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Valorization of farm pond biomass as fertilizer for reducing basin-scale phosphorus losses

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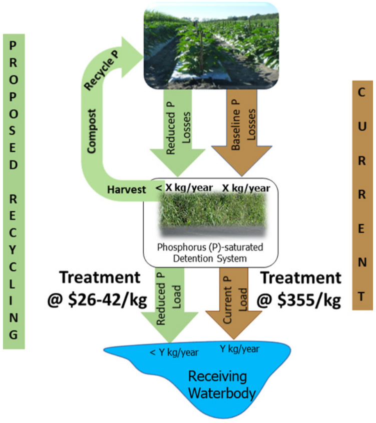
HIGHLIGHTS

- Biomass harvesting-composting (H-C) can sustain SDSs as P sinks in the long-term.
- Recycle-reuse of drainage P is economically feasible across cropping intensities.
- State-funded payment for services program (PS) can valorize harvested biomass.
- Basin-scale adoption of H-C can significantly offset P pollution in the Everglades.
- PS-based dispersed P treatment is almost 90% less costly than state-funded treatment systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Long-term fertilizer phosphorus (P) inputs are causing phosphorous saturation of agricultural soils globally. The saturation is spreading to the edge-of-the-farm stormwater detention systems (SDSs) from where the legacy P is potentially being released to downstream surface waters. We use site-specific and literature data for P-saturated SDSs, to develop and evaluate the biogeochemical and economic feasibility of a P recycling program that targets both low (LIC, sugarcane) and high intensity cropping (HIC, fresh-produce) systems within a watershed. The focus is to close the P cycle loop to rejuvenate P sink function of SDSs. It involves harvesting and composting the SDS's biomass and it's on-farm use as an organic fertilizer for crops. Results showed that harvesting-composting can conservatively increase the P retention from 50% to 77% for HIC and almost complete treatment for LIC. Beyond potentially increasing yield and improving soil health, compost use can further increase in-field retention of P (and water). Additional costs incurred in harvesting and composting can be offset by the economic value of compost and the reduction in State's expenditure on regional P treatment systems. Treatment costs were \$26/kg of P for HIC and \$42/kg for LIC, 10 times less than the current state expenditure of \$355–\$909/kg P using constructed wetlands. We propose an incentivized, payment for services (PS) program, where producers are paid for P recycling. The PS program considers the intensity of cropping systems and their location along the drainage network from headwaters to the outlet, to achieve basin-scale P load reduction. The LIC SDSs recover regional P

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by passing the public water through them while recycling is implemented at the HIC. The estimated basin-scale P retention with harvest-compost approach was 854 metric tons, 5 times the P that entered the Everglades Protection Area in 2018, at 88%–93% less cost than the State treatment systems.

1. Introduction

Agricultural soil phosphorus (P) imbalance stemming from the increase in fertilizer use on croplands has made agriculture a driver of the eutrophication of freshwater as well as coastal ecosystems, worldwide (MacDonald et al., 2011). In the developed world, coastal United States stands out with respect to the P surplus found in the agricultural soils (MacDonald et al., 2011). The extent of the “excess P in ecosystems” problem in the United States and elsewhere can be attributed to the focus of P treatment programs on cleaning up the waterbodies at the end of the watershed, ignoring the fact that majority of P losses occur along the way (Jacobs et al., 2017). Once the P is lost from the farm, it is replaced by newly mined phosphate creating a never-ending P demand, supply for which is likely to exhaust global P reserves.

Agricultural production is not only one of the leading causes of P pollution but also the highest user of P reserves, globally. In the last 75 years, global P mining has increased four times given the demands from agricultural sector (Jacobs et al., 2017). The current known P reserves, depending on the trend of use, will last for 50 to 200 years (Herrera-Estrella and López-Arredondo, 2016). It is important to develop solutions that reduce both agricultural P losses as well use of inorganic fertilizer P.

1.1. Agricultural stormwater detention systems

To capture the nutrients lost with the farm drainage, and reduce the downstream flooding risk, detention system at edge of the farm location is a common occurrence in the southeastern United States and other parts of the world. Agricultural stormwater detention systems (SDSs) is also regulatory requirement within watersheds draining into P-limited waterbodies such as the iconic Florida Everglades, a UNESCO world heritage site. The SDSs, a priority water quality best management practice (BMP) designated by the State in the Everglades basin, are designed to store at least the first inch (2.54 cm) of drainage from a 1 in 25 years, 3-day storm (SFWMD, 2013). In addition to reducing volume and therefore reducing P loads, they retain P loads through biological (plant uptake), chemical (soil adsorption), and physical (sedimentation) processes. The impounded features such as SDSs or farm ponds are ubiquitous and are present in the farms throughout the world, covering approximately 7.7 million ha worldwide (Likens, 2010). They are used for a multitude of purposes other than nutrient treatment (e.g. water source for irrigation and livestock) and growing at a rate of 1 to 2% annually in the United States (Likens, 2010). Costing as high as $1 million (~14 ha; Shukla, 2014), SDSs is an expensive BMP to implement. Producers have to set aside a part of their farm which results in significant cost, especially in coastal regions of the southeastern United States where the land values are higher than normal. In addition, there is significant investment involved in the construction, operation, and regulatory maintenance of the SDS.

1.2. Phosphorus saturation of agricultural Stormwater detention systems

A significant knowledge gap exists with regards to the P treatment effectiveness of aged SDSs (Shukla et al., 2017a). Environmental policy makers rely heavily on SDSs for water quality improvements based on “expected” P treatment rates due to lack of field-data. To fill this knowledge gap, two separate field studies (Shukla et al., 2017a; Shukla et al., 2017b) were conducted between 2008 and 2011 to characterize the functioning of two aged SDSs (one each in a sugarcane and fresh-produce cropping system) in processing water and P inputs. All SDSs are designed to function as a BMP which retains both water and nutrients in the farm drainage to reduce losses. Water and nutrient fluxes measured after two decades of their construction, show them to be almost saturated with P (Fig. 1b and d). Furthermore, desorption of "legacy P" from the sugarcane farm SDS was observed under excessive wet conditions due to P dilution caused by a tropical rainfall event as well as high drainage volume causing the P flux from the soil to the water column (Shukla et al., 2017a). The fresh produce farm SDS was a consistent P sink on annual basis but functioned as a source for multiple rainfall events. Annual positive P treatment for fresh-produce SDS was mainly because volumetric water retention was large enough to offset any soil P release (Shukla et al., 2017b).

Although, both SDSs were P-saturated, the extent of saturation was higher at the fresh-produce farm. Tillage and cropping system type are known factors impacting the P concentration of farm drainage (King et al., 2015). Higher P concentrations in subsurface drainage post-tillage have been reported (King et al., 2015). Cropping systems with higher P application are shown to have higher drainage P concentration (King et al., 2015). With fresh-produce farms producing multiple crops within a year, practices such as tillage and establishment of raised beds and stubble removal for each crop occur multiple times. This increases the inputs (water, fertilizers) applied per unit area as well as their losses leading to higher drainage P concentration and making fresh-produce a high-intensity (HI) cropping system. Furthermore, multiple tillage and crop removal enhances the mineralization of resident organic P in soil and plant (above and below ground). Sugarcane is a low-intensity (LI) crop. An average of three crops (one plant cane and two ratoon crops) are harvested annually before the crop is plowed under and replanted.

The convergence of evidence from the baseline water and nutrient budgets showed 1) "legacy P" inputs have saturated the surface soil with P; 2) with majority surface soils exhibiting negative soil P storage capacity (SPSC), aged SDSs are increasingly at a risk of P release especially after a large rainfall event; 3) extent of P saturation is higher at SDSs located in HI than LI cropping systems; and 4) sustainable retention of P in these systems is only possible if the "surplus P" is somehow removed from the soil to reduce the surface soil P density and restore its P adsorption capacity. When P saturation and release risks are seen with the high cost of construction, operation and maintenance, it becomes clear that while constructing SDSs can offer significant P treatment during early years, they can't guarantee sustained treatment of P loads from farms. Efforts should focus on finding economical approaches to keep the SDSs a consistent sink of P in the long-term. Economically feasible solutions, once found, can be a part of policy decisions (Shukla, 2014; Shukla et al., 2017a; Shukla et al., 2017b).

1.3. Sustainable management of stormwater detention systems as phosphorus sinks

The issues relating to the use of SDSs for managing watershed-scale P are not just limited to the scarcity of data, they go beyond the biogeochemical sciences, into the realm of policy and management decisions. With respect to P-related issues in agriculture, we are faced with 1) diminishing P reserves because of never-ending demand from agriculture and 2) loss of excess P to downstream waters due to limited to no remaining soil P sorption capacity in edge-of-the-farm treatment systems. Plant uptake and soil adsorption are the major P retention

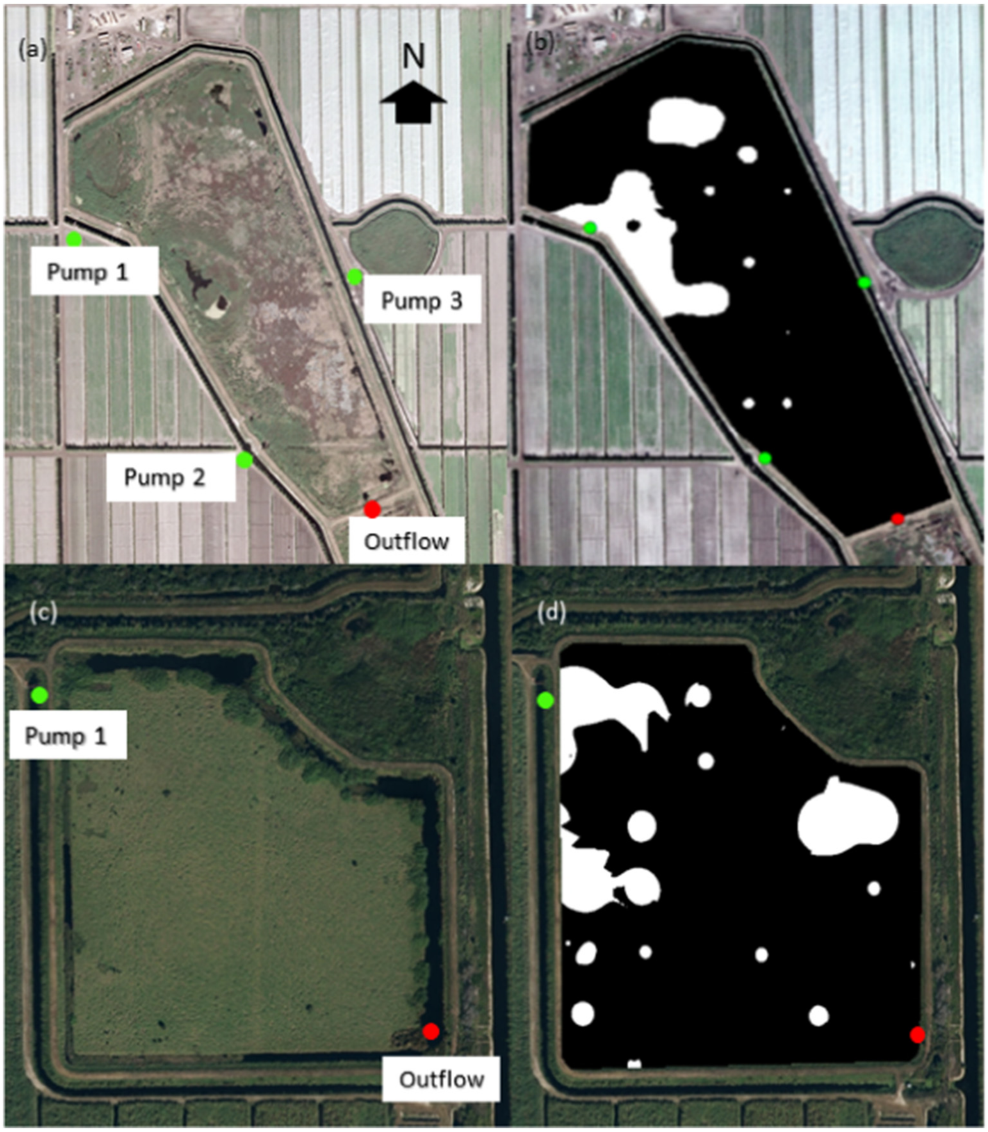

Fig. 1. (a) Stormwater detention system (SDS) located in the fresh-produce farm, (b) surface soil phosphorus storage capacity (SPSC) trend at the fresh-produce farm SDS, (c) SDS located in the sugarcane farm, (d) SPSC trend at the sugarcane farm SDS. Black color represents soil with negative SPSC values and white with positive
(Modified from Shukla et al., 2017a and Shukla et al., 2017b)

processes at play inside SDSs and unless excess soil P is extracted and P release due to vegetation die-off is prevented, SDSs cannot be maintained as P sinks in the long-term (Shukla, 2014). Past studies have suggested three major ways of achieving P capture and recycling which include 1) integrating agriculture practices such that the P waste from one can be utilized as a source for another (e.g. using waste from livestock operations as P source for organic farming system; Nowak et al., 2015); 2) tail water recovery practices for water and nutrient recycling (Karki et al., 2018); and 3) harvesting the aboveground biomass, adding value to it by composting, and its on-farm application (Shukla, 2014; Quilliam et al., 2015; Cobo et al., 2018). Practice 1 and 2 have limitations. Functional integration of crop and livestock production is conducive only at selected farms or regions (Nowak et al., 2015) and nutrient levels in the recycled water have been found to be insufficient to lead to any significant reduction in fertilizer use (Karki et al., 2018). Harvesting-composting has been suggested as a potential solution to capture and recycle lost nutrients (Shukla, 2014; Quilliam et al., 2015; Shukla et al., 2017a; Shukla et al., 2017b; Carson et al., 2018). However, its effectiveness, whether in terms of reducing P discharges or being economically feasible has not yet been evaluated. Once composted and applied on the farm, it increases the soil's ability to retain both irrigation and rainwater (Pandey and Shukla, 2006) and enhances soil microbial diversity and health (Nair and Ngouajio, 2012) with potential production benefits.

Environmental benefits are rarely featured among the critical reasons for resource recovery on agricultural landscapes (Quilliam et al., 2015). One of the reasons for such a practice is the narrow view which associates negligible economic value to the nutrients lost with agricultural stormwater. However, given its diffused nature, agricultural non-point source pollution as well as recovery of lost P should be evaluated at watershed-scale instead of farm-scale. A watershed-scale analysis can bring to light the impact of reuse-recycle practices which cannot be fully evaluated at farm-scale.

With producers already investing a considerable amount to build and maintain SDSs to comply with current regulations, it is not realistic to expect them to bear the additional financial burden of harvesting and composting the biomass. They are already bearing the additional costs to implement multiple in-field BMPs to comply with current water quality regulations in the Everglades basin. Such a situation provides opportunity for a public-private partnership where the State pays for the sustainable management of the aged SDSs in a watershed through biomass harvesting and composting. This paper is an effort towards evaluating the biogeochemical and economic feasibility of innovative harvesting-composting strategy, if implemented at SDSs located in agricultural systems. Specific objectives include 1) evaluate biomass harvesting from SDSs-composting as a management alternative to reduce farm P losses from a LI sugarcane and HI fresh-produce farm in the Everglades basin in South Florida, USA; 2) design a circular economy framework based on the payment for services (PS) concept, allowing the producers to adopt the harvesting-composting without added financial burden and the public to benefit from P removal from regional waters; 3) design a policy mechanism to implement the incentivized PS program at basin-scale by taking cropping system intensity and SDS location within the watershed into consideration.

2. Methods and material

The study sites are two SDSs located in the western Everglades basin at a sugarcane and fresh-produce (vegetable) farm (Fig. 1). A typical SDS in the Everglades basin is an embankment enclosed area typically located at the downgradient end of the agricultural farm. The SDSs are typically surrounded by two ditches, one each on the internal and external perimeter. The outer ditch serves as the collector of drainage from the network of ditches in the farm. The inner ditch is discontinuous, and a result of excavation required to acquire soil to build the embankment. To protect the crop from soil saturation resulting from flooding of production fields, farm drainage is pumped from the outer ditch into the SDS via axial flow pumps (Fig. 1a and c). The discharge structure is usually a culvert-riser board structure with weir or an orifice set at predesigned level to allow the spillage volume after the regulatory storage is achieved in the SDS. The SDS is designed on the “fill to spill” concept. Once the level inside the SDS reaches the discharge structure control elevation, water is discharged to a public canal, other drainage features from where it eventually reaches the Everglades National Park after passing through constructed wetlands termed as Stormwater Treatment Areas (STAs). We evaluate two SDSs, one each located in a HI (fresh-produce) and LI (sugarcane) cropping system (Fig. 1) to address the cropping intensity factor within a watershed. Physical characteristics of both SDSs such as areal extent, soil type, vegetation type, etc. are presented in Table 1.

Table 1
Characteristics of study sites.

Characteristic	Fresh-produce farm SDS	Sugarcane farm SDS
Farm area contributing drainage	112 ha	122 ha
Cropping system intensity	High	Low
Stormwater Detention Systems' area (ha)	14.85	14.16
Crop cultivated in the farm	Tomato, bell pepper, eggplant, etc.	Sugarcane
Inflow pumps	Three of capacity 37.85 m^3/min, each	One of capacity 22.71 m^3/min
Discharge structure	Two corrugated aluminum culverts, each fitted with riser boards	One sharp-crested, rectangular orifice fitted in a corrugated aluminum pipe
SDS vegetation	torpedo grass (*Panicum repens*), smartweed (*Polygonum hydropiperoides*), water lettuce (*Pistia stratiotes*), cattail (*Typha* spp.), primrose willow (*Ludwigia peruviana*), and Carolina willow (*Salix caroliniana*)	Para grass (*Brachiaria mutica*)
SDS Topography (above mean sea level, NAVD 88)[a]	Lowest elevation = 3.29 m	Lowest elevation = 2.92 m
	Highest elevation = 7.73 m	Highest elevation = 7.47 m
	Average floor elevation = 5.49	Average floor elevation = 5.09

[a] Lowest elevation is the deepest point in the inner ditch. Highest point is the highest point on the embankment. NAVD 88 is the North American Vertical Datum established in 1988.

2.1. Hydrologic, and water quality data

Hydrologic, and water quality data were collected at both SDSs to establish the baseline water and P retention. The sugarcane SDS was monitored between August 2008 and 2010 and the fresh-produce SDS between July 2009 and 2011. Monitoring details for the sugarcane farm and fresh-produce farm SDS can be found in Shukla et al. (2017a, 2017b), respectively.

2.2. Soil and plant data

A grid-based approach was used to determine soil sampling locations at both sites. A total of 69 and 50 surface (0–10 cm) soil samples were collected at the fresh-produce and sugarcane SDS, respectively. The samples were analyzed for Mehlich1-Aluminum (Al_{M1}), Mehlich1-Iron (Fe_{M1}), and Mehlich1-Phosphorus (P_{M1}). The Mehlich1 parameters was used to calculate phosphorus saturation ratio (PSR_{M1}) and soil phosphorus storage capacity ($SPSC_{M1}$) using Eqs. (1) and (2), respectively.

$$PSR_{M1} = \frac{{}^{P_{M1}}\!/31}{{}^{Fe_{M1}}\!/56 + {}^{Al_{M1}}\!/27} \tag{1}$$

$$SPSC = (Threshold\ PSR_{M1} - PSR_{M1}) \times [(Fe_{M1}/56) + (Al_{M1}/27)] \times 31 \times X \tag{2}$$

The PSR_{M1} is the threshold to which soil can effectively retain P. For Florida soils, $PSR_{M1} > 0.1$ indicates that the soil is at an environmental risk of releasing P (Nair, 2014) however, whether P adsorption or release would occur depends on the overlying water column's soluble reactive P (SRP) concentration (Fig. 2). The SPSC is a quantitative measure of P loss risk (Nair and Harris, 2004). In Eq. (2), X is the conversion factor where SPSC (mg kg^{-1}) is calculated using parameters derived from the Mehlich1 extraction instead of acid ammonium oxalate as an extractant and the value of X is 1.3 for A and E horizons of South Florida's sandy mineral soils (Nair et al., 2016). A raster map of SPSC was created from point SPSC values estimated from Eqs. (1) and (2) using the inverse distance weighing technique. Soil samples were analyzed for Mehlich1-Aluminum (Al_{M1}), Mehlich1-Iron (Fe_{M1}), and Mehlich1-Phosphorus (P_{M1}). Excess soil P was estimated for each raster grid and all unique values were summed to estimate the total excess surface soil P for the sugarcane and fresh produce SDSs.

Macrophyte species and their respective dominance areas were identified through ground and aerial (helicopter) surveys at both sites. The sugarcane farm SDS was covered by Para grass (*Brachiaria mutica*). Five macrophyte species were identified at the fresh-produce farm SDS - torpedo grass (*Panicum repens*), smartweed (*Polygonum hydropiperoides*), water lettuce (*Pistia stratiotes*), cattail (*Typha* spp.), primrose willow (*Ludwigia peruviana*), and Carolina willow (*Salix caroliniana*). Each vegetation type was sampled by harvesting all the above ground plant tissue in a 1 m × 1 m quadrat. Two replicates of each vegetation type were sampled, dried, shredded and analyzed for TP using EPA method 365.1. The total P assimilated in the aboveground tissue of each plant species was calculated using the tissue P density, dry weight of the tissue sampled in the quadrat, and SDS area covered by the vegetation. Calculations showed that a total of 240 kg and 145 kg P was assimilated in aboveground plant tissue at the fresh-produce and sugarcane farm SDS, respectively.

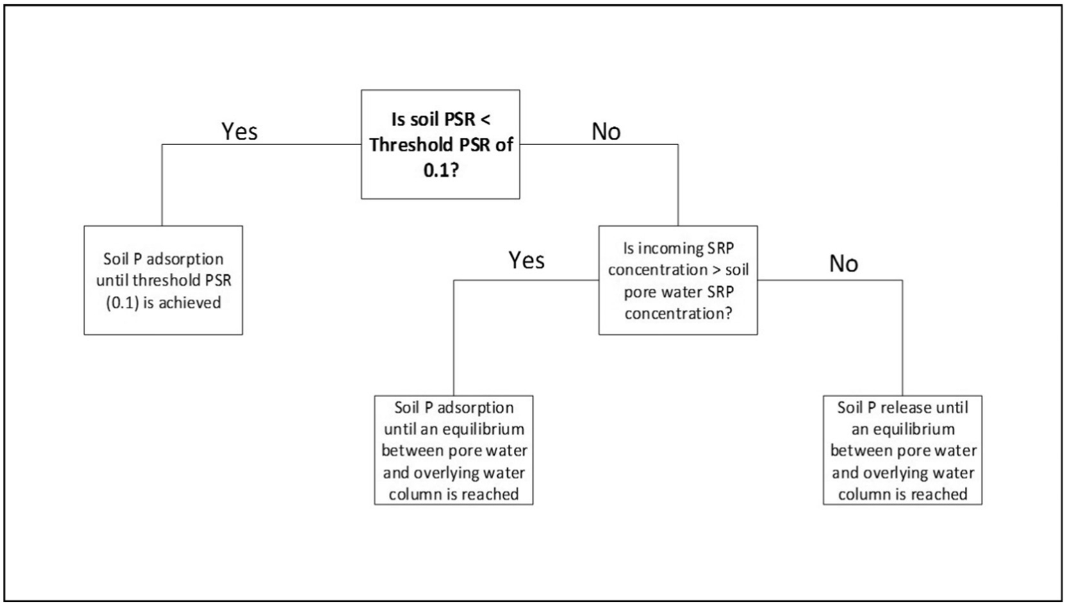

Fig. 2. Soil phosphorus (P) adsorption and release at stormwater detention systems explained with respect to soil phosphorus saturation ratio (PSR) and incoming soluble reactive P (SRP) concentrations.

Given that both SDSs contain invasive plants, we considered two different biomass harvesting scenarios, one depicting the "as is" situation, and another promoting the ecological health of the SDS ecosystem by replacing the invasive plants with native plants after the first harvest. Maidencane (*Panicum hemitomon*) was selected as the desirable plant species (David, 1999; Holm and Sasser, 2008) for replacing invasive vegetation in the SDSs and evaluating the second scenario. None of the SDSs had any maidencane vegetation therefore, P density of aboveground maidencane tissue from Hubbard et al. (2004) was used for the analyses.

2.3. Evaluation of harvesting and recycling strategies

The hydrologic, water quality, soil and vegetation data collected at the SDSs along with literature values were used to quantify the effectiveness of harvesting-composting approach. Main assumptions in evaluating the impact of harvesting-composting at the two SDSs included: 1) harvestable area is 75% of the total SDS area; 2) moisture, N and P loss on composting is 35%, 2%, and 0.3% by mass, respectively (Haaren et al., 2010); 3) rate of compost application is 5 ton/acre; and 4) sediment is the major source of P for the aquatic weeds (Carignan and Kalff, 1980). Although shoot systems are also known to take up P from overlying water, it is considerably less compared to the roots (Robach et al., 1995). 72% of P uptake during macrophyte regrowth is sourced from water column and the remaining 28% from soil (Carignan and Kalff, 1980). Using 75% harvestable area is based on the conditions prevailing at the two SDSs - parts of the SDS had internal ditches, jurisdictional wetlands that cannot be harvested without obtaining clearance from the state. Additionally, there are other deeper sections which are difficult to harvest by machines.

2.3.1. Economic analyses

The data on costs of biomass harvesting and, transportation were collected through personal communication with farmers and private contractors including a composting facility in the region (Table 2). The cost of composting and the value of the finished compost were obtained from the owner of a private composting facility (Florida Soil Builders, Inc.) and the US Environmental Protection Agency (USEPA, 2000; Table 2).

The unit cost of treating stormwater P using STAs in the Everglades basins ranges between $355 and $909/kg of P treated (Sano et al., 2005). Given that payment for services (PS) is still a budding concept, no data are available with regards to the compensation that may be provided to the farmers in exchange for the additional P retention services post-implementation of harvesting-composting. Due to lack of any compensation estimates, the minimal amount ($355/kg) that the State spends to treat P using STAs was used as the conservative financial incentive the State would provide the farmers under the PS program. Economic feasibility of proposed strategy was evaluated using the net present worth (NPW) analysis (Eq. (3)). A positive NPW indicates the economic feasibility of the project while a negative value is an indication of an unfeasible project.

$$NPW = -C_0 + \sum_{i=1}^{t} {}^{C_i}/(1+D)^i \tag{3}$$

In Eq. (3), C_0 is the initial investment, C_i is the annual cash flow in year *i*, D is the discount rate assumed to be 5%, and t is the useful life of the project assumed to be 50 years for the analyses. All monetary values are expressed in 2018 dollars.

After evaluating harvesting-composting at the farm-scale, a scale-up was evaluated for the Everglades basin assuming: 1) increased P retention through harvesting-composting is same for all farms within a crop

Table 2
Cost (2018 US dollars) of implementing proposed management alternatives.

Cost category	Cost	Source/additional information
Harvesting	$450/acre	PC
Planting new vegetation	$550/acre	PC
Hauling feedstock and finished compost to and from the composting unit	$9/ton of material	FSB***/Fixed price for a 50-mile radius
Composting	$12/ton of feedstock	USEPA, 2000
Market price of compost[a]	$29/ton	FSB
Compost application	$6/ton	FSB

*PC-Personal communication with the fresh-produce grower; **RHT – RHT Engineering, Inc.; ***FSB - Florida Soil Builders, Inc.

[a] Benefit to the producer.

intensity category (e.g., high) within the basin; 2) citrus, a significant land use in the basin, is an average cropping intensity system; 3) SDSs P retention value for citrus farms can be calculated as an average of sugarcane and fresh-produce values.

3. Results

3.1. Biomass harvesting and on-farm recycling

Phosphorus capture and recycling, and decreased dependency of agriculture on inorganic P fertilizers has been touted as the only strategy to reduce the P footprint of agriculture while meeting the global agricultural demands in the long-term (Nowak et al., 2015; MacDonald et al., 2011).

Studies in the past have proposed composting as a way of closing the loop on agricultural P losses; however, to our knowledge there have been no studies which have evaluated its water quality as well as economic effectiveness. One reason for the lack of such systematic studies has been due to unavailability of climatic, physical, biogeochemical, and economic data for the systems evaluated. We combine the plant, soil, water quantity and quality, and economic data collected at the two SDSs to evaluate the impact of proposed harvesting and recycling, and its economic feasibility.

3.1.1. The "as is" scenario

The "as is" scenario would entail harvesting all aboveground vegetation at both SDSs each year without establishing native plants. Harvesting of existing plants would result in mining of 145–240 kg of P from the two SDSs. Not a 100% of the SDS area may be harvestable, therefore, the harvestable P was assumed to be 75% of the total P stored in aboveground vegetation i.e. 109 kg for the sugarcane and 180 kg for the fresh-produce SDS (Fig. 3c).

The volume reduction at the fresh-produce farm SDS was 48% i.e. 48% (430 kg) of the incoming drainage P load (895 kg; Table 3) in 2009–2011 was retained without considering soil adsorption or any other biogeochemical process. Detailed hydrologic and P load time series analyses for the fresh-produce SDS are presented in Shukla et al. (2017b). With annual harvesting, another 360 kg (two harvests of 180 kg each) will be taken up by the vegetation for the two-year period. Of the 360 kg removal, 259 kg (72%) will be sourced directly from water column; this will increase the P retention from 50% (Fig. 3a) to 77%. Another 101 kg (28%) P will be sourced from the soil. Vegetation harvesting would not only lead to removal of P sequestered in plants but also lead to enhanced P treatment in future due to utilization of surplus soil P which is currently at a risk of being released to the water column and discharged out of the SDS.

Raster analyses showed that the soil contained approximately 1035 kg of excess labile P which is at risk of release. Analyses of P stored in aboveground plant tissue along with the soil P showed that this excess P could be mined in approximately ten harvests (101 kg/year) if aboveground vegetation is harvested annually (Fig. 3b). The "excess labile P" in this case is defined as the plant available P in the soil, which if mined/extracted, could eliminate the risk of soil P release i.e. bring down the soil phosphorus storage capacity (SPSC) to zero from negative values that currently exist within most of the SDS.

Once the biomass is harvested, it would be composted. After moisture, N and P losses, annual compost production from the fresh-produce farm SDS would be 241 metric ton. The elemental N and P content of the resulting compost would be 793 kg and 179 kg, respectively. Given that most of N and P required for commercial crop production is derived from synthetic fertilizers, utility of compost as a nutrient source is evaluated by adjusting it by a factor by 0.3 due to lower availability of nutrients (Haaren et al., 2010). The annual biomass harvested from the fresh-produce farm SDS would provide 238 kg and 54 kg of elemental N and P, respectively for crop uptake.

The 50-year NPW estimate i.e. the net current value of all expenses and profits in the next 50 years, of the proposed harvesting and recycling, using the prevailing costs (Table 2), was $858,000 i.e. an annual positive cash flow of $17,000 for the farmer. The final compost product would be sufficient for 9% of the farming area if applied at a recommended rate of 5 metric ton per acre within the raised plant beds. Furthermore, in the long-term, the benefits

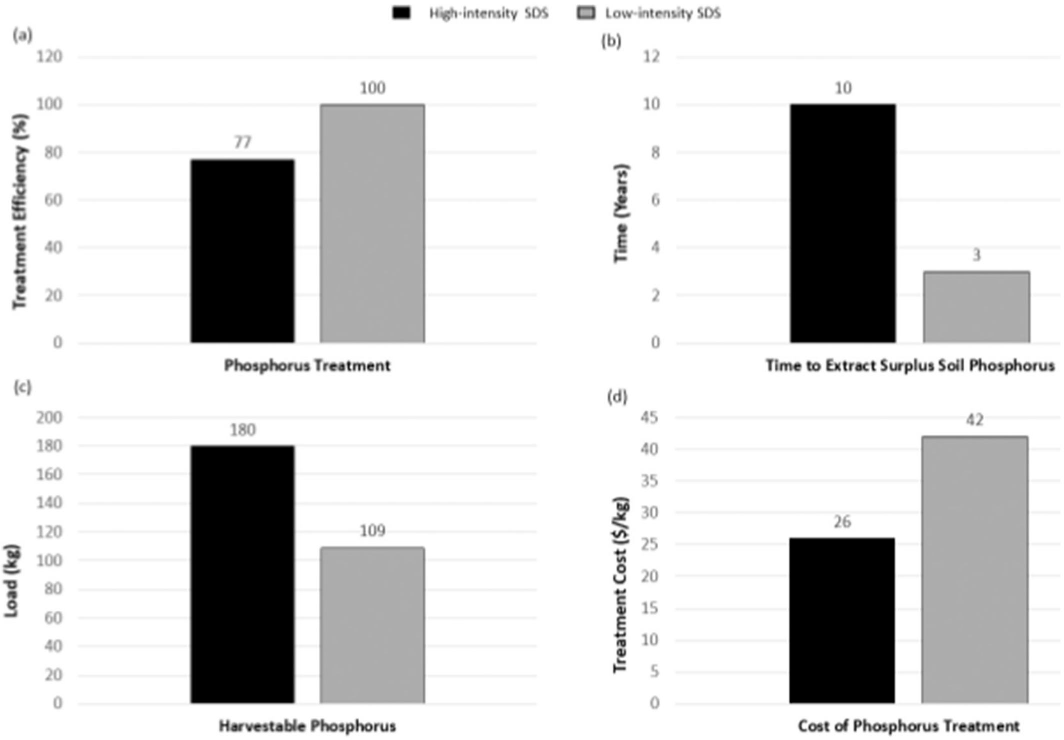

Fig. 3. Phosphorus (P) treatment efficiency of the stormwater detention system (SDS) after biomass harvesting (a), Time to extract surplus soil P from the SDS (b), harvestable P at the SDS (c), and cost of additional P treatment at the SDS (d) located in a high-intensity (fresh-produce) and low-intensity (sugarcane) cropping systems.

Table 3
Water (m) and total phosphorus (TP; kg) fluxes for fresh produce (2009–2011) and sugarcane (2008–2010) detention systems (SDSs).

Component	Fresh produce SDS		Sugarcane SDS	
	(2009–2011)		(2008–2010)	
	Water (m)	TP (kg)	Water (m)	TP (kg)
Inflow (Pump) 1	5.31	379	6.89	69
Inflow (Pump) 2	3.22	303	–	–
Inflow (Pump) 3	2.14	182	–	–
Backflow to SDS	0.84	25	–	–
Rainfall	2.52	7[a]	2.37	6[a]
Total inflow[b]	14.03	895	9.26	75
Surface outflow	7.34	443	4.83	50
Evapotranspiration	2.78	–	2.49	–
Surface retention[c]	6.69	452	4.43	25
Surface retention efficiency[d]	48%	50%	48%	33%

[a] Includes dry atmospheric TP mass deposition = 0.9 x TP deposition through rainfall (Ahn and James, 2001); Rainfall TP concentration = 9.39 μg/l (Ahn, 1998)

[b] *Inflow* 1, 2, *and* 3 + *Rainfall* + *Dry atmospheric deposition* + *Backflow*

[c] Total inflow-Surface outflow.

[d] $\frac{\text{Total inflow} - \text{Surface outflow}}{\text{Total inflow}} \times 100\%$.

would not be limited to only financial incentives rather it would also lead to reduced drainage volume and P leaching (Shukla and Pandey, 2008), creating a “two in one” conservation program, source control as well as capturing lost P before it reaches public waters. A study by Shukla and Pandey (2008) at the same HI farm showed a 30% increase in plant available water. Using a conservative estimate of 15% reduction in drainage and hence the incoming P loads, P retention could be as high as 90%. Higher in-field water retention would lead to increased rainfall and irrigation retention, reduce groundwater pumping resulting in cost savings in addition to potential enhanced production and environmental benefits. If the state were to not incentivize the proposed harvesting and recycling program, 50-year cost of P recovery (not including the cost and in-field water and P retention benefits of composting) will be $26/kg, 93% less than the State's current expenditure ($355/kg, Sano et al., 2005; Fig. 3d).

The surplus P in the sugarcane farm SDS surface soil (0–10 cm) was approximately 96 kg. The P content of the aboveground tissue of para grass which covers the entire SDS was 145 kg out of which 109 kg (75%) was assumed to be harvestable (Fig. 3c). Each harvest would lead to an additional retention of 78 kg (72%) P from the water column and extract 31 kg (28%) from the soil. The excess soil P could be mined out of the SDS with only three harvests, much sooner than the fresh-produce farm (Fig. 3b). The sugarcane SDS received 75 kg of P in 2008–2010 (Table 3). Detailed hydrologic and P load time series can be found in Shukla et al. (2017a) for the sugarcane farm SDS. The SDS retained 48% of the incoming drainage volume (Table 3). If 72% of the P needed for plant growth would be sourced from incoming drainage, the outgoing P load could almost be negligible (Fig. 3a).

Analyses of drainage, soil, and plant P data from the sugarcane SDS showed that approximately 54 metric ton of compost would be sourced from the biomass (para grass). The compost would be sufficient to cover 4% of the total farmed area. The elemental N and P content of the compost would be 1068 kg and 108 kg, respectively i.e. 320 kg and 33 kg of readily available N and P, respectively. The 50-year NPW of the project was estimated to be $468,000 i.e. a net annual positive cash flow of almost $9000 for the sugarcane farmer. In absence of any financial incentive from the state, the 50-year cost of P removal through biomass harvesting at sugarcane SDSs will be $42/kg, 88% less than the State's spending of $355 kg/yr (Sano et al., 2005; Fig. 3d). We propose that compost application for both fresh produce and sugarcane farm be rotated from field to field each year to eventually cover the entire farm.

3.1.2. Establishing native plants for improved ecological health

Dominant vegetation type at the fresh-produce SDS is torpedograss whereas for sugarcane farm it is para grass. Both these grasses are considered invasive species for the Everglades ecosystem (UF/IFAS, 2018a; UF/IFAS, 2018b). One of the most serious weeds in Florida, management of torpedograss costs approximately $2 million, annually (UF/IFAS, 2018a). Para grass is known to impediment water flow by forming floating mats in ditches and canals (UF/IFAS, 2018b). Given the negative impacts of these species on ecological health of the SDSs and the Everglades ecosystem, we designed another scenario aimed at establishing the native vegetation in the SDSs. Among the various native species in the region, maidencane (*Panicum hemitomon*) was chosen for P removal and crop fertility benefits. It has relatively higher aboveground N and P content (Hubbard et al., 2004) and is adaptable to dry as well as flooded conditions observed within the SDSs during the dry and wet seasons in subtropical Florida, respectively. The mean aboveground tissue N content of maidencane is 2.62% (Hubbard et al., 2004), greater than any current plant species at the two SDSs. The P tissue content of maidencane (0.42%) is marginally less than only that of water lettuce (0.45%).

Replacing the current vegetation with maidencane at the fresh-produce farm SDS would mine 1035 kg of excess soil P in two harvests, but it is to be expected that a new plant species would take some time to fully establish. We used a conservative period of two years for establishing the maidencane plants. After allowing for establishment of maidencane, its annual harvesting will facilitate the entire excess P at the fresh-produce SDS to be assimilated in plant tissue in four years. The established maidencane would source 72% (1207 kg) of the tissue P content from the water column, annually, and the P load discharge from the fresh-produce SDS would be negligible.

The annual compost production from maidencane biomass at the fresh-produce farm would be 1297 metric ton. The elemental N and P content of the compost would be 10,453 kg and 1676 kg, respectively. For comparison to nutrient availability in synthetic fertilizers, the final compost product would be equivalent to 3136 kg N and 503 kg P. For a compost application rate of 5 metric ton/plastic acre, 47% of the production area that contributes drainage to the SDS could be amended with compost which would lead to a considerable reduction in drainage (an average of 109 cm/yr; Shukla and Pandey, 2008), thereby reducing the P losses. The 50-year NPW of the project would be $10,271,400 i.e. a net positive cash flow of $205,000/year for the farmer assuming the State would pay $355/kg of P removed. To put the efficiency of using maidencane for P removal in perspective, the cost of P removal with harvesting and recycling would be merely $6/kg of P removed.

At the sugarcane farm SDS, establishing maidencane could lead to almost all excess P being mined out of the system in 3 years (two years to establish maidencane and one to harvest). Given that the area of the fresh-produce and sugarcane farm SDS is almost similar (14.85 fresh produce, 14.16 ha sugarcane), other environmental and financial benefits will be similar between the two systems.

4. Discussion

4.1. Cost efficiency for land use intensities

The SDSs in high intensity (HI, fresh produce) farms store more P per unit area (overlying water column + soil) because of P input, and soil characteristics. As a result, it is more profitable to implement the proposed strategy at the HI farms as they provide "more bang for the buck". The SDSs in low intensity (LI) farms (sugarcane) store an order of magnitude less P which makes them a costly candidate for implementing the harvesting-composting alternative. Disparity in P storage among HI and LI farm SDSs led us to explore ways by which the P storage density of the LI farm SDSs can be increased and implementation of proposed alternative be made more profitable and effective at basin-scale from the standpoint of reducing P loads to the downstream ecosystems.

The PSR and SPSC values show that the surface soils at both SDSs are P saturated (Fig. 1b and d). However, soil never becomes completely incapable of sorbing P (Kleinman, 2017). Before saturation ($PSR < 0.1$ for Florida soils), P is adsorbed tenaciously to maintain a low solution SRP concentration, but after saturation ($PSR > 0.1$), P sorption/release becomes strongly dependent on the dissolved P levels in the overlying water column (Fig. 2). For example, after a large storm which results in dilution of drainage P in the SDS, previously adsorbed P (legacy P) from saturated soils is likely to be released to the water column and eventually be discharged out of the SDS. Once saturated, the soil's tendency to function as sink or source can be determined by the decision tree diagram shown in Fig. 2. Applying this concept at the LI farm SDSs, their P storage per unit area can be increased by passing regional water (canals) with higher SRP concentrations than the SDS's soil pore water. Moving the P in public water to the SDS would increase the soil P density within the SDS. This would enhance the profitability of the proposed management alternative for the producer while benefitting everyone from basin standpoint because irrespective of the source of high SRP, basin-scale P losses to the target waterbody will be reduced. Taking the regional P from canals and storing it in the SDS will be considered an environmental service provided by the LI farms.

4.2. Intensification-based phosphorus management policy

The current state-regulated BMP program for P reduction in the Everglades basin is flexible and allows producers to adopt from a range of practices. However, the agricultural land use intensity is normally not considered in deciding the "best" management practice or strategy for a specific cropping system. This is especially true for SDSs that are assumed to maintain their P treatment efficiency in perpetuity. While building SDSs may have been the best way of achieving regulatory compliance, their current P retention efficacy to meet regulatory P targets is questionable because of their age and associated P saturation. The two main outcomes from this study with regards to enhancing P retention are 1) harvesting, composting and on-farm use of compost is the sustainable alternative for SDSs irrespective of the cropping system intensity; and 2) SDSs in HI cropping systems (e.g. fresh-produce) have accrued more P over the years compared to SDSs in LI farms (e.g. sugarcane) which makes them a better candidate for implementing the harvesting-composting strategy. When viewed in conjunction with the current agricultural land use in the Everglades basin, a land use-specific watershed P management policy is likely to be beneficial for both public and producers.

Sugarcane production covers >7 times (250,300 ha) the area covered by high intensity row crops (33,864 ha) in the basin. The SDSs account for at least 10% of the farm area, meaning that 25,000 ha of SDSs serve LI sugarcane farms which have potential to retain more P than they are currently retaining. On the other hand, the 3400 ha of SDSs serving the HI farms have already been used to their full potential and there is no policy mechanism in place to sustain them as long-term P sinks. We propose a two-phased approach for basin-wide P load reductions - local (Phase 1) and distributed nutrient recovery system (Phase 2), both supported by a public-private partnership through a payment for services (PS) approach. In the PS approach, State is the buyer of the P treatment service and the agricultural producer is the seller. The first phase of the policy will involve voluntary participation by the willing HI crop producers in recovering and recycling P through biomass harvesting-composting. It would be most beneficial for the State (buyer) to compensate the producers at a rate near this low cost ($26–$42/kg of P). At the same time, the producer (seller) reaps the benefits of obtaining the compost at a cost below the prevailing market price. Given the availability of state funds, Phase 1 may continue for 5 or more years until all willing HI crop producers have implemented harvesting-composting.

Depending on whether the P load reduction targets are met, the state can recruit LI farm owners while offering a higher compensation for passing high P regional waters through their SDSs and implementing harvesting-composting. Passing regional waters through LI farm SDSs will increase soil P density while offsetting the higher cost of P recovery ($42/kg), a result of lower soil P density in SDSs receiving drainage from LI farms. In an event where the P concentrations leaving the basin are still higher than the target, the state may have to increase the compensation under the PS program to make the adoption of the system more financially attractive. In any case, by paying producers to help recover P from their own farms as well as that from other farms which have entered regional waters (e.g. drainage canal, streams, rivers), the state will alleviate long-term continued spending on P removal. While developing P management policy with regards to SDSs, the percent of watershed area under specific land use, land use intensity, SDS age, and location with respect to target waterbody will need to be considered.

4.3. Basin-scale payment for services program implementation

We explain the proposed policy using C-139, a sub-basin in the Everglades watershed as an example (Fig. 4). Fig. 4 shows part of C-139 that is drained by a canal (L2) which receives flows from farms with different land use intensities. The canal flows into a constructed wetland (STA 5) from where the treated water flows to the Everglades National Park (ENP). In this case, the HI farms (row crops) are located towards the downstream end of the canal, while the LI farms (sugarcane) are located on the upstream side (Fig. 4). In most watersheds, conservation funds are limited which requires identification of priority sites for funding. The P discharges from HI farms located close to the STA are least likely to be treated before being discharged to the ENP. Because of high P losses and relatively short distance between the farm and the ecologically sensitive waterbodies (The Everglades) or regional treatment system (STA 5), there is limited potential for P retention in the L2 canal. Therefore, reducing discharges from HI farms closer to STA5 would be a priority and funds would first be allocated to implement harvesting-composting at such farms (Fig. 4). Next would be the HI farms located further away (upstream) from the STA. Once the available funds to cover the willing HI farms are exhausted, the next step would be to use the water quality data to verify if the changes in P loads have occurred and are enough to meet the load reduction. If the load reductions are not met, focus will be shifted towards LI (e.g. sugarcane) farms. Furthermore, there is a concentration gradient along the L2 canal; the concentrations increase as drainage from farms with intensity higher than pastures (ranchlands) and sugarcane farms joins L2 (Fig. 4). To increase P storage at LI farms, the best alternative would be to pass the canal water with SRP concentrations higher than those existing in the LI farm SDSs. Passing the water from regional public canal at location B (Fig. 4) through the nearby LI farm SDS would be more beneficial than passing water at location A because of higher concentration gradient. Again, the priority for selecting specific LI farms for receiving PS funds would be based on the combination of their location relative to the watershed outlet (STA5) and P concentration in the regional canal. For

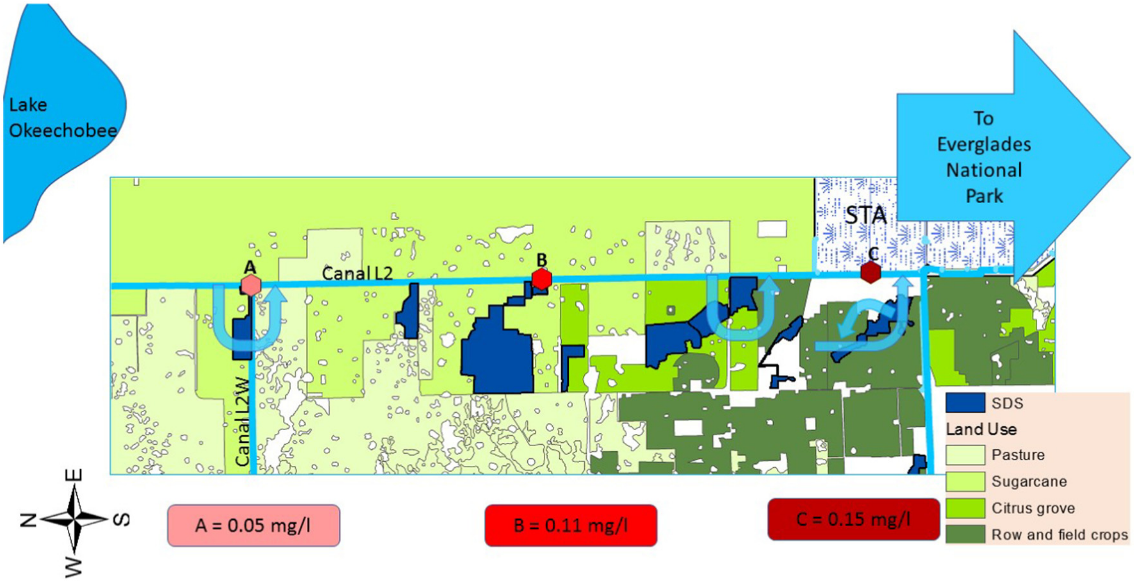

Fig. 4. Proposed local and distributed nutrient recovery system, an example from C-139 basin in the Everglades watershed. Row and other field crops mainly include fresh vegetables.

example, if a sugarcane farm is located at the downstream end, it would receive PS funds first, to cover the installation of a pump to pass the public water (L2) through the SDS as well as to implement the biomass harvest-compost strategy. This process of bringing willing farms under the PS program could continue until the P load reduction targets are either met or significant progress has been made.

The process of implementing PS in Fig. 4 is merely an example, and the land use arrangement in other parts of the watershed may not follow the same pattern and sub-watershed specific priorities need to be identified. We have presented here the case for regional P treatment by utilizing the potential of LI farm SDSs and biomass harvest-compost strategies. To put it in basin perspective, the state can potentially reduce 854 metric tons of P entering the Everglades at 88%–93% reduced price. If the proposed PS program were to be implemented, it would be a 100% offset against the P load that entered the Everglades Protection Area in Water Year 2018 (151 metric tons; SFWMD, 2019).

5. Conclusion

Agricultural stormwater detention or farm ponds are ubiquitous. Although their numbers and densities vary within watersheds, SDSs are present throughout the world. With continued use, SDSs are transitioning to P sources especially after large rainfall events. Aggregating such P losses at a watershed scale can put into perspective the potential future water quality challenge, aged SDSs pose to the receiving waterbodies. Hydrological response (dilution) to water quality like the soil P release after large rainfall events limits the P treatment by SDSs in the long-term. We conclude that to prevent the P release from SDSs, reducing the soil P density is the most economical and environmentally feasible option. Biomass harvesting and composting can prove to be a sustainable method of extracting the surplus soil P. Results showed that P treatment cost by harvesting-composting is 88% ($42/kg) to 93% ($26/kg) less than the publicly funded treatment systems. Furthermore, depending on the incoming P load, treatment efficiency can be increased from 77% to 100%. If financially compensated by the State at $355/kg of P treated (minimum cost of public treatment systems), producers could receive $9000 to $17,000 per year in lieu of implementing the proposed strategy. Impact of biomass harvesting on P treatment efficiency of the SDSs is a function of cropping system intensity and dominant macrophyte types in the SDSs. Making provisions to financially compensate producers for additional P removal depending on the cropping system intensity and location of the farm with respect to the receiving waterbody can help develop a flexible, yet effective market-like payment for services (PS) policy without being an economical burden to farmers who are already facing restrictive regulations in the P regulated basins. Depending on the financial incentives and interest of farmers, basin-scale cooperative(s) for composting can be formed for harvesting, distribution and application of compost. Closing the P loop through recycling will not only help reduce P loads but also help regain the soil productivity by enhancing the organic matter with additional potential benefit such as soil health and enhanced carbon sequestration. This may be another economically beneficial service to the public provided by the farmers, if carbon markets are developed in future to address climate change. The financial incentives provided to farms through a PS approach discussed here can create a win-win by slowing down the consumption of P reserves and reducing downstream P losses. Future efforts should be focused on system analyses to quantify the impact of composting on water, P, and carbon footprint, simultaneously. Field-testing and demonstrating the harvesting-recycling approach through a pilot project will lead to its wider acceptability and adoption by producers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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