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Evaluation of an Operational Demonstration of a Potential Aquatic Plant Control and Nutrient Mitigation Technology in Lake Okeechobee, Florida

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PURPOSE: This technical note describes the findings from a field-demonstration project conducted in 2022 that aimed to mechanically harvest water hyacinth (*Eichhornia crassipes* (Mart.) Solms) in Lake Okeechobee, Florida; macerate the harvested plant material; and pump it as a slurry to a terrestrial disposal site as a potential novel technology to reduce total phosphorus (TP) in the system.

BACKGROUND: Water hyacinth is an invasive, free-floating aquatic plant that has required active management for over 100 years in the United States (Penfound and Earle 1948). In the absence of frequent and effective water hyacinth control to maintain populations at the lowest feasible level (known as *maintenance control*), this plant limits access and navigation, degrades fish and wildlife habitat, and can host disease vectors (Joyce 1985; Penfound and Earle 1948; Schreiner 1980; Seabrook 1962; Ofulla et al. 2010). Water hyacinth has occupied Lake Okeechobee since at least 1905, and the lake remains jointly managed by the US Army Corps of Engineers–Jacksonville District (SAJ) and the Florida Fish and Wildlife Conservation Commission (Langeland and Jacono 2012). Primarily, water hyacinth control operations on Lake Okeechobee are accomplished using frequent applications of registered aquatic herbicides to keep populations as low as possible (Jessica Fair, biologist, SAJ, pers. comm., November 2021, phone).

Lake Okeechobee is a historically eutrophic water body that continues to undergo declines in water quality and increases in harmful algal blooms (Havens et al. 1994; Kramer et al. 2018). Despite the set goal for total maximum daily load (TMDL) of TP for Lake Okeechobee of 40 $\mu g\ L^{-1}$ (parts per billion), TP has continued to increase from 93 to 133 $\mu g\ L^{-1}$ since 1986 (Siders and Havens 2020).* This TP value equates to over 454 t (500 tn) of phosphorus inputs per year. While some phosphorus leaves the system through water discharge, much of the nutrient load remains within the main lake as legacy phosphorus (Missimer et al. 2021). James and Pollman (2011) estimated phosphorus-mitigation requirements in Lake Okeechobee would take at least 15 years, cost $0.5 to $3 billion (2002 US dollars; USD), and consist of large-scale chemical (alum) and dredging operations. Because of the difficulty associated with managing phosphorus inputs, several methods for removing legacy phosphorus are currently being explored to reduce TP.

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Like many invasive free-floating aquatic plants in the absence of management, water hyacinth quickly accumulates biomass that contains plant nutrients such as phosphorus (Cornwell et al. 1977; Imaoka and Teranishi 1988; Reddy et al. 1989, Reddy et al. 1990; Reddy and Debusk 1984; Reddy and Tucker 1983; Rogers and Davis 1972). For decades, scientists and entrepreneurs have investigated the use of water hyacinth for nutrient removal in high-nutrient waters, such as sewage, and subsequent use of the plant material (Aremu et al. 2012). Thus, because of the high nutrient loading in Lake Okeechobee coupled with the system's ability to produce large water hyacinth populations, the state of Florida awarded a project to a private business in 2022 to demonstrate technology that proposed the maceration and hydraulic pumping of mechanically harvested water hyacinth plants to an upland disposal site. The present study's objective was to make general observations and collect operational data for future consideration of the technology in US Army Corps of Engineers (USACE) aquatic-plant control operations and nutrient-mitigation efforts.

MATERIALS AND METHODS: The project targeted 14.2 ha (35 ac) of water hyacinth located in an area northwest of Indian Prairie Canal (27.034896, −80.934926) on Lake Okeechobee. Prior to initiation of the demonstration in the spring of 2022, the site was not managed for floating plants to ensure sufficient biomass was present. At the harvest site, two traditional mechanical harvesters were used (Figure 1). One harvester consisted of a cutting width of approximately 2 m with a payload area approximately 15 m long. The second harvester was slightly smaller at approximately 1 m wide and 10 m long. The macerator, generators, hydraulics, and various other equipment were placed on a floating barge that was moved via tugboat. Other machinery included several large generators and a hydraulic pump located on the barge to run the macerator and loading conveyor (elevator), as well as two boats and four diesel-powered pump stations to move macerated material to the disposal field. Observations showed that this operation required six workers at peak production: two harvester operators, a tractor driver, two barge operators (macerator and other equipment), and another individual filling fuel tanks.

Dissimilar from other harvesting operations, which commonly haul harvested material by truck to disposal sites, this project used a large macerator to reduce plant material to a slurry that was subsequently transported through hose by a series of pumping stations to a field approximately 10.5 km (6.5 miles) from the harvesting area (Figures 2–4). Once the slurry reached the disposal site, a hose with two large spray nozzles attached to a tractor were used to distribute the slurry across the upland area. The process of collecting, macerating, pumping, and disposing was integrated into a continuous operation, which has not been conducted before to the authors' knowledge.

To quantify nutrient content and plant biomass, random grab samples of plant material, water, and the liquid portion of the macerated material were collected and sent to Waters Agricultural Laboratories in Camilla, Georgia, for macro- and micronutrient content analyses. Likewise, four random 1 m^2 quadrats of water hyacinth plants were collected at the demonstration site to determine average biomass. Samples were collected using a PVC frame early in the project (March 2022), placed in laundry bags, and transported to the University of Florida, where collected plants were dried in a forced-air oven at 60°C until constant moisture level was achieved then weighed for dry biomass. To monitor efficacy, harvesters were equipped with GPS loggers that recorded points when the harvester head was activated (cutting). Likewise, orthomosaic imagery (2.7 cm $pixel^{-1}$) of the demonstration site was collected at the initiation of the project (March 2022) and at the conclusion of the project (July 2022) using an unmanned aircraft system flown at 120 m

(393 ft) and stitched using drone-deploy software to compare spatial changes in floating-plant community over time.

Figure 1. Aquatic-plant harvester collecting water hyacinth at the study site in Lake Okeechobee, Florida.

Figure 2. Floating barge containing a plant elevator, macerator press (juicer), generators, and a hydraulic pump.

Figure 3. Water hyacinth plants being transferred from the elevator into the macerator press (juicer).

Figure 4. Macerated plant material being applied to the nearby agricultural field as a slurry.

RESULTS AND DISCUSSION: On average, both harvesters harvested and unloaded a full load of plants in approximately 15 min. According to these observations, harvesting a 14.2 ha (35 ac) area would take approximately 885 h (110.6 eight-hour workdays). This estimate assumes that no breakdowns occur and that plants do not reproduce or spatially increase within the target area, do not move outside nonharvested areas via wind or water currents, and do not fragment into individual plants (that is, the plants remain in mats). This time estimate also varies according to the distance between the macerator and the target area (travel time) and the water depth, which are typical limiting factors of most mechanical harvesting operations (Sperry et al. 2021). An additional limitation for harvesting rates observed during the field demonstration was the maximum speed the macerator could accept and process the plant material. However, the contractor could control the amount of water mixed per load of plant material to ensure smooth operation of the macerator and pumps; therefore, the rate of maceration varied according to operator.

Average water hyacinth biomass in the demonstration site was 1.07 kg m^{-2} (0.22 lb ft^{-2}) or 10,659 kg ha^{-1} (9,510 lb ac^{-1}), which is consistent with early season medium-sized water hyacinth (Sperry et al. 2021). Unfortunately, plant biomass samples were not collected later in the season that would have likely resembled more mature plants (bull hyacinth) containing higher biomass. Nutrient levels in plant material were consistent with previously reported levels in the literature (Tables 1 and 2; Reddy et al. 1990). Although both macro- and micronutrient levels in the liquid portion of the macerated material was higher than lake water (background), the liquid values do not account for nutrient levels found in the dried plant material. Therefore, most of the nutrient content of the slurry was most likely bound up in the solid fraction of the slurry (plant material).

Table 1. Macronutrients from lake water, macerated liquid, and dried water hyacinth plants in Lake Okeechobee.

Source Material	**NO_3**	**NH_4**	**N**	**P**	**K**	**Mg**	**Ca**	**S**
	mg L^{-1}							
Lake water (*n* = 4)	0.7	0.2	—	0.01	6	10	44	34
Macerator liquid (*n* = 4)	5.3	1.6	—	2.2	145	24.3	65	523
	% by weight							
Water hyacinth	—	—	2.3	0.3	3.6	0.6	2.3	0.4

Note: For a full list of the spelled-out forms of the chemical elements used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 265, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Table 2. Micronutrients from lake water, macerated liquid, and dried water hyacinth plants in Lake Okeechobee.

Source Material	**B**	**Zn**	**Mn**	**Fe**	**Cu**
	mg L^{-1}				
Lake water (*n* = 4)	0.1	0.01	0.01	0.01	0.01
Macerator liquid (*n* = 4)	0.9	0.02	0.5	0.7	0.01
	% by weight				
Water hyacinth	23.3	21.5	355.3	2571	6.5

According to the observed nutrient contents in early samples (March 2022), 0.4 ha (1 ac) of water hyacinth contained 12.9 kg (28.5 lb) of phosphorus and 99.2 kg (218.7 lb) of nitrogen. According to the area of the demonstration site (14.2 ha, or 35 ac) and assuming 100% water hyacinth coverage with no increase in plant size, a total of 452.7 kg (998 lb) of phosphorus and 3,472.3 kg (7,655 lb) of nitrogen could theoretically be removed from the system. However, as mentioned previously, plants in the demonstration site increased in size and rapidly multiplied via asexual reproduction leading into the summer months. Therefore, the exact amount of nutrient contents removed during the demonstration is unknown.

Aside from a few equipment breakdowns, weather events, and other unforeseen circumstances, the operation largely ran continuously, and the maceration and pump systems were able to move all plant material off-site. However, mechanical harvesting of free-floating invasive plants is generally difficult, as once plant mats begin to break up, many small clumps (miniature mats) and individual plants are loosened up and can move with wind and water currents (Figure 5). These small clumps and individual plants extend harvesting time compared to harvesting dense mats because of broader distribution and opportunity to escape harvest. An additional challenge in the operation was shallow water levels. Harvesters generally require a draft of 0.5 to 1 m (18 to 36 in.), depending on harvester size and fullness; however, certain areas appeared limited because water depth was too shallow for the required draft (Figure 6). GPS tracking data indicated harvesters spent the majority of the operation around the edges of the cattail (*Typha latifolia* L.) and bulrush (*Schoenoplectus californicus*) marsh, where water hyacinth plants were densest and the harvesters were likely quicker to obtain a full load (Figure 7). However, much of the shallow-water marsh areas where larger water hyacinth plants were located could not be harvested (Figure 5). Because these shallow areas could not be effectively managed with harvesting equipment, these areas ultimately served as refugia, which quickly reinfested the demonstration site by July 2022 (Figure 8). After the monitoring period, the contractor informed the study team that personnel were able to deploy smaller harvesters and a long-reach excavator to collect plants in these marsh areas; however, these efforts were not monitored to the author's knowledge.

The amount of potential nutrients available in plants are considerably small relative to the annual nutrient inputs into Lake Okeechobee. While the demonstration project did show proof of concept and that the technology could likely be incorporated along with current harvesting operations under ideal conditions, the level of water hyacinth control provided was not equivalent (or practical) to the current practices used at Lake Okeechobee. Future research and demonstrations involving the use of the maceration and transportation of aquatic materials via pumps and hoses for nutrient mitigation should consider targeting sources of greater nutrient loads such as consolidated and unconsolidated sediments or floating tussocks. Missimer et al. (2021) reported phosphorus-rich sediments were primarily found in the eastern portions of Lake Okeechobee. TP content of those sediments ranged from 731 to 1353 mg kg^{-1}, and the authors estimated 4.6×10^6 kg of TP reside in sediments lake-wide (Missimer et al. 2021). Tussocks, which are common among many Florida lakes and rivers, are frequently managed via mechanical harvesting or shredded to maintain access and navigation and improve wildlife habitat (Alam et al. 1996; Hujik 1994; Mallison et al. 2010). Future investigations could focus on the incorporation of the observed maceration and material-transport technologies for tussock-removal operations.

Figure 5. Free-floating water hyacinth plants (*foreground*) and water hyacinth plants contained by cattail marsh (*background*) in the demonstration site on Lake Okeechobee.

Figure 6. Aquatic-plant harvester operating in shallow water.

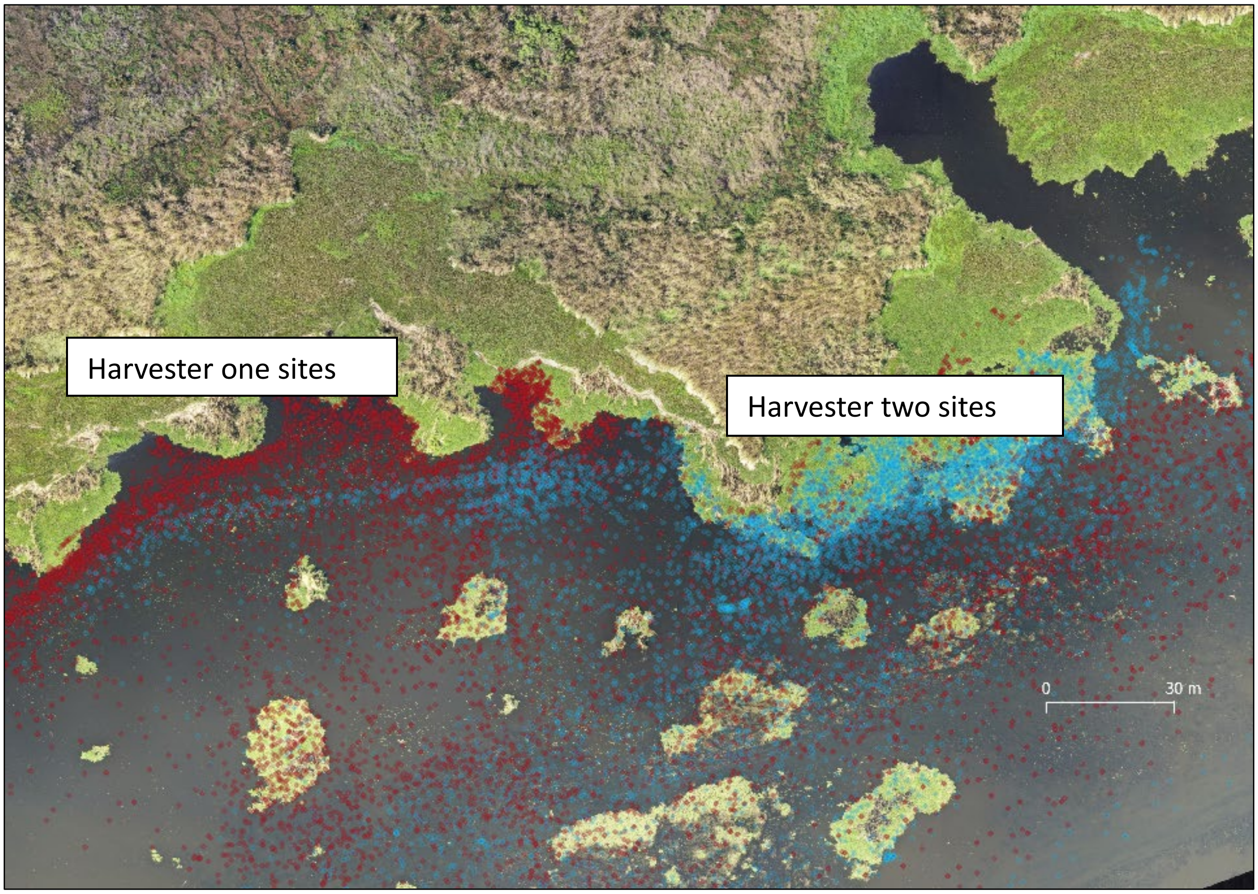

Figure 7. GPS log of mechanical harvester activity during the demonstration project. Harvester one sites shown in *red* (mostly west and offshore), and harvester two sites shown in *blue* (mostly east and offshore) on Lake Okeechobee. Harvester activity was most concentrated around edges of cattail and bulrush marsh compared to offshore.

Figure 8. Orthomosaic imagery (2.7 cm pixel^{-1}) of the demonstration site premanagement in March 2022 (*top*) and postmanagement in July 2022 (*bottom*) on Lake Okeechobee.

CONCLUSIONS: Mechanical harvesting has been frequently deployed for aquatic plant control over the past century. Similar to other plant management methods, harvesting has advantages and disadvantages. The technology observed in this field demonstration focused on improving the efficiency of a common disadvantage in mechanical harvesting operations–transport of harvested materials. Despite this advancement, the use of this technology as a stand-alone option for selective and efficacious aquatic plant control in public waterways, especially for free-floating plants like water hyacinth, would likely be limited to highly specific sites. Potential suitable sites would need to contain the following characteristics to improve efficiency: (1) an area where free-floating plants commonly accumulate, (2) near a suitable disposal site that can accept macerated slurry, and (3) deep enough water with minimal obstacles (stumps) to allow for loaded harvester draft and barge mobility. However, for the purposes of nutrient removal, this technology does appear to have significant potential in other settings and focus on more nutrient-rich materials (for example, sediments and tussocks) to achieve greater impacts compared to invasive aquatic plants.

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