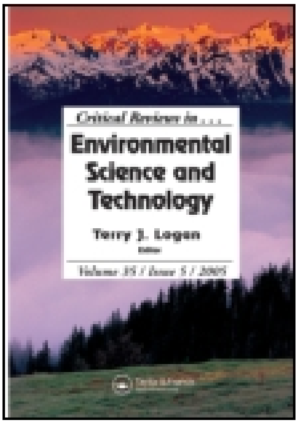

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Best Management Practices and Long-Term Water Quality Trends in the Everglades Agricultural Area

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The Everglades Agricultural Area (EAA) in South Florida, part of the historical Everglades, was initially drained in the early 20th century for agriculture and flood protection. The organic soils have been subject to subsidence caused by organic matter oxidation. Soils are deeper east of Lake Okeechobee compared to soils south of the lake. The area is mostly planted to sugarcane and other crops such as rice, vegetables, and sod. Concerns about quality of water leaving the EAA led to a regulatory program for mandatory best management practices (BMP) since 1995 to reduce phosphorus (P) loads out of the EAA by 25% compared to historical levels. The program is highly successful, with 100% grower participation and exceeding P load reduction required by law. Trend analysis conducted on selected EAA farms, subbasins, and whole basin show, in general, decreasing trends in P concentrations, drainage flow, and P loads. Differences are noted between farms and subbasins due to factors that include rainfall distribution, water management practices, irrigation water quality, soil type/depth, and cropping systems. Water management practices were the dominant factors affecting P loads out of the EAA. Water management research that targets farms with deeper soils is recommended to achieve additional P load reductions. Other practices to improve BMP performance include minimizing generation and transport of sediments from farm

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canals. The quality of irrigation water from Lake Okeechobee is of concern of its impact on BMP performance.

KEYWORDS: Best Management practices, drainage, Everglades, Agricultural Area, Florida, organic soil, phosphorus, sugarcane, water quality trends

1 THE EVERGLADES AGRICULTURAL AREA

1.1 Introduction

The Everglades is the largest contiguous body of organic soils in the continental United States (Hammar, 1929; Stephens, 1956) originally occupying approximately 778,000 ha (L. A. Jones, 1942). A portion of the northern Everglades was drained at the beginning of the century for agricultural and urban purposes, becoming what is known today as the Everglades Agricultural Area (EAA). The EAA basin is located south and east of Lake Okeechobee and north and west of three Water Conservations Areas (WCAs) in Florida (Figure 1). The EAA comprises an area approximately 283,300 ha planted mostly with sugarcane (*Saccharum* spp.), with the remaining arable land planted to winter vegetables, sod and rice (*Oryza sativa* L.). Sugarcane production in South Florida expanded after the political unrest in Cuba in 1960. From 1960 to 1964 new sugarcane mills were constructed near the southern and eastern shores of Lake Okeechobee and sugarcane production increased from 20,600 to 90,200 ha (Fairbanks, 1969). By the, 2000–2001 harvest the total acreage reached 183,874 ha, with about 75% grown in the organic soils of the EAA (Baucum et al., 2006). The Florida sugar industry is a major component of the agricultural economy of the state, with revenues contributing over $2 billion a year to the economy of South Florida (Alvarez and Polopolus, 2002). Sod production in Florida has an estimated value of more than $300 million a year, with 37,670 ha planted in 2003. Around 23% of sod production in Florida is grown on organic soils around Lake Okeechobee (Haydu et al., 2005), making it a major agricultural commodity in South Florida. Vegetable acreage in the EAA was around 2,500 ha in 2007/08 harvest.

1.2 Geology and Soil Formation

The majority of the organic soils within the EAA are underlain by the Pleistocene-age Fort Thompson formation consisting of alternating beds of limestone, shell, sand, and marl, which are often perforated by solution holes. These beds were deposited during the inundation of ocean waters. Near the southern border of the EAA, this rock formation grades into another formation of softer and more porous rock called Miami oolite. Along the western

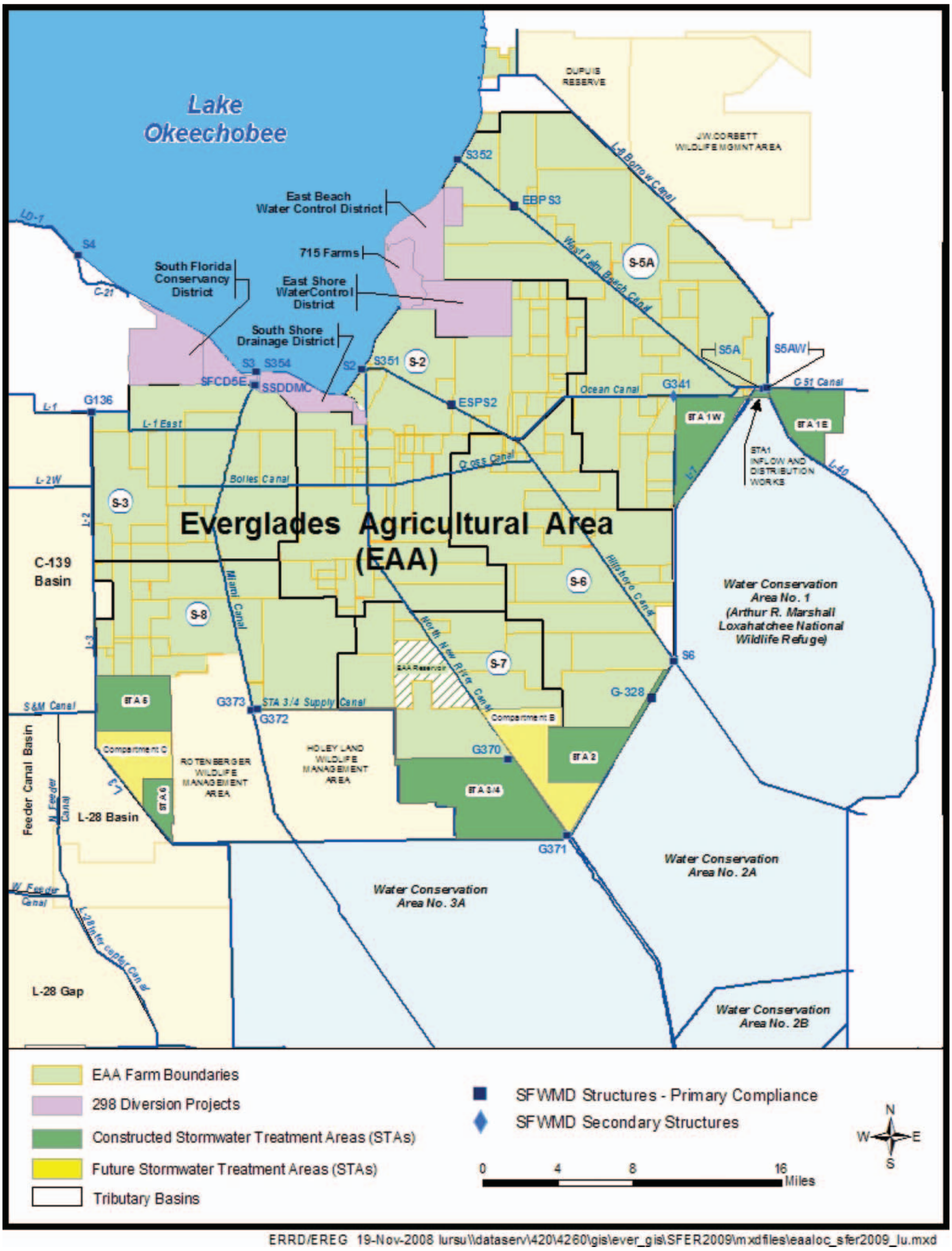

FIGURE 1. The Everglades Agricultural Area (EAA) basin and primary compliance water control structures used to assess load reduction performance. The subbasins S5A, S2/S6, S2/S, and S3/S8 are indicated. Water Conservation Areas (WCA), storm treatment areas (STA), and irrigation structures from Lake Okeechobee (S352, S2, S3) are also indicated on the map. (This figure is available in color online.)

edge, the organic soils are underlain by sandy material (Cooke, 1945; Snyder et al., 1978). In past geologic times, Lake Okeechobee overflowed its south and eastern rims during the rainy season each year, inundating the Everglades basin and providing a suitable environment for accumulation of the present organic soils. The majority of these soils were derived from growth of emergent reed and sedge-like plants, mainly sawgrass (*Cladium jamaicense* Crantz). Histosols in the EAA began to form approximately 4,400 years ago (McDowell et al., 1969). Initially, it took about 800 years to produce the first 7.6 cm of the basal muck peat, composed of a mixture of marl and organic matter.

Historically, the Everglades basin was inundated for a large part of the year. Water was high enough to maintain anaerobic conditions permitting continuation of peat development until shortly after 1906, when the Everglades Drainage District began construction of the first drainage canal. By 1914, the peat average depth was 3.65 m (Stephens, 1956). This depth corresponds to an average accumulation of 8.4 cm per century. Although the early attempts at draining the area were unsatisfactory for commercial farming, the water balance was disturbed to a point that aerobic conditions were prevalent. After this time, the process of peat accumulation was reversed and destruction of the soil by microbial oxidation began (Stephens, 1956).

1.3 Soil Types and Soil Subsidence

The soils of the EAA, classified as Histosol (suborder: saprist), were formed under anaerobic conditions (Snyder and Davidson, 1994). These organic soils generally contain more than 85% organic matter by weight, and are derived from hydrophytic vegetative residues (Cox et al., 1988; Snyder, 1994). The organic soils in the EAA are classified on the basis of their organic matter content, degree of decomposition of the organic material, depth of organic material over mineral layer, and composition of mineral layer (Rice et al., 2005). Except for organic soils found adjacent to Lake Okeechobee (Torry series), most soils in the EAA have a mineral content less than 35%.

Drainage of organic soils for agricultural purposes results in the loss of soil through rapid breakdown of organic matter resulting in what is known as soil subsidence. *Subsidence* of the organic soils in the EAA is defined as a loss of soil depth and volume caused by shrinkage, compaction, and water and wind erosion. However, biological oxidation of soil organic matter accounts for most of the soil loss (Volk, 1973). Subsidence has been reported to be greatest during the first few years after drainage (Thomas, 1965). Stephens and Johnson (1951) concluded that the rate of subsidence would be approximately 30.54 cm (12 inches) per decade. Shih et al. (1979) reported a subsidence rate of 2.54 cm (1 inch) per year across the EAA. In more recent studies scientists have re-measured surface elevation along base subsidence lines in 1997 and concluded that the average subsidence rate has decreased to 1.45 cm (0.57 inch) and speculated that maintenance of higher water table in recent years was one of the major reasons for the reduction of the subsidence rate (Shih et al., 1998). The higher water tables have been observed to cause decreased rates of microbial activity and soil organic matter oxidation (Morris et al., 2004).

The depth of the organic soils (O horizon) has been measured across the EAA for the Soil Survey of Palm Beach County in 1973 (McCollum et al., 1978) and in 1988 by the use of ground-penetrating radar (Cox et al., 1988). The main soil series in the EAA with O horizon depth in parenthesis are Torry (>130 cm), Terra Ceia (>130 cm), Pahokee (92–130 cm), Lauderhill (51–92 cm), and Dania (<51 cm). It is noted that the northeastern EAA (S5A and S6 subbasins) have the deepest soils. Terra Ceia and Pahokee are the dominant soil series in the S5A subbasin, while Lauderhill and Pahokee are the dominant series in the S6 subbasin. The south and southwestern EAA (S7 and S8 subbasins) have the shallowest soils where Lauderhill and Dania are the dominant soil series. The depth of the soil and proximity to the limestone bedrock may have a direct implication on drainage and quality of drainage water leaving these soils.

2 BEST MANAGEMENT PRACTICES PROGRAM IN THE EAA

2.1 Best Management Practices Permit—Rules and Regulations

Best management practices (BMPs) have been implemented in the United States and worldwide to reduce phosphorus (P) pollution, eutrophication, algal blooms, fish kills, and improve water quality (Keipert et al., 2008; Sharpley et al., 2000; Sharpley et al., 2001; Way, 2007; Zeimen et al., 2006). BMPs for P include manure management (Garcia et al., 2008; Sharpley et al., 2007), soil testing, and use of P indices (DeLaune et al., 2004; Sharpley et al., 2008). Other BMPs target P transport mechanisms in the watershed (Kleinman et al., 2006; Sharpley et al., 2008). Concerns about water quality out of the EAA led to a mandatory BMP program for reducing P loads from the EAA farms in South Florida. The program was implemented basin-wide in 1995 as required by the Everglades Forever Act (EFA) passed by the Florida State Legislature in 1994 and amended in 2003.

In accordance with the EFA, BMP implementation guidelines for the EAA have been outlined in a South Florida Water Management District (District) regulatory rule, Chapter 40E-63, Florida Administrative Code (FAC). Rule 40E-63 states that the use of Everglades Works of the District within the EAA basin requires a permit for a BMP plan for each crop or land use within each subbasin or farm. The BMP plans are comprehensive, generally consisting of nutrient management, water management, and sediment controls.

2.2 BMP Plans and Implementation

BMP plans are implemented by individual permittees and approved through the regulatory program with the intent of providing a comprehensive plan. Table 1 provides a general description of BMPs that can be implemented to meet permit requirements. The list is not exhaustive and implementation of other applicable BMP options is allowed. The BMPs are divided in four basic categories consisting of water management practices, nutrient control practices, control of sediment and particulate matter, and pasture management (if applicable). The District must ensure that BMP plans between different permittees are consistent and comparable. To accomplish this task, a system of BMP equivalents was developed by assigning points to BMPs within the four basic categories (Table 1).

Three BMPs commonly employed by most EAA growers are application of P fertilizers according to calibrated soil tests, banding of P fertilizer using specialized application equipment, and fertilizer spill prevention under nutrient control practices (Table 1). Farm basins differ in their water management BMPs (e.g., the amount of rainfall they detain before drainage pumping is initiated). Rainfall detention amounts are 1.27 cm (0.5 inch) or 2.54 cm (1 inch). Farms with shallow depth commonly detain 1.27 cm, while deeper soils farm adopt the 2.54 cm detention. Farms that employ the 1.27 cm rainfall detention BMP usually adopt additional sediment controls in order to achieve a 25-point total of BMP points. Another BMP that varies between farms is the number and type of particulate matter and sediment control practices. The sediment control BMPs focus on both minimizing the transport of sediments off the farm and removing accumulated sediments from canals. Examples of sediment BMPs include laser leveling of fields, constructing ditch and canal sumps to trap sediments, slow drainage velocity near pumps, and a canal cleaning program (Table 1).

2.3 Monitoring for P Load Reduction by the District

The EFA mandates a basin level monitoring program to assess overall BMP program effectiveness. Total phosphorus (TP) loads from the surface water runoff attributable to the lands within the EAA basin have been evaluated on an annual basis, since initial implementation of BMPs, taking into account changes brought about from lands converted to Stormwater Treatment Areas (STAs), inflow sources from external basins, and the addition of new water control structures. For the EAA, runoff is generally directed to regional STAs before entering the Everglades Protection Area. To interpret TP measurements taken at inflow and outflow water control structures defining the boundary of the basin, it is important to recognize that water leaving the basin through these structures is a combination of farm- and urban-generated runoff and water passing through the basin canals from external basins. This

TABLE 1. Best Management Practices (BMP) summary and BMP equivalent points for the Everglades Agricultural Area (EAA)

BMP	PTS	DESCRIPTION
WATER MANAGEMENT PRACTICES		*MINIMIZES THE VOLUME OF OFFSITE DISCHARGES*
1/2 inch water detention	5	Delay pumping based on rain gage measurements.
1 Inch water Detention	10	Detention (in farm canals and soil profile) measured on a per-event basis—rainfall versus runoff
Improved infrastructure	5	Water table management plan; controlling levels in canals and field ditches using internal water control structures, fallow fields, aquatic cover crop fields, prolonged crop flood; effective irrigation and discharge plans
Other	tbd	Properly constructed and maintained storage system; greater detention with water management plan having target water table levels and structure operating procedures; monitored water table
NUTRIENT CONTROL PRACTICES		*MINIMIZES THE MOVEMENT OF NUTRIENTS OFF-SITE* **Limited Applicability*
Fertilizer application control	2 1/2	Uniform and controlled boundary fertilizer application (e.g., banding at the root zone; pneumatic controlled-edge application such as AIRMAX); calibrated application equipment; setbacks from canals
Fertilizer spill prevention	2 1/2	Formal spill prevention protocols (handling, transfer, education)
Soil testing	5	Avoid excess application by determining P requirements of soil
Plant tissue analysis	2 1/2	Avoid excess application by determining P requirements of plant
Split P application*	5	Applying P proportionately at various times during the growing season; total application not exceeding recommendation
Slow release P fertilizer*	5	Applying specially treated fertilizer that breaks down slowly thus releasing P to the plant over time
PARTICULATE MATTER AND SEDIMENT CONTROLS		*MINIMIZES THE MOVEMENT OF PARTICULATE MATTER AND SEDIMENTS OFF-SITE (Each consistently implemented across the entire basin acreage.)*
		• leveling fields • cover crops
Any 2	2 1/2	• ditch bank berm • raised culvert bottoms
Any 4	5	• sediment sumps in canals • stabilized ditch banks
Any 6	10	• sediment sumps in field ditches • aquatic plant management
		• canal/ditch cleaning program • debris barriers at outfall
		• slow drainage velocity near pumps
		• sediment sump upstream of drainage structure

TABLE 1. Best Management Practices (BMP) summary and BMP equivalent points for the Everglades Agricultural Area (EAA) *(Continued)*

BMP	PTS	DESCRIPTION
PASTURE MANAGEMENT		*PLAN FOR ON FARM OPERATION AND MANAGEMENT PRACTICES*
Pasture management	5	• reduce cattle waste nutrients in discharges by "hot spot" management (i.e., plans for placement of drinking water, feed and supplements, cow pens, and shade) • low cattle density
OTHER BMPs		*OTHER PRACTICES PROPOSED*
Urban xeriscape	5	Use of plants that require less water and fertilizer
Det. pond littoral zone	5	Vegetative filtering area for on-site storm water runoff
Other BMP proposed	tbd	BMP proposed by permittee and accepted by SFWMD

pass through water includes discharges from Lake Okeechobee, and several tributary drainage areas that historically discharged to Lake Okeechobee that are now diverting a majority of discharges into the EAA. The tributary areas are referred to as the Chapter 298 District diversion areas (298 districts). Depending on the inflow source and the entry point into the EAA basin, water quality within the basin can be influenced, although the extent of the influence is generally difficult to interpret.

Presently, the basin-level compliance determination is based on monitoring at various inflow and outflow points defining the boundary of the subbasins (S5A, S2/S6, S2/S7, and S3/S8) in any given water year (WY) and the conveyance canals serving those subbasins (Figure 1). Farm-level discharges from individual farms are monitored as well for TP and flow. Farm-level compliance determinations would only be made in the event that the basin-level monitoring indicates the EAA as a whole has not met the EFA required performance level for P reductions.

2.4 Phosphorus Load Reduction in the EAA Exceeds the 25% Mandated by Law

The EFA mandates specific performance levels for controlling P in discharges from the EAA. The EAA basin is required to achieve a reduction of the TP loads discharged from the basin of 25% when compared to the pre-BMP baseline period (October 1, 1978 to September 30, 1988). The legislature also provided for a tax incentive credit against the Everglades Agricultural Privilege tax for any P load reductions achieved in excess of 25% in order to encourage BMP performance and maximize load reduction. Basin-level compliance determinations are made annually and are based on a WY spanning 12 consecutive months beginning on May 1 and ending on April 30 (i.e., WY08, is May 1, 2007 to April 30, 2008). Since WY96, which was the

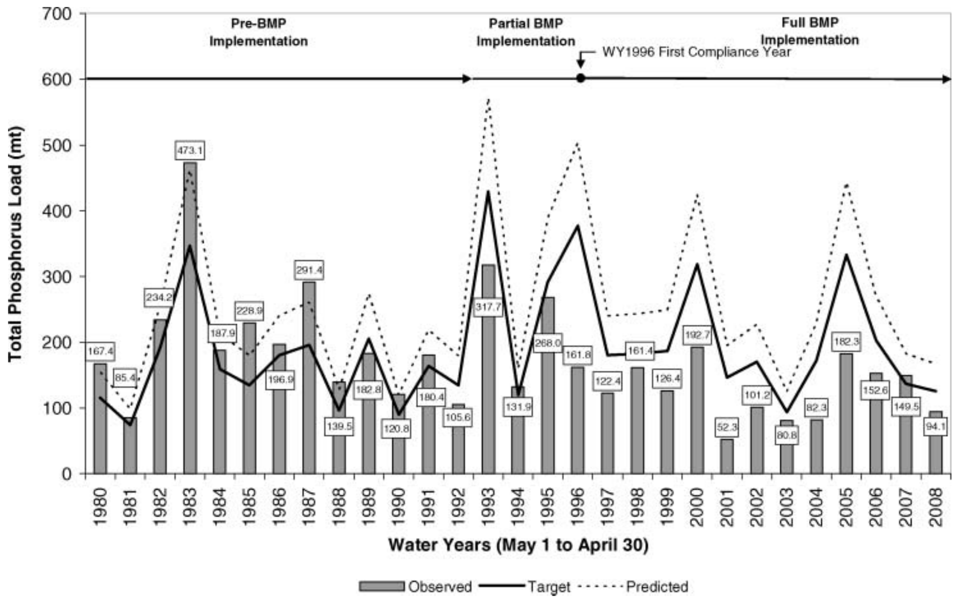

FIGURE 2. Annual basin-level total phosphorus load from the Everglades Agricultural Area (WY1980–2008).

mandated first year of compliance evaluation for TP load reductions, the EAA basin has consistently achieved compliance. Figure 2 shows the annual TP loads observed from EAA runoff in comparison to the target load for that year, and in only one instance (WY07) did the observed annual TP load exceed the target load resulting in an 18% reduction compared with baseline conditions. However, the basin remained in compliance because the rule requires three consecutive years in failing to meet the 25% reduction requirement as evidence the basin has not achieved the desired performance level. Overall, the present BMP program has been successful in achieving an approximate 50% long-term average load reduction overall from the EAA basin (Figure 3).

3 LONG-TERM WATER QUALITY TRENDS IN THE EAA AFTER IMPLEMENTING BMPS

3.1 Water Quality Trends of Selected EAA Farms

Seasonal Mann-Kendall trend analysis of aggregated monthly metrics of flow, P concentration, and P load was conducted on randomly selected farms with different size, soil classification, and cropping systems from various subbasins in the EAA (Table 2). Water quality parameters of these farms were obtained from the EAA-BMP permit database. The SAS program used for Mann-Kendall analysis was adopted from Winkler (2004). The farms were either strictly

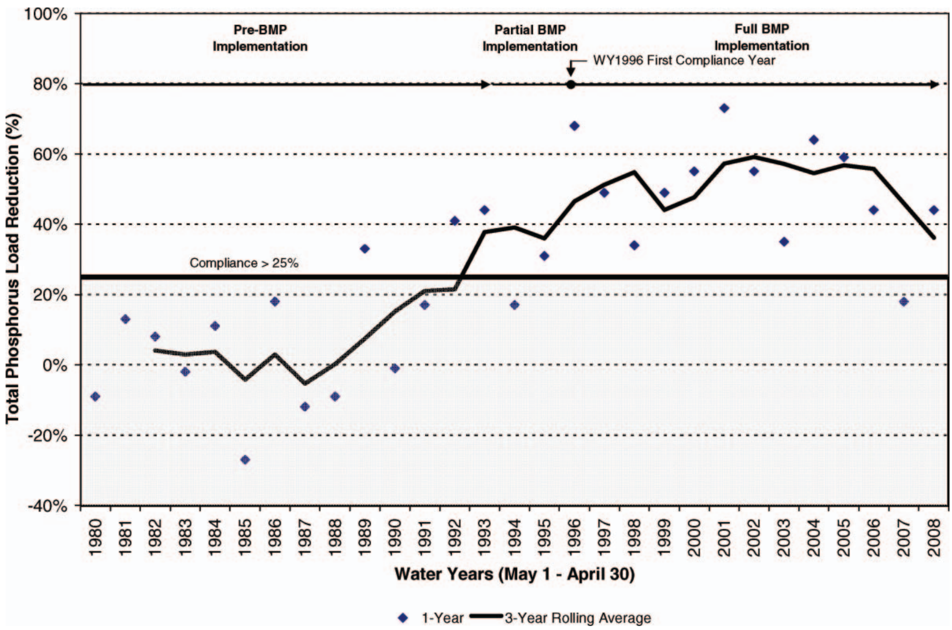

FIGURE 3. Annual basin-level total phosphorus load percentage reduction from the Everglades Agricultural Area (WY1980–2008). (This figure is available in color online.)

sugarcane or had mixed crops that may include vegetable production and sod in addition to sugarcane. All of these farms had similar nutrient control practices. The number and type of particulate matter and sediment controls varied between farms. The rainfall detention BMP was either 1.27 or 2.54 cm (Table 2). The mean monthly flow-weighted total P (FWTP) ranged from a low of 0.078 mg L^{-1} in Farm #1 (a sugarcane farm) to a high of 0.230 mg L^{-1} in Farm #3 (a mixed-crop farm). The monthly unit area P load (UAL) also varied from a low of 6.96 g P ha^{-1} $month^{-1}$ in Farm #5 to a high of 46.92 g P ha^{-1} $month^{-1}$ in Farm #3.

Trend analysis show the monthly FWTP has a decreasing trend in all the farms selected (Table 3). This shows the success of the nutrient control practices, which are universally used by all growers and effectively reduce P concentration in drainage water. This may also indicate lower mineralization rates of organic P due to higher water tables. The unit area drainage volume (UAV), however, had decreasing trend in six farms and insignificant trends in four farms (Table 4). The insignificant trends in UAV could be a combination of small-size farms, shallow soils, and mixed cropping systems with little capacity for rainfall retention and detention. Similarly, UAL had decreasing trends in six farms and insignificant trends in four farms (Table 5). Three of the insignificant trends in UAL are sugarcane farms, which is in contrast with an earlier analysis on 10 research farms where all sugarcane farms showed

TABLE 2. Characteristics of 10 selected EAA farms in the Everglades Agricultural Area: Monitoring period, subbasin location, crops, farm size and mean monthly unit area load (UAL), unit area volume (UAV), and flow-weighted total P (FWTP)

Farm #	Monitoring months[a]	Subbasin	Soil classification[b]	Crops	Farm size (ha)	Rainfall detention (cm)	Mean monthly FWTP (mg L^{-1})	Mean monthly UAV (cm $month^{-1}$)	Mean monthly UAL (g P ha^{-1} $month^{-1}$)
1	112	S7	Lauderhill/Dania	Sugarcane	130	1.27	0.078	8.92	10.12
2	112	S6	Lauderhill/Pahokee	Mixed	707	2.54	0.165	6.25	17.30
3	112	S5A	Terra Ceia/Pahokee	Mixed	606	1.27	0.230	11.48	46.92
4	112	S8	Lauderhill/Dania	Sugarcane	1538	2.54	0.122	8.17	17.11
5	112	S6	Lauderhill/Pahokee	Sugarcane	548	2.54	0.170	2.39	6.96
6	104	S6	Lauderhill/Pahokee	Sugarcane	255	2.54	0.116	6.15	13.67
7	103	S6	Lauderhill/Pahokee	Mixed	480	1.27	0.101	9.86	17.80
8	103	S5A	Terra Ceia/Pahokee	Sugarcane	716	2.54	0.078	6.57	9.38
9	103	S7	Lauderhill/Dania	Sugarcane	4352	1.27	0.133	5.44	12.14
10	103	S8	Lauderhill/Dania	Sugarcane	276	1.27	0.044	26.28	17.83

[a]July 1992 to April 2002.
[b]Soil depth (O horizon) of the soil orders: Terra Ceia ≥130 cm; Pahokee = 92–130 cm; Lauderhill = 52–91 cm; Dania ≤51 cm.

TABLE 3. Trend analysis for monthly flow-weighted total phosphorus (FWTP) in drainage water by farm location for the 10 farms in the Everglades Agricultural Area

Farm	Months[a]	Kendall K	*z*	*p*	Trend	Season	Sen slope
1	62	−489	−5.844	<.001	decreasing	seasonal	−.001
2	67	−1465	−7.923	<.001	decreasing	nonseasonal	−.013
3	85	−1523	−5.777	<.001	decreasing	nonseasonal	−.004
4	95	−1753	−5.633	<.001	decreasing	nonseasonal	−.006
5	79	−1287	−5.444	<.001	decreasing	nonseasonal	.003
6	59	−1241	−8.11	<.001	decreasing	nonseasonal	−.023
7	71	−265	−2.622	.009	decreasing	seasonal	.008
8	63	−1030	−6.108	<.001	decreasing	nonseasonal	.017
9	79	−1662	−7.033	<.001	decreasing	nonseasonal	−.012
10	86	−1169	−4.357	<.001	decreasing	nonseasonal	.000

Note. Samples for FWTP were only taken during drainage flow.
[a]July 1992 to April 2002.

TABLE 4. Trend analysis for monthly unit area drainage volume (UAV) by farm location for the 10 farms in the Everglades Agricultural Area

Farm	Months[a]	Kendall K	*z*	*p*	Trend	Season	Sen slope
1	112	−266	−1.375	.169	insignificant	seasonal	.000
2	112	−423	−2.201	.028	decreasing	seasonal	.000
3	112	−620	−3.012	.003	decreasing	seasonal	−.498
4	112	−400	−1.91	.056	decreasing	seasonal	−.214
5	112	−342	−1.674	.094	decreasing	seasonal	.000
6	101	−449	−2.652	.008	decreasing	seasonal	.000
7	103	−29	−0.155	.877	insignificant	seasonal	.000
8	99	−134	−0.783	.434	insignificant	seasonal	.000
9	101	−309	−1.719	.086	decreasing	seasonal	−.058
10	101	−237	−1.308	.191	insignificant	seasonal	−.395

[a]July 1992 to April 2002.

TABLE 5. Trend analysis for monthly unit area P load (UAL) by farm location for the 10 farms in the Everglades Agricultural Area

Farm	Months[a]	Kendall K	*z*	*p*	Trend	Season	Sen slope
1	112	−280	−1.447	.148	insignificant	seasonal	0.000
2	112	−385	−2.018	.044	decreasing	seasonal	0.000
3	112	−645	−3.142	.002	decreasing	seasonal	−1.498
4	112	−581	−2.779	.005	decreasing	seasonal	−0.559
5	112	−105	−0.514	.607	insignificant	seasonal	0.000
6	100	−496	−3.038	.002	decreasing	seasonal	0.000
7	103	40	0.216	.829	insignificant	seasonal	0.000
8	98	−78	−0.478	.632	insignificant	seasonal	0.000
9	98	−548	−3.251	.001	decreasing	seasonal	−0.187
10	100	−299	−1.665	.096	decreasing	seasonal	−0.324

[a]July 1992 to April 2002.

decreasing trends in UAL (Daroub et al., 2009). It is worth nothing that none of the farms had increasing trends in FWTP, UAV, or UAL.

3.2 Long-Term Water Quality Trends in EAA Basin

Seasonal Kendall trend analysis of aggregated monthly metrics of flow, P concentration, and P load by subbasin in the EAA basin from 1992–2002 was conducted by Daroub et al. (2009). The data, obtained from the District DB-HYDRO[1] database, was aggregated into the hydrological basins in the EAA: S5A, S6/S7, and S8 subbasins. The S6 and S7 subbasins have the same inflow structure (S-2) although they are monitored separately for outflow (Van Horn et al., 2008). Inflow parameters indicate what is entering each subbasin from Lake Okeechobee. Outflow parameters indicate what is leaving each subbasin to downstream ecosystems. All the inflow parameters (flow, P concentration, and P load) had insignificant trends during that time period except for inflow P concentrations from the S5A subbasin (S352 structure) with an increasing trend in P concentration (Kendall K of 1128; Table 6). This suggests that irrigation water P concentration into the S5A basin was increasing during the time period of 1992–2002.

The outflow drainage and runoff from the different subbasins and the EAA basin had significant decreasing trends except for the S8 subbasin (Table 6). This indicated lower drainage volumes from the subbasins with exception of S8. One logical explanation is the shallow soils in the S8 subbasin with less capacity to hold water. The outflow P concentrations and loads had a decreasing trend in all subbasins except for the S6/7, which had insignificant trends in both concentrations and loads. The decreasing trend in the S5A subbasin is a combination of decreasing trends in P concentrations and drainage flow despite the increasing inflow trend in P concentrations. The pronounced decreasing trends in concentration and loads out of the EAA basin and subbasins despite the insignificant trends in the inflow parameters clearly indicate the success of the BMP program (Daroub et al., 2009). Some practices control the transport of sediments and particulate P and may reduce the loads coming out of EAA farms with canal sediments acting as sink for P (Stuck, 1996; Stuck et al., 2001). Phosphorus may have been used by the crops, retained in the soil due to adsorption (Porter and Sanchez, 1992) and precipitation reactions, or retained in canal sediments (Stuck et al., 2001). Farm canals accumulate organic sediments rich in P from biological growth in the canals and particulate P can account up to 70% of total P loads (Stuck et al., 2001). Management practices to control floating aquatic vegetation growth include mechanical harvesting and chemical

[1](http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu)

TABLE 6. Seasonal Mann-Kendall trend analysis of aggregated monthly metrics by subbasin in the Everglades Agricultural Area from 1992–2002

Basin[a]	Months	Kendall K	*z*	*p*	Trend
		Inflow flow			
S5A	117	−267	−1.198	.231	insignificant
S6/7	117	−289	−1.299	.194	insignificant
S8	117	−715	−1.682	.093	insignificant
EAA	117	−385	−1.728	.084	insignificant
		Inflow concentration			
S5A	105	1128	5.898	0.000	increasing
S6/7	101	175	0.927	.354	insignificant
S8	117	−175	−0.783	.434	insignificant
EAA	117	692	1.628	.104	insignificant
		Inflow load			
S5A	117	24	0.104	.918	insignificant
S6/7	117	−190	−0.853	.394	insignificant
S8	117	−425	−1.908	.056	insignificant
EAA	117	−192	−0.860	.390	insignificant
		Outflow flow			
S5A	117	−772	−3.471	.001	decreasing
S6/7	117	−545	−2.448	.014	decreasing
S8	117	−330	−1.481	.139	insignificant
EAA	117	−599	−2.691	.007	decreasing
		Outflow concentration			
S5A	115	−1993	−4.815	0.000	decreasing
S6/7	115	388	0.935	.350	insignificant
S8	117	−541	−2.43	.015	decreasing
EAA	103	−745	−2.12	.034	decreasing
		Outflow load			
S5A	117	−799	−3.592	.001	decreasing
S6/7	117	−340	−1.526	.127	insignificant
S8	117	−584	−2.624	.009	decreasing
EAA basin	117	−662	−2.975	.003	decreasing

Note. Data from the South Florida Water Management District DBHYDRO database.
[a]Basin or subbasin name.

spraying that are used at various levels. Dredging canal sediments is done on some farms once every few years with sediments put back on the field.

3.3 Irrigation Water TP Concentration Trends from Lake Okeechobee

Monthly means of water TP concentrations from 1992 to 2006, for the three inflow structures from Lake Okeechobee into the EAA (S-352, S-2, and S-3), were analyzed to determine the impact of the 2004 and 2005 hurricane seasons on irrigation water TP concentration trends (Daroub et al., 2009). The EAA inflow TP concentrations represent irrigation water TP concentrations. Structure S-352 provides irrigation water to the West Palm Beach

TABLE 7. Trend analysis of phosphorus concentrations of irrigation water supplied by the three main inflow structures from Lake Okeechobee to the Everglades Agricultural Area subbasins from 1992 to 2006

Lake inflow structure[a]	Subbasin	*N*	Kendall K	*z*	*p*	Trend	Sen slope[b]
S-352	S5A	289	7224	6.513	0.001	Increasing	.0075
S-2	S6/7	165	132	0.185	0.854	Insignificant	.0002
S-3	S8	169	2635	3.581	0.001	Increasing	.0033

Note. Data from the South Florida Water Management District DBHYDRO database.
[a]Structure S-2 supplies water to the North New River and Hillsboro canals, Structure S-3 supplies irrigation water to the Miami canal, and Structure S-352 supplies irrigation water to the West Palm Beach canal.
[b]Sen slope provides an idea of relative slope of change; slope for concentration is in mg $L^{-1}yr^{-1}$.

Canal, which services farms in the S5A subbasin. Structure S-2 provides irrigation water to the North New River and Hillsboro canals. The North New River Canal services farms in the S7 subbasin; the Hillsboro Canal services farms in the S6 subbasin. Structure S-3 provides irrigation water to the Miami Canal, which is the source of irrigation water for farms in the S8 subbasin (Figure 1).

Trend analysis of irrigation water TP concentration data collected during flow conditions revealed significant increasing trends for irrigation water P concentration for two of the three structures (Daroub et al., 2009; Table 7). Results of the trend analysis using all data collected under flow and ambient conditions showed an increasing trend for all three inflow structures (Daroub et al., 2009). Kendall K (7224) with a *z* score of 6.513 and Sen slope value of 0.0075 mg L^{-1} yr^{-1} was observed at the S-352 structure during flow conditions, indicating the greatest increase in P concentration out of the S-352 structure. The increase is equivalent to 0.105 mg L^{-1} over a 14-year period. This analysis confirms that P concentration of irrigation water supplied to the EAA basin has been increasing due to the impact of 2004 and 2005 hurricane seasons and is greatest at the S-352 structure that supplies irrigation water to the S5A subbasin through the West Palm Beach Canal. Total P concentrations in the lake had a mean of 0.100 mg L^{-1} until 1995 and increased in the following 5 years to an average of 0.140 mg L^{-1} (James et al., 2006). Two active hurricane seasons in 2004 and 2005 resulted in much higher TP concentration in the lake compared to the previous 10-year average (e.g., average P concentration for WY05 was 0.236 mg L^{-1}, reflecting the impact of the two hurricane seasons).

4 FACTORS CONTRIBUTING TO VARIABILITY IN P LOADS

Since its inception in 1995, the BMP program has been acknowledged to be very successful in reducing EAA basin P loads (Van Horn et al., 2008).

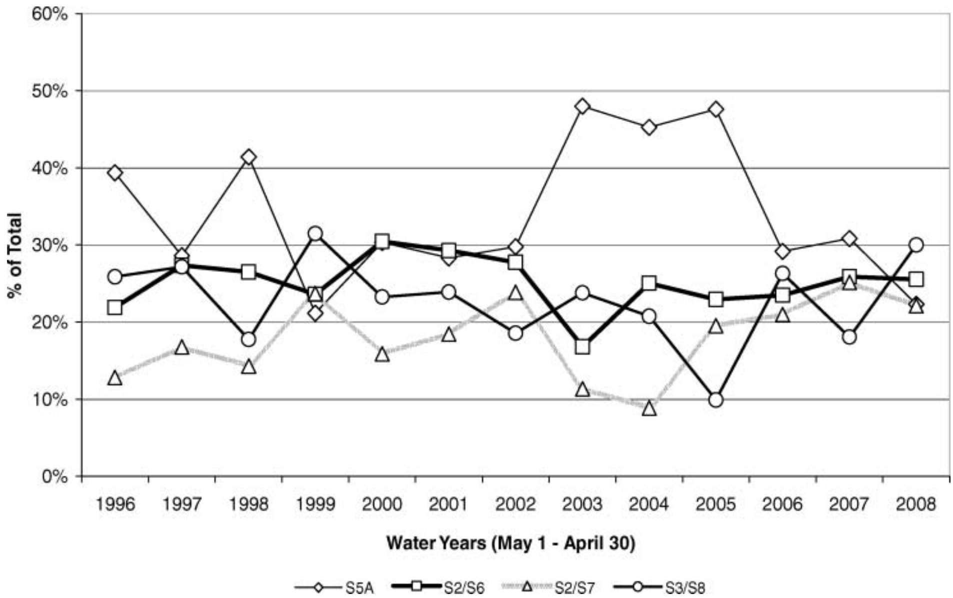

FIGURE 4. The Everglades Agricultural Area subbasins (S5A, S2/S6, S2/S7, and S3/S8) annual total phosphorus load percentage relative contribution trend of basin total (WY1996–2008).

Growers implement similar BMPs, however higher P concentrations and loads have been measured in the S5A and S6 subbasins compared with the S7 and S8 subbasins. A wide range of variation is seen in TP loads; however, the range of variation has become more evenly distributed in the past 3 years (Figure 4). Possible reasons for the differences in TP loads between the four subbasins may include rainfall distribution, water management practices, irrigation water quality, soil type/depth, and cropping systems (Daroub et al., 2007). Analysis of how environmental and farm management factors affect BMP performance on EAA farms may allow additional improvements in BMP performance.

4.1 Rainfall

Rainfall across the EAA basin averages 1371 mm per year, but varies both temporally and spatially (Ali and Abtew, 1999). Approximately two thirds of the rainfall occurs during the wet season—from June to October. The amount and distribution of rainfall directly impacts EAA farm drainage volume and associated P load (Izuno et al., 2001). Rainfall variation in both spatial and temporal distribution influence runoff patterns throughout the basin. For instance, a basin wide average rainfall amount of 940 mm occurring in two separate water years can produce markedly different runoff volumes and TP loads. Since WY96, runoff volumes between the subbasins have typically shown an evenly distributed and narrower range of variation when based on the percentage contribution of each (typically 20–30% each) to the total EAA basin runoff volume (Pescatore et al., 2009). To account for the influence of rainfall on farm P load when comparing BMP performance on an annual basis (usually by WY), annual EAA basin P load is adjusted for rainfall amount and distribution using a model developed by the District (Whalen and Whalen, 1996). The model allows for comparisons of post-BMP implementation annual basin P loads with the pre-BMP 10-year baseline period (October 1978 to September 1988). The rainfall adjustment procedure can also be applied to compare an individual EAA farm's annual P load and BMP performance across years (Rice et al., 2002). Comparisons of annual rainfall adjusted farm P load on 10 EAA farms revealed that rainfall and its variability was a major factor influencing annual farm P loads. In a later study that used multiple statistical analyses to determine factors that affect farm P loading on the same 10 EAA farm data set, rainfall was highly correlated with farm P load at the monthly time scale (Daroub et al., 2007). Multivariate regression analysis revealed that drainage pumping volume to rainfall ratio was a better predictor of farm P load at both the monthly and annual time scales than rainfall alone (Daroub et al., 2007). Lang et al. (2010) showed positive correlation of P load with rainfall, preceding month's rain and drainage pumping to rainfall ratio. Reduced drainage pumping after BMP implementation has been reported by Rice et al. (2002) and was thought to be the main factor behind the measured P load reductions in their study on 10 EAA farms.

4.2 Water Management Practices

Water management was found to be the key factor that influenced P load on 10 EAA farms (Daroub et al., 2007; Grunwald et al., 2009; Lang et al., 2010). Grunwald et al. (2009), using tree-based modeling, suggested that hydrologic/water management properties are the major controlling variables to predict P unit area load in the EAA. Water management variables included pumping to rainfall ratio, rainfall, and irrigation P load and concentration. Stepwise regression analysis identified canal water level management, percentage sugarcane acreage, percentage fallow plus flooded field acreage, and irrigation water P concentration as explanatory variables that impact farm P loads (Lang et al., 2010).

Another water management factor that was a significant predictor variable in farm P load regression equations was canal head difference (Daroub et al., 2007). *Canal head difference* was defined as the difference in canal elevation between the exterior District main conveyance canal and the farm interior main drainage canal. The two variables, drainage pumping volume to rainfall ratio and canal head difference, were significant water management factors that affirm the important role that water management plays in determining EAA farm P load (Daroub et al., 2007). Phosphorus load reduction and improving BMP performance can be attained by lowering drainage volume through improving internal drainage within a farm (Lang et al., 2010). Drainage volume reductions are accomplished by installing water control structures (culverts with riser boards) and land leveling (Lang et al., 2010).

4.3 Irrigation Water Quality

During the dry season (November to May), growers irrigate their crops using irrigation water sourced from Lake Okeechobee, which is recharged via rainfall and runoff from watersheds north of the lake. The irrigation water is sourced from Lake Okeechobee via District canals that transect the EAA from Lake Okeechobee to the WCAs. Water quality in Lake Okeechobee has degraded over the past several decades, mainly due to elevated P concentrations resulting from man-induced hydrologic and land use modifications (Aumen, 1995) and the active hurricane seasons in 2004 and 2005 (James et al., 2006). The increased P levels caused by sediment resuspension in the lake (James et al., 2006) and the elevated P concentrations of irrigation water from Lake Okeechobee has led to concerns about the impact of the irrigation water quality on BMP performance. The effects of irrigation water on EAA farm P load have not been investigated fully. However, Daroub et al. (2007) reported that irrigation water P concentration and irrigation demand were important in the monthly farm P load multivariate regression prediction equations using data from 10 EAA farms. Irrigation water P concentration was found to have a direct relationship with increased P loads for the sugarcane farms. A number of assumptions were made to calculate irrigation water P concentration and demand and thus their conclusions were reported as being preliminary (Daroub et al., 2007). Further research on the effects of irrigation water quality on farm P load in the EAA is warranted. Phosphorus cycling in main and farm canal sediments, as well as in soils, is critical. Lake Okeechobee water can be passed through main canals directly to STAs, or transported into farm canals, and used for irrigation. Phosphorus sorption/desorption, precipitation reactions, and release from organic matter oxidation can occur in soils and sediments. Soluble P can also be taken up by aquatic plant vegetation in farm and main canals and changed into sediments of variable physical and chemical characteristics. Soluble P is taken up by growing plants in soils and taken out of the cycle except for residues put back in the soil.

4.4 Soil Type and P Dynamics

When organic soils are drained and exposed to the aerobic conditions required for row crop agriculture, soil microbes oxidize the soil organic matter and transform stable organic P compounds into more labile mineral P forms (Ingebritsen et al., 1999). Deeper EAA organic soils have more capacity to hold water, but at the same time have more soil mass exposed to oxidizing conditions and have greater potential to mineralize more P on a per-area basis than shallow organic soils. Shallow soils on the other hand have less capacity to hold water, but the proximity to the underlying limestone bedrock increase the likelihood that soluble P is adsorbed or precipitated upon interaction with limestone ($CaCO_3$) bedrock. Among soils collected from 18 EAA farms, P sorption was correlated with ash content, pH, total Ca, and free carbonates (Porter and Sanchez, 1992). Soils that have been under cultivation for many years to high P requirement crops were reported to have a greater potential for high P loads due to a larger reservoir of soil P (CH2M Hill, 1978). Shallow EAA organic soils also generally tend to have higher Ca content, higher pH, and lower percentage of soil organic matter than deeper soils, which is speculated to have increased P sorption capacity. The increased P sorptive capacity is thought to be the result of mixing the soil with the underlying calcium carbonate rock through cultivation (Castillo and Wright, 2008). Janardhanan and Daroub (2010) reported, however, that Langmuir P sorption maxima (S_{max}) in selected EAA soils correlated positively with soil pH, noncrystalline and poorly crystalline Fe and Al, mineral matter, and correlated negatively with soil organic matter and water extractable P. Langmuir P S_{max}, however, was not increased by shallower soils or increased $CaCO_3$ content (Janardhanan, 2007; Janardhanan and Daroub, 2010).

Soil depth also influences farm drainage practices and farm water holding capacity. Shallow soils can accommodate and hold less rainfall before becoming saturated and requiring drainage than deeper soils (Garcia, 2000). Additionally, in a study of six EAA farms, field drainage rate was not impacted by drainage pumping rate (Garcia, 2000). Factors that appeared to influence field drainage rate were underlying caprock porosity, evapotranspiration rate, and surface groundwater elevation. Increased drainage rates from sugarcane fields resulted in lower P concentrations, but greater TP loads due to increased drainage volumes under the faster drainage treatment (Coale et al., 1994b). Soil depth was shown to be significant in farm P load prediction equations for 10 EAA farms (Daroub et al., 2007), and correlated with P concentration in drainage water (Lang et al., 2010). Water management research that targets farms with deeper soils is recommended to achieve additional P load reductions (Lang et al., 2010).

4.5 Cropping Systems

The major crops grown in the EAA—sugarcane, sod, winter vegetables, and rice—vary by P fertilization and water management needs (Bottcher and Izuno, 1994). Due to fertilization and water management differences, it would be expected that drainage water P concentration would differ by farm type. In a water quality study conducted by CH2M Hill (1978) on three farm types—sugarcane, vegetable, and cattle—no differences in drainage water

P concentration were found between the cattle and sugarcane farms, but approximately 3 times higher P concentrations were found in drainage water from the vegetable farm. Higher P requiring and excess water sensitive crops such as winter vegetables and sod have more potential to negatively impact farm P loads than crops with lower P fertility requirements and better excess water tolerance such as sugarcane and rice (Izuno et al., 1991). The majority of P exported from sugarcane production fields originates from soil P mineralization since Coale et al. (1994a) found that there were no differences in drainage water P concentration from production sugarcane and fallow fields. In a previous study, Coale et al. (1993) showed that P removal by sugarcane harvest was 180% of that applied as P fertilizer, indicating that the vast majority of P available for plant uptake is generated from the soil P pool and not directly from fertilizer application.

Rice is planted as a cover or sequential crop in the EAA. It has many benefits for the cropping system and the environment (e.g., reduced soil subsidence, destruction of soil pests and pathogens, uptake of residual fertilizers [Jones et al., 1994]). Flooded rice fields may serve as seasonal water retention ponds allowing water normally pumped off-farm during the wet season to be stored in rice fields. However, direct off-farm discharge of rice field drainage water (drawdown water) for harvest or other cultural operations has been shown to negatively impact annual farm P loads (Izuno et al., 2001). Flooding lowers the redox potential of the soil solubilizing Fe phosphates and increasing P concentration in drainage water.

5 CONCLUSIONS

The BMP program implemented in the EAA farms basin-wide since 1995 is a success story. To date, the P load reduction has averaged more than 50% and has consistently exceeded the goal set by the Everglades Forever Act requiring farmers to reduce the P loads by 25% from historic baselines. The success of the program can be attributed to 100% implementation by EAA growers, state regulation that requires all growers to have a BMP permit to farm and discharge water, and an incentive program to keep privilege tax at a minimum if reduction goals are exceeded. Growers in the EAA are also required to fund research and extension programs for continuing education on effectiveness of new and improved BMPs. BMP application has become an integral part of every grower's operating mode, and there is a strong emphasis on continuing research and education on BMP implementation and effectiveness. Trend analysis on P concentrations and loads from selected farms, EAA basin, and subbasins showed, in general, decreasing trends reflecting the success of BMPs. Differences, however, remain in water quality between subbasins due to many factors including rainfall, irrigation water quality, cropping rotations, water management, and soil type/depth.

Water management variables were the dominant factors affecting P loads out of EAA farms. Phosphorus load reduction and improving BMP performance can be attained by lowering drainage volume by improving internal drainage within a farm (Lang et al., 2010). Other practices to improve BMP performance include reducing the generation and transport of sediments from farm canals and canal cleaning. Phosphorus concentrations are also reduced though lower P fertilizer inputs and band application of fertilizers. Analysis of the irrigation water from Lake Okeechobee was shown to have a general increasing P concentration trend from 1992–2006 with the highest trend in the pelagic zone on the east side of the lake into the S5A subbasin. These elevated TP values in Lake Okeechobee may pose future risk to degrade water quality on farms. In particular, the S5A subbasin may be at risk to be impacted by increasing P levels. Future researchers should focus on improved water management and the impact of irrigation water quality, as well as understanding P cycling in EAA canal sediments and organic soils.

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