Potential of Managed Aquatic Plant Systems (MAPS) for high rate carbon capture and related co-benefits

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EXECUTIVE SUMMARY

Aquatic plants have been cultivated for centuries as a way to effectively recover essential nutrients such as organic carbon, phosphorus and nitrogen. By the nineteen seventies aquatic plant cultivation was being used for the reduction and recovery of nitrogen and phosphorus in domestic wastewaters. By the early years of the twenty first century they were also being used to treat surface waters impaired by excessive levels of these nutrients. This purposeful cultivation of select aquatic plants within an engineered framework is known as Managed Aquatic Plant Systems or MAPS. The MAPS technology is now being applied to programs associated with the U.S. Clean Water Act (PL92-500)—specifically section 303(d) which requires identification of waters that are impaired; the allocation of reduced levels of the involved pollutant(s) known as a Total Maximum Daily Load or TMDL; and subsequent implementation of actions and technologies to facilitate this reduction. For example, Indian River County, Florida relies upon three MAPS facilities to help meet its TMDL allocations for the Indian River Lagoon—and are in the process of planning a fourth facility.

The MAPS technology relies upon frequent and sustained harvesting of accumulated biomass, and its associated nitrogen and phosphorus loads, to facilitate high rates of nutrient removal. MAPS operations can remove phosphorus at rates 20 times greater per unit area than unharvested treatment wetlands. In addition to high rates of nitrogen and phosphorus removal, MAPS facilitate high rates of carbon capture. For example, MAPS that are based upon the cultivation of the floating aquatic plant, water hyacinth, (WH-MAPS) can capture atmospheric carbon at the rate of 14 metric tons per hectare per year, or about 20 times the capture rate of the Amazon Forest and 100 times the rate of capture from croplands and grasslands. A MAPS centered around an Algal Turf Scrubber® can offer similar performance. MAPS offers the highest rate of terrestrial carbon sequestration, and could become an important contributor to the efforts to reduce net greenhouse gas accumulation in the atmosphere.

While MAPS has been shown to be effective in nutrient reduction and water quality enhancement, its need for frequent harvesting and the attendant biomass management has impeded its expansion within the water treatment community, largely because of a reluctance to commit to the agricultural aspects of MAPS. However, it is the agricultural attributes of MAPS that can offer a number of co-benefits, including the possibility of using compost generated from the aquatic plant biomass for soil renovation, and high rates of protein and fiber production—WH-MAPS can yield about 5 to 6 times the protein per acre per year as soybeans.

For MAPS to become established as a comprehensive global water treatment/carbon capture/agricultural technology, additional development work needs to be completed. It is suggested this be done through a four year, two phase, full scale demonstration facility located contiguous to Lake Okeechobee in South Florida. This facility will serve to verify treatment and carbon capture capabilities, while developing innovative facility design, harvesting methods and implementation strategies, as well as identifying the value of products from the harvested biomass.

I. INTRODUCTION

The late Lynne H. Nelson, a well-known historian at the University of Kansas noted that early cultures in Central America used aquatic plants to capture carbon and critical nutrients to replenish their farmland soils.[1]

"The Mayans dredged long, parallel canals through the swamps of the area, periodically cut the water hyacinths that soon clogged the canals and threw the vegetation between the canals. This slowly built up the level of the land between the canals to the point where it formed well-drained strips capable of producing corn, land that was regularly fertilized by new loads of water hyacinths. Meanwhile, the Mayans would net the fish that thrived in the canals. Fish and corn formed their basic diet."

While Dr. Nelson may have been mistaken about water hyacinths, as they are not native to Central America, there were other indigenous aquatic plants, such as water lettuce and rooted *Pontederia* species which would serve the same purpose. By rebuilding the soil with composted aquatic plants, the Mayans were able to replenish the thin veneer of topsoil typical of many tropical ecosystems, and hence ensure sustainability within one site. They also, unknowingly perhaps, sequestered atmospheric carbon.

It was not until the 1970's that technological society gained an appreciation for the wisdom of the Mayan's strategy. Following the passage of the 1972 Clean Water Act or CWA (PL 92-500), serious attention was directed towards the deleterious impact heavy nutrient loading from poorly treated wastewater was having on the nation's surface waters. The Federal funding for wastewater upgrades through section 201 of the CWA subsequently incentivized development of innovative nutrient management technologies. Among these innovations was the use of aquatic plants. Throughout the seventies and into the early eighties considerable research and development work, both public and private, targeted the use of aquatic plants to satisfy nutrient reductions associated with Advanced Wastewater Treatment (AWT) standards. Later the use of aquatic plants would expand into nutrient load reduction within impaired surface waters.

During the early period of development, two approaches to aquatic plant-based water treatment emerged. The first approach involved extensive wetland systems—both "natural" and created. These were typically dominated by submerged and emergent aquatic plants, which received flows at comparatively low loading rates. The plants were not actively harvested, but rather shed tissue to the sediments which accumulated excess nutrients. The net result was a reduction of nutrients within the water column and subsequent storage of those nutrients within accruing sediments. As these extensive systems are not in steady state, accumulated sediment eventually interferes with system performance and requires removal as was noted at the City of Orlando's Easterly Wetland Treatment System—see Picture 10 further in the text.[2]

[1] http://vlib.iue.it/carrie/reference/worldhistory/sections/18civili.html
[2] Sees, M. and K. Rothfeld (2013) The Orlando Easterly Wetlands and its Role in Meeting Orlando's Future Wastewater Demands 29th Annual ASCE -EWRI Water Resources Seminar

The second approach was intensive pulse-stabilized aquatic plant systems, typically oriented around the cultivation within an engineered platform of select aquatic plant species, e.g., water hyacinth. This cultivation involves frequent partial harvest of a productive standing biomass such that the system is sustained as a quasi-steady state. In Ecology, systems such as this, when steady state is ensured by consistent influence by external forces, are known as pulsed-stabilized, a term suggested by the famous Ecologist, Eugene Odum[3]. An example of a pulse-stabilized system is a salt marsh ecosystem which relies upon fluctuating tides to remove accumulated sediments and necrotic material. A more familiar example would be when the external energy associated with a homeowner and her/his mower ensures a well-maintained lawn at a relatively constant height and appearance. Anyone who has a grass lawn knows that without the mowing, the grass would continue to grow and eventually give way to a diversity of taller, woodier plants more commonly known as weeds.

This intensive pulse-stabilized approach, later to be labelled Managed Aquatic Plant Systems or MAPS by a group of Florida engineers and scientists, offers the benefit of long-term stability; a greater rate per unit area of biomass, protein and fiber production; much higher rates per unit area of carbon capture and nutrient removal when compared to extensive systems as well as other stabilized (mature or climax) ecosystems or cultivated lands; and resource recovery and product development. However, to those involved in operations of wastewater treatment facilities, the principal disadvantage of MAPS is the labor and equipment demands associated with frequent harvesting of the system and the subsequent processing and disposition of the harvested biomass. These are the agricultural aspects of the MAPS technology which have had little appeal to wastewater operators, water resource managers, or those involved in aquatic plant control. Ironically, this disadvantage becomes a distinct advantage when the project goal includes high yield of biomass, and consequently a high rate of carbon capture and storage.

The remainder of this discussion is oriented around the potential application of MAPS for Carbon Capture Utilization and Sequestration or Storage (CCUS) or carbon off-sets[4]; the economic, engineering and agricultural challenges attendant with implementation of such application; and the number and nature of ancillary or co-benefits, including nutrient reduction and water quality enhancement; restoration of Soil Organic Carbon (SOC); bioenergy; reduction of herbicide use in aquatic environments; establishment of a new agro-industry; and high rate protein and fiber production.

While MAPS can and does include cultivation of a number of different wetland species, this text is limited to two MAPS technologies which have been most widely studied, implemented and documented in terms of overall performance and productivity—the cultivation of water hyacinths (*Eichhornia crassipes (*Mart.) Solms) or WH-MAPS and the cultivation of an algal turf community composed of a diversity of periphytic and

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[3] Odum, W.E., E.P. Odum and H.T. Odum (1995) Natures pulsing paradigm *Estuaries,* Vol 8, No. 4 pp 547-555
[4] Carbon off-sets may be considered any reduction in emissions of carbon dioxide or other greenhouse gasses made in order to compensate for emissions made elsewhere.

epiphytic (attached) algae as the primary producers, known as Algal Turf Scrubber® or ATS™-MAPS. Both MAPS technologies have been applied to the treatment of wastewaters and to the renovation of impaired surface waters related to the Total Maximum Daily Load (TMDL) program per Section 303(d) of the CWA. As an example of current operations, Indian River County, Florida (Vero Beach) presently relies upon MAPS for both TMDL nutrient compliance and for industrial wastewater treatment. The County has three MAPS facilities in operation, and a fourth presently is awaiting construction. Their oldest facility, known as Egret Marsh Stormwater Park, includes a four-acre ATS™ unit associated with downstream lakes and wetlands created specifically for bird and wildlife habitat[5]. A video of this system which has been in operation for 10 years is found at https://vimeo.com/375731448?ref=fb-share&fbclid=IwAR1fCVnlhNdI33XZXBu3MkXkrJv8sJF_q2yg1-j1ng8R0w19TQFSwmyoM6o.

II. CLARIFICATION OF TERMS AND METRICS

The remainder of this review is centered around the carbon capture (sequestration) and storage rates or carbon off-set rates through MAPS as compared to extensive wetland systems, cultivated (agricultural) crops, and naturally evolved mature ecosystems; the efforts required for subsequent removal, processing, reuse, and storage of carbon captured by MAPS; the nature of co-benefits of MAPS technology; considerations regarding research and development needs; and suggestions related to long-term implementation.

However, before initiating this review, some clarification of terms and metrics may be helpful. For anyone trying to understand the science of global climate change and the cycling of carbon through the biosphere, it does not take long to become confused with the terms used to describe and quantify the movement of carbon into and from the atmosphere. First, it is necessary to understand the difference between carbon (C) and carbon dioxide (CO_2). For each unit of weight as carbon, there are 3.67 units of carbon dioxide. It is not uncommon for scientists to refer to carbon dioxide emissions as "tons of carbon in carbon dioxide". But more commonly, reference is made to the amount of carbon dioxide in atmospheric emissions. For example, in 2018, annual global discharge of carbon dioxide to the atmosphere from human sources (anthropogenic) was about 37.1 billion metric tons per year which is equivalent to 10.1 billion metric tons of carbon in carbon dioxide per year[6]. Another approximately 0.60 billion metric tons of carbon in methane (CH_4) are released into the atmosphere. To avoid confusion regarding methane, this review will be limited to carbon in carbon dioxide, unless otherwise noted.

Recognizing the movement and storage of carbon through our biosphere is important for understanding the relative distribution of recyclable (recirculating) carbon. Over 73% (39,000 billion metric tons) of this carbon is in the ocean, with only 1.5% (about 780

[5] One of the constructed wetlands at Egret Marsh was designed specifically to accommodate the threatened species, the Wood Stork (*Mycteria americana).* This bird has been challenged by the loss of many of Florida's shallow freshwater marshes. At Egret Marsh high quality effluent from the ATS™ is applied to this created wetland and has served the intended purpose as can be seen in the cover photograph.
[6] https://www.scientificamerican.com/article/co2-emissions-reached-an-all-time-high-in-2018/

billion metric tons) in the atmosphere. Another 18.9% is in fossil fuels and 4.7% in soils (pedologic), and about 1.2% in biological matter (biotic), both living and detrital.[7] The relatively small amount of carbon in the atmosphere makes it vulnerable to perturbations in other compartments, most notably fossil fuels, and the degradation of soils related to agricultural practices.

Effective management of carbon dioxide in the atmosphere revolves around two basic strategies:

1) Reducing the net amount of carbon dioxide released to the atmosphere, e.g., by reducing fossil fuel consumption, among other measures such as off-sets.

2) Increasing the rate of sequestration and storage of carbon dioxide from the atmosphere or emission gasses, such as through capture of point sources from power plant emissions and subsequent storage within geologic formations, or net reduction from the atmosphere through enhanced rates of photosynthesis, carbonization, and subsequent storage.

The term carbonization refers to the retention of a portion of atmospheric carbon captured through photosynthesis which is retained in the biosphere—the term bio-sequestration is often used as well. Conversion of a part of this retained carbon into stable humic substances and secondary carbonates is called terrestrial sequestration. Capturing carbon from the atmosphere using engineering techniques for the injection of industrially emitted carbon dioxide into geologic strata is called geologic sequestration[8].

Geologic sequestration will likely be developed as an important CCUS strategy, as it provides the advantage of a relatively small footprint when compared to terrestrial sequestration. But there is uncertainty regarding environmental impacts associated with large scale subterranean storage, and presently the costs are high. Certain geologic sequestration technologies do include some resource recovery, but there are limited co-benefits. Both geologic and terrestrial sequestration technologies will need to be included as part of a comprehensive strategy to reduce atmospheric carbon dioxide.

Within the available literature there is confusion between the terms sequestration and storage. The most common explanation suggests sequestration is the actual process of capturing carbon from the atmosphere so it can be moved into a reservoir, while storage is incorporation of sequestered carbon into some sort of long-term reservoir. However, variations to these definitions can be found in the literature. Quite often the two terms are used interchangeably, which contributes to the confusion revolving around their use. For purposes of this discussion, we will abide by the descriptions given—sequester meaning initial capture, storage meaning long-term placement in a reservoir. Trees for example sequester carbon from the atmosphere and can provide extensive storage of large amounts of this carbon as new plant tissue. Note for example that the Amazon

[7] Lai, Rattan (2010) Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. BioScience 60 No.9 (708-721)
[8] Ibid, footnote 5

may store as much as 76 billion metric tons of carbon. However, if the trees are harvested or destroyed—such as done in the Amazon at an alarming rate--much of the stored carbon is lost to the atmosphere, and the forest can then become a net emitter of atmospheric carbon dioxide. A new growth of trees can make-up for this loss, but the net effect is minimal net storage. Forests and other plant communities which are protected however can store extensive quantities of carbon for long periods, hence the importance of protecting major ecosystems such as the Amazon.

It is also possible to use sequestered carbon as an off-set to fossil fuel consumption through bio-fuel production or secondary reductions of carbon emissions. Consider for example the conversion of aquatic plant tissue to usable fuel through hydrothermal liquefaction, which is discussed later in this text. However, regardless of whether the sequestered carbon is stored or serves as an off-set, it is necessary to establish a clear inventory of carbon emissions used in the capture, storage or off-set, and to deduct these losses from the final calculation.

Once a forest or any ecosystem matures to a state of balance (climax state), much of the additional net carbon captured from the atmosphere tends to be countered by losses through respiration. For example, Rödig[9] found that the Amazon forest stored carbon in the soil and new biomass (Net Ecosystem Production or NEP) at a net rate of about 0.70 metric tons of carbon per hectare each year or 0.19 grams of carbon per square meter each day or 1.71 pounds of carbon per acre each day. (Note that one hectare is equal to 10,000 square meters or 2.47 acres). In comparison, the net carbon capture (sequester) through frequent harvest of a 2 acre WH-MAPS full scale demonstration system near Okeechobee, Florida[10], over a 17 month operation, considering dry hyacinth at about 30% carbon[11], was documented at an NEP of 13.02 metric tons of carbon per hectare per year or 3.57 grams of carbon per square meter per day or 31.8 pound of carbon per acre per day, with the harvest frequency of about once every four days, and an average standing crop of 15,500 pounds of dry biomass. This rate is nearly twenty times higher than that noted for the Amazon and is indicative of the potential carbon capture rate associated with MAPS facilities. This comparison is shown in Table 1. This will be discussed in more detail later in the text.

For further clarification, consider the nature of Net Ecosystem Productivity or NEP. Net Ecosystem Productivity typically is the difference between gross primary production (GPP) and total ecosystem respiration, with GPP being the amount of carbon captured through photosynthesis, and respiration is the amount of carbon converted to carbon

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[9] Edna Rödig *et al* 2018 *Environ. Res. Lett.* **13** 054013

[10] South Florida Water Management District; Florida Department of Agriculture and Consumer Services; and Florida Department of Environmental Protection (2004) S-154 Pilot ATS™-WHS™ Aquatic Plant Treatment System Q4-Q5 Report. Prepared by HydroMentia, Inc. Ocala, Florida

[11] As noted in Parra, J.V. and C.C. Hortenstein (1974) Plant nutritional content of some Florida water hyacinths and response by pearl millet to incorporation in three soil types. Hyacinth Control Journal 12: 85-90. Note that the average noted by Parra and Hortenstein for samples taken from 19 Florida surface waters was 34.9% carbon on a dry weight basis. Cultivated systems have shown similar percentages.

Table 1: Comparative Net Ecosystem Productivity (NEP) WH-MAPS

SYSTEM	Net Ecosystem Productivity (NEP) Carbon Capture Rate			
	metric tons of carbon per hectare per year	pounds of carbon per acre per year	grams of carbon per square meter per day	pounds of carbon per acre per day
Amazon Forest	*0.70*	*624*	*0.19*	*1.71*
WH-MAPS Okeechobee	*13.02*	*11,607*	*3.57*	*31.8*

dioxide to support the metabolic needs of the ecosystem. NEP then represents the total amount of organic carbon in an ecosystem available for storage[12]. It is basically the residual carbon not readily accessed by the organisms within the ecosystems. Within many MAPS units—including the WH-MAPS and ATS™-MAPS-- the amount of biological material present at any time may be considered the standing crop, which in the case of most MAPS facilities includes not only the plant material but basically all biotic and abiotic materials within the community. Because aquatic plants are so productive this standing crop expands both in weight and volume at a rapid rate. When the MAPS unit is maintained so additional growth over a set period is harvested such that the crop is returned to the initial standing crop, then that harvested amount may be viewed as the NEP[13]. This is noted in the schematic shown as Figure A

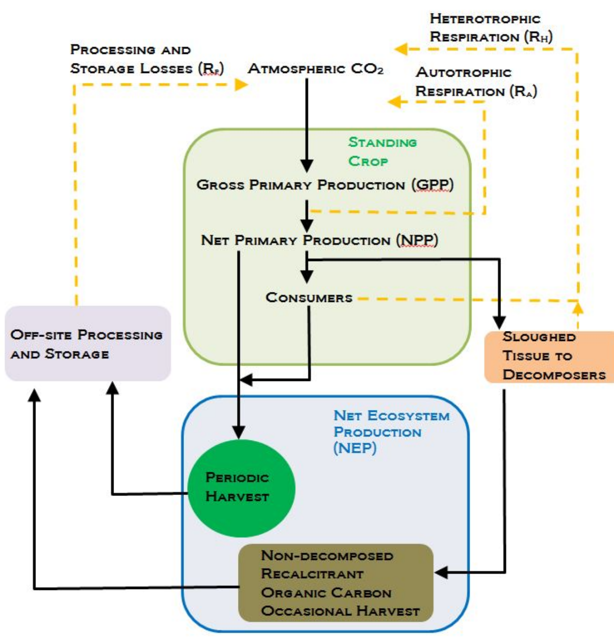
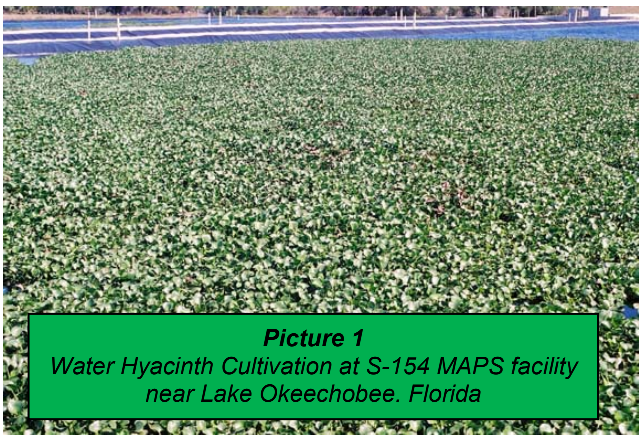


Figure A: *Carbon dynamics of a water hyacinth based Managed Aquatic Plant System (WH-MAPS)[14].*

[12] Lovett, G.M., J.J. Cole and M.L Pace (2006) Is Net ecosystem production equal to ecosystem carbon accumulation? *Ecosystems* 9: 1–4
[13] In some cases, sediment losses from sloughed material may be excluded with programmed harvesting. This sloughed material may also be periodically recovered.
[14] This schematic is based upon the assumption that influx of organic carbon from external sources is negligible, as is the release of organic carbon outside of that harvested NEP.

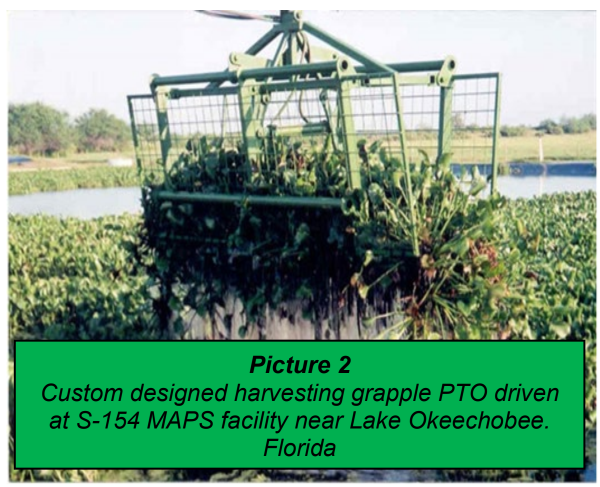
Unlike most crop agriculture, harvesting associated with both the WH-MAPS and ATS™-MAPS includes removal of almost all community components. This, in addition to the high rate of photosynthesis, enhances carbon capture by including most consumers and associated detritivores, except for of some of the more mobile species, such as fish and some insects. Note that a major challenge to optimizing net carbon storage or utilization (off-set) is to minimize carbon losses associated with processing and storing the captured NEP. This is discussed in section V.

III. REVIEW OF WATER HYACINTH AND SIMILAR FLOATING AQUATIC PLANT MAPS



Picture 1
Water Hyacinth Cultivation at S-154 MAPS facility near Lake Okeechobee. Florida

Now consider the first MAPS mention—water hyacinth MAPS or WH-MAPS. Water hyacinth is a floating aquatic plant originally native to Brazil, but now ubiquitous worldwide within the tropical and subtropical latitudes. Some pictures of a WH-MAPS operation near the City of Okeechobee, Florida are seen in the imbedded pictures within this section. It is paradoxical that the water hyacinth's rapid rate of growth and expansion which generates so much contempt for this plant as an invasive species, is also what makes it an ideal candidate for Managed Aquatic Plant Systems and for capture of nutrients and atmospheric carbon. Water hyacinth, in terms of biomass generated per unit area per unit time, is perhaps the most productive vascular plant on earth. Under ideal conditions it can increase in biomass by over 5% each day, doubling its weight every 13 days, with a capability of producing in freshwater a harvest of 250 pounds of dry matter every day per acre under high nutrient conditions (secondary wastewater effluent) when adequate space, micro-nutrients, sunlight, and warm temperatures are available. This daily production per acre typically contains about 75 pounds of carbon as organic carbon, 40 pounds of protein,75 pounds of fiber, and 42



Picture 2
Custom designed harvesting grapple PTO driven at S-154 MAPS facility near Lake Okeechobee. Florida

Picture 3
Custom designed water hyacinth chopper at S-154 MAPS facility near Lake Okeechobee. Florida

pounds of ash. However, if the growing crop is not partially harvested at a frequency of every 3-14 days, then it will expand horizontally until all available space is consumed, and then will grow vertically, developing dense thick mats, which can eventually become floating islands known as tussocks or sudds. Once these mats form, neither light nor oxygen exchange is available to the underlying water. The waterway then becomes anoxic and impassable to conventional navigation. Hence, billions of dollars have been spent to chemically control water hyacinths on lakes and rivers around the world to avoid these conditions. It is no wonder this plant is so disliked.

But suppose the hyacinths were treated as an agricultural crop, and harvested at a frequency that sustained a relatively constant standing crop and maintained an area of open water for expansion, thereby allowing the plants to sustain their high growth rate? This harvest then would represent the NEP and a net capture of both carbon and the potentially polluting nutrients of nitrogen and phosphorus.

As noted, the Mayans more than a thousand years before the present recognized the benefits offered by aquatic plants grown in their canals. This advantage of high nutrient uptake began to again receive a great deal of interest in the nineteen seventies, with recognition of the damage to our freshwater resources attendant with nutrient pollution. Since that time, extensive research has been done related to the growth and tissue characteristics of water hyacinths, resulting in several engineered systems applied to both wastewaters and impaired surface waters. Much of the early work is summarized in a 1978 review by Taylor and Stewart[15] and a more detailed assessment by Gopal in 1987[16]. In 1984 a design model (HYADEM) related to water hyacinth MAPS was developed around the Monod equation and first order kinetics[17] [18]—an approach commonly used in other wastewater systems such as activated sludge[19]. This model has been used successfully for unit sizing and performance projections related to water hyacinth growth rates, nutrient removal rates, and harvesting frequency and quantities.

Research and practical application of the WH-MAPS technology began in earnest around 1974, largely in response to the need for wastewater upgrades as delineated within section 201 of the Clean Water Act (PL92-500). Specifically, nutrient removal from domestic wastewater was an EPA priority, as eutrophication of lakes and estuaries was becoming problematic nationwide. Much of the vanguard work was done by Bill Wolverton at NASA[20]; Thomas Furman at the University of Florida[21]; and two South

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[15] Taylor, J.S. and E.A. Stewart (1978) Hyacinths in *Advances in Water and Wastewater Treatment Biological Nutrient Removal* edited by M.P. Wanielista and W.W. Eckenfelder. Ann Arbor Science Publishers, Ann Arbor Michigan ISBN 0-250-40282-3

[16] Gopal, B. (1987) Water Hyacinth Elsevier, New York ISBN 0-444-42706-6

[17] Monod, Jacques (1949). "The growth of bacterial cultures". *Annual Review of Microbiology*. **3**: 371–394

[18] Stewart, E.A., D.L. Haselow and N.M. Wyse (1984) A practical model for water hyacinth-based wastewater management –design and operation Water Reuse Symposium III, San Diego, California

[19] G. Tchobanoglous,G and F.L. Burton.(1991) Wastewater engineering: treatment, disposal and reuse/Metcalf and Eddy, Inc. McGraw Hill. ISBN 0-07-041690-7

[20] Wolverton, B.C., R.C. McDonald and J. Gordon (1975) Water hyacinths and alligator weed for final filtration of sewage. NASA Technical Memorandum TM-X72724

[21] Cornwell, D.A., J. Zoltek, C.D. Patrinely, T. deS. Furman, and J.I. Kim (1977) Nutrient removal by water hyacinths. JWPCF, Vol. **49**. No. 1

African researchers, Charles Musil and Charles Breen[22]. This led to extensive investigation into the potential of water hyacinth cultivation as an Advanced Wastewater Treatment (AWT) technology in the United States. By the late seventies, a 3-acre water hyacinth based nutrient removal pilot project was constructed and operated at the City of Lakeland, Florida wastewater treatment facility. The results of this effort clearly demonstrated the effectiveness of this highly productive floating aquatic plant to remove nitrogen and phosphorus from secondary wastewater effluent. The findings were presented in a paper given at EPA's 1979 Aquaculture Systems for Wastewater Treatment Conference in Davis, California[23]. After the Lakeland study, several full-scale hyacinth based wastewater projects were conducted into the mid-eighties[24]

However, by the late eighties, the need for AWT technology began to fade as provisions were established to permit the use of advanced secondary treatment (without extensive nutrient removal) for wastewater effluent reuse for commercial and residential irrigation. Also, when nutrient removal was required, bacterial based Biological Nutrient Removal (BNR) such as the Bardenpho Process[25] proved more practical for wastewater treatment applications than MAPS, with its higher land requirements and harvesting demands. But WH-MAPS has since proved to be well suited for managing long term nutrient reduction within targeted impaired surface waters as required by many TMDL allocations. Investigations conducted north of Lake Okeechobee in Florida[26], in Polk County near the City of Mulberry, Florida[27] and in Indian River County, Florida[28] all showed promising results related to such applications. In addition, cultivation of water hyacinths within impaired waters in Chinese reservoirs has shown promise as a means of nutrient reduction within eutrophic lakes, while impeding the development of Cyanobacterial phytoplankton blooms through allelopathy—plant production of specific toxins targeting competing organisms[29]. Recent investigations in Florida to efficiently harvest aquatic plants from native surface waters as a means of both nutrient removal and aquatic plant management have gained some institutional interest[30] [31]. The

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[22] Musil, C.F. and C.M. Breen (1977) The application of growth kinetics to the control of *Eichhornia crassipes* (Mart) Solms through nutrient removal by mechanical harvesting *Hydrobiologia* **53**:165

[23] Stewart, E.A. (1979) Utilization of water hyacinths for control of nutrients in domestic wastewater. Seminar Proceedings and Engineering Assessment Aquaculture for Wastewater Treatment. U.S. E.P.A. MCD-67 Sacramento,

[24] Stewart, E.A., D.L. Haselow and N.M. Wyse. (1987). Review of operations and performance data on five water hyacinth systems in Florida. *Aquatic Plants for Water Treatment and Resource Recovery* edited by K.R. Reddy and W.H. Smith. Magnolia Press, Orlando, USA.

[25] Bernard, J.L. (1978) The Bardenpho process In *Advances in Water and Wastewater Treatment Biological Nutrient Removal* edited by M.P. Wanielista and W.W. Eckenfelder . Ann Arbor Science Publishers, Ann Arbor Michigan ISBN 0-250-40282-3

[26] Ibid, footnote 8

[27] HydroMentia, Inc Ocala, Florida (2013) New Wales Algal Turf Scrubber® pilot program—performance report Prepared for The Mosaic Company, Lithia, Florida

[28] Van Ert, Nemoto and Associates, Inc. (2018) Pilot plan study for full-scale managed aquatic plant pollutant removal system—final report for stages 1,2 and 3 Prepared for Indian River County Public Works Dept, Stormwater Division, Vero Beach, Florida

[29] Summary of Chinese efforts in water hyacinth cultivation found at https://www.pasop.org/the-chinese-apply-water-hyaicnths

[30] https://www.southcentralfloridalife.com/stories/glades-commissioners-back-biomass-harvesting-pilot-project,11386

[31] Response to REQUEST FOR INFORMATION (RFI) NON-HERBICIDE TREATMENT AND REMOVAL OF AQUATIC PLANTS FROM FLORIDA WATERS (2020) Florida Fish and Wildlife Conservation Commission. submitted by ASBRO, LLC,Punta Gorda, Fl

mechanical harvesting and recovery of aquatic plants from surface waters has been called *in-situ*-MAPS. As methods of harvesting, processing and conveyance of plants improves and *in-situ*-MAPS gains efficiency, it could be used to reduce the use of herbicides for aquatic plant control, a stated intent of the Florida Fish and Wildlife Conservation Commission (FWC) [32].

There is more than sufficient in-field data to ensure a WH-MAPS—including *in-situ*-MAPS-- when professionally designed and operated, can provide effective, high-rate nutrient reduction from impaired surface freshwaters. WH-MAPS can provide phosphorus removals from 6 to 20 grams of phosphorus per square meter per year (53 to 178 pounds per acre per year), or 7 to 20 times higher than extensive wetland systems such as the Stormwater Treatment Areas (STA) in the Florida Everglades Basin[33]. Accordingly, the WH-MAPS can capture carbon at rates at or exceeding 1,300 grams per square meter per year (11,600 pounds per acre per year).

However, the WH-MAPS is applicable only to sub-tropical and tropical climates, and to freshwater at salinities less than 2 parts per thousand (ppt). Therefore, its applicability in the United Sates is limited to all of Florida, and southern parts of Georgia, Louisiana, Mississippi, Alabama, Texas, Arizona, New Mexico, and California. However, it could well serve agrarian dominated countries within the tropical and subtropical zone which could benefit not only from the environmental services related to carbon capture, but also from water quality improvement associated with nutrient removal and recovery, and from products associated with generated protein, fiber and bio-energy. The possible application for tropical and subtropical agrarian communities was considered in an unsolicited 2011 proposal sent to the Carter Foundation and in a 2014 document entitled “Thoughts and Discussions Regarding the Development of a new Agro-Industry based upon Cultivation of Select Aquatic Plants”[34].

While the growth dynamics and nutrient removal capability of WH-MAPS has been well documented, the agricultural aspects of the technology have not been as seriously investigated. Some improvements in harvesting efficiency were developed by HydroMentia, Inc. of Ocala, Florida (see pictures 2 and 3), but much more efficient methods are needed to meet the demands of large-scale systems as would be required for a serious carbon sequestration program. Also, there is need for more efficient crop processing methods, and investigations into the costs and value of viable products. The relative economic viability of various implementation strategies needs to be seriously explored as well. These and other R&D efforts could be supported through a full scale demonstration project, as discussed further in Section IX.

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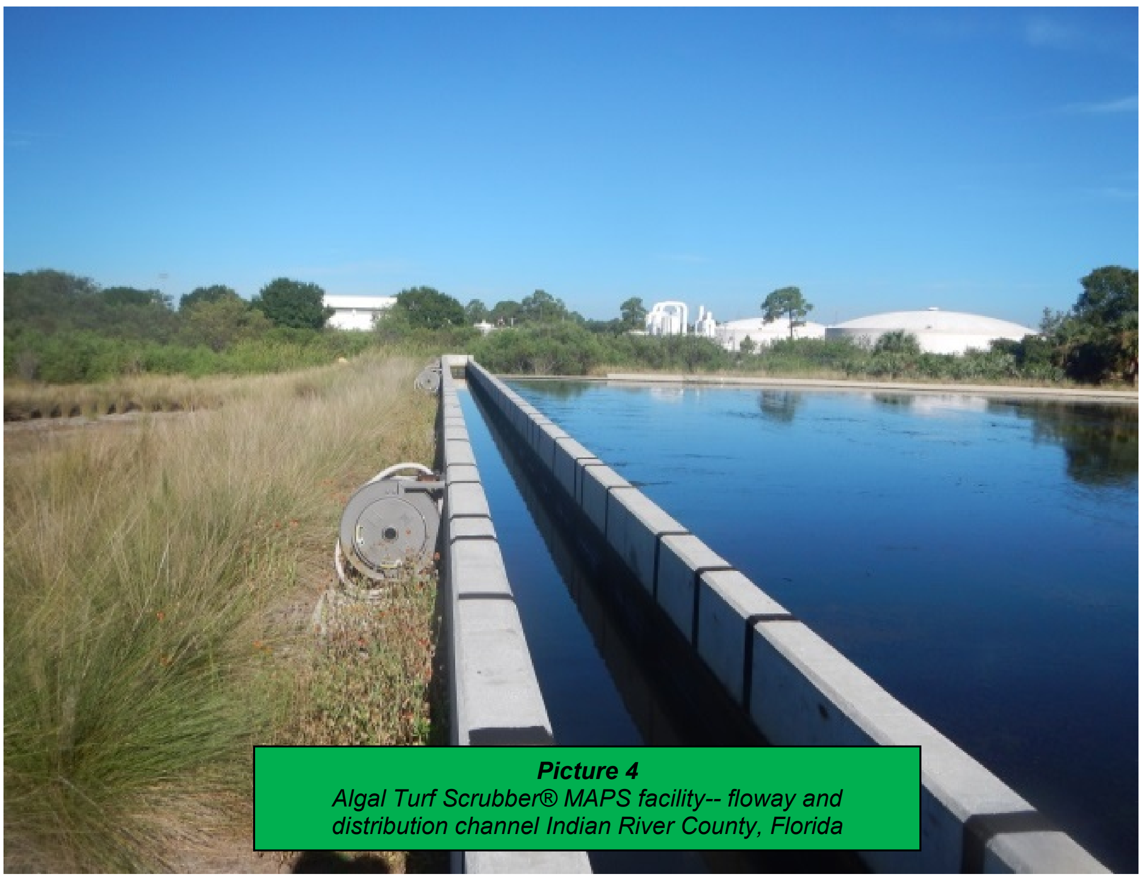
[32] Extensive use of herbicides in Florida has become controversial because of the impact these chemicals have on important fish and wildlife habitat, and the uncertainty related to both short and long term toxicity. Eric Sutton, Executive Director Fish and Wildlife Conservation Commission in a December 11, 2019 FWC meeting was very clear about his concerns regarding the use of herbicides when he said “*We would like to see a future that doesn’t have to rely upon herbicides for treating the invasive plants.”*

[33] South Florida Water Management District (2018) South Florida Environmental Report – Volume I Chapter 5B: Performance and Operation of the Everglades Stormwater Treatment Areas West Palm Beach, Florida

[34] Hyacinth Proposal and Thoughts and Discussions in PASOP Technical Documents https://www.pasop.org/technical-documents

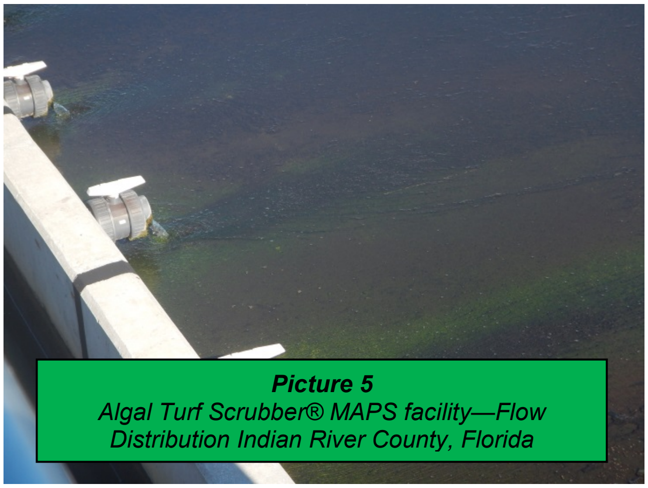
IV. REVIEW OF ALGAL TURF SCRUBBER® (ATS™-MAPS)

The role of attached benthic (bottom dwelling) algae to modulate nutrient dynamics within coral communities was studied extensively during the nineteen seventies by Walter Adey, Director of Marine Laboratories for the Smithsonian[35]. His work led to the development of methods for promoting and sustaining these algae in an aquarium setting in which corals were cultivated. This technology came to be called Algal Turf Scrubber® or ATS™, which was patented in 1982 by Dr. Adey and assigned to the Smithsonian Institution (Patent US43332634A)[36]. After gaining some experience with the ATS™ on a relatively small scale, it became evident it may have wider application in the removal and recovery of nutrients on a large scale. By the mid-nineties, a full-scale demonstration project was established in central California for the reduction of nutrients in secondary wastewater effluent[37].

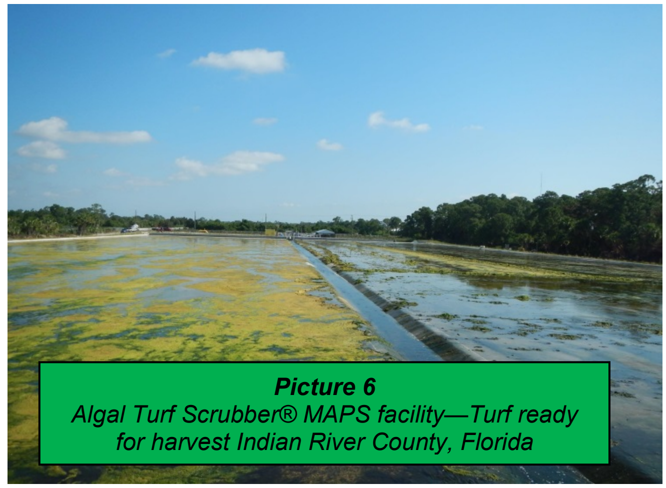


Picture 4
Algal Turf Scrubber® MAPS facility-- floway and distribution channel Indian River County, Florida

[35] Connor, Judith and Adey, Walter H. 1977. "The benthic algal composition, standing crop and productivity of a Caribbean algal ridge." *Atoll Research Bulletin* 211: 1– 15
[36] Adey, Walter H. and Goertemiller, T. 1987. "Coral reef algal turfs - master producers in nutrient poor seas." *Phycologia* 26: 374– 386.
[37] Adey, Walter H., Craggs, R., Jensen, K., St. John, M., Green, F. B., and Oswald, W. 1995. Phosphorus removal from wastewater using an algal turf scrubber. in Proceedings of the International Association on Water Quality, March 26, 1– 11.



Picture 5
Algal Turf Scrubber® MAPS facility—Flow Distribution Indian River County, Florida



Picture 6
Algal Turf Scrubber® MAPS facility—Turf ready for harvest Indian River County, Florida

Eventually arrangements were made with a Florida company, HydroMentia, Inc. to expand the ATS™ to larger scale MAPS operations (ATS™-MAPS) designed for nutrient removal from impaired surface waters. The full-scale ATS™-MAPS is composed of a sloped impermeable floway—see Pictures 4 through 9. Feed water is distributed equitably along the floway width at a rate that facilitates shallow (≤ 2 inches) laminar flow at velocities of around 1.0 feet per second. Attached algae—both periphytic and epiphytic—grow on this surface as a turf community, which includes consumers as well as accumulated detritus. The entire turf, which represents Net Ecosystem Production (NEP) is harvested typically every 7 to 30 days. After harvest, a residual starting crop of about 10 dry grams per square meter remains, which serves as the seed for new turf development. The harvest frequency is determined from growth rates documented from pilot studies. The operational strategy is to maintain high growth rates while developing sufficient crop density to facilitate optimal carbon and nutrient capture rates. As with water hyacinths (WH-MAPS), a growth dynamic model (ATSDEM) was developed for ATS™-MAPS which has proven valuable in initial sizing and performance projections related to harvest amount and frequency and effluent water quality[38].

Picture 7
Algal Turf Scrubber® MAPS facility—Turf harvesting Indian River County, Florida

Picture 8
Algal Turf Scrubber® MAPS facility—Harvested turf recovery Okeechobee County, Florida

[38] Ibid. footnote 10

Presently, harvesting is accomplished using a flexible scraper attached to a small tractor (Picture 7). The harvested material is moved down the floway into a collection flume and the filamentous components captured by a FlexRake®[39] (Picture 8) while the suspended components are delivered to a settling unit.

Picture 9
Algal Turf Scrubber® MAPS facility—Composting of harvested turf Okeechobee County, Florida

Once harvested the material can be windrow composted (Picture 9), which presently represents the lowest energy demand processing strategy. However, other products of perhaps higher value are worthy of future investigation as detailed in Section VI. These would include biochar and energy products from processes such as pyrolysis, hydrothermal liquefaction and anaerobic digestion; protein and fiber products including livestock feeds, paper and rattan furniture[40]; and various extracts such as Omega-3 fats[41]. Since 2000, several potential applications of ATS™-MAPS have been pilot tested, with some being fully implemented, and presently in operation.

The Egret Marsh Stormwater Park in Indian River County, in South Central Florida, as mentioned, is the earliest large scale ATS™-MAPS systems implemented by a county government, having been placed in operation in 2010—and which is presently in operation[42]. The first year of operation was managed and documented through a CWA 319(h) grant, including documentation of quantity and quality of harvested material[43]. As with WH-MAPS, the NEP as represented by harvested material, exceeded values seen in other cultivated systems and mature ecosystems. The comparative carbon captured at Egret Marsh is noted in Table 2.

The relative similarity of the carbon capture rates between the two MAPS system is noteworthy. The Egret Marsh ATS™ was operated at lower incoming nutrient levels than the Okeechobee WH-MAPS, and had lower tissue carbon content—about 19.2% of dry weight--hence the slightly lower carbon removal rate The algae tissue also has much higher ash content at about 60% as compared to circa 16% for water hyacinth.

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[39] FlexRake® is the registered name of a product produced by Duperon® of Saginaw Michigan. There are several other products on the market which might also meet the same needs.
[40] Rattan type furniture made from water hyacinth fiber is available in the market. see https://www.rattanland.com/articles/choose-water-hyacinth-furniture-for-your-home-119.php
[41] Doughman, S.D., S. Krupanidhi and C.B. Sanjeevi (2007) Omega-3 fatty acids for nutrition and medicine: considering microalgae oil as a vegetarian source of EPA and DHA *Curr Diabetes Rev* 2007 Aug;3(3):198-203.doi: 10.2174/157339907781368968.
[42] See Egret Marsh Video at https://vimeo.com/375731448?ref=fb-share&fbclid=IwAR1fCVnlhNdI33XZXBu3MkXkrJv8sJF_q2yg1-j1ng8R0w19TQFSwmyoM6o
[43] HydroMentia, Inc (2011) Egret Marsh Stormwater Park Algal Turf Scrubber® 319(h) Grant Quarterly Performance Report Quarter Four Final Report Contract # G0143 Prepared for: Indian River County and Florida Department of Environmental Protection

Table 2: *Comparative Net Ecosystem Productivity (NEP) WH-MAPS and ATS™-MAPS*

SYSTEM	Net Ecosystem Productivity (NEP) Carbon Capture Rate			
	metric tons of carbon per hectare per year	pounds of carbon per acre per year	grams of carbon per square meter per day	pounds of carbon per acre per day
Amazon Forest	0.70	624	0.19	1.71
WH-MAPS Okeechobee	13.02	11,607	3.57	31.8
ATS™-MAPS Indian River County Egret Marsh	8.90	7,934	2.44	21.74

Unlike the WH-MAPS, the ATS™-MAPS can perform in temperate climates, although quite often operations must be terminated during the winter months in regions characterized by frequent freeze events. Also, ATS™-MAPS do not function well when organic carbon inputs are high, e.g., Biochemical Oxygen Demand (BOD) greater than 25 milligrams per liter, or when suspended solids are so high as to shroud and thus impede the growth of the algal biomass—again above 25 milligrams per liter. However, ATS™-MAPS have been shown to function quite well in fluctuating salinities, even when these fluctuations are diurnal in response to tidal changes, such as in an estuary[44].

Experience has shown that ATS™ can be sensitive to certain toxins, including surfactants and herbicides such as glyphosate, and possibly to moieties associated with such chemicals. The widespread use of herbicides in Florida for example, can threaten the efficacy of any MAPS system, although ATS™ has been shown to be particularly sensitive[45]. Many of the concerns associated with ATS™ function can be countered by establishing a process train in which the receiving unit process is either a WH-MAPS such as shown schematically as Figure B, or in cases were the climate is temperate, an emergent or submerged plant MAPS. The advantages of such an arrangement go beyond protection from potential toxins. The WH-MAPS facilitates settling of suspended solids and reduction of BOD, as well as offering protection from various toxins. In addition, the pH within the WH-MAPS is typically between 5.7 and 7.0, which increases solubility of carbon dioxide in the water. As the ATS™-MAPS tends to consume dissolved carbon rather quickly, the pH of a freshwater with comparatively low alkalinity can be driven to above 9.5. The high carbon dioxide levels from the WH-MAPS effluent help buffer the rate of pH increase, while enhancing algal turf productivity. In addition, the ATS™-MAPS adds dissolved oxygen to the incoming WH-MAPS flow which is often low in dissolved oxygen. The ATS™-MAPS effluent dissolved oxygen levels during the day are typically well above saturation, and near saturation at night because of high reaeration coefficients associated with shallow laminar flows. So, the WH-MAPS and ATS™-MAPS are complimentary, and there are situations, particularly in sub-tropical and tropical climates, where design should be targeted towards a MAPS with WH and

[44] HydroMentia, Inc. (2009) Powell Creek Algal Turf Scrubber® Pilot Final Report prepared for Lee County, Florida
[45] Florida Department of Environmental Protection (20120 Algal Growth Inhibition Report for Taylor Creek Watershed (2012) Tallahassee, Florida (can be found under technical documents at www.pasop.org)

ATS™ in series. Such is what was suggested for removing and recovering legacy phosphorus from Florida's Lake Okeechobee[46]

As with WH-MAPS, if ATS™-MAPS is going to be applied worldwide over extensive areas as a carbon capture technology, more efficient harvesting and processing methods will need to be developed, as well as lower cost floway designs. These needs are addressed in Section VIII.

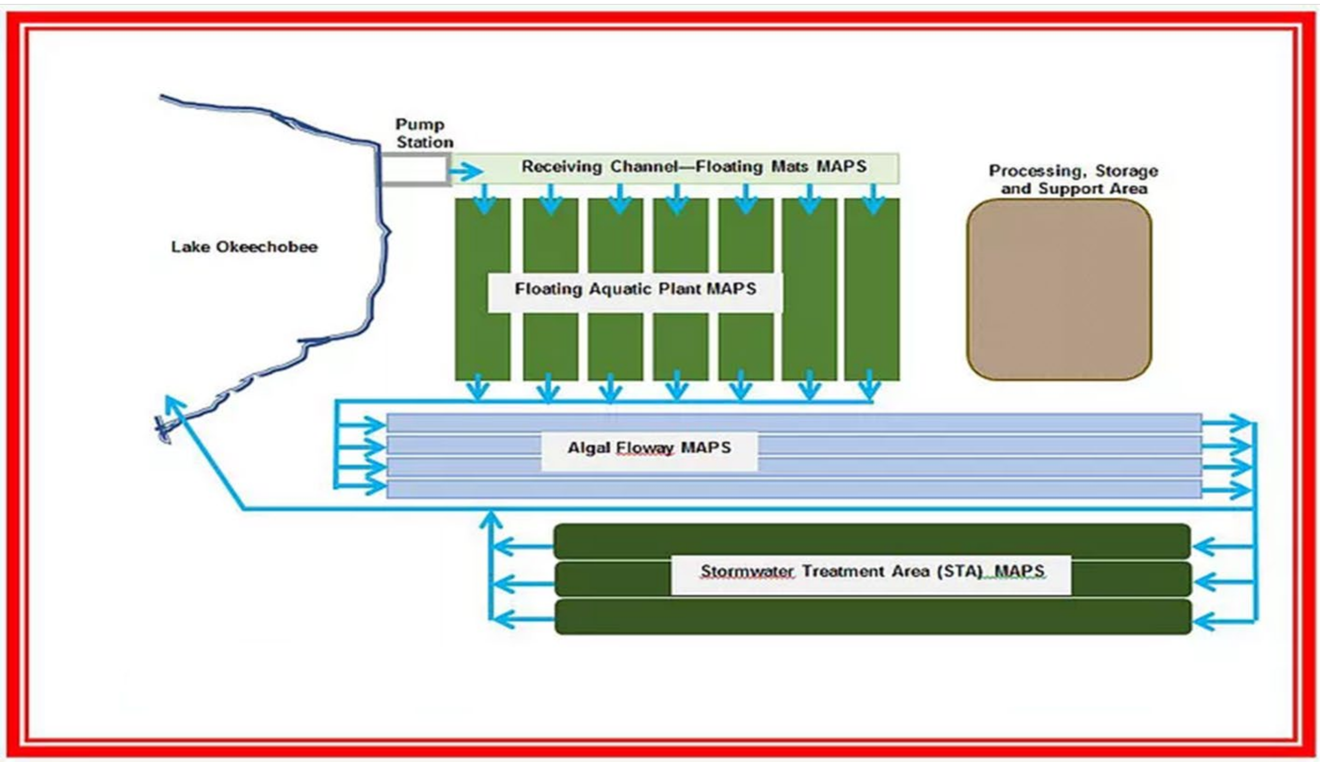

Figure B: *Schematic of suggested WH-MAPS (Floating Aquatic Plant MAPS) and ATS™-MAPS (Algal Floway MAPS) process train for Lake Okeechobee, Florida*

V. COMPARISON OF MAPS CARBON CAPTURE RATES AND PROTEIN AND FIBER PRODUCTION RATES WITH OTHER MEANS OF TERRESTRIAL SEQUESTRATION

As noted in a study of carbon sequestration in aquatic systems by Lolu et. al., wetlands offer the most effective terrestrial carbon sink[47]. Certainly, existing fossil fuel stores find genesis in organic carbon, much of which accumulated within ancient wetland, lake, estuarine and marine ecosystems. There is some irony in the fact that human induced

[46] https://www.pasop.org/a-plan-for-the-kissimmee-okeechobee and https://www.pasop.org/implementing-maps
[47] A.J. Lolu, A. S. Ahluwalia, M. C. Sidhu, Z. A. Resh (2018) Carbon Sequestration Potential of Macrophytes and Seasonal Carbon Input Assessment into the Hokersar Wetland Wetlands (2019) 39:453–472 https://doi.org/10.1007/s13157-018-1092-8

eutrophication (often called hyper-eutrophication) of many of the world's wetlands and open water systems, while considered undesirable in terms of water quality, biodiversity, recreation and fishery development, actually represents an increase in not only the rate of ecological succession but also the rate of carbon sequestration and storage[48]. Theoretically, one potentially effective means of sequestering and storing substantial quantities of atmospheric carbon would be to continue fertilization of these systems. Of course, this is not recommended, in fact it is usually illegal, because of the deleterious impacts upon other important ecological features and human health, as well as concerns regarding generation of methane, a potent Greenhouse Gas (GHG).

MAPS of course, represent a highly managed form of wetland and accordingly demonstrate high rates of carbon, nitrogen and phosphorus capture. When compared to other wetland and open water systems as well as terrestrial croplands and grasslands, the net capture of carbon is considerably higher.

As previously shown in Tables 1 and 2, a WH-MAPS facility near Okeechobee, Florida, when harvested at the average rate of once every four days, resulted in capture of about 13.02 metric ton of carbon per hectare per year or 11,607 pounds of carbon per acre per year. A WH-MAPS in Kissimmee, Florida used to remove nutrients from secondary wastewater effluent is estimated to have captured carbon at a similar rate of 14.23 metric tons of carbon per hectare per year or 12,636 pounds of carbon per acre per year. In a recent demonstration study in Indian River County, Florida, of another floating aquatic plant MAPS—water lettuce (*Pistia stratiotes*)—annual biomass production rates were found to be around 6.54 dry grams per square meter per day.[49] If this biomass is 30% carbon as with water hyacinth, the carbon capture rate is estimated at 7.00 metric tons of carbon per hectare per year or 1.92 gram of carbon per square meter per day or 6,240 pounds per acre per year.

The ATS™-MAPS facility in Indian River County, Florida known as Egret Marsh[50] demonstrated carbon capture rates similar to WH-MAPS, as noted previously in Table 2. Another ATS™-MAPS facility in Indian River County, Florida which served as a design pilot for a facility presently in operation in Indian River County, Florida known as Osprey Marsh (see Pictures 4-6), demonstrated somewhat higher carbon capture rates of 10.62 metric tons per hectare per year or 2.92 gram of carbon per square meter per day or 9,467 pounds per acre per year[51].

A one year ATS™-MAPS demonstration project in Lee County, Florida on an estuarine tributary to the Caloosahatchee River revealed carbon capture rates estimated at 7.63

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[48] For example look at the values associated with Lake Apopka in Table 3 showing pre and post anthropogenic pollution.
[49] Ibid footnote 33
[50] Ibid footnote 43
[51] HydroMentia, Inc. (2011) Pilot Algal Turf Scrubber® For PC South Monthly Performance Reports Summary Report Work Order # PCS-1_ prepared for Indian River County, Florida Stormwater Division Public Works Department

metric tons of carbon per hectare per year or 3.06 grams of carbon per square meter per day or 6,802 pounds of carbon per acre per year[52].

An ATS™ demonstration project designed to treat low phosphorus effluent (circa 34 micrograms per liter as total phosphorus) from one of the Stormwater treatment Areas (STA-1W) in South Florida yielded an annual wet algae harvest of 10,938 pounds or at 7.7% solids and 17.6% carbon dry weight, 148 pounds of carbon per year on a platform of 0.028 acres[53]. This is equivalent to 6.09 metric tons of carbon per hectare per year, or 1.66 grams of carbon per square meter per day or 5,380 pounds of carbon per acre per year.

Consider the comparative rates of carbon capture with other terrestrial sequestration methods, including wetlands, lakes and mature ecosystems, croplands and grasslands. The sedimentation rate in Lake Apopka, a hypereutrophic lake in Central Florida was dated and calculated by Reddy and Graetz[54]. Prior to the influx of anthropogenic nutrient loads—circa 1854—these rates were estimated at about 0.091 metric tons of carbon per acre per year, or ten times less than that from 1959 to 1989 at 0.906 metric tons of carbon per hectare per year, indicating the impact of extensive nutrient loading to the lake during this latter period.

Brezonik and Engstrom dated sediments and estimated the rate of accretion within the depositional zone of Lake Okeechobee in Florida. They found an average rate of 474 dry grams per square meter per year of sediment, or at 45% carbon, about 0.52 metric tons per hectare per year or 0.14 grams of carbon per square meter per day or 464 pounds of carbon per acre per year[55].

Prior to disruption of historic flow patterns and the introduction of large scale agriculture the Everglades in South Florida generated a peat layer over about 5,000 years. Gleason and Stone estimated this rate of sedimentation at about 8.4 cm per 100 years[56]. Craft and Richardson found the peat to be about 45% organic C, with a bulk density of 0.12 grams per cubic centimeter, with an accretion rate similar to Gleason and Stone at 0.80 millimeters per year or 8.0 centimeters per 100 years. This can be calculated at 0.43 metric tons of organic carbon per hectare per year or 0.12 grams of carbon per square meter per day or 385 pounds of carbon per acre per year[57].

The South Florida Water Management District (SFWMD) in West Palm Beach, Florida manages about 50,000 acres of Stormwater Treatment Areas (STA), which are created

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[52] Ibid footnote 40

[53] HydroMentia, Inc. (2009) STA-1W Algal Turf Scrubber® Pilot Final Performance Report prepared for: South Florida Water Management District, West Palm Beach, Florida, USA

[54] Reddy, K.R. and D.A. Graetz (1990) Final Report Internal nutrient budget for Lake Apopka # 15-150-01-SWIM prepared for St. Johns River Water Management District, Palatka, Florida, USA

[55] Brezonik P.L. and D. R. Engstrom (1997) Modern and historic accumulation rates of phosphorus in Lake Okeechobee, Florida *Paleolimnology* 20: 31–46, 1998. 31 c 1998 Kluwer Academic Publishers.

[56] Gleason, P. J and P. Stone (1994) Age, origin, and landscape evolution of the Everglades peatland In Everglades: The Ecosystem and its Restoration edited by S.M Davis and J.C. Ogden. St. Lucie Press, Delray Beach Florida. ISBN 0-9634030-2-8

[57] Craft, C and C. Richardson (2008) Soil characteristics of the Everglades peatland. In The Everglades Experiment: Lessons for Ecosystem Restoration. 10.1007/978-0-387-68923-4_3

extensive wetlands designed to reduce phosphorus from agricultural waters prior to release to the Everglades National Park. These STA units together reduce phosphorus within the water column at a rate of about 0.80 grams of phosphorus per square meter per year[58]. This STA is an extensive treatment unit in which periodic harvesting is not conducted unlike the more intensive MAPS technology. Subsequently, the Net Ecosystem Production (NEP) is represented by accreted organic residuals[59]. The carbon captured and stored within the STA sediments may be approximated based upon field data showing the phosphorus content within accreted material is about 800 milligrams per kilogram or 0.08% as an average. The sediment accretion rate therefore is estimated at 1000 grams per square meter per year, or assuming this sediment is 40% carbon, 400 grams of carbon per square meter per year, or 4.0 metric tons per hectare per year or 1.10 grams of carbon per square meter per day or 3,566 pounds of carbon per acre per year. These extensive wetlands can serve as substantial carbon sinks. However, as the system accumulates sediments, measures are needed to remove the accumulated material in an effort to recover desired treatment performance. Shown in Picture 10 is the removal of accrued sediment from a treatment wetland in Orlando Florida[60].

Picture 10
City of Orlando Florida Easterly Wetland Treatment Facility—removal of accrued sediment

Terrestrial croplands, pasture and grasslands can provide carbon capture and storage, but the rates are considerably lower than with MAPS, and other wetland systems. Sommer and Bassio estimated cropland could average carbon capture at about 0.135 metric tons per hectare per year or 0.04 grams of carbon per square meter per day or 124 pounds of carbon per acre per year under improved management practices. They found similar potential with grasslands at 0.125 metric tons per hectare per year or 0.03 grams of carbon per square meter per day or 111 pounds of carbon per acre per year.[61] The comparative carbon capture rates are noted in Table 3.

[58] In comparison MAPS units typically reduce phosphorus at a rate ranging from 4 to 20 grams of phosphorus per square meter per year.
[59] Ibid footnote 29
[60] Ibid footnote 2
[61] Sommer, R., Bossio, D.(2014) Dynamics and climate change mitigation potential of soil organic carbon sequestration, *Journal of Environmental Management*, Volume 144, 1 November 2014, Pages 83–87, DOI: 10.1016/j.jenvman.2014.05.017

It is clear that MAPS systems out-perform other terrestrial platforms in terms of carbon capture. This is due to the sustained high rate of productivity, and the capture of nearly the entire net ecosystem productivity (NEP). To put this in perspective it is helpful to consider also the protein production capability of MAPS compared to the protein yield of soybeans, which is around 1,200 pounds per acre per year[62]. The annual harvest from the WH-MAPS in Okeechobee, Florida as referenced previously[63], was found to be 15.4% protein on a dry weight basis, with the annual protein production at about 5,958 pounds per acre per year, or nearly five times that of soybeans. Similarly the ATS™-MAPS known as Egret Marsh in Indian River County[64] showed similar protein production capabilities, at 6,436 pounds per acre per year at 15.6% protein on a dry weight basis. Similar trends are also associated with Fiber production. These comparative numbers are shown in Table 4.

Table 3: *Comparative Carbon Capture Rates WH-MAPS and ATS™-MAPS to other terrestrial sequestration platforms*

SYSTEM	Net Ecosystem Productivity (NEP) Carbon Capture Rate			
	metric tons of carbon per hectare per year	pounds of carbon per acre per year	grams of carbon per square meter per day	pounds of carbon per acre per day
TERRESTRIAL SEQUESTRATION MAPS OPERATIONS				
WH-MAPS Okeechobee	*13.02*	*11,607*	*3.57*	*31.80*
WH-MAPS Kissimmee	*14.23*	*12,686*	*3.90*	*34.75*
WL-MAPS (Water Lettuce) Indian River County	*7.00*	*6,240*	*1.92*	*17.10*
ATS™-MAPS Egret Marsh	*8.90*	*7,934*	*2.44*	*21.74*
ATS™-MAPS Osprey Marsh	*10.62*	*9,467*	*2.91*	*25.94*
ATS™-MAPS Powell Creek, Lee County, Florida (estuarine)	*7.63*	*6,802*	*2.09*	*18.64*
ATS™-MAPS STA-1W, Palm Beach County, Florida	*6.05*	*5,380*	*1.66*	*14.78*
OTHER TERRESTRIAL SEQUESTRATION SYSTEMS				
Amazon Forest	*0.70*	624	*0.19*	*1.71*
Lake Apopka, Florida before extensive nutrient loading circa 1854	*0.09*	*81*	*0.03*	*0.22*
Lake Apopka, Florida after extensive nutrient loading (1959-1989)	0.91	808	0.25	2.21
Lake Okeechobee, Florida (1900-1996)	0.52	464	0.14	1.27
Historic Everglades	0.43	385	0.12	1.05
Stormwater Treatment Areas South Florida	4.00	3,566	1.10	9.76
Cropland (arable land and permanent crops)	*0.14*	*123*	*0.04*	*0.34*
Grasslands (permanen meadows and pastures)	*0.13*	*111*	*0.03*	*0.31*

Table 4: *Comparative Protein production rates WH-MAPS and ATS™-MAPS to soybeans*

SYSTEM	Annual Protein Production			
	metric tons of protein per hectare per year	pounds of protein per acre per year	grams of protein per square meter per day	pounds of protein per acre per day
Soybean Cultivation	*1.35*	*1,200*	*0.37*	*3.29*
WH-MAPS Okeechobee	*6.68*	*5,965*	*1.83*	*16.32*
ATS™-MAPS Indian River County Egret Marsh	*7.22*	*6,436*	*1.98*	*17.63*

62 https://www.agdaily.com/crops/soybean-plant-facts-value-agriculture/#:~:text=Randy%20Dowdy%20holds%20the%20world,pounds%20of%20protein%2Drich%20meal
63 Ibid footnote 10
64 Ibid footnote 43

The co-benefit of high levels of protein and fiber production are significant, and indicate the potential MAPS has not only as a provider of substantial environmental services associated with carbon and nutrient capture and recovery, but as an important agro-industry whose benefits are not only attendant with high production, but also secondary benefits such as those related to the offering of a sustainable fiber substitute, which can reduce carbon losses from carbon sinks associated with periodic harvest of forests. A more thorough review of the co-benefits are presented in Section VII.

But while MAPS does actually result in effective capture of carbon, it needs to be recognized that as with any technology under consideration, the net storage must be calculated as the difference between the initial carbon captured and the carbon lost in this capture and subsequent processing, transport and storage. Having noted this, even if losses as high as 50-75%, the net storage remain higher than most other platforms. In addition MAPS, as noted, offers several co-benefits.

VI. HANDLING, PROCESSING, AND STORAGE OPTIONS ASSOCIATED WITH MAPS

a. Initial Considerations

While it is evident that MAPS can facilitate high-rate capture of carbon through terrestrial carbonization, which may also be considered sequestration, the percentage of this captured carbon which is secured through long-term storage, or which delivers quantifiable and legitimate off-sets, depends upon the efficiency of all facets of the MAPS operation. Major operational components include:

- Delivery of flow to the land based ponds, floways etc. This is typically done through high volume low-head pumps such as propeller pumps, axial flow pumps, or Archimedes type pumps. The energy required for pumping if associated with expenditure of fossil fuels will reduce the net carbon capture. Such would not be the case if sustainable energy sources such as solar, wind or bioenergy were used. (Except for an initial burden from manufacture, transport and installation.)
- Harvesting of the biomass requires considerable energy, and as noted previously, there is a need for development of innovative, more efficient methods of harvesting. Some initial work has been done by HydroMentia, Inc.[65] regarding water hyacinths, as shown in Picture 2 and Picture 3. Similarly some improvements have been made in the harvesting of algal turf in ATS™-MAPS units by HydroMentia, LLC[66] and Indian River County, Florida (see Picture 7). For large scale MAPS systems to be effective, further improvements in

[65] Ibid footnote 10
[66] HydroMentia LLC , previously HydroMentia, Inc. is working with several clients in the mid-Atlantic area to reduce the complexity of algal turf harvesting through elimination of the FlexRake and segregation of fiber and high suspended solids liquid components.

harvesting are necessary, with emphasis upon more automated, higher rate methods which may incorporate volume reduction and mechanical dewatering; minimization of overland transport of excess water; and efficient logistical design of the MAPS facility.

- Processing of harvested biomass will require some reduction of net carbon capture. There are a number of processing options available, and each results in products of varying value, and each requires some investment of carbon, either through oxidation of biomass or through burning of fossil fuel, e.g. for drying. Within this review of processes, consideration will be limited to Composting; Bioenergy; Livestock Feed/Protein; and Fiber products.

b. Compost

Composting involves the biological decomposition and stabilization of organic substrates, typically under aerobic conditions, that allow development of thermophilic temperatures as a result of biologically produced heat, to yield a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land.[67] Windrow composting is the least energy demanding aerobic composting method (See Picture 9), and has been used to process harvested biomass in many of the projects cited herein. At the project in Okeechobee County, Florida[68] when water hyacinths were chopped and then mixed with algal biomass harvested from an ATS™ along with a small amount of straw as a bulking agent, the finished compost as noted in Table 5, demonstrated a weight reduction of 88%, a moisture weight loss of 94% and a carbon loss of 44% after 95 days. The volume reduction was estimated at 83%. It is noteworthy that even with a feedstock moisture content of 91%, the material composted readily with daily mixing during the first few days.

There are many references related to composted aquatic plants. For example Stibolt and Contreras[69] recommend water hyacinth as a compost feedstock for organic vegetable cultivation in Florida.

Albano et. al.[70] with the USDA, investigated the performance of compost generated from harvested algal turf associated with Indian River County's Egret Marsh facility as a soil substrate. The composted algae showed superior performance over commercially available peat based substrate, but had a bulk density somewhat above the suggested upper range (0.80 grams per cubic centimeter as compared to 0.70 grams per cubic centimeter as the recommended upper value). The bulk density could be adjusted

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[67] Definition taken from Haug T.H. (1993) The Practical Handbook of Compost Engineering Lewis Publishers, CRC Press Boca Raton, Florida ISBN 0-87371-373-7
[68] Ibid footnote 10
[69] Stibolt, G. and M. Contreras(2013) Organic Methods for Vegetable Gardening in Florida University of Florida Press, Gainesville, Florida ISBN 978-0-8130-4401-9
[70] Albano, J.P., J. Owen, J. Altland, T. Evens, S. Reed, T. Yeager
Composted Algae as an Alternative Substrate for Horticultural Crop Production: Chemical and Physical Properties
U.S. Horticultural; Research Laboratory, USDA, ARS, 2001 S. Rock Rd., Fort Pierce, FL, 34945-3030

through blending with lighter materials, but research into potential blends was not pursued by the USDA.[71]

Aerobic composting is an effective way of reducing moisture content while producing a beneficial product. The trade-off is an investment of about 40-50 percent of the organic carbon which is oxidized and emitted to the atmosphere as carbon dioxide. This generates the heat needed to evaporate the excess water. However, even at 50% carbon loss to the atmosphere, the carbon capture rate is still considerably higher that other terrestrial sequestration options (see Table 3).

Table 5: *Compost production characteristics from harvests of WH-MAPS and ATS™-MAPS*

	Compost Feedstock		Finished Compost		Differential
Content	**%**	**Pounds**	**%**	**Pounds**	**Pounds**
Total Weight	-	52,888	-	6,589	46,299
Total Moisture	91	48,111	45	2,978	45,133
Total Dry Weight	9	4,772	55	3,611	1,161
Ash (percent dry weight)	46	2,174	60	2,174	0
Total Organic Solids as dry weight	54	2,598	40	1,437	1,161
Total Carbon as dry weight estimate*	30	1,432	22	802	630

Biodegradable Carbon	44.0%	630
Nonbiodegradable Carbon	56.0%	802

* Total carbon is estimated as (100-%ash dry weight)/1.8 as cited by Haug[72]

The question is, how to store this compost such that it retains the attendant carbon for an extended period? Certainly the use of compost to increase the soil organic content (SOC) would be an effective way of not only improving general soil health, but also increasing the soil's rate of carbon sequestration. The application of MAPS compost to degraded soils would be congruent with the 4 per mille proposal offered during the 2015 Paris Accords on Climate Change. This proposal includes a goal of increasing the Soil Organic Content (SOC) by 4 parts per thousand, with the suggestion that if this were accomplished it would increase the carbon sequestration in soils by 2-3 billion tons of carbon per year, or 20-35% of the present day Greenhouse Gas (GHG) emissions.[73]

While the 4 per mille goals is seen as overly ambitious by some[74] because of political, economic, as well as scientific reasons, most critics agree that improving SOC in soils has many co-benefits such as enhanced nutrient content, protection against erosion losses, and improved retainage of moisture. More pessimistic expectations of carbon

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[71] If composted aquatic plants from MAPS operations could be adjusted to meet the specification of Canadian Pea, which is used extensively by Florida's large foliage industry, it would save money for the farmers, ad provide some carbon off-sets associated with mining and transporting Canadian Peat to Florida.
[72] Haug T.H. (1993) The Practical Handbook of Compost Engineering Lewis Publishers, CRC Press Boca Raton, Florida ISBN 0-87371-373-7
[73] Minasny, B. et.al (2015) Soil Carbon 4 per mille *Geoderma* 292 59-86
[74] Amundson, R. and L. Biardeau (2018) Opinion: soil carbon sequestration is an elusive climate mitigation tool.PNAS November 13, 2018 115 (46) 11652-11656; https://doi.org/10.1073/pnas.1815901115

sequestration potential through improved management of soils suggest only 1.9 to 3.9% of the 87 year GHG emission scenario (2014 to 2100) SRES-A2[75] may be achievable[76]. This is attributable largely to the fact that in time SOC levels reach equilibrium in terms of carbon sequestration, resulting eventually in negligible net storage. Hence carbon sequestration rate in soils is time limited, and should be considered a short term measure regarding carbon capture and storage. Therefore, should MAPS technology expand to become a significant carbon capture technology on a global scale, storage or off-set strategies may need to go beyond increasing SOC.

However, on smaller scale projects, such as those in Florida, composting of MAPS harvests provides a reasonable means of capture and storage of atmospheric carbon and improving soil quality. Studies by the University of Florida[77] indicate a potential market for compost in Florida of about 42 million tons annually. The value of bulk compost however was found to average only about $30 per ton, which from a business perspective limits the market to about a fifty mile radius. However, from a carbon storage perspective the range could be higher if enhanced valued carbon credits were to be incorporated into the business model. For example consider a 16 cubic yard dump truck which can hold about 19,200 pounds or 9.6 tons of compost at 45% moisture. The carbon in this load will be circa 2,300 pounds. The truck can be expected to emit about 1 pound of carbon per mile, so a haul range of 150 miles, including a return trip, will reduce the net carbon capture by only 13%. However, present pricing of carbon credit at about $20.81 per metric ton, would, from a business perspective, allow only a modest increase in range. Consequently, the economics of MAPS compost will remain range limited, unless environmental service subsidies, including both carbon capture and nutrient removal, are established at higher value.

Certainly one potentially viable scenario regarding MAPS based carbon capture and storage would involve application by agrarian societies in which the compost could be applied in the proximity of the MAPS production facilities. For this concept to be functional, a nearby water source which contains sufficient amount of nutrients, would be required. Large riverine systems such as the Mississippi in the United States and parts of the Nile in Africa, as well as large lakes such as Lake Okeechobee in Florida, or Lakes Tanganyika and Victoria in Africa would be potential candidates. Many of these areas already suffer from degraded or desertified soils, so compost application would provide substantial benefits.

c. Bioenergy

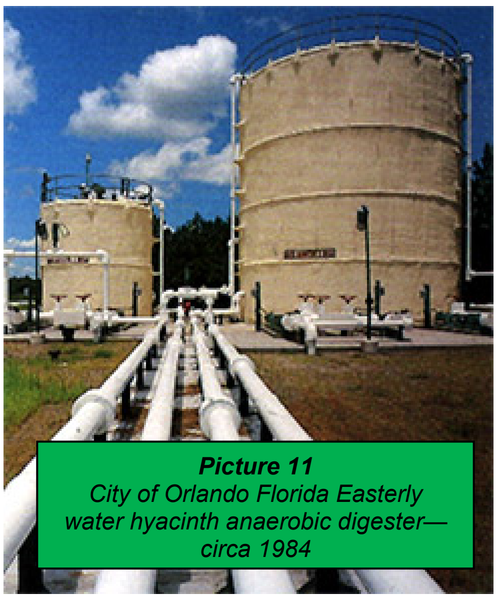
In the late seventies and early eighties there were several investigations initiated to determine the effectiveness of using water hyacinth for biogas generation through

[75] Special Report on Emission Scenarios (SRES) (2000) Intergovernmental Panel on Climate Change ISBN: 92-9169-113-5

[76] Sommers, R. and D. Bossio (2014) Dynamic and climate change potential of soil organic carbon sequestration *Journal of Environmental Management* 144 83-87

[77] Shiralipour. A and E. Epstein (2005) Preliminary compost assessment Okeechobee, Florida region University of Florida , Biomass Programs, Gainesville, Florida. Prepared for HydroMentia, Inc. Ocala, Florida

anaerobic digestion. Much of this research was supported by the Gas Research Institute (GRI) in response to rising fossil fuel prices[78]. Results from an anaerobic digester experimental test unit located at Disney facilities in Orlando, Florida indicate that up to 0.33 cubic meters of methane at standard temperature and pressure was produced for each kg of organic (volatile) solids fed to the unit. (This amounts to 5.29 cubic feet of methane per pound of organic solids). The feed material was chopped and ground water hyacinths grown in domestic wastewater. The biogas generated was about 60% methane by volume, with much of the remainder as carbon dioxide. The BTU value of the gas was about 600 BTU per standard cubic foot or about two thirds of natural gas.



Picture 11
City of Orlando Florida Easterly water hyacinth anaerobic digester—circa 1984

A full scale anaerobic digester was installed and operated at the City of Orlando's Easterly Iron Bridge Wastewater Treatment Facility in the early eighties—see Picture 11. The feed material was chopped water hyacinths at about 4-5% solids. The system produced about 600 BTU per standard cubic foot biogas at the rate of about 4.80 standard cubic feet per pound of volatile solids.[79]

Biogas can be produced effectively from water hyacinths, but the process is comparatively expensive and carbon dioxide attendant with the methane is released with the burning of the biogas unless it can be scrubbed before burning. Separating the carbon dioxide from the methane increases overall costs. By the early nineties natural gas prices had dropped and interest in anaerobic digestion of biomass waned. It is however a technology that deserves reconsideration, recognizing that substantial reduction in capital and operating costs and improvement in system efficiency and operational expenses are needed to gain feasibility.

In recent years there has been a renewed interest in pyrolysis, which involves thermal decomposition of materials at elevated temperatures in the absence of oxygen. There has been particularly interest in the production of biochar and attendant biofuels. Biochar is a recalcitrant material which effectively secures carbon for long-term storage. Biochar production may also result in gasses available for combustion. Biochar has

[78] Chenoweth, D.P. (1987) Biomass Conversion Options In. Aquatic Plants for Water Treatment and Resource Recovery. Pp 621-642 Edited by K.R. Reddy and W.H. Smith. Magnolia Publishing Company, Orlando, Florida. ISBN 0-941463-00-1

[79] Unpublished data gathered by author.

been shown to improve soil performance. It is not unreasonable to expect that biochar could also be stored in deeper soil strata, in what might be considered a "reverse coal" strategy. However this approach has not yet been widely considered.

Trials have been conducted for producing biochar from water hyacinths through pyrolysis[80.] The biochar produced captured only a comparatively small amount of the carbon associated with the hyacinth biomass—about 14%. Information was not provided regarding the value of associated gasses. The greatest challenge with conversion of aquatic plants though pyrolysis is the need to dry the product before processing. As most aquatic plants are 90 to 96% moisture, dewatering is an formidable challenge both in terms of process and costs. Once water hyacinths or other aquatic plants are dried, their value as a protein or fiber product may be far greater than the biochar value. Pyrolysis and biochar production therefore from aquatic plants may be difficult to justify both in terms of costs and carbon storage.

A technology similar to pyrolysis, but more amenable to processing wet biomass is Hydrothermal Liquefaction (HTL), which involves thermal conversion of wet biomass into crude-like oil under moderate temperature and high pressure. Work has been done on the Hydrothermal Liquefaction of water hyacinth.[81] The testing was done at various temperatures and residence times, with and without alkali catalyst. The highest bio-oil yield was 23%, with the remainder as gasses, solid residue and water soluble oxygenated hydrocarbons. The bio-oil was composed of both aliphatic and aromatic fractions.

The use of the bio-fuels generated through HTL of aquatic plants needs further exploration. Because of their high productivity, aquatic plants such as water hyacinth could yield significant quantities of bio-oil. Of concern however would be the disposition of residues, and whether they could be converted to resources or carbon sinks at a reasonable costs rather than imposing additional costs as a waste product.

Considerable effort in recent years has been directed towards the recovery of oils from algae as a fuel. Most of this has targeted phytoplankton (suspended algae) or what is commonly called microalgae. However some work has also been done on marine macro-algae (seaweed). In her recent book, Ruth Kassinger[82] gives a summary of progress made in generating fuel from algae.

There have been some studies related to the direct extraction of oils from attached algae harvested from the Egret Marsh ATS™-MAPS as conducted by Van Ert[83]. The initial results however were apparently not that promising. However, Blersch, Calahan

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80 Ebhin Masto, R., S. Kumar , T.K.Rout, P. Sarkar ,J. George and L.C.Ram (2013) Biochar from water hyacinth (*Eichornia crassipes*) and its impact on soil biological activity *Catena* Volume 111, December 2013, Pages 64-71

81 Singh, R., B. Balagurumurthy, A Pradish an T. Bhaska (2015) Catalytic hydrothermal liquefaction of water hyacinth *Bioresource Technology* Volume 178, February 2015, Pages 157-165 https://doi.org/10.1016/j.biortech.2014.08.119

82 Kassinger, R. (2018) Slime: How algae created us, plagued us, and just might save us Mariner Books Houghton Mifflin Harcourt. New York. ISBN 9780544432932

83 Personal communications with Matt van Ert of Van Ert-Nemoto and Associates LLC Vero Beach, Florida

and Adey in a recent article suggested that ATS™ while offering valuable environmental services through water quality enhancement as well as carbon capture, also generates large quantities of biomass that could yield valuable energy products beyond direct oil extraction. They suggested that direct extraction of oils from algal turf may be a less feasible approach than techniques such as fermentation to yield butanol, and hydrothermal liquefaction, or pyrolysis to generate bio-crude[84].

d. Livestock Feed and Protein Production

The ability of aquatic plants to out produce terrestrial crops in terms of protein and fiber (see Table 4) must be considered most significant, as these compounds are critical to human and animal health. In an article in the World Economic Forum it was noted that:

accessible, affordable, healthy and sustainable protein is critical to human nutrition and economic development[85].

As the trend in protein consumption shifts towards a preference for animal protein as noted by the UN Food and Agriculture Organization (FAO), and as the world population stretches towards 10 billion, an increased demand for protein in animal feeds can be expected. In an assessment of the status of protein sources for the animal industry by FAO[86], it was stated that:

innovative developments in the feed industry should be sought with a view to providing alternative sources of proteins and new amino acid technologies.

MAPS could be one these "innovative developments", considering their high rate of protein production.

There has been considerable research and field investigations related to the use of aquatic plants for protein and fiber production both for human consumption and for animal feeds, although very few have resulted in a marketable product. One exception regarding protein is the company Parabel[87] which is producing in Florida the protein Lentein from the floating plant, duckweed (*Lemna minor*). Lentein is viable for human consumption as well as a component of animal feeds.

In the Philippines Monsod produced a meal from water hyacinth which was added as a supplement to fortify flour, noting the hyacinth meal to be particularly high in the

[84] Blersch, D., D. Calahan and W. Adey (2015). Weeds in the algae garden – A source of biomass for the algae-to-biofuels program. Ecological Engineering. 85. 275-282. 10.1016/j.ecoleng.2015.10.014.
[85] https://www.weforum.org/agenda/2019/01/how-can-we-produce-enough-protein-to-feed-10-billion-people/
[86] Speedy, A.W. (2002) Protein sources for the animal industry: Overview of world fed protein needs and supply. FAO, Rome, Italy file:///C:/Users/Allen/Documents/John%20Kerry/FAO%20animal%20feed%20protein.pdf
[87] https://www.parabel.com/

vitamins A, B-12, and E. However this supplement was never developed into a marketable product[88].

Gopal in his 1987 review of water hyacinth, referenced a number of studies related to water hyacinth as an animal feed[89]. He noted that the major impediment to the production of livestock feeds from aquatic plants is with the large percentage of moisture in the plants—typically circa 95% by weight. Once harvested, without dewatering, the plants degrade quickly, and without some effort to aerate the biomass such as mechanical mixing or injection of forced air, the value can be quickly lost. However, it was noted during the Lake Okeechobee project previously cited[90], that dairy cattle accepted fresh chopped water hyacinths, which was blended with other green-chop materials. Over the course of one year several thousand pounds of chopped water hyacinths were fed to dairy cattle. However, while there was documented no deleterious effects, and their appeared to be no reluctance regarding acceptance, no effort was made to determine the extent of any benefits.

A 1988 feed trial on beef and dairy cattle using a feed blend which included 20% chopped and mechanically dewatered water hyacinth was conducted in Florida and submitted to the Florida Department of Agriculture and Consumer Services (FDACS) by Amasek, Inc of Cocoa, Florida[91]. The trials on beef cattle were conducted on a control group receiving no water hyacinth and a test group in which the feed blend contained 20% water hyacinths. Each group received the same amount of feed by weight. The hyacinth blended feed was found to be palatable, and showed comparable weight gain to the test group. It was determined that the use of water hyacinth material up to 20% of the feed appears reasonable and should be investigated further.

The 1988 dairy feed trial phase involved replacement of cottonseed hulls from a standard feed mix with 10% chopped and mechanically dewatered water hyacinth. The test group performance was comparable in terms of weight gain, milk production and milk butterfat content to the control group. The replacement of cottonseed hulls with water hyacinth provided evidence that the fiber within water hyacinths facilitated maintenance of desirable butterfat content. The hyacinth blended feed was found to be palatable, with maintenance of performance and no detrimental effects.

In 1990 the University of Florida, College of Veterinary Medicine[92] conducted feed trials on rabbits. Two test group of rabbits were fed a blend in which alfalfa was replaced, or partially replaced with dried and pelletized water hyacinths which had been mechanically dewatered through a screw press. A control group was evaluated in parallel with the test groups using traditional alfalfa based feed. The testing was conducted over two generations. There was no significant differences between the test

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[88] Monsod, G.G. Jr.(1979) Man and the Water Hyacinth Vantage Press, New York.
[89] Ibid footnote 16
[90] Ibid footnote 10
[91] Amasek, Inc. (1988) Development and marketing alternatives for cattle feed produced from water hyacinths submitted to Florida Department of Agriculture and Consumer Services, Tallahassee, Florida
[92] Moreland, A.F. and B.R. Collins (1990) Water Hyacinth (Eichhornia crassipes) grown in municipal wastewater as a source of organic matter in rabbit food prepared for AMASEK, Inc, Cocoa, Florida by University of Florida, College of Veterinary Medicine, Gainesville, Florida.

and control groups in terms of feed palatability, weight gain, fecundity, teratogenic effects (congenital malformation) or tissue heavy metal content. They assessed the water hyacinth as a satisfactory substitute for alfalfa in rabbit feed.

A strong argument can be made for pursuing the use of aquatic plants, including attached algae, as an animal feed ingredient, considering the high rate of protein production. If processed efficiently, plants such as water hyacinth as well as attached algae, could off-set the carbon and land investments associated with the use of terrestrial crops. While encouraging, there is need for additional development work both in terms of the production costs and optimal feeding strategies.

e. Fiber Products

As noted previously hyacinth fiber is presently used in making furniture. This is a small but high end market which can absorb higher production costs, and does not demand a huge supply of plant material. So from a carbon sequestration and storage perspective it is not presently of real significance. But the fibers are also used in textiles when blended with polyester, and it can also be used in producing fiber board and rope[93]. Gopal identified several efforts to make paper from water hyacinths[94]. In general, water hyacinths were assessed as being a poor candidate for producing high quality paper Monsod claims to have developed a process for producing high quality paper from water hyacinths, although his claims were not substantiated by studies at the University of Florida, which found the hyacinth pulp to be of poor quality for paper production.[95]

In India efforts have been undertaken to produce highly absorbent sanitary pads from water hyacinth fiber[96]. However this concept has not yet been brought to market successfully. Van Ert-Nemoto also investigated the use of water hyacinths to produce a variety of paper products from water hyacinths and algae harvested from MAPS units in Florida, as well as some work related to development of bioplastics from algae harvested from the Egret Marsh ATS™-MAPS facility[97]. However the findings from this work have yet to be published.

The potential advantage of using aquatic plants produced within a MAPS platform for fiber products is the off-set of carbon sinks associated with pulp from harvested trees, and the possibility of developing a viable biodegradable plastic. Additional research and development is needed to determine long-term, widespread feasibility.

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[93] https://www.technicaltextile.net/articles/water-hyacinth-a-promising-textile-fibre-source-7619
[94] Ibid footnote 16
[95] Ibid footnote 88
[96] https://www.globalcitizen.org/en/content/indian-students-turned-water-hyacinths-into-pads/
[97] Ibid footnote 83

VII. CO-BENEFITS OF MAPS

a. Discussion

While the environmental service benefits associated with the high rate of carbon capture makes Managed Aquatic Plant Systems (MAPS) an attractive technology, there is a diversity of co-benefits that can expand this appeal—some of them quite obvious, others more subtle. Should MAPS become an globally established technology which provides meaningful environmental and economic advantages, there will likely emerge an even more complex network of feedback benefits (co-benefits), some of which as yet have not been identified.

To date the development of MAPS technology has been restrained by a limited vision of its potential. Considered solely a water treatment technology, very little serious attention has been given to its superior rate of carbon capture or its unique approach to highly productive agriculture. For example, while long known as a means of producing protein at rates 4-6 times higher than soybeans, there has been little effort to exploit this advantage. Considering the importance of protein as a global commodity, one can only explain this as being a result of parochialism—or to use a popular aphorism, not seeing the forest for the trees. People concerned with water treatment or water management in general tend to "stay in their lane", and have no real interest in crop-based agriculture or becoming farmers. To most in the water treatment sector, the aquatic plant crop, in spite of its captured carbon, protein, nutrients and fiber, is simply a waste product, the disposal of which costs money and detracts from the appeal of the MAPS technology. Similarly, those interested in the hydraulic management (flood control) of waters tend to not venture into either the realm of water quality or the agricultural aspects of the MAPS technology. As an example of this "stay in your lane" mentality, consider the following statement from the U.S. Army Corps of Engineers (USACOE) in response from an inquiry by E. Allen Stewart of ASBRO, LLC as to why MAPS was not considered as a way to maintain high water quality in the USACOE planned reservoirs in the Okeechobee-Everglades basin:

"*Water quality improvement is not a project objective or within the existing authority of the U.S. Army Corps of Engineers"*[98].

Another impediment to the acceptance of MAPS, is the use of plants which are considered invasive. Water hyacinths, and to a lesser extent plants such as water

[98] Letter dated April 12, 2017 to E. Allen Stewart II from Col. J.A. Kirk, District Commander USACOE, Jacksonville, Florida

lettuce and duckweed, are seen as a threat to navigation and water quality within native surface waters. This contempt carries over to the MAPS technology, and rejection often is based upon a bias against harvesting or against certain plants. This is noted in an 2017 email to E. Allen Stewart from a staff member from the South Florida Water Management District*:*

" Harvesting of vegetation in the STAs (Stormwater Treatment Areas—see page 17) *, however, is not conducted for several reasons, including:*
Mechanical removal is very expensive and will cause downtime. Any mechanical removal of vegetation on a large-scale would be disruptive to the STA ecosystem. Floating aquatic vegetation (FAV), which could benefit from routine harvesting, is not encouraged in the STAs as target vegetation. Control (i.e. herbicide control) *of FAV, such as water lettuce or hyacinth, is mainly conducted in cells targeted for SAV* (submerged aquatic vegetation) *where FAV can shade out the SAV and in the vicinity of water control structures to prevent flow obstruction. We currently do not have biomass* ***disposal*** *locations and a viable market for plant byproducts, such as conversion to biofuel, has not materialized in South Florida."*

This statement clearly indicates the lack of interest in the agricultural aspects of MAPS, and the desire to avoid highly productive aquatic plants such as water hyacinth. To change attitudes a more expansive view of MAPS is essential. The following partial list of co-benefits strengthen the argument in favor of a comprehensive MAPS program.

b. Co-benefit #1: Water quality enhancement

The U.S. 1972 Clean Water Act or CWA (PL92-500) was enacted in response to widespread deterioration of the quality of the nation's waters. Specific events such as a fire on the Cuyahoga River in Ohio[99] as a result of extensive industrial pollution; the algal blooms on Lake Erie[100] caused by excessive inputs of phosphorus; and expansive sewage pollution of Florida's Tampa Bay[101] were significant motivators for congressional action to restore and protect water quality. Through Federal funding and a well-planned facilities' planning and implementation program, the CWA resulted in significant improvement in the nation's wastewater infrastructure, and accordingly improvement in overall water quality. However, as the twenty-first century arrived, it was evident that further action was required, as increased development and poorly managed pollution control largely related to agricultural operations; proliferation of septic tanks; relaxation of wastewater nutrient removal standards; and deterioration of a now aging wastewater infrastructure continued to degrade water quality.

In an effort to mitigate the impacts of this degradation, by the early nineties the EPA had actively initiated the Total Maximum Daily Load (TMDL) program as delineated within

[99] https://ohiohistorycentral.org/w/Cuyahoga_River_Fire
[100] Scavia, D. et. al. (2014) Assessing and addressing the re-eutrophication of Lake Erie: Central Basin hypoxia. *Journal of Great Lake Research* Vol 40:2. 226-246 https://doi.org/10.1016/j.jglr.2014.02.004
[101] https://www.tampabay.com/news/environment/water/tampa-bays-historic-cleanup-could-serve-as-blueprint-for-lake-okeechobee/2285814/

section 303(d) of the CWA[102]. The TMDL program was designed to have States identify surface waters that were impaired by pollution, and then set allocations for the pollutants assessed as most contributory to the pollution[103]. The most common of these pollutants were the plant nutrients, nitrogen and phosphorus which, when at high concentrations, facilitate widespread outbreaks of algae and invasive plants.

While there are a number of activities from which these nutrients are released into impaired waters, including urban runoff; domestic and industrial wastewater treatment and effluent reuse facilities; septic tank seepage; agricultural runoff; and atmospheric fallout, it is the ability of technological society to convert atmospheric nitrogen into ammonia nitrogen and to extract phosphorus sequestered as apatite rock and convert it to available phosphate[104] that are the root sources of a major portion of nutrient pollution. For example, prior to society's ability to manufacture such large quantities of nitrogen and phosphorus fertilizers, it is estimated that the watershed of Lake Okeechobee received about 300 metric tons of phosphorus annually, primarily from atmospheric fallout. This has increased to an estimated 3,300 metric tons annually as a result of increased phosphorus fertilization[105]. Consequently, algae blooms have become more prevalent, as have explosive growths of invasive aquatic plants.

Picture 12
Blue Green Algae 2018 St. Lucie River

Recently the impact of excessive nutrients and the algal blooms they have precipitated have begun to have significant human health and economic consequences. For example In Lake Okeechobee, in 2018, the USACOE was forced to release millions of gallons of nutrient enriched waters from the lake into two canal systems designed to divert excess freshwater into two major estuaries—the Caloosahatchee system on Florida's west coast, and the St. Lucie system on Florida's east coast. The result was development of extensive blooms of the potentially toxic Cyanobacteria—also known as Blue-Green algae—see Picture 12. Blooms such as these are known as Harmful Algae Blooms or HAB. As this HAB invaded residential canals, it then moved into the estuarine and marine environments. Shortly after these releases, a bloom of the toxic algae *Karenia breve ,* known as "red tide" developed, causing a massive kill of marine life, including dolphins, manatees, and

[102] https://www.epa.gov/tmdl
[103] The EPA and the States were slow in responding to the CWA requirement for TMDL developments until environmental groups filed lawsuits in more than three dozen states to compel compliance with the law's requirements.
[104] Phosphate mining in Florida accounts for 75% of the nation's phosphorus fertilizer and 25% of the worlds demand.
[105] https://www.pasop.org/a-plan-for-the-kissimmee-okeechobee

sea turtles, as well as fish and invertebrates. This bloom covered a stretch of Florida's west coast of nearly 100 miles[106].

On the east coast of Florida, the Blue-Green algae infested canals contiguous to local residences, marinas, recreational areas, and commercial properties, and impacted water quality along parts of the Atlantic shoreline. The health threats to humans and other animals were significant, as Blue-Green algae is potentially toxic[107]. The aesthetic impacts on both coasts did serious damage to the economy, both in loss of property values[108], and in loss of tourism, Florida's major economic driver.

In response to these events in South Florida, the Governor initiated a Blue-Green Algae Task Force to not only identify the cause of the outbreak, but what measures could be taken to correct the existing problems and prevent their reoccurrence[109]. In addition the State senate authorized the University of Florida to conduct a thorough, objective review of water quality conditions associated with Lake Okeechobee and the Northern Everglades Basin[110]. In both reviews, the large amount of available phosphorus that had accumulated within the basin and within the lake sediments directly—which was labelled "legacy phosphorus"-- was identified as a major concern. It was estimated that over 100,000 metric tons of legacy phosphorus was available within the basin, and could result in annual loadings of 500 metric tons of phosphorus to Lake Okeechobee every year for 200 years. Considering the upper load allocation to the lake as established through the TMDL is 149 metric tons[111], it is understandable that both sets of investigators recognized legacy phosphorus as a serious problem, and dealing with it would take extraordinary measures. As stated by the Blue-Green Task force in their consensus report:

Legacy nutrients, as indicated previously, are a concern in the South Florida landscape and the task force recommends that their contribution to loading figure prominently in the Lake Okeechobee, Caloosahatchee and St. Lucie River and Estuary BMAPs (Basin Management Action Plan). *The task further recommends that projects with the demonstrated potential to expedite legacy nutrient removal merit special attention and be designated as priority projects.*

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106 https://www.vox.com/energy-and-environment/2018/8/30/17795892/red-tide-2018-florida-gulf-sarasota-sanibel-okeechobee

107 P.A.Cox, S.A. Banack, S. J. Murch, U. Rasmussen, G. Tien, R.R. Bidigare, J.S. Metcalf, L.F. Morrison, G.A.. Codd, and B. Bergman (2005) Diverse taxa of cyanobacteria produce β-*N*-methylamino-L-alanine, a neurotoxic amino acid
PNAS April 5, 2005 102 (14) 5074-5078 **https://doi.org/10.1073/pnas.0501526102**

108 In 2015, the Florida Association of Realtors completed a study to assess the impact of water quality and clarity on property values in Lee and Martin counties from 2010 through 2013. The study determined that the ongoing problem of polluted water in the Caloosahatchee and St. Lucie rivers and estuaries has resulted in a negative impact on property values. The study determined that water quality and clarity had an impact of $541 million on Lee County's aggregate property values and $428 million on Martin County's aggregate property values.

109 A review of the findings of the Task Force may be found at https://www.pasop.org/blue-green-algae-task-force

110 University of Florida, Water Institute, W, Graham Director. (2015) Options to Reduce High Volume Freshwater Flows to the St. Lucie and Caloosahatchee Estuaries and Move More Water from Lake Okeechobee to the Southern Everglades An Independent Technical Review by the University of Florida Water Institute Gainesville, Florida

111 Total Maximum Daily Load for Total Phosphorus Lake Okeechobee, Florida (2001) Prepared by: Florida Department of Environmental Protection (FDEP) 2600 Blairstone Road Tallahassee, FL 32303 for the US Environmental Protection Agency (EPA)

A similar statement was made by the UF Water Institute in their reporting:

Beyond existing and planned approaches, the substantial reservoir of legacy phosphorus in the Northern Everglades Watersheds will necessitate new and more aggressive strategies to combat the mobility of phosphorus.

Picture 13
Large bass in lake receiving high quality effluent from an ATS™-MAPS facility in Indian River County, Florida

MAPS technologies are well suited to be one of these "aggressive strategies". A conceptual MAPS program for Lake Okeechobee was offered in a report on the www.pasop.org website.[112] Suggested was a total of about 90,000 acres of a series of external kidney like arrangements in which water from the Lake and perhaps associated tributaries would be treated and returned to the lake at a higher quality. This return flow would be stripped of a large portion of the nutrient loads, which would be removed and recovered through the MAPS operation—see Figure B.

The benefits offered by a MAPS program such as that proposed would offer the following water quality associated benefits.

1) **Improved fisheries and wildlife habitat.** Return flows from a MAPS will contain high levels of dissolved Oxygen (DO) as well as significantly reduced biodegradable organics, suspended solids and nutrients. These waters have been shown to be ideal for promoting a healthy fishery—see Picture 13.
2) **Economic benefits.** Obviously improved water quality would have a positive impact on economic factors such as property value, recreational opportunities, and tourism associated with fisheries, hunting and other outdoor activities—ecotourism.
3) **Long term removal and recovery of legacy nutrients**. As the MAPS effluent with its reduced nutrient levels re-enters the lake, the sediments will release nutrients into the water column, resulting in long term extraction of legacy nutrients.

[112] Ibid footnote 105

4) **Reduction in herbicide use for aquatic plant management within the lake**. Invasive plants respond to high nutrient levels. When these plants are killed by herbicides, the nutrients they hold are released to the water column and continue to promote plant growth. Through MAPS, as nutrient levels are reduced within the lake, the rate of growth of aquatic plants will eventually decline, hence reducing the need for herbicide application. In the interim, MAPS development will encourage advancement in aquatic plant harvesting and processing of aquatic plants, which may result in cost reduction for in-lake harvesting systems (*in-situ* MAPS) as a replacement for herbicides.
5) **Recovery of nutrients can reduce the demand for inorganic sources.** As noted, about 3,300 tons of phosphorus is imported to the Lake Okeechobee basin annually. If MAPS recovered phosphorus could be recycled within the basin, a substantial reduction in these imports may be realized.
6) **MAPS crops, particularly water hyacinth, can be antagonistic to Cyanobacteria and other HAB's[113].** The ability to prevent and control HAB's has widespread health benefits as well as significant economic benefits.
7) **MAPS programs are sustainable.** As a pulse stabilized system MAPS programs offer long term reliability, and hence greater predictability. Sustainable, predictable systems tend to stabilize local economies and social dynamics in general.
8) **MAPS is well suited for remote agrarian communities**. Not only can MAPS ensure high quality water, but through recovery of nutrients and carbon, a dynamic sustainable agricultural base can be established.

c. Co-Benefit #2: Establishing MAPS as a new agro-industry

It might be said that MAPS represents an agricultural solution to an agricultural problem. The present agricultural problem throughout Florida and the nation in general, revolves largely around the loss of nutrients to contiguous waters as well as with degradation of soil. MAPS is agriculture which can capture and recycle lost nutrients through the cultivation of aquatic plants. In other terms, Managed Aquatic Plant Systems (MAPS) represent a variant of typical agriculture, with the primary intent not only to optimize and sustain productivity of the targeted crop as with conventional agriculture, but also to maximize reduction of pollutants from an impaired water source. In other words, MAPS operations do not involve adjustment of nutrient levels in the feed water to ensure high levels of crop production and quality, but rather involve adjustment of crop selection and operational strategies to ensure high rates of nutrient capture from the raw feed water,

[113] Q. Hongji, Z. Zhang, H. Liu, D. Li, X. Wen, Y. Zhang, Y. Wang, S. Yan (2016) Fenced cultivation of water hyacinth for cyanobacterial bloom control *Environ Sci Pollut Res* (2016) 23:17742–17752 DOI 10.1007/s11356-016-6799-6

such as a nutrient enriched, impaired surface water. With conventional agriculture the crop is the primary product, while with MAPS, enhanced water quality and captured atmospheric carbon are also primary products. This approach represents a significant paradigm shift from the general acceptance of agriculture as a net pollutant contributor, to the reality that there are forms of agriculture that can offer substantial net pollutant removal and recovery.

A MAPS program can coordinate its operations to accommodate local agricultural needs—for example in Okeechobee County, large scale MAPS may result in production of a high quality dairy feed ingredient, which will facilitate reduction of remote source inputs while ensuring reuse of legacy phosphorus. In other areas, compost from MAPS could be used to restore soils and improve their ability to sequester carbon. The net effect in both cases is to reduce both the loss of carbon to the atmosphere, while reducing agricultural source nutrient loads.

As an agro-industry MAPS would require less land for protein and fiber production, and could replace the use of food crops for energy production. In remote areas MAPS could help agrarian societies become less dependent upon outside goods such as fertilizers and fuel. In fully developed countries MAPS would bolster and help stabilize the agricultural economy through job creation and sustainable environmental services.

d. Co-benefit #3: MAPS offers high rate protein and fiber production

While the high rate of protein and fiber production has been noted in previous sections of this review, it is of such potential importance that it is worth mentioning again. The use of MAPS systems to provide substantial quantities of usable protein and fiber has been impeded not only by bias as mentioned in Section VII-a, but also by the demands of effective dewatering, which is discussed in Section VIII. Furthermore, additional investigations into the nature of MAPS produced protein and fiber is essential, to be followed by objective assessment of markets and final processing and distribution costs.

e. Co-Benefit #4: MAPS potential as economic base for remote agrarian societies

It is possible that MAPS could serve as the economic foundation for remote agrarian communities if provided sufficient financial and technological support. Already there is some action being taken to exploit the protein and compost value of hyacinths which grow in Lake Victoria as explained in at least two YouTube files[114]. If the ingenuity of the local communities is combined with recent and proposed advances in MAPS technology, a comprehensive economic and social framework might be established which offers benefits to the local community and to society at large in terms of environmental services such as carbon sequestration and water quality enhancement. A schematic of such a framework was included in an unsolicited proposal to the Carter Foundation[115], and is shown as Figure C. Note that the external arrangement noted in

[114] https://www.youtube.com/watch?v=4fIGd5mOBD4 and https://www.youtube.com/watch?v=7Eb1atlh17U
[115] Ibid footnote 34

Figure C could either be replaced or augmented by *in-situ*-MAPS—i.e. harvesting directly from the water source.

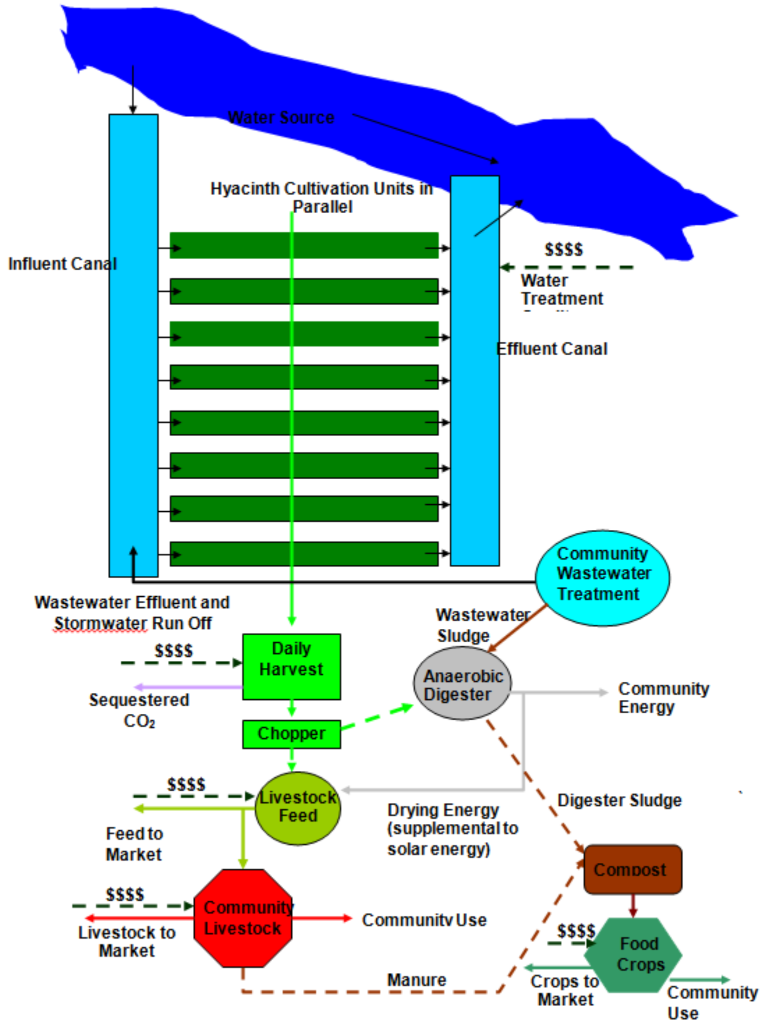

Figure C: *Schematic of WH-MAPS (Floating Aquatic Plant MAPS) cultivation and resource recovery facility that would be applicable in remote agrarian communities contiguous to a surface water source.*

VIII Research and Development Needs

a. Harvesting and Chopping WH-MAPS and other floating aquatic plant MAPS

As mentioned earlier in the text, harvesting methods for WH-MAPS have evolved towards light weight grapples as shown in Picture 2, with conveyance through open channel to a pick-up conveyor to a chopper as shown in Picture 3. This technology to be able to accommodate more expansive systems, needs to advance towards more efficient, higher rate equipment that combine not only harvesting, but also volume reduction through chopping, followed by orderly deposition of the harvest to or near a processing area. Harvesting and volume reduction should be done at as high a rate as practical followed by volume reduction through chopping, all within the same piece of equipment—much as with many traditional Combines. In addition subsequent transport to final processing should be achieved with the lowest practical expenditure of labor and energy.

Chopping to particles about ¼ inch reduces the wet density of about 250 pounds per cubic yard (this varies with degree of compaction) for loose whole hyacinths to about 1,500 pounds per cubic yard for chopped wet hyacinths or about an 84% volume reduction. Chopping also increases surface area significantly, making the material more amenable to dewatering, drying and composting. Considering the benefits associated with chopping, it makes sense that the chopping equipment could be incorporated into a harvesting Combine. Chopping using a modified forage type chopper worked well at the Okeechobee project[116]--see Picture 3.

To accommodate such a Combine the cultivation ponds shall be designed to allow a retractable cantilevered pick up unit to extend about 10 feet into the pond where it picks up the plants via one or more conveyor systems and delivers them at a continuous rate to a chopper system also mounted on the Combine. The chopped hyacinths can then be delivered via conveyor to a windrow on a receiving pad which runs parallel to the running course of the Combine. A conceptual schematic of this strategy is shown in Figure D. This appears to be a logical framework from which a water hyacinth harvesting and chopper Combine could be developed for use in conjunction with engineered land based "kidney" type units similar that shown in Figure B. However other equipment strategies may also be considered.

Equipment costs, and labor and energy expenditures depend upon the rate of harvesting and the associated logistic demands. Consider for example a 500 acres system that might be located next to Lake Okeechobee. If the system is designed to treat water from Lake Okeechobee, and reduce phosphorus levels to an annual average of circa 49 micrograms per liter, which is the targeted in-lake TMDL concentration, it is possible to use the aforementioned HYADEM model for initial sizing and operational demands. A spreadsheet of a HYADEM model run for wet season and dry season conditions is seen in Figure E.

[116] Ibid footnote 10

Five hundred acres of hyacinth cultivation ponds to treat water from Lake Okeechobee would accommodate an average daily flow of 190 million gallons per day, and are projected to reduce total phosphorus concentrations from 140 micrograms per liter to 49 micrograms per liter, with a total annual phosphorus removal of about 52,447 pounds or 26 tons. Carbon capture annually would be about 2,540 metric tons at a rate of 12.5 metric tons per hectare per year.

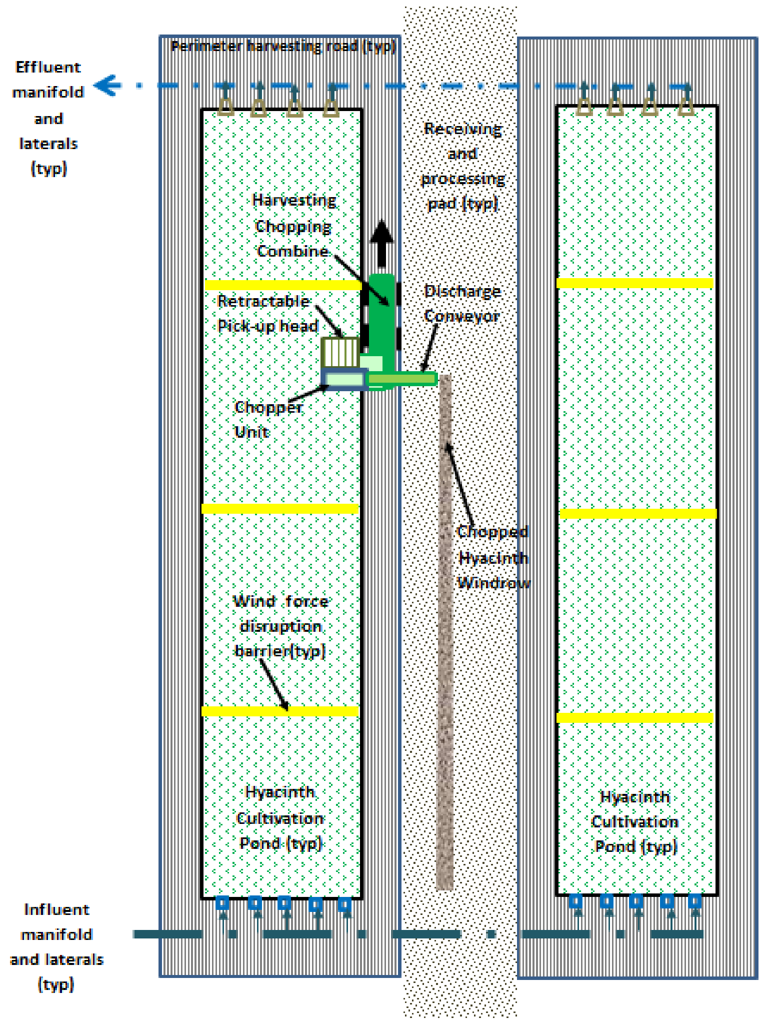

Figure D: *Schematic of conceptual hyacinth Combine and cultivation pond layout (Not to Scale)*

One possible layout may include 20 such ponds in parallel of 25 acres each, with a length to width ratio range of about 12:1 to 20:1. The hyacinth crop would require harvesting at the rate of 1,795 wet tons once every four days during the wet season and 3,355 wet tons once every ten days during the dry season. If the harvesting/chopping is done in one 10 hour day, then the Combine would need to handle a maximum of about 336 wet tons per hour. With a standing crop density of 4.5 wet pounds per square foot, the area harvested with each harvest event would be about 34.1 acres, so the areal rate would be about 3.41 acres per hour. If the pick-up swath is 10 feet, then the Combine average speed would have to be about 2.82 miles per hour or 4.14 feet per second, which is about a typical walking speed.

This is a rather substantial mechanical burden, and it may be determined that several smaller units are more practical. Regardless, the development of a machine such as this will require some creative and innovative agricultural engineering. However, there are certainly as complex, if not more complex, machines than that conceptualized here which are presently being used in agriculture to harvest a variety of crops.

b. Biomass management ATS™-MAPS

The algal turf community typical of that sustained on an Algal Turf Scrubber® or ATS™-MAPS needs to be harvested about every 7 to 30 days, depending upon growing conditions. As a general rule, when the algal turf biomass has grown to a density such that the rate of accumulation of necrotic tissue equals the rate of primary production (photosynthesis), then the system is no longer providing net carbon capture or nutrient reduction. Harvesting should occur well before this condition is established, but not so early as to prevent development of sufficient biomass to efficiently reduce nutrients and capture atmospheric carbon. A growth curve typical for ATS™ is noted in Figure F[117]. To the extent practical pilot testing for each specific application should be used to develop growth curves to determine a reasonable rate of harvesting.

The harvesting approach as used at the Egret Marsh ATS™[118] involves a scrapper blade and a small tractor moving parallel to the flow, and relies upon flow to deliver dislodged algae to a pick-up rake—see Pictures 6 through 9. This strategy was modified for the South Canal (Osprey Marsh)[119] system in Indian River County by eliminating flow during the harvest period, and using the tractor/scraper to move perpendicular to the flow to an interceptor channel—Picture 7.

In an effort to eliminate the expense of a pick-up rake and reduce flow during harvesting, a modified design is now being considered to include a storage and drainage pad parallel to the entire floway length as noted in the schematic shown as Figure G. This allows a shorter harvesting run and facilitates movement of the algae to a drainage pad on the periphery of the floway which runs parallel to the floway. This

[117] Ibid footnote 53
[118] Ibid footnote 53
[119] Ibid footnote 51

creates a drainage windrow which can then be moved to a contiguous composting pad. This approach reduces the amount of water involved in harvesting, and allows both filamentous and most of the suspended solids to be accumulated in one area.

HYADEM Wet Season Lake Okeechobee SAMPLE		HYADEM Dry Season Lake Okeechobee SAMPLE	
INPUTS		INPUTS	
Influent Average Daily Flow (mgd)	190	Influent Average Daily Flow (mgd)	190
Days	175	Days	190
Average Total Nitrogen mg/l [(influent + Effluent)/2]	2.24	Average Total Nitrogen mg/l [(influent + Effluent)/2]	2.29
Daily Nitrogen Supplementation lb	0.00	Daily Nitrogen Supplementation lb	0.00
Influent Total Nitrogen (mg/l)	2.50	Influent Total Nitrogen (mg/l)	2.50
Influent Total Nitrogen including Supplementation mg/l	2.50	Influent Total Nitrogen including Supplementation mg/l	2.50
Influent Total Phosphorus (mg/l)	0.140	Influent Total Phosphorus (mg/l)	0.140
V'ant Hoff Arrhenius Coefficient	1.08	V'ant Hoff Arrhenius Coefficient	1.08
Average Air Temperature (degrees C)	23.30	Average Air Temperature (degrees C)	19.80
Maximium Specific Growth Rate (1/day)	0.050	Maximium Specific Growth Rate (1/day)	0.050
Wet Crop Density (lb/sf)	4.50	Wet Crop Density (lb/sf)	4.50
Density Adjustment Factor	1.00	Density Adjustment Factor	1.00
Half Rate Concentration (mg/l TN)	5.00	Half Rate Concentration (mg/l TN)	5.00
Incidental Nitrogen Loss C_n	0.00	Incidental Nitrogen Loss C_n	0.00
Days between harvests	4	Days between harvests	10
Growing Area (acres)	500	Growing Area (acres)	500
Percent Coverage	85.00%	Percent Coverage	85.00%
Plant Nitrogen Content (% dry weight)	2.60%	Plant Nitrogen Content (% dry weight)	2.60%
Plant Phosphorus Content (% dry weight)	0.30%	Plant Phosphorus Content (% dry weight)	0.30%
Plant Carbon Content (% dry weight)	32.00%	Plant Carbon Content (% dry weight)	32.00%
Percent Solids Harvest	5.00%	Percent Solids Harvest	5.00%
In-Pond sloughed Plant percent solids	3.00%	In-Pond and sloughed Plant percent solids	3.00%
OUTPUTS		OUTPUTS	
Target Standing Crop (Wet Tons-Post Harvest)	41,654	Target Standing Crop (Wet Tons-Post Harvest)	41,654
Field Water Hyacinth Growth Rate (1/day)	0.013	Field Water Hyacinth Growth Rate (1/day)	0.010
Sloughing Rate (1/day)	0.002	Sloughing Rate (1/day)	0.002
Net Specific Growth Rate (1/day)	0.011	Net Specific Growth Rate (1/day)	0.008
Average Pond Depth (ft)	3.00	Average Pond Depth (ft)	3.00
Hydraulic retention time (days)	2.57	Hydraulic retention time (days)	2.57
Hydraulic Loading Rate (cm/day)	35.54	Hydraulic Loading Rate (cm/day)	35.54
Mean Plant Age days	55	Mean Plant Age days	71
Average Daily Growth (Wet Tons)	536	Average Daily Growth (Wet Tons)	426
Number of harvests per period	44	Number of harvests per period	19
Average Daily Growth (Dry Tons)	26.8	Average Daily Growth (Dry Tons)	21.3
Average Harvest (Wet Tons)	1,795	Average Harvest (Wet Tons)	3,355
Average Harvest (Dry Tons)	89.8	Average Harvest (Dry Tons)	167.8
Average Period Harvest (Dry Tons)	3,927	Average Period Harvest (Dry Tons)	3,187
Average Sloughing for period (Wet Tons)	14,637	Average Sloughing for period (Wet Tons)	15,988
Average Sloughing for period (Dry Tons)	439	Average Sloughing for period (Dry Tons)	480
WHS™ Effluent Total Nitrogen (milligrams per liter)	**1.97**	**WHS™ Effluent Total Nitrogen (mg/l)**	**2.08**
WHS™ Effluent Total Phosphorus (micrograms per liter)	**39**	**WHS™ Effluent Total Phosphorus (mg/l)**	**59**
Nitrogen Removal lb per day	836	Nitrogen Removal lb per day	665
Nitrogen Removal lb per period	146,329	Nitrogen Removal lb per period	126,393
Nitrogen Removal Rate lb per acre per year	610	Nitrogen Removal Rate lb per acre per year	486
Nitrogen Removal Rate grams per square meter pe year	68	Nitrogen Removal Rate grams per square meter pe year	54
Phosphorus Removal pounds per day	161	Phosphorus Removal pounds per day	128
Phosphorus Removal pound per period	28,140	Phosphorus Removal pound per period	24,306
Phosphorus Removal Rate pounds per acre per year	117.39	Phosphorus Removal Rate pounds per acre per year	93.39
Phosphorus Removal Rate grams per square meter per year	13.16	Phosphorus Removal Rate grams per square meter per year	10.47
Carbon Captured pounds per day	17,152	Carbon Captured pounds per day	13,646
Carbon Captured pound per period	3,001,626	Carbon Captured pound per period	2,592,685
Carbon Capture Rate pounds per acre per year	12,521	Carbon Capture Rate pounds per acre per year	9,961
Carbon Capture Rate grams per square meter per year	1,405	Carbon Capture Rate grams per square meter per year	1,117

Total Nitrogen Removed lb annually	**272,723**
Total Phosphorus Removed lb annually	**52,447**
Average Annual Phosphorus Concentration micrograms per liter	**49**
Carbon Captured lb annually	**5,594,311**
Carbon Captured metric ton annually	**2,540**
Carbon Captured rate metric tons per hectare per year	**12.5**
Harvest wet ton annually	**142,278**
Sediment wet ton annually	**30,625**
Total Harvest + Sediment dry ton annually	**8,033**

Figure E: *Typical HYADEM run—500 acre WH-MAPS Lake Okeechobee*

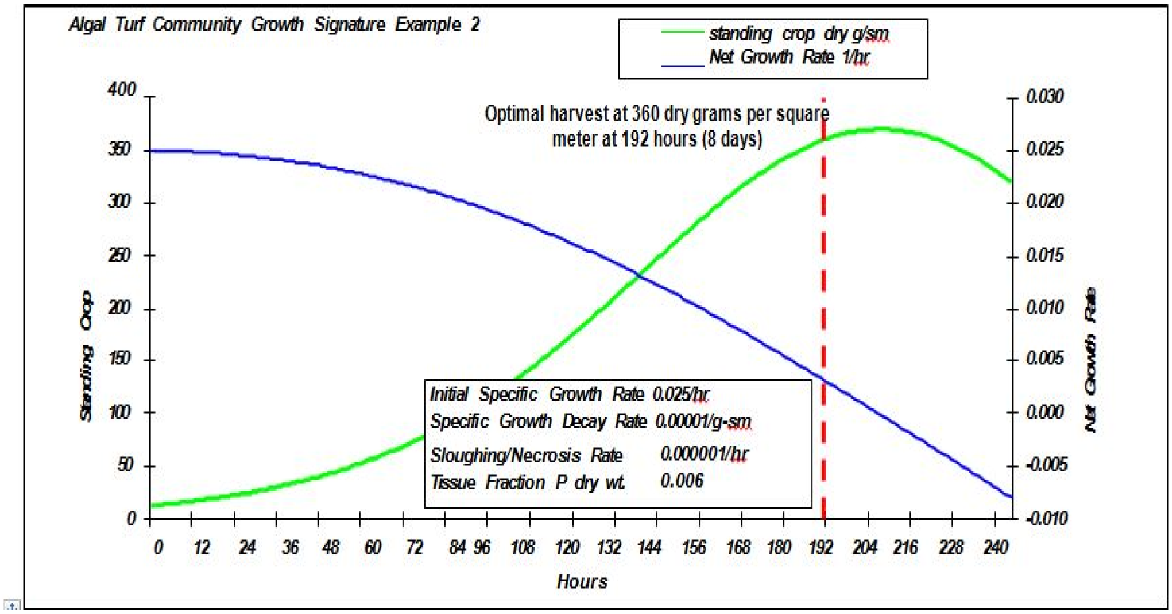

Figure F: *Idealized growth curve for ATS™ unit*

The drainage water, and the water used to flush a floway after harvest to remove loose residual solids, are collected in a series of drainage ponds. Gates and valves are used to divert flows as required. The challenge is to optimize efficiency of the tractor/scraper unit, and to effectively manage drainage waters which contain residual organic solids. It is possible that some of the harvesting steps can be automated.

Using the ATSDEM model as previously referenced, consider the same conditions in terms of flow and influent water quality as with the HYADEM run per Figure E. The ATSDEM model run for the wet season is shown as Figure H, and an annual summary in Figure J. Note that at 190 MGD, the ATS™ size is limited to about 76 acres. However, the carbon capture rate of 9.2 metric tons per hectare per year is comparable to that noted for the HYADEM run of 12.5 metric tons per hectare per year. The length and hydraulic loading rate for ATS™ units is often restrained by the availability of carbon in the incoming flow. As the algae grows it can consume dissolved carbon dioxide in the water and carbon associated with carbonate alkalinity at such a rate that diurnal pH levels in the effluent can exceed 10.0. This high pH then can impede growth and may fall outside water quality standards. To avoid these high pH values the growing area needs to be sized accordingly. As a general rule, system design is based on a hydraulic loading rate of +/-20 gallons per minute for each foot of width, and the length typically set in the range of 300-500 feet. Pilot testing however is recommended for each specific applications to confirm these design parameters or to justify any planned deviation from them.

c. ATS™ design, construction and operational refinements

While ATS™ is presently an accepted and applied technology, there remains a need for further refinement of system design and reduction of construction and operational costs. The design and materials of construction for the floway for example can have profound influence on both initial and operational/maintenance costs. Early systems were developed around high density polyethylene (HDPE) liner as the base for the floway, with a grid material overlain to secure and promote filamentous algae. The floway slopes were typically set at about 0.5%, or 2.5 feet over a 500 foot floway length. Flow was introduced in surges using an automatic siphon, as there was indication that surging flow stimulated growth and nutrient uptake. At the Egret Marsh facility[120] the HDPE proved problematic as gas pockets would deflect the liner, and the liner also was vulnerable to damage during harvesting, as was the overlying grid. In addition, setting a level base for the floway was difficult, and perturbations would create dry areas along the floway. Eventually the HDPE was replaced with cast-in-place concrete with a roughened surface. This proved to be an effective fix, but concrete would be an expensive option for larger systems that might approach 100 acres or more. Further investigations are needed to test the efficacy of various options, including asphalt and better designs using HDPE.

There is also questions regarding the optimal slope of the floway, or if any slope is needed at all. A shallow weir at the effluent end of the floway might be used to establish a working depth. This idea has been tested on a pilot level, but needs further testing before it can be considered an acceptable design. A flat ATS™ surface would reduce the earthwork requirements considerably, so this is an option worthy of a thorough investigation, as is field verification of the efficacy of surging influent.

a. Mechanical dewatering and drying

Depending upon the targeted end product, harvested aquatic pant biomass may need to be conditioned in preparation for final processing. With water hyacinths and other vascular aquatic plants, chopping would typically be the first step in this conditioning. If windrow composting is the selected process, then the chopped biomass needs to be placed on a drain pad, then after draining, the material may be mixed with other products to either serve as bulking agents or for their added value, or both. Because

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[120] Ibid footnote 53

there is little conditioning required for composting, it is a reasonable process selection for early development efforts.

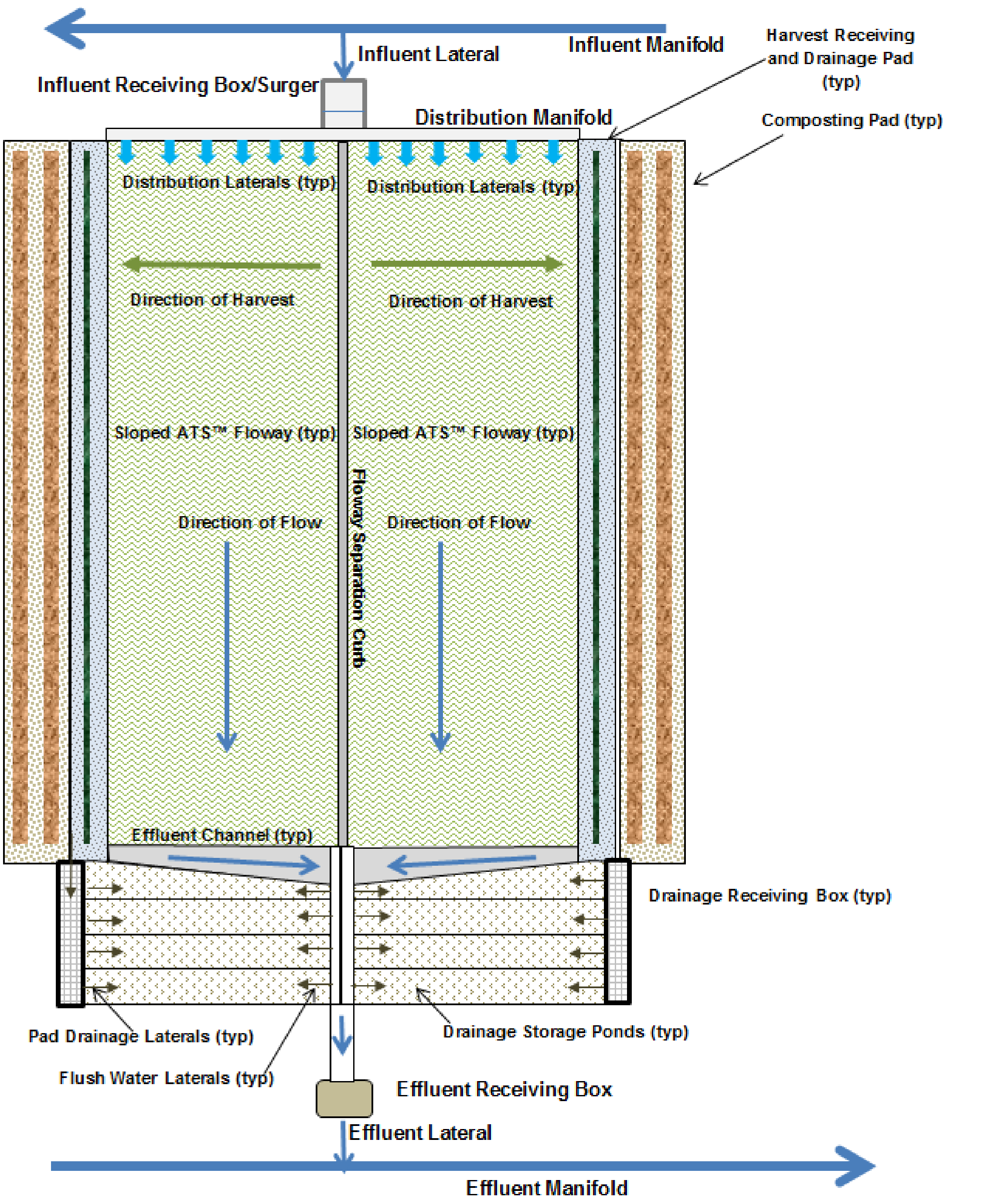

Figure G: *Schematic of recent design approach for ATS™ layout (Not to Scale)*

ATSDEM ANALYSIS
SAMPLE OKeechobee wet Season

Panel A Velocity Conditions

Floway slope (s)	Manning n	Manning Factor (1)	Manning Factor (2) Match	LHLR gpm/lf	LHLR cfs/lf	LHLR liters/sec-lf	Average flow depth (d) ft	Average Velocity fps	Flow length interval ft
0.006	0.012	0.00463	0.00463	19.99	0.045	1.279	0.041	1.08	1.08

Panel B Process Conditions

Water T[1] °C	Optimal T °C	Θ	K_{sp} as ppb TP	K_{sh} as LHLR gpm/ft	net μ_{max} 1/hr	S_o ppb Total P	Harvest Cycle days	Z_{ave} dry-g/m²	Z_0 dry-g/m²	S^*_p Total Phosphorus ppb	N_o mg/l Total N	N* Total Nitrogen mg/L
23.3	27.0	1.03	50	9.3	0.0125	140	29	129.37	10.00	4	2.50	0.30

Panel C Performance

Control Time Seconds	Control Volume liter	Final Total P S_f ppb	Total Flow Time seconds	Total P % removal	Floway Length ft	Areal Loading Rate TP g/m2-yr	Areal Loading Rate TP lb/acre-year	Areal Removal Rate TP g/m2-yr	Areal Removal Rate TP lb/acre-yr	Average Production dry-g/m²-day	Area per time sequence m²	Final Total N N_f mg/L	Areal Loading Rate TN g/m2-yr	Areal Loading Rate TN lb/acre-year	Areal Removal Rate TN g/m2-yr	Areal Removal Rate TN lb/acre-yr
1	1.279	126	461.0	10.07%	500	120	1,068	12.07	107.63	13.44	0.101	2.38	2,140	19,080	100.58	897

Panel D System Design

Total Flow mgd	Total Floway Width ft	Floway Area acres	Total P removed lb/period	solids % wet harvest	Moisture % compost	Total Dry Harvest tons/wet season	Total Wet Harvest tons/wet season	wet Season Compost Production tons	Performance Period days	μ_{net} 1/hr	Total N removed lb/period	Total N % Removal
190	6,600	75.78	3,911	8%	40%	783	9,437	979	175	0.0043	32,589	4.70%

Panel E Carbon Dynamics

Number of harvest events	Carbon % dry weight	wet Harvest per harvest event tons	dry Harvest per harvest event tons	Total Carbon Capture wet season metric tons
6	20%	1,564	130	142

Panel F pH Dynamics

Influent pH	Influent Alkalinity mg/l as $CaCO_3$	Influent Available Carbon mg/l	Estimated Diurnal Effluent pH	Algae Tissue Carbon % dw
7.00	170	50.83	7.97	20%

1. Do not enter water temperatures higher than optimum Temperature

Note: Inputs in Blue Print

Figure H: *Typical ATSDEM spreadsheet –190 MGD Okeechobee*

	DRY SEASON	WET SEASON	Total Annual
Acres	76	76	76
Flow ADF as MGD	190	190	190
Days per season	190	175	365
Days between harvests	30	29	-
Net Productivity dry grams per square meter per year	12.2	13.4	12.8
Phosphorus Removal Rate grams per square meter per year	11.0	12.1	11.5
Nitrogen Removal Rate grams per square meter per year	91.5	100.6	95.8
Phosphorus Removed lb	3,862.0	3,911	7,773
Nitrogen Removed lb	32,185.0	32,589	64,774
Carbon Captured metric tons	141	142	283
Carbon Capture rate metric tons per hectare per year	8.8	9.7	9.2
Harvest events	6	6	12
Dry Harvest per harvest event tons	122	130	-
Wet Harvest per harvest event tons	1,474	1,564	-
Dry Harvest per season tons	775	783	1,558
Wet Harvest per season tons	9,333	9,437	18,770
Compost Produced tons	968	979	1,947

Figure J: *ATSDEM summary spreadsheet –190 MGD Okeechobee*

However, other products as noted may have higher value and justify costs associated with additional conditioning. Such conditioning needs to include reduction of water content—which composes 90-95% of the biomass weight. As noted, composting offers one option for dewatering, but it results in about 40% loss of carbon and the decomposition of certain components such as protein, which might otherwise give the product higher value.

The logical initial step in dewatering is through presses, such as horizontal screw presses, such as those manufactured by Vincent Press of Tampa, Florida [121], as well as other companies. Early work by Bagnall at the University of Florida showed that hyacinths when chopped then pressed, gave up about 70% of the water to the juice or liquor. However this liquor captured up to 60% of the protein[122].

A horizontal screw press was used to recovery the cake product to prepare for feed trials for beef and dairy cattle, as well as rabbits[123], with recovery of adequate quantities of protein and fiber. The cake was dried using a custom designed indirect heat rotary dryer.

Field tests conducted by HydroMentia, Inc. indicated that about 50% of the hyacinth solids are diverted to the liquor fraction, and that the cake was reduced to about 60% moisture[124]. A reasonable mass balance for dewatering chopped water hyacinths or similar aquatic biomass is shown as Figure K.

While this schematic appears rather simple, the actual allocation of water and solids needs to be verified through more exhaustive field trials. These trials are essential for determining the efficiency of dewatering options. For example, in dryer regions of the world it may be possible to facilitate effective drying through capture of solar heat along with air with low moisture content. In such a situation, mechanical dewatering (pressing) might be avoided. In other areas, the costs of fossil fuel expenditures required for drying may be prohibitive if mechanical dewatering is excluded.

When pressing is necessary, there is question as to the fate of the liquor, which can be expected to be about 97% water. Options such as centrifugation might be considered, but the product value needs to be compared to the energy costs both in terms of money

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[121] https://vincentcorp.com/?gclid=CjwKCAjwx6WDBhBQEiwA_dP8rQT27-G9HlcfTMJliIlX-Bds5BKkHndPlTY0ha9sdG_A3B-t22b-zRoCJwAQAvD_BwE

[122] Bagnall, L.O.(1973) Mechanical recovery of water hyacinth press liquor solids Am. Soc. Agric. Engrs. Paper ASAE 73-562

[123] Ibid footnotes 91 and 92

[124] HydroMentia, Inc. unpublished data circa 1998

and carbon losses. It may be more efficient therefore to use the liquor as a wetting agent for finished compost to solicit a second composting phase.

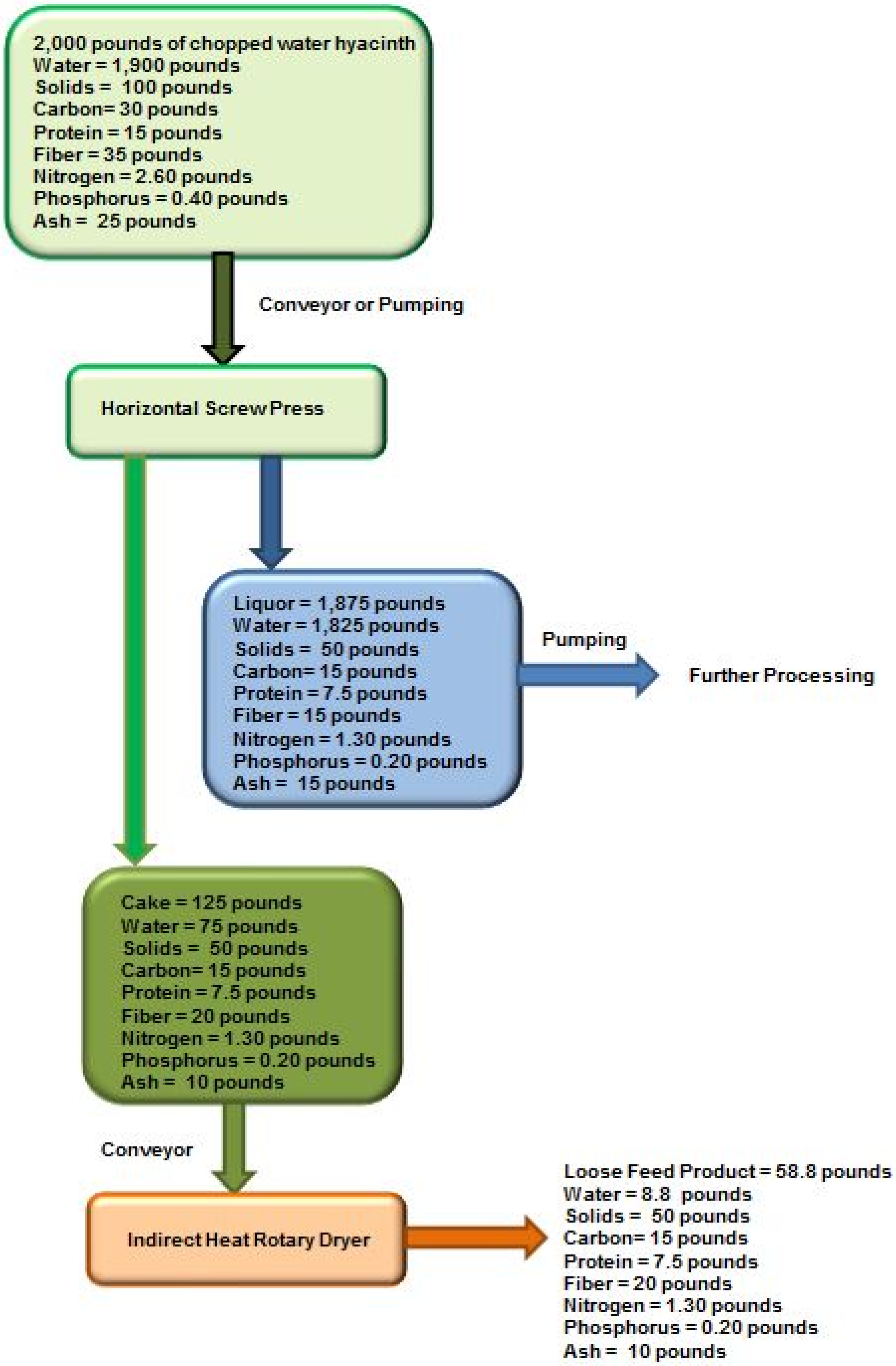

Figure K: *Generalized MAPS Dewatering Flow Chart*

IX Implementation Strategy

Effective application of Managed Aquatic Plant Systems (MAPS) can provide invaluable environmental services which include, but are not limited to, efficient removal and recovery of nutrients and other pollutants from impaired surface waters; high-rate capture of atmospheric carbon as carbon dioxide—probably the highest rate of any terrestrial sequestration option; and impressive production rates of protein and fiber. Additionally, as a consequence of these benefits, MAPS has the potential to evolve into a large scale agro-industry which can provide a number of other social, environmental and economic co-benefits.

If all of these benefits are to be realized, it is necessary to develop workable implementation strategies that ensure justifiable compensation for these services, and which encourage sustainable partnerships between the benefactors, i.e. society, and the service providers. While local, state and federal institutions would be strategic partners involved in the administration and oversight, the development and implementation of essential refinements and innovations will rely heavily upon cooperative coordination between institutional entities and the private sector. This means there needs to be established meaningful incentives to entice private participation.

As noted, even though MAPS technology has been extensively investigated, and has contributed, and continues to contribute, to improved water quality, its development as combined water treatment/agricultural technology have not been vigorously pursued. Nor, until recently, has its potential contributions to carbon capture been seriously considered. Consequently, in the United Sates, MAPS has been viewed only as a water treatment technology, and is often rejected in favor of extensive wetlands such as STA's because of the intensive management demands associated with MAPS operations and the general thought that harvested aquatic plants are waste products, the disposal of which simply escalates costs.

To escape this mindset, a full-scale MAPS Demonstration, Research and Development facility contiguous to an impaired water body such as Lake Okeechobee in Florida would not only provide verification of water treatment and carbon capture capabilities, but also serve as a framework for essential research and development on issues such as those noted in Section VIII. Central to this implementation strategy would be a pay-for-performance agreement between the service provider and the institutional administrators. This agreement would include provisions for payment to the service provider as a dollar value for each pound of specific pollutant removed and captured.

These pollutants could be, but not limited to, phosphorus, nitrogen or carbon, or a combination of these. A review of the pay-for-performance concept can be found at https://www.pasop.org/a-plan-for-the-kissimmee-okeechobee .

Pay-for-performance is not a new idea. In fact it is presently being applied by the St. Johns River Water Management District (SJRWMD) to a project within the Lake Apopka basin in Central Florida[125]. The South Florida Water Management District (SFWMD) which has oversight on Lake Okeechobee water management, is also familiar with pay-for-performance projects, and recently sought bids for such a project just north of the lake[126].

To be effective for long-term operations, such as would be necessary for a large regional MAPS facility, it is necessary that the prospective bidder/service providers be provided assurance that the pay-for-performance fees will be available for an extended period, e.g. circa 50 years. This will provide the bidder/service provider the level of confidence needed to justify front end capital investments. To date, pay-for-performance bids have included provisions for only 5 years, which is quite often insufficient time for amortization of front end costs, which makes bidding impractical for many technologies, including MAPS operations. In addition, typically entities which have sought to implement pay-for-performance projects give no allowance for technological development, nor do they offer any incentives for private sector investors to take the risk of funding such development when project terms are temporally limited. For example, note the email cited on page 31, Section Vii(a) from the SFWMD:

"*We currently do not have biomass **disposal** locations and a viable market for plant by products, such as conversion to biofuel, has not materialized in South Florida."*

Of course the reason such markets have not materialized is because there has been little incentive offered to do so. Long term pay-for-performance commitments would offer such incentive.

It seems reasonable therefore that in regions such as South Florida it would be advantageous for administering entities assigned with the responsibility of environmental protection and restoration, e.g. SFWMD, to make a blanket offer that any entity which documents removal of phosphorus, nitrogen and carbon from the Kissimmee-Lake Okeechobee Basin, or from the atmosphere as carbon dioxide in the case of carbon, in a manner properly permitted and deemed environmentally protective, will be paid a fee of $_____ for each pound documented as being so removed, and that this offer will be guaranteed for a period of at least 50 continuous years. All costs associated with the design, permitting, land procurement, construction, research and

[125] https://www.sjrwmd.com/streamlines/phosphorus-free-project-is-latest-step-in-lake-apopkas-recovery/

[126] South Florida Water Management District, 2021. TITLE: RE-BID LAKE OKEECHOBEE S-191 BASIN SURFACE RUNOFF PHOSPHORUS REMOVAL USING INNOVATIVE TECHNOLOGIES NUMBER: 6000001188 ISSUE DATE FEBRUARY 26, 2021 Attn: Procurement Bureau B-1 Building, 2nd Floor West 3301 Gun Club Road West Palm Beach, FL 33406: FEBRUARY 26, 2021

development, monitoring, and operations and maintenance of involved facilities shall be assumed by the bidder/service provider.

Such an offer would reduce the risks and accordingly would be expected to motivate technological advancements, including the development of viable products from harvested aquatic plants, and the identification of markets for these products. But the next question is how will entities like SFWMD find the money to pay the expected fees?

First of all, they are already paying well over $100 per pound ($227 per kilogram) of phosphorus removed from the water column through the STA program. Such was noted in a study by the University of Florida Institute of Food and Agricultural Sciences (IFAS) in which costs on the basis of dollars per kilogram of phosphorus removed were calculated based upon a 50 year net present worth evaluation[127]. The costs ranged from $268 to $1,346 per kilogram of phosphorus removed for STA's, $77 per kilogram removed for Reservoir Assisted STA's (RASTA) and $24 per kilogram of phosphorus removed for MAPS facilities. While the water quality conditions were not identical for each facility compared, which could bias the results somewhat, there is indication that MAPS is more than competitive. Any competitive advantage MAPS might have would be enhanced once product value has been established and receptive markets identified.

So back to the question of long term funding for fees. Suppose a series of MAPS facilities were implemented contiguous to Lake Okeechobee or its tributaries such that 2,000,000 pounds of phosphorus was removed annually and 130,000 metric tons of carbon captured and stored as compost, assuming a 40% carbon loss during processing. (This would require about 80,000 acres, including maintenance and processing area.) Suppose a fee of $100 per pound of phosphorus removed had been negotiated along with $30 per metric ton of carbon sequestered and stored. This would amount to nearly $204 million as an annual fee. Collection of these fees could be through a utility structure in which the benefitted user base would be charged. This base would not only include residents, but also visitors. The theme park area west of Orlando lies within the basin, and the annual visitation is about 70 million persons a year. A surcharge of just $3 per visitor would cover the utility fee. Obviously user charge structure will vary with different basins, and some will not have the advantage of so many visitors. But it is likely that the individual user cost can be kept at a reasonable level, and commensurate with the value of service provided.

To support the initial investigations necessary to determine the conditions for viability and subsequently to facilitate global application of MAPS, a full scale MAPS Demonstration Facility is suggested. This Demonstration Facility needs to be large enough to justify similitude for planning and design of anticipated expansion to large regional MAPS facilities, and for testing of harvesting and processing innovations. It is suggested that the facility, which could be contiguous to Lake Okeechobee, be a combined WH-MAPS and ATS™-MAPS in series, with the WH-MAPS composed of two

[127] Sano D., A. Hodges, and R. Degner (2005) Economic Analysis of Water Treatments for Phosphorus Removal in Florida Institute of Food and Agricultural Sciences, Food and Resource Economics Department, University of Florida, Gainesville, Florida.

parallel ponds of 25 acres each in a configuration similar to that noted in Figure G. Each pond would be of approximate dimension of 300 feet by 3,630 feet. The ATS™ would include a total headworks width of about 1,800 feet and a floway length of 500 feet. Six floways in parallel, each 300 feet wide, would be constructed to allow field testing of various hydraulic loading rates; surging vs. non surging; and various floway slopes, including no slope.

Influent from Lake Okeechobee would be provided by a low head, high flow variable speed pump with a capacity of up to 25 MGD. Effluent would be released back to Lake Okeechobee sufficient distance from the intake to avoid short-circuiting.

Included in Table 6 is a summary of the various tasks and general activity to be associated with the proposed Demonstration Facility for a two year operational Phase 1. An interim and final Phase 1 report will be completed and distributed for review and comment.

Phase 2 would be a continuation of Phase 1 operations. Investigations will be initiated into biomass product development beyond composting. This would include assessment of the state-of-the-art of the various options, followed by pilot testing if deemed appropriate. Products to be considered would be as noted in Section VI—although not necessarily limited to just those listed. It is anticipated this work will be coordinated with private-sector production companies, academic Institutions, and involved governmental entities.

During Phase 2 fabrication and testing of a Hyacinth Combine Prototype will be completed, and the harvesting regime established around his Combine. Also harvest innovations for ATS™-MAPS will be considered, and if deemed appropriate, will be assessed in terms of costs, reliability, and efficiency.

By the end of Phase 1, design criteria related to ATS™ floway slope and surging should be established. For all MAPS units, critical input parameters related to the two design models will be determined. These include maximum growth rate, limiting nutrient, half rate concentration of the limited nutrient, and the V'ant-Hoff Arrhenius coefficient for adjusting growth rate to temperature changes.

As a final note, it should be recognized that the recommendation to conduct the MAPS Demonstration Facility in the United States, and specifically in Florida, is because of infrastructure, climate and academic support available. It is important that the results of the demonstration facilitate adjustments for application for remote tropical/subtropical agrarian communities, as it is likely MAPS will be a good fit for this demographic, and could provide significant environmental and economic benefits to these communities.

Table 6: *Anticipated activity for two year phase 1 MAPS Demonstration Facility-Lake Okeechobee*

Task/Activity PHASE 1 2 years of operation	WH-MAPS	ATS™-MAPS
Facility Layout	Two parallel 25 acre Water Hyacinth ponds to receive influent from the lake via variable speed, low head, high volume pump rated at 25 MGD Average Daily Flow	Six parallel 500 feet long floways all in series with the water hyacinth ponds. Each floway with 300 foot width with varying slopes and operational conditions to facilitate comparative performance. Total area 21 acres
Harvest equipment	Initially a grapple type pick-up and forage chopper (Picture 2 & 3) until Combine design and testing completed. Harvest projections 14,500 wet tons per year.	Small tractor with scrapper and side drainage pad per Picture 7 and Figure G. Harvest projections 2,500 wet tons per year.
Biomass Management	Biomass to be windrow composted in pad between two ponds per Figure D. Projected compost 1,362 metric tons (2,500 cubic yards) per year. Carbon capture and storage 155 metric tons per year.	Biomass to be windrow composted in pad contiguous to drainage pad per Figure G. Projected compost 328 metric tons (600 cubic yards) per year. Carbon capture and storage 98 metric tons per year.
Monitoring	Continuous Influent Flow Monitoring. In-situ continuous influent and effluent temperature (water and air), pH, conductivity. Weather Station. Composite influent and effluent water quality for nutrients, organic carbon, suspended solids. Influent and effluent grab samples for ortho-P, alkalinity, heavy metals and pesticide/herbicide screen, acute toxicity, cyanotoxins and BMAA. Chopped plants weighed after 1 hour drainage after harvest. Compost weighed after 90 days of processing. Samples for percent moisture, carbon, phosphorus and nitrogen, protein, fiber, ash for fresh chopped plants and compost.	Continuous Effluent Flow Monitoring. In-situ effluent continuous temperature (water and air), pH, conductivity. Composite effluent water quality for nutrients, organic carbon, suspended solids. Influent and effluent grab samples for ortho-P, alkalinity, heavy metals and pesticide/herbicide screen, acute toxicity, cyanotoxins and BMAA.. Harvested plants weighed after 4 hours drainage after harvest. Compost weighed after 90 days of processing. Samples for percent moisture, phosphorus and nitrogen, protein, fiber, ash for fresh algae and compost.
Compost Quality and Value Analysis	Coordinate with IFAS to assess general quality of compost product, and proceed with initial field tests. Conduct initial market review. Consider blends with ATS™-MAPS compost and other products.	Coordinate with IFAS to assess general quality of compost product, and proceed with initial field tests. Conduct initial market review. Consider blends with WH-MAPS compost and other products.
Pay-for-Performance Negotiations.	Initiate negotiations for long term pay-for-performance agreement. Complete after Phase 1	
Utility District/Authority Development	Initiate talks with state legislature and local administrators and stockholders about establishing a Utility District or Authority for pay-for-performance fees.	