determine whether this is a short- or long-term phenomenon. In general, our studies suggest that soils previously or continuously flooded have a lower release potential, and higher phosphorus retention rate, than soils that were drained and then flooded.

We are uncertain of the effects of fluctuating water tables on high phosphorus soils (wetland or upland); however, leaching studies suggest there is a significant desorption potential. Equilibrium phosphorus concentrations in wetlands (as discussed earlier) are often high (in the mg L^{-1} range) due to antecedent phosphorus loading. When systems receive waters with low phosphorus concentrations (lower than EPC values), they tend to function as sources of phosphorus to surface water. Therefore, it is important to better quantify this phenomenon in a landscape such as the Okeechobee Basin where phosphorus loads are being reduced.

Inundation and Hydroperiod. Four isolated wetlands have been monitored for about 800 days since late 2003. During this time, the wetlands were “completely dry” about 25% of the time. Two of the wetlands were “quite dry” (less than 20% of their observed maximum area) approximately 90% of the time. In these two wetlands, drainage ditches were more effective (i.e., cut to lower elevation) than in the other two wetlands that were “mostly dry” only approximately 50% of the time. Once again, the depth to which ditches need to be cut could depend on the soil types, i.e., depth to the spodic horizon.

Ditch Flow. The ditches draining all four wetlands failed to flow during approximately 70 to 85% of the monitoring period. The lowest 10% of ditch flows (including zero flow) represented more than 90% of the observations in two wetlands and more than 80% in the other two.

Groundwater Exchange with Uplands. A working hypothesis among many managers was that isolated wetlands collected water from within the landscape and this water was drained by ditches. However, our current findings show that isolated wetlands monitored in our study collect water from uplands via subsurface and overland flow only during and shortly after rain events and then slowly release water to the atmosphere, groundwater and to ditches. The release to groundwater occurs over much longer times than the release to ditches. Isolated wetlands that have been ditched drain to these ditches for relatively short periods following rain events. Between rain events (i.e., the majority of the time), isolated wetlands discharge via subsurface flow to groundwater beneath the surrounding upland soils. Thus, in general, we found that because regional groundwater level is suppressed by ditch networks, wetland surface water feeds groundwater in surrounding uplands and this is a significant component/proportion? of yearly water loss from wetlands.

Restoration. "Hydrologic restoration" of ditched isolated wetlands by placing weirs or other physical structures immediately downstream of depressional wetlands is likely to temporarily increase the residence time of water in the wetland and uplands immediately adjacent to the wetland. This may provide more contact time between the phosphorus and the soils, thereby increasing retention. However, water held back in this fashion will eventually drain to the landscape-scale ditch network via subsurface pathways if groundwater levels are lower than the water levels in the ditch. Effective "Ecological restoration" of ditched wetlands will therefore likely require that weirs be placed farther downstream so that the regional groundwater level is raised.

Riparian Wetlands

Riparian areas likely provide many functions within landscapes such as the Okeechobee Basin. Hydrology and soil properties of riparian buffers are thought to be fundamental to their functions. For example, riparian areas are reported to provide water quality services by retaining sediments and nutrients such as phosphorus from surface and subsurface inflows. We have no information regarding the management of these areas within the Basin to maintain riparian integrity and enhance their effectiveness to store phosphorus on a long-term basis. Knowing the hydrology and biogeochemical characteristics of riparian soils would help us estimate their contribution to phosphorus storage within the basin.

Constructed Wetlands

On-going research efforts show that constructed wetlands containing aquatic macrophytes (cattail, water hyacinths, submerged aquatic vegetation [SAV]) and water-tolerant pasture grasses (floralta limpograss and paragrass), can effectively remove phosphorus from both on-farm wastewaters and basin runoff. Research currently is underway to evaluate the best approaches for minimizing outflow phosphorus concentrations from these wetlands, as well as for reducing management costs and enhancing their sustainability. For some vegetation types, biomass harvesting has been shown to enhance wetland phosphorus removal performance, and likely improves sustainability. Water hyacinth and paragrass appear to be the most favorable vegetation types evaluated under a management regime of periodic harvest. Tilling of water hyacinth biomass into the soil may be a feasible alternative to harvesting. Constructed wetlands potentially can be used as edge of field systems, and at the farm and sub-basin scale in a cumulative effort to reduce phosphorus loads to Lake Okeechobee. Furthermore, it is likely that constructed wetlands can be integrated with chemical amendment application strategies to improve their overall phosphorus retention capacity and sustainability.

Streams

In general, phosphorus is stored by mineral components in stream sediments, while in wetland soils phosphorus storage is controlled by soil organic matter content.
Studies published in 1998 suggest that stream sediments that were impacted by dairy effluent tended to store less phosphorus than wetland soils; however this depended on site conditions, soil depth and nutrient loadings. We found during the 1990s that phosphorus stored in stream sediments tends to have a greater potential to release phosphorus at the

landscape-scale relative to wetland soils. Further, wetland soils had the capacity to retain additional phosphorus loads (taking into account phosphorus loads at that time) at the landscape scale (unpublished results). These dynamics between soil/sediments and overlying water could change dramatically following implementation of BMPs within the basin. Thus, it is important to quantify these interactions at the landscape scale in an effort to reduce P loads to the Lake on a long-term basis.

Lake Okeechobee

Suspension of phosphorus-laden sediments in Lake Okeechobee following severe weather (e.g., hurricanes) increase both the turbidity and P concentration of the water body. The nature (clay mineralogy) of the suspended colloidal materials and the water column chemistry influence suspension stability and water column phosphorus loads. Long-term stability (or easy dispersion of re-settled material) could have long-term impacts on water quality. Very little is known about the reactivity of suspended particles with respect to phosphorus release and retention.

- Lake Okeechobee mud sediment contains significant quantities of the magnesium silicate minerals sepiolite and palygorskite. These mineral particles are extremely small (nano-scale), with very low density and fibrous crystal habit, all properties that favor long-term re-suspension. However, their provenance and role in Lake turbidity have not been investigated.
- The mud sediments also contain dolomite, smectite, and calcium phosphate. These minerals, along with sepiolite and palygorskite, are abundant constituents of phosphatic geologic formations, suggesting that they may have been transported to the lake via streams traversing these formations.
- The provenance and composition of the mud sediment is pertinent to management issues related to phosphorus source and turbidity, as well as to possible effects of Kissimmee River canalization or restoration. For example, the rate of magnesium silicate delivery to the lake would relate to the longevity of prospective dredging benefits.
- Mud sediments of the lake probably also contain a lot of suspension-prone colloidal organic matter, which might scavenge soluble Ca by specific adsorption (forming organo-Ca complexes), accounting for the drop in dissolved inorganic calcium.
- Resuspended particles high in iron oxides may be more reactive in scavenging dissolved phosphorus from the aerobic water column.

Educational Programs

Awareness among agricultural producers, crop consultants and land managers about phosphorus management practices is crucial for successful monitoring of BMP adoption and implementation in the LOB. During the past 4 years, a training program on nutrients and land management has trained 182 people including crop consultants, agricultural and fertilizer industry representatives, producers, and personnel from various state agencies, etc. The educational program is led by the UF/IFAS faculty in collaboration with the USDA-NRCS, the FDEP, and the FDACS. Topics covered include- the NRCS Policies and Planning, CAFO/AFO regulations, Comprehensive Nutrient Management Plans, Soils of Florida, Use of County Soil Survey Reports, Manures and Waste Management, Nutrient Management, the Florida Phosphorus Index, Nutrient Movement and Water Quality.

Other educational activities include: information transfer from this project to the Environmental Service Pilot Project; providing technical information and on-camera talent to highlight water quality issues and BMP integration efforts in a PBS documentary to air in 2006-2007 related to Everglades restoration; and the continued collaboration between a CSREES grant titled *"Wetland Enhancement Decision-Making Tools/Training for Landowners and Technical Service Provide"* and this project.

Unknown – Research Needs

Watershed-Scale

There has been a large investment in monitoring infrastructure at the Buck Island Ranch and the Palaez ranch in the LOB. Monitoring at these ranches should continue in order to build a long-term record of water fluxes and phosphorus-load from cow-calf operations under a wide range of land management and climatic conditions. Maintaining this type of intensive monitoring at a few strategic locations will allow development of improved hydrologic and water quality models which will have the capability to extrapolate these observations into predictions over the entire region.

The LOB is undergoing land use changes. Several ranches are expected to be converted to small ranchettes or other more intensive agricultural operations. Currently, it is not known what effect these land use changes will have on the hydrology (total flow, peak flow, and residence time) and P discharges. To meet the TMDL for Lake Okeechobee, it is important to understand the effect of land use changes on the water quality. The Pelaez ranch is likely to be converted from a cow-calf operation to small ranchettes over the next few years. Monitoring at this site should continue during and after this conversion to quantify the effect of this land use change on phosphorus loads, as well as help quantify the lag time between land activities and the resulting phosphorus discharges.

Due to the high phosphorus loadings and generally high phosphorus concentrations in the watershed north of the lake, it is unlikely that strictly ecologically engineered systems alone (e.g, STAs) will adequately reduce loadings to the extent needed to meet the TMDL target for Lake Okeechobee. Therefore, additional remedial measures may be needed to meet the TMDL goal. Several potential strategies are described in the following sections.

There is a need to obtain a better estimate of soil phosphorus storage and the sustainability of that storage in different landscape units such as uplands, wetlands, streams and ditches. Knowledge of the environmental parameters controlling storage are needed to adequately ascertain the phosphorus dynamics in the system. Understanding relationships between and among landscape properties and soil phosphorus within a spatially explicit context will improve our ability to translate results from site-specific/farm scales to the basin scale. We need to determine soil test indicators to better estimate thresh-hold concentrations and phosphorus storage/release potential spatially, at the landscape level, and also over time.

Organic and inorganic soil amendments could play a role for in-situ remediation of phosphorus "hot spots" in the Basin. This may include not only uplands, but also some of the isolated wetlands that may have been already saturated with phosphorus. Edge of field, farm and sub-basin-scale constructed wetlands could be used to intensively manage phosphorus-laden waters, either alone or in combination with chemical amendments.

Some specific research needs for each landscape unit of the Lake Okeechobee Basin are described below:

Uplands

To evaluate the feasibility of using water table management to control phosphorus loss in drainage water from upland soils we need to address several questions:

- What are the soil parameters that will control the retention and release of phosphorus to drainage water during water table manipulation? Will soils behave differently based on profile characteristics suggesting that water table manipulation may be feasible for some soils and not others?
- Is the currently observed phosphorus release from some soils only a temporary response to raising the water table? How long will this phosphorus release continue and will it eventually stabilize at a low level?
- Does the initial phosphorus source influence the retention and release of phosphorus? For example, phosphorus from dairy manure does behave differently in soil than phosphorus from beef cattle manure.
- What biogeochemical processes regulate organic phosphorus mineralization in grassland pasture root zone during high water-table conditions?
- What is the spatial extent and distribution of spodic horizons critical for transport processes of phosphorus?
- What is the travel time from the soil surface to the spodic layer, and from the spodic layer to the ditches?
- What percent of the water infiltrating into the soil and reaching the spodic layer moves laterally to the ditches and what percent of it moves below the spodic layer and does it go through the spodic itself or through breaks in the spodic layer?

Remedial measures may include retrofitting some farms or ranches for strategic application of chemical amendments to immobilize soluble phosphorus. Note, however, that we do not promote widespread application of alum or WTRs on farms until additional assessments can be performed on their long-term effectiveness and potential adverse impacts. Since chemical amendments are viewed as a potential key solution, it is important to conduct basic studies to determine the biogeochemical controls regulating the long-term effectiveness of phosphorus retention. Studies also should be performed to address some testing of amendment impacts on crop (e.g. pasture grasses) growth and tissue quality. In addition to amendments, edge of the field, farm and sub-basin managed constructed wetlands maybe very effective in reducing phosphorus loads. Application of chemical amendments may also modify the soil hydrologic properties which may affect the movement of water within the soil. Studies by UF-IFAS in 2006 have shown that organic amendments can affect the water retention properties of the soil as well as upflux of water from the water table. The effect of chemical amendment on the water movement within the soil needs to be quantified to better understand the total effect of amendments on the phosphorus movement within the soil.

On-going studies suggest that it may be feasible to reduce soluble phosphorus in dairy manure by dietary manipulations other than those involving reductions in phosphorus concentrations or forms. Additional studies need to be conducted to focus on the importance of feed supplements such as magnesium and calcium as potential controlling factors in phosphorus solubility of dairy manure. Any dietary manipulation that reduces soluble phosphorus in manure without adversely affecting animal health would assist in reducing phosphorus loss from manure-impacted soils. The same may be true for beef cattle operation, where total phosphorus import in feed is smaller than in dairy operations but is a major phosphorus input to cow-calf operations.

The ability to interpret analytical results of soil, tissue and water tests, and formulate nutrient recommendations for specific intended use, is a crucial aspect of maintaining desired water quality. Recent studies show that remote sensing techniques, visible/near infrared diffuse reflectance spectroscopy (VNIRS) can be used as a substitute for wet chemistry methods to determine soil and plant tissue concentrations. These methods are rapid, cost-effective and non-destructive to samples. Regional VNIR spectral libraries for the LOB would facilitate the monitoring of phosphorus in soils and tissue across the basin at different time periods. These space-time monitoring techniques offer new avenues to document change in phosphorus in soils and vegetation, and ecological status that occurs across the whole basin. Additional validation and calibration of the method is needed for use of this method at the watershed scale.

Remote sensing (e.g. ASTER, Quickbird, IKONOS satellite imagery) based mapping of landscape characteristics (e.g. land use, land cover, Leaf Area Index, Normalized Difference Vegetation Index) provides dense data grids (e.g. 15 to 1 m spatial resolution) that can be related to sparser measured field observations (e.g. soil phosphorus) across the basin. Novel geostatistical upscaling methods are rooted in the approach of environmental correlation relating sparse (costly and labor-intensive analytical datasets such as dissolved, particulate and total phosphorus) to dense remotely-sensed environmental data to predict soil properties across the whole basin. Such multivariate geostatistical methods include cokriging, regression kriging, kriging with an external drift, spatial stochastic simulations and others. The geospatial output maps describe gradual changes in soil phosphorus or other properties across large landscape units.

Remote sensing techniques are valuable to derive landscape information grids across large basins at high spatial resolutions.

Ditches

Cattle/Ditch Interactions and Effects on Water Quality. The effect of ditch access by cattle on downstream water quality is not adequately known at this time. Grazing, trampling and direct deposition of animal waste within water conveyance ditches likely contributes to downstream nutrient loading. Because of the proximity of these animal activities to surface water the potential impacts to water quality are greater. However, the specific extent of these actions relative to similar animal activities within wetlands or upland areas is also not quantified. Thus, we need basic information relative to this effect to provide information on herd management from a soil biogeochemical perspective. Innovative GPS-based monitoring of cattle movement could elucidate the frequency of cattle-ditch interaction and their impact on water quality.

Phosphorus Assimilative Capacity. Quantification of ditch EPC or nutrient assimilative capacity has not been extensively evaluated. Water flows in ditches are often ephemeral, making them prone to phosphorus release upon reflooding after a drawdown period, a phenomenon that also can be influenced by soil organic matter and mineral soil components. Ditches are also often groundwater discharge points to surface waters. Evaluating existing EPC in ditches and determining the effectiveness of soil amendments to lower ditch EPC would be valuable, as it would provide a management method for reducing phosphorus concentrations in ditch surface waters. For example, selected farm/pasture ditches that receive and convey surface flows could be supplied with an amendment onto the ditch bottom sediments. By contrast, other ditches that likely receive subsurface flows from adjacent pastures could be equipped with a subsurface amendment "barrier", consisting of amendments tilled to appropriate depth(s) into soils adjacent to the ditch. Such a barrier potentially would remove phosphorus from subsurface pasture flows just before they enter ditches. Experimental parcels for testing these amendment approaches would be fenced to exclude animals. Studies could be performed to assess phosphorus removal performance of "amended" vs. "unamended" ditches (and/or wetlands). Obviously, key factors to evaluate would be the overall ability of the amendments to reduce phosphorus concentrations under various flow/load regimes, as well as the longevity of the amendments to retain phosphorus.

Monitoring studies should be conducted over a large section of the ditch and efforts are needed to quantify the residence time of water in different types of ditches (ditch slope, depth, and width) for different hydrologic conditions (dry versus wet period,). This may include mesocosm studies in several ditches in different parts of the basin that will further enhance the understanding of the phosphorus retention capacity of these ditches. The data from the actual in-ditch studies on phosphorus retention can be combined with the residence time data to develop BMPs that will optimize the phosphorus retention in the ditches. Ditch cleaning is a major management factor but little is know about its effects on nutrient transport. Projects to examine the effect of ditch cleaning and ditch vegetation management on nutrient transport might help determine whether specific practices could be adopted that minimize nutrient runoff or enhance nutrient retention.

Isolated Wetlands

Soil Accretion Rates. Because organic matter appears to play a significant role in P assimilative capacity within isolated wetlands, a better understanding of factors regulating carbon deposition and quality characteristics needs to be developed. Investigating litter recalcitrance and decomposition rates of common vegetation species is ongoing under existing projects. However, sediment accretion rates within wetlands are not well defined. It is important to understand how these rates can be influenced by various grazing management practices and hydrologic management regimes. Better information about soil accretion rates will enable us to predict phosphorus storage as a function of accretion.

Practices to Lower Wetland EPC. Mechanisms to lower EPC within wetland soils should be investigated. The lower the EPC, the lower the potential concentration of phosphorus discharged to downstream waters. Although the storage potential of phosphorus is high in wetlands, the water column concentration in isolated wetlands can often be high, resulting in greater than desired phosphorus discharge concentrations. Application of soil amendments directly to wetland soils during dry periods, or in association with a downstream discharge point, may provide a means to lower phosphorus concentrations from the water column, thereby lowering surface water phosphorus concentrations.

Selected farm/pasture isolated wetlands that receive and convey surface flows could also have amendments applied onto the soil surface. The potential of both organic (high carbon to phosphorus ratio organic materials) and inorganic amendments should be tested. Experimental parcels would be fenced to exclude animals (in case of toxicity concerns). Studies could be performed to assess phosphorus removal performance of “amended” vs. “unamended” wetlands.

Hydrological Restoration. The following questions need to be addressed to improve hydrologic restoration of isolated wetlands.

1. What is the residence time of water in the wetlands with different topographical and vegetation characteristics
2. Where in the landscape should weirs be placed to restore hydrology and/or ecology of isolated wetlands?
3. How should the weirs be managed? For example, at what elevation should the weirs be kept, should the weirs be constant throughout the year or they should be changed seasonally to increase the phosphorus retention?
4. How will elevated water levels in the pastures affect phosphorus release from upland soils? How long will this release be sustained?
5. What are the biogeochemical processes regulating release of both organic and inorganic phosphorus into the water column?
6. What are the dynamics of phosphorus exchange and transport among uplands, wetlands, and ditches?

Methods to address the above questions could include monitoring water and phosphorus export from pastures with weirs located at different distances away from the isolated wetland-ditch interface. Current field monitoring is focused at the wetland-scale with limited ranch-scale monitoring. It is important to increase this scale to larger pasture and ranch-scale monitoring and to identify sites where weirs have been (or can be installed) at such locations. With this approach, we would be able to estimate the impact of weir location and the cumulative effect of locating weirs at different locations on restoring landscape hydrology at several escalating spatial scales.

While field studies are critical to understanding the phosphorus movement within a ranch, testing all the possible scenarios through field studies may not be feasible. Therefore, efforts are needed to develop or modify existing hydrologic/water quality models and utilize the monitoring data to improve their predictive capabilities. Predictive capability for water flow and phosphorus transport in the integrated continuum of uplands-wetlands-ditches is needed. Hydrologic and biogeochemical understanding will be coupled in such a predictive model. Existing hydrologic models (such as MIKE-SHE/MIKE 11, WAM, ACRU or new models) could be coupled with appropriate biogeochemical reactions. These reactions and associated parameters will be specific for the different systems of upland soils, wetlands, and ditches. Application of such a model calibrated to field data will enable prediction of phosphorus exchange among uplands/wetlands/ditches. Management scenarios that would be costly and time-consuming to evaluate by field trial will be evaluated using the model. Examples of such scenarios include predicting the effects of: (a) downstream distance of weir location on water and phosphorus storage within the landscape; (b) static versus dynamic management of weir board height on water and phosphorus storage and discharges from the landscape, (c) focused application of amendments (e.g., WTRs) at hydrologic interfaces such as along the edges of ditches, and (d) effects of fencing on phosphorus discharges from a ranch.

Accuracy of hydrologic model predictions depends on the availability of long-term hydrologic and water quality data that includes dry, normal, and wet years. Long-term monitoring of hydrologic restored wetlands at the current four sites: Buck Island, Palaez, Larson, and Beatty ranches) should be continued. Data collected from these sites should be incorporated in the models described above.

Riparian Wetlands

We have little information on the hydrology and soil characteristics of riparian buffers in the Okeechobee Basin. Riparian areas provide water quality services by retaining sediments and nutrients and buffering surface and subsurface inflows. Thus, the strategic use of riparian buffers in the Okeechobee Basin may be a useful management practice, as they are applied wide-scale in other agricultural watersheds. Some of the questions that would need to be answered could include:

- Are riparian wetlands a significant land portion of the LOB?

- Are riparian wetlands/buffers receiving their water inputs from surface or subsurface inputs or both?
- How long are waters retained in these systems? Long water residence times would indicate the potential for increased nutrient storage and retention.
- What are the nutrient loads that are being discharged to and retained by these systems?
- What are the phosphorus characteristics of riparian wetland soils/sediments and is phosphorus stored in readily available forms or in recalcitrant forms? Knowing this would help managers determine whether phosphorus is stored on a short- or long-term basis.
- What are the most effective types of riparian wetlands: forested, emergent marsh, open water type areas?

Constructed Wetlands

The use of constructed wetlands at field-scales has only been partially addressed; work undertaken has included using both passive and actively-managed wetland configurations. However, the following questions need to be addressed:

- What are the most appropriate configurations to help store water and/or retain phosphorus on a long-term basis?
- Where does one best deploy a constructed wetland for phosphorus removal: edge of field, edge of farm, at the sub-basin-scale or a combination of all? Strategically placing constructed wetlands in the landscape may result in better treatment effectiveness.
- Can constructed wetland soils be amended to increase their effectiveness for long-term P retention, and what are the best amendments?
- Can tilling of plant biomass of productive species such as water hyacinth into wetland soils be an effective means of sequestering phosphorus on a sustainable basis? Can sustainability of phosphorus storage be enhanced by the use of chemical amendments?
- At the various scales previously mentioned, can constructed wetlands be used to effectively retain and/or treat periodic storm runoff pulses, as opposed to just steady state flows?

Long-term monitoring of existing constructed wetlands should be continued to gain insight into the longevity of certain configurations to effectively retain phosphorus. Using constructed wetlands in conjunction with amendment applications should be investigated as intensive remedial measures that may be suitable for integrating into a particular BMP.

Streams

Prior investigations on streams in the Okeechobee Basin suggest that most streams have been impacted by phosphorus loadings. Thus, streams are now storing more phosphorus than they historically did due to increased loadings from uplands. It has been demonstrated that under increased phosphorus loadings, mass phosphorus storage also increases. The biogeochemical properties that govern long-term phosphorus storage in streams may be different in wetlands and other landscape units. While we have addressed some of these fundamental processes in the past, there remain additional research needs. For example,

- In a landscape that is undergoing decreases in phosphorus loadings, what happens to stream sediments that have elevated sediment phosphorus concentrations?
- Are water inputs into streams mostly surface or subsurface?
- There is little information on travel time of waters in streams. A better understanding of water residence times would be useful for estimating the potential nutrient reductions achievable in streams. Such information could be obtained by modeling, or by performing chemical tracer studies in strategically important streams of the LOB.
- Effect of cattle accessing stream systems on sediment and water quality?

Lake Okeechobee

Currently, Lake Okeechobee is turbid as a result of suspension of mud sediments into the water column following severe weather (e.g., high winds associated with storms and hurricanes). The nature (clay mineralogy) of the suspended colloidal materials and the water column chemistry influence suspension stability and water column phosphorus loads. Long-term stability (or easy dispersion of re-settled material) could have long-term impacts on water quality. Preliminary data show that suspended solids contain fine magnesium silicate particles which tend to stay suspended in the water column. In addition, suspended organic matter can also complex dissolved calcium thus affecting settling of particles. It is critical to understand the reactivity of suspended solids with respect to phosphorus retention and settling characteristics. Some of the basic questions to be addressed for in-lake management of suspended solids and associated phosphorus include:

- What are the physico-chemical and mineralogical characteristics and settling rates of suspended solids?
- What factors (such as ionic chemistry of the water column, organic matter content, pH, and others) influence the settling rates?
- What is the contribution of available nutrients to the water column from resuspension and diffusion?
- What is the reactivity of suspended solids in the water column with respect to phosphorus retention and release?
- What in-lake management strategies (such as addition of Ca-based or Al-based chemical amendments) can be used to settle suspended solids?
- How quickly can the nutrients settle out of the system and how stable are the settled suspended solids?
- How much of the phosphorus is removed permanently from the available pool by formation of stable minerals with calcium and magnesium?

Synthesis and Development of Management Tools

It is essential to synthesize the research output from different subprojects conducted at different spatial and temporal scales in the LOB. This can be accomplished by integrating the mapped soils, land use (wetland, upland, etc.) and other environmental properties at site-specific, farm and basin scales into a geodatabase. This database will be the core access point for information and knowledge sharing. Knowledge gained on ecosystem processes (e.g. phosphorus fate and transport) will be translated into algorithms stored in the form of objects (classes) within an existing model framework housed at IFAS/UF. For example, one algorithm might describe the effect of amendments on phosphorus retention in wetlands, while another algorithm describes the effect on soil phosphorus of water table fluctuations. Routing routines will be developed to connect objects to build a knowledge management modeling system that works across different spatial scales. Because the model is object-oriented it is scalable and easy to update with new information that becomes available. After testing and validating the system it can be used in scenario mode to evaluate land use change, hydrological restoration, best management practices and more.

It is important that all new research initiatives lead to the development and implementation of management tools/approaches for rapidly reducing phosphorus loads to Lake Okeechobee. Information from the above research projects should be disseminated to the clientele, producers, managers, and agencies, through extension educational programs such as demonstrations, in-class and hands-on training sessions, fact sheets, electronic media such as videos, CD-ROMs, web-sites, radio/TV-spots, etc. Because the primary objective of several of these projects is to address one or more of the specific aspects of water quality, tool(s) should be generated that can be readily implemented. Examples of such tools include enhancements to the Florida P-Index, enhancements to the diagnostic soil, tissue testing, laboratory/field tests to assess phosphorus retention capacities of soils and wetlands, characterization of wetlands, etc.

Contributors

M. Adjei; M. Annnable; P. Bohlen; M. Brenner; K. L. Campbell; M. Clark; T. A. DeBusk; E. Dunne; D. A. Graetz; W. D. Graham; S. Grunwald; W. G. Harris; J. Jawitz; R. Mylavarapu; G.A. O'Connor; V. D. Nair; J. E. Rechcigl; K. R. Reddy; D. Rhue; S. Shukla, M. L. Silveira, and L. Sollenberger

Contact: K. R. Reddy (krr@ufl.edu)

List of Publications

Dunne, E. J, K. A. McKee, M. W. Clark, S. Grunwald, and K. R. Reddy. 2007. Phosphorus in agricultural ditch soil and potential implications for water quality. Journal Soil and Water Conservation. 62:244- 252.

Dunne, E. J, J. Smith, D. B. Perkins, M. W. Clark, J. W. Jawitz, and K. R. Reddy. 2007. Phosphorus storages in historically isolated wetland ecosystems and surrounding pasture uplands. Ecological Engineering. 31:16–28.

Dunne, E. J., K.R. Reddy, and M.W. Clark. 2006. Biogeochemical indices of phosphorus retention and release by wetland soils and adjacent stream sediments. Wetlands. 26:1026-1041.

Dunne, E.J, K.R. Reddy, and M.W. Clark. 2006. Phosphorus release and retention by soils of natural isolated wetlands. International Journal of Environmental Pollution. (In press).

Fisher, M. M, K. R. Reddy, and R. T. James. 2005. Internal Nutrient Loads from Sediments in a Shallow, Subtropical Lake. Lake and Reservoir Management. 21:338-349.

Reddy, K. R., M. M. Fisher, Y. Wang, J. R. White and R. Thomas James. 2007. Potential effects of sediment dredging on internal phosphorus loading in a shallow, sub-tropical lake. Lake and Reservoir Management. 23:27-38.

List of Thesis and Dissertations