Vascular Aquatic Plants for Mineral Nutrient Removal from Polluted Waters

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A very serious problem arising from modern technology is pollution. One of the more widespread types of pollution is the addition of large quantities of inorganic nutrients, particularly nitrogen and phosphorus, to freshwater lakes and streams. Nutrients are present in industrial and municipal effluents, and in runoff and drainage from agricultural operations. Dissolved nutrient levels in many waters have increased during recent years (22, 23), greatly accelerating the natural process of eutrophication. Enhanced growth of bacteria, algae, and higher aquatic plants occurs in nutrient-enriched waters. Plant populations often reach nuisance proportions and interfere with beneficial uses of natural waters.

Research on more effective techniques to remove mineral nutrients from effluents prior to release into natural waters is badly needed (1). Just as relevant is the need for methods of nutrient removal from natural waters that have become dangerously eutrophic. Aquatic vegetation absorbs large amounts of nutrients and its removal might constitute an effective means of stripping nutrients from effluents or natural waters.

Several studies have dealt with nutrient removal from sewage by harvesting planktonic algae, but rather elaborate and expensive techniques are required to harvest phytoplankton (15). Several authors (4, 12, 22, 23) have hinted at the possibility of using higher aquatic plants for nutrient removal, but this idea has not been treated in detail. The present paper presents an argument for nutrient removal with vascular plants. The feasibility of such operations is not known, but hopefully this treatment will stimulate research on and discussion of the subject.

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If plants are removed, a disposal problem arises. Recent research (3, 4, 5, 9, 21) revealed that vascular aquatic plants have food plant qualities, either as raw materials for leaf protein extraction or as fodder. But leaf protein is probably not a suitable protein concentrate for use in technologically advanced nations at the present time (13). Aquatic angiosperms have a high moisture content and are difficult to harvest by mechanical means (3, 4, 5, 18), so their direct commercial possibilities in more advanced nations are not bright. However, if the plants were removed for nutrient abatement purposes, they could probably be dried and used as a feedstuff. The food value would offset the cost of removal to some extent.

Management of Native Vegetation

Nuisance aquatic angiosperms are usually eradicated with herbicides (21). Fish and other desirable organisms are sometimes killed directly by the herbicide. When large quantities of vegetation are destroyed, the resulting decomposition may deplete the dissolved oxygen supply and kill all aerobic organisms (26). Even when herbicide treatments are otherwise successful, nutrients in dead aquatic plants are quickly released (7). Space and nutrients soon become available for growth of other species. For example, Lake Seminole near Chattahoochee, Florida, contained several thousand acres of *Eichhornia crassipes* (water hyacinth). These plants were killed with herbicides, but the original aquatic weed infestation was rapidly replaced by *Alternanthera philoxeroides* (alligator weed). Herbicide treatments are usually successful for limited weed eradication in most lakes, particularly where fertility is not high.

In view of problems associated with extensive herbicide treatments, methods of vegetation management should be developed for fertile lakes where nutrient removal is not required. Large stands of particularly undesirable species could be reduced by partial herbicide treatment and more desirable native species encouraged. In tropical and subtropical regions, perennial species such as *E. crassipes* or *Pistia stratoites* (water lettuce) could be confined in particular areas of the lake throughout the year. Nutrients contained in these plants would not be available for other species, and the extensiveness of the *E. crassipes* or *P. stratoites* stands could be controlled by partial herbicide treatment. Encouragement of vascular plants in shallow water areas of temperate zone lakes that are plagued with nuisance crops of phytoplankton might effectively reduce nutrient levels and limit phytoplankton production. High nutrient levels during the winter would not present a problem. By such manipulations, species that conflict least with water uses would dominate nutrient cycles without serious habitat alteration.

Nutrient levels in some shallow, weed-infested, eutrophic lakes could be reduced by removal of natural vegetation. Fish mortality problems associated with herbicide treatments would be eliminated. Again, care must be exercised to insure that reinfestation would be by desirable species. The removal of most species from natural waters would require underwater harvesting equipment (18) and would be very expensive. This type of removal would be most effective if the source of pollution had been eliminated and a single harvest would significantly reduce nutrient levels. Phytoplankton dominates the flora of deep lakes, and even some shallow eutrophic lakes contain large quantities of planktonic algae rather than extensive stands of vascular plants. However, the removal of phytoplankton is not feasible with existing technology.

Species for Cultivated Systems

Nutrients could possibly be stripped from effluents by aquatic plants prior to their release into natural waters, or plants could be cultivated in lakes and then harvested. Species for these operations must not only produce large standing crops per unit area, but must have a rapid growth rate. The plants must accumulate large quantities of mineral nutrients, particularly the nitrogen and phosphorus generally associated with artificial eutrophication (22, 23). Only species that can be harvested by relatively simple means could be employed. In addition, the plants should have reasonable nutritive value as a feedstuff for economic reasons.

Non-planktonic algae and submerged and floating leafed vascular plants would be very difficult to harvest, and most species do not produce large quantities of biomass (3, 21). Many species of emergent and floating plants might be used, but based on my experiences (3, 5, 6, 10, 11), four species, *Eichhornia crassipes*, *Alternanthera philoxeroides*, *Justicia americana* (water willow), and *Typha latifolia* (cattail), appear most suitable. Chemical analyses

TABLE I
STANDING CROP, PRODUCTIVITY, AND YIELD DATA FOR FOUR SPECIES OF AQUATIC VASCULAR PLANTS

Species	Standing crop (Metric tons dry wt/ha)	Maximum productivity (g dry wt/m²/day)	Maximum yield[c] (Metric tons wt/ha/year)
Eichhornia crassipes[a]	12.8	14.6	54.7
Justicia americana[b]	24.6	31.1	113.5
Alternanthera philoxeroides[c]	8.0	17.0	62.0
Typha latifolia[a]	15.3	52.6	192.0

[a] Penfound (26)
[b] Boyd (6)
[c] Based on maximum productivity rates for 365 days.

TABLE II
MEAN MINERAL NUTRIENT COMPOSITION OF DRIED SAMPLES OF WATER PLANTS FROM YOUNG STANDS

Constituent	*Eichhornia*[a,b] *crassipes*	*Justicia*[c] *americana*	*Alternanthera*[a,b] *philoxeroides*	*Typha*[d] *latifolia*
Ash (%)	18.11	16.07	14.72	6.75
Nitrogen (%)	2.64	2.02	2.87	1.37
Phosphorus (%)	0.43	0.12	0.32	0.21
Sulfur (%)	0.33	0.18	0.29	0.13
Calcium (%)	1.00	0.90	0.52	0.89
Magnesium (%)	1.05	0.41	0.52	0.16
Potassium (%)	4.25	3.28	5.20	2.38
Sodium (%)	0.34	0.17	0.37	0.38
Iron (ppm)	250	1085	720	120
Manganese (ppm)	3940	112	440	412
Zinc (ppm)	50	265	90	30
Copper (ppm)	11	26	15	37

[a] Boyd (5)
[b] Lawrence (19)
[c] Boyd (6)
[d] Boyd (8)

indicated that these plants have a relatively high nutritive value (3, 5). In the cultivated systems, high nutrient concentrations will be present in the water, and near maximum levels of protein should be obtained for each species. Maximum crude protein values found in natural stands of these species are as follows: *E. crassipes*, 30%; *A. philoxeroides*, 20%; *T. latifolia*, 15%; and *J. americana* 29%. Large quantities of leaf protein concentrate can be extracted from *J. americana* and *A. philoxeroides*, but I have been unable to extract significant amounts of protein from the other two species. Standing crop data and productivity estimates are high (Table I). Environmental mineral nutrient levels would be high and interspecific competition lacking in the cultivated systems. Plants would be removed at some fairly continual rate or several crops would be harvested annually. Conditions for growth would approach the optimum. In tropical regions it might be possible to devise cultivation techniques that would enable plants to grow all year at rates obtained during short periods of their normal yearly cycles. Several months of high production might even be obtained in colder climates. Theoretical maximum rates of annual production (12 months) are given in Table I. The estimate for *E. crassipes* is probably very low. Westlake (31) estimated that a yield of 150 metric tons per hectare could be obtained under optimum conditions. If even 50% of the maximum values was actually obtained, it would represent a yield much higher than obtained with crop plants. The mineral composition of these species is reported in Table II. Considerable interspecific differences in nutrient composition are obvious, but values for macronutrients are within the ranges expected for typical forage species (24). Levels of certain micronutrients are higher than those reported in many terrestrial plants (24). Samples of the same species from different sites vary greatly in mineral concentrations. Samples from fertile sites have higher mineral levels than those from infertile sites (6, 11), so when cultured on nutrient-rich effluents, these plants would probably contain 1.5 to 2.0 times higher values than those reported in Table II. Levels of crude protein decline as these species age (6, 9, 10), and values for most minerals follow a similar trend. However, the plants would be harvested when young, and high tissue concentrations of most constituents would be assured. These facts

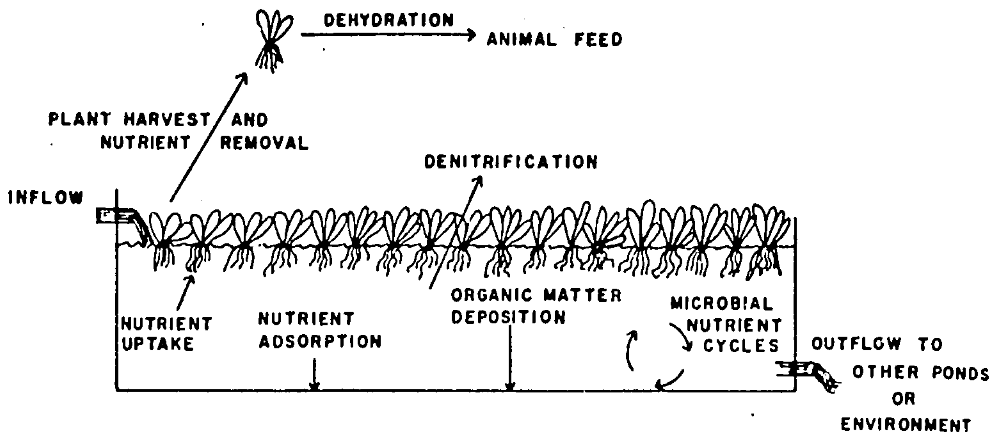

FIG. 1. Diagram of the processes involved in mineral nutrient removal from effluents by water hyacinths (*Eichhornia crassipes*).

are important from the standpoint of using the plants as a feedstuff. From the point of view of nutrient removal, dry matter standing crop is the decisive factor regulating the quantities of mineral nutrients per unit area of a particular species, even though large temporal and site variations in mineral levels are common (Boyd, unpublished data).

Nutrient Removal from Effluents

Municipal sewage treatment facilities remove considerable quantities of nutrients from waste water, but the effluents still contain levels of nitrogen and phosphorus that are much higher than concentrations in natural waters. Many industrial and agricultural effluents are not treated prior to release into the environment. Nutrients could possibly be stripped from certain high nutrient content effluents by aquatic angiosperm populations. Not only would this system remove nitrogen and phosphorus, but other nutrients capable of stimulating plant growth would be removed. Research to determine the efficiency of nutrient removal must be conducted, but dense plant stands should be capable of reducing mineral nutrient concentrations to very low levels. This is a definite advantage over most methods that are slanted at removing only certain key nutrients from waste water. Ponds could be constructed and stocked with aquatic plants. The principles of nutrient removal in plants are somewhat different from those regulating biological degradation of wastes in sewage ponds (25) and oil refinery effluent holding ponds (14), but certain aspects of operation will be similar. Shallow holding ponds require a shorter holding period than relatively deep holding ponds. A series of small ponds in which the waste water travels from one pond to the next is more effective than a single large pond. The size and design of vascular plant holding ponds will ultimately depend to a large extent upon methods of harvesting the plants. Suitable effluent retention times and the efficiency of the ponds can be determined by monitoring nutrient levels in the inflow and outflow.

Eichhornia crassipes would be ideally suited for nutrient removal systems (Fig. 1). This plant is not rooted and floats on the surface, so mechanical removal would be facilitated. Plants could be harvested at a continual rate and the population maintained in a rapidly expanding phase throughout the growing season. Mineral uptake rates per unit of dry matter increase are greater in plants in a rapid growth phase (6, 10). Waters beneath dense hyacinth stands are anaerobic (26), and additional nitrogen would be lost through denitrification. There would be considerable microbial activity beneath the hyacinths, and nutrients would be absorbed by these organisms. In addition, considerable organic matter would reach the water by the loss of root fragments from the hyacinths and the leaking of soluble organic compounds from the roots. Therefore, the outflow would be anaerobic and probably have a fairly high biological oxygen demand (BOD), and it might prove necessary to use conventional sewage holding ponds to reduce the BOD prior to final release.

Schemes for cultivating the other species that are emergent, i.e., rooted to the substrate with shoots extending above the surface of the water, would be similar to that for *E. crassipes*. Aerial shoots of *J. americana* and *A. philoxeroides* have crude protein values about one fourth higher than levels in samples of entire plants (6), but aerial shoots are only about 25% of the total standing crop. Therefore, it would not be practical to harvest the emergent growth with floating equipment. The ponds could be drained and allowed to dry to some extent without damaging the plants and modified forage harvesting equipment used to remove the entire above-ground portion of the stand. Both species will regrow rapidly from rootstocks, and two or more crops could be produced per year, even in temperate climates. *Typha latifolia* cultivation would be similar to techniques for *J. americana* and *A. philoxeroides*, except that the ponds could be dried to the point that conventional harvesting equipment could be employed without seriously impairing the quality of the plants.

Ponds for culturing emergent species could be three to four feet in depth. As long as the ponds remain aerobic, bottom soils would remove phosphorus from solution regardless of depth. In relatively deep ponds with dense stands, waters would probably become anaerobic since most of the gas exchange for these species is with the atmosphere. However, where space permits, *T. latifolia* could be cultured in water 6 to 12 inches deep. This would allow for better aeration and maximize soil adsorption of phosphorus. Regardless of the system of cultivation, the soils will gradually increase in phosphorus content, and equilibrium levels in outflowing waters would probably increase to an excessive level. At this time, ponds could be dried and used for the cultivation of conventional forages until soil phosphorus levels are reduced.

The effectiveness of the systems will depend upon having enough plant biomass to remove large quantities of nutrients at all times. Therefore, plant populations must be established prior to the release of effluents. In nutrient rich waters, phytoplankton frequently produces dense growths and prevents the development of rooted species simply by light limitation. This could be prevented by starting higher plants in very shallow water initially and raising the water level as the plants grow. Obviously, light limitation will not be a factor with *E. crassipes*. Particularly with the use of emergent species, several ponds will be needed. Ponds could be started at progressively later dates, and times of harvest would be staggered. This would insure the application of the technique throughout the growing season. Just as important, this would insure a constant supply of plants for use as feedstuffs.

E. crassipes does not occur in temperate climates, but this species could be introduced in the early spring, and large populations could be obtained in a few weeks. This plant is not capable of overwintering in temperate regions, so there would be no danger of it escaping into natural waters and becoming a nuisance. The three emergent species can overwinter and regrow from rootstocks, so once established, the cultures would be self-perpetuating. There would be some danger of introducing *A. philoxeroides* as a pest in some regions, but *J. americana* and *T. latifolia* are comparatively less important as economic pests.

Using maximum production data for the emergent plants (Table I), an estimate of 75 metric tons/hectare/year for *E. crassipes* and average mineral levels in Table II, quantities of nutrients that could conceivably be removed in plant biomass were calculated (Table III). In temperate climates, the removal values would decrease as a function of growing season.

TABLE III
QUANTITIES OF ELEMENTS (kg/ha) THAT COULD BE REMOVED PER YEAR BY CONTINUAL CULTURE OF SOME AQUATIC PLANTS

Element	*Eichhornia crassipes*	*Justicia americana*	*Alternanthera philoxeroides*	*Typha latifolia*
Nitrogen	1980	2293	1779	2630
Phosphorus	322	136	198	403
Sulfur	248	204	180	250
Calcium	750	1022	322	1709
Magnesium	788	465	322	307
Potassium	3188	3723	3224	4570
Sodium	255	193	229	730
Iron	19	123	45	23
Manganese	296	13	27	79
Zinc	4	30	6	6
Copper	1	3	1	7

These values represent large quantities of nutrients. For example, based on an estimated annual per capita contribution of 4.0 kg nitrogen and 1.4 kg phosphorus to treated sewate (22), the removal would correspond to the nitrogen contribution of 500 persons and the phosphorus contribution of 225 persons per hectare per year. Plant removal would also represent a large tonnage of feedstuffs. Using crude protein values calculated from nitrogen data in Table II and protein extractability data from Boyd (3), quantities of crude protein in fodder and amounts of extractable leaf protein concentrate (LPC) were calculated (Table IV). The digestibility of fodder from these plants is not known, so conversions to animal production cannot be made. Leaf protein concentrates from *A. philoxeroides* and *J. americana* are similar to protein concentrates from crop plants (20). LPC is a suitable protein supplement for inclusion in human diets (28). Assuming a generous protein requirement of 70g of protein a day for humans (29), the protein from one hectare of *J. americana* could satisfy the protein requirements of 301 persons for one year. About 50% of the dry matter would be retained as a fibrous residue following extraction. This material contains considerable protein and would probably be suitable as a ruminant animal feedstuff.

Although the proposed nutrient removal systems would probably be adaptable to a variety of effluents, it would be most suitable for situations where the effluent is of comparatively small volume, but concentrated in nutrients. One such source of pollution is feed lot production of cattle. The drainage from the lots could be diverted into holding ponds for nutrient removal, and the harvested plants could be processed and fed to the animals. This

TABLE IV
METRIC TONS OF CRUDE PROTEIN IN FODDER OR PROTEIN IN LEAF PROTEIN CONCENTRATE THAT COULD BE OBTAINED ANNUALLY FOR CONTINUAL CULTURE OF ONE HECTARE OF SOME AQUATIC VASCULAR PLANTS

Species	Crude protein in fodder	Crude protein in leaf protein concentrate
Eichhornia crassipes	12.4	—
Justicia americana	14.3	7.7
Alternanthera philoxeroides	11.1	4.7
Typha latifolia	16.4	—

would be ideal since handling and transportation of the plants would be kept to a minimum. Nutrient removal and plant utilization would also be handled by the same organization, and maximum economy would be realized.

Some Anticipated Problems

A number of problems that may be encountered in the cultivation of aquatic plants have been pointed out earlier. Several others deserve mention, and perplexities not considered here will undoubtedly arise. Mosquito production is usually associated with areas of extensive vascular aquatic vegetation (27), so the use of aquatic plants for nutrient removal would lead to mosquito infestations. Insecticide applications would control the mosquitoes, but insecticides having short residual activity must be employed if the plants are to be used as feeds. Careful attention will also have to be given to the possibility of pathogen (particulary virus) transfer from waste water to plants to animals to humans. This problem would be most critical with municipal sewage. The unsuitability of feedstuffs from plants grown on certain wastes will not preclude the use of plants for nutrient removal. Plants could be disposed of as green manures. However, the plants should be used as a feedstuff if possible since green manures are of very low economic value.

Percentage dry matter values for freshly harvested *T. latifolia*, *J. americana*, and *A. philoxeroides* are as high as dry matter values for forage crops. These species could be sun-cured as fodder, dehydrated, and processed into meals or even fed as a green roughage in the same manner as conventional crops. *E. crassipes* contains about 95% moisture and could not be fed as a green roughage. The moisture content is too high for conventional forage drying processes to be economical. Some of the excessive moisture content is due to adherent water associated with the root system. Much of this water can be removed by draining for a few hours. This will increase the dry matter content to 8 to 10%, but a period of sun drying will still be necessary before mechanical dehydration is practical. Low percentages of dry matter in *E. crassipes* would necessitate that processing equipment be located as near the point of harvest as possible to prevent cost of transporting material of high water content.

Nutrient Removal from Natural Waters with *Eichhornia crassipes*

The limitations of removing nutrients from natural waters by harvesting native vegetation have already been discussed. However, it should be possible to establish and confine populations of *E. crassipes* at desired sites in lakes or streams. These floating rafts could be removed when the plants reach a suitable size. Rafts could be started at different times, and plants in a rapid phase of growth would be present throughout the growing season. By removing plants at a rate sufficient to balance nutrient input with natural nutrient losses, a nutrient balance could be achieved. The process of artificial enrichment could be reversed by removing plant-bound nutrients in excess of input.

When added to lakes, phosphorus is rapidly removed from solution by adsorption onto hydrosoils (16, 17). This phosphorus is not rendered entirely unavailable since hydrosoil phosphorus and dissolved phosphorus exist in equilibrium (17, 30). The equilibrium concentration increases with increased hydrosoil phosphorus (30). Reductions in hydrosoil phosphorus could be effected by plant uptake. Plants would remove nutrients from the water, thereby displacing the phosphorus equilibrium, and additional phosphorus would be released from the mud. This would be particularly helpful in reducing hydrosoil phosphorus following cessation of nutrient enrichment.

E. crassipes could be grown in lakes of any size or depth. In temperate regions, *E. crassipes* would have to be introduced in the spring. Comparatively larger populations would be required in temperate climates than in tropical regions if the annual addition of nutrients is to be removed in a few months. This method would fail in areas with very short growing seasons, as would the techniques for stripping nutrients from effluents.

Conclusions

Aquatic plants have potential as feedstuffs in certain nations, but the economics of harvesting and processing would prohibit their direct utilization as a forage in technologically advanced nations. However, nutrient pollution is accelerating rates of eutrophication of natural waters in many areas. Aquatic plants produce large standing crops and accumulate large amounts of nutrients. Systems based on the harvest of aquatic plants have potential application in removing nutrients from effluents and natural waters. Large quantities of all elements essential for plant growth would be removed in proportion to their compositional ratios in the particular species. Plants could subsequently be used as forage to partially offset the cost of nutrient removal. The actual feasibility of these systems must be tested with pilot studies. These studies will require an interdisciplinary approach, and much research will be required. This paper has been intended to merely point out the apparent potential of aquatic angiosperms for nutrient removal. If usable, such systems would turn undesirable nutrient pollution into fertilizer to increase aquatic plant production, and the economics of nutrient pollution abatement would be improved.

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