Ryther, J. H., DeBusk, T. A., Hanisak, M. D., & Williams, L. D. (1978). Freshwater macrophytes for energy and wastewater treatment. In P. E. Greeson, J. R. Clark, & J. E. Clark (Eds.), *Wetland functions and values: The state of our understanding: proceedings of the National Symposium on Wetlands held in Disneyworld Village, Lake Buena Vista, Florida, November 7-10, 1978.* Minneapolis: American Water Resources Association.

Freshwater macrophytes for energy and wastewater treatment[1]

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[1] Contribution No. 4312 from the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543 and Contribution No. 122 from the Harbor Branch Foundation, Inc., RFD No. 1 - Box 196, Fort Pierce, Florida 33450. This research was supported by Contract No. EY-76-S-02-2948 with the U.S. Department of Energy

Proc. National Symposium on Wetlands, Lake Buena Vista, Fla. Nov. 7-9, 1978

Abstract:

Freshwater weed crops are capable of simultaneously providing advanced treatment (nutrient removal) of wastewater passed through them and producing biomass that may be converted to fuel by anaerobic digestion. Performance of both functions depends upon the rate of primary organic production of the plant species in question.

Annual yields of the floating species _Lemna minor_ (duckweed) and _Eichhornia crassipes_ (water hyacinth) and of the submerged species _Hydrilla verticillata_ were determined in central Florida. Yields of duckweed and _Hydrilla_, 13.5 and 15.3 m tons/ha.year respectively, are comparable to many temperate terrestrial food and grass crops. The yield of water hyacinths, 88.3 m tons/ha.year, is among the highest documented for any plant species on earth.

A one thousand hectare water hyacinth farm is capable of producing 10^{12} BTU of energy per year as methane gas and, at the same time, of removing the nutrients from the wastewater of a population of 700,000 people.

Background:

The cultivation of photosynthetic crops for the specific purpose of converting their biomass to fuel is a new and, as yet, untried concept. The basic technology for such an undertaking is, of course, available in agriculture and the related fields involved in the production of food and fiber. However, the monetary value of plants grown for food or fiber is an order of magnitude greater than their potential value as fuel (Greeley, 1976), even if all of their stored energy were recoverable. In view of the increasing world demand for food and fiber, it therefore seems unlikely that crops presently in production will find competitive use as an energy source in the foreseeable future, with the exception of those portions of cultivated plants that are currently treated as waste.

It follows, then, that species not presently cultivated must be grown for this new purpose, and that they must be grown in areas that are not suitable for the cultivation of food and fiber crops. Further, and most important, they must be produced within the framework of an entirely new budgetary concept, one that is based upon an energy rather than a financial balance sheet. The latter is, of course, always an important factor, particularly when alternative uses of the product (as discussed above) or the land used to grow it are considered. But costs and values of such commodities as food and energy change so rapidly that long-range projections of the economic feasibility of energy plantations are at best tenuous.

It is incontestable, however, that the cultivation, harvest, processing, and conversion to fuel of crops grown as an energy source must consume less energy than the crops are capable of producing. Furthermore, the energy cost accounting must extend back to include the production of capital equipment, machinery, and fertilizer as well as the direct operational budget. Such an energy cost accounting has been done for the 1970 U.S. corn crop by Pimental et al. (1973), who found an energy output:input ratio of 2.82. Considering not just the edible portion but the entire plant, which is more relevant to the subject of energy conversion, a ratio between 5 and 9 is obtained (UK-ISES, 1976). Other investigators have estimated energy output-input ratios for major crops at 3.3 for corn, 5.4 for wheat, 16.0 for alfalfa, and 37 for timber (Burwell, 1978).

However, only about half of the energy contained in the plant biomass is recoverable through fermentation to methane with present technology (e.g., Christopher and Hobson, 1976), and the conversion itself is an energy-consuming process. Whatever the final net accounting, it is clear that an energy output:input ratio greater than one is necessary for a viable operation; the greater the ratio, the more attractive the concept of an energy plantation becomes. In this connection, it seems likely that a new plant cultivation technology will need to be developed for energy production, for the improved food yields of modern agricultural technology in recent years have been accomplished only at the cost of decreasing energy output:

input ratios (Pimental et al., 1973; Pain and Phipps, 1975). In conclusion, then, it would appear that the new concept of energy plantations must involve species of plants not now in cultivation, areas unsuitable or marginal for food and fiber production, and a new culture technology aimed at achieving the maximum productivity at the least possible expenditure of energy.

One of the major energy costs in growing photosynthetic crops for fuel is that of fertilizer, particularly nitrogen. According to Payne and Canner (1969), the production and processing of one pound of nitrogen fertilizer, beginning with atmospheric nitrogen, requires 8,400 kilocalories (33,600 BTU). One ton of plant biomass, assuming that half of it could be converted to methane or some other fuel, could produce the equivalent of 6-12 million BTU depending upon the crop (Klass, 1974; Burwell, 1978). But one ton of the plant biomass contains some 100 lbs. or more of nitrogen. If provided as commercial fertilizer, this amount of nitrogen would cost roughly 4 million BTU to produce—one to two-thirds of the energy obtainable from the plant material. Pimentel et al. (1973) came to roughly the same conclusion with respect to the energetics of corn production in the United States, showing that the energy required to produce the nitrogen fertilizer amounted to 32% of the energy contained in the crop (presumably double the energy recoverable through fermentation). Clearly, some new source of nutrients is needed if energy farming is ever to succeed. Indeed, this represents one of the more important elements, perhaps <u>the</u> most important, of the "new technology" discussed above that must be developed for energy farming.

The recycling of domestic and agricultural wastes is one promising means of obtaining nutrients. Not only are such nutrients produced free, but large expenditures of both money and energy will soon be required by existing national legislation for the removal of these substances from wastewater prior to its release to the environment. A properly managed energy farm may serve as an efficient mechanism for the removal of nutrients from wastewater passed through the plant population. For example, a ten square-kilometer (3.9 square-mile) energy farm producing biomass at the modest rate of 25 dry metric tons per hectare per year (10 t/acre.year), with a nitrogen content of 5% of its dry weight, could assimilate all of the nitrogen in the wastewater of 1.4 million people.

The utilization of wastewater to grow plant crops can thus accomplish two energy-related objectives simultaneously: (1) the production of biomass for energy conversion without the need for energy-intensive commercial fertilizers, and (2) the removal of nutrients from wastewater without the large expenditure of energy needed for conventional physical-chemical methods of tertiary sewage treatment. Whatever the energy balance of the first process, which cannot yet be determined, the second process alone certainly seems capable of achieving a significant conservation of energy, which utilization of the by-produce (plant biomass) can only enhance. It is quite conceivable, in other words, that the major accomplishment of energy plantations may lie in the area of conservation rather than in new energy production.

The potential of freshwater macrophytes:

Freshwater macrophytes grow throughout the world in ponds, lakes, rivers, and canals. Particularly where such natural or man-made aquatic areas receive nutrient inputs from wastewater, agricultural drainage and other sources, the plants spread rapidly, choking the waterways and generally interfering with or degrading navigation, irrigation, disease and insect control, fisheries production and utilization, and water quality. Esthetic, recreational and economic values of aquatic areas are all adversely affected by excessive growth of aquatic weed species, a problem that has become increasingly chronic in tropical and sub-tropical climates. Over $3 million is spent annually in Florida alone for aquatic weed control.

Properly managed as "aquatic farms", however, such crops could become valuable resources, providing biomass for conversion to fuel and at the same time providing a biological tertiary wastewater treatment function, removing the nutrients from wastewater prior to its discharge to the natural environment.

As a biomass source, aquatic macrophytes fulfill the important prerequisite discussed earlier of having no existing value for food or fiber and of occupying areas that do not have the potential for growing other agricultural crops. Furthermore, acreage would not need to be pre-empted from other uses for biomass production, but rather areas that are already heavily infested with aquatic weeds could be managed and harvested.

Aquatic plants are already in use in many parts of the world for the purpose of removing nutrients from wastewater. For example, the senior author has compiled a bibliography of 138 references on the subject up to February, 1978 (Ryther, unpublished bibliography). There is little question from that extensive literature that sewage effluent represents a complete and effective source of nutrition for a great variety of aquatic plant species and, conversely, that properly managed crops of such plants are effective in performing the nutrient removal function of an advanced wastewater treatment system. However, both the economic and the energy cost effectiveness of aquatic plant farms, whether for biomass production as an energy source or as advanced wastewater treatment systems, appear to be marginal at best (e.g., Robinson et al., 1976; Lecuyer, 1976; Markarian et al., 1977; Taylor and Stewart, 1978). Part of the reason for that may be the fact that the values and benefits have seldom been considered for the two uses together, as a single symbiotic system. But the fact remains that both uses have relatively low value per unit of plant crop.

All of the engineering and economic analyses mentioned above have stressed productivity or yield (organic matter produce per unit of area and time) as the single most important factor in determining cost:benefit ratios. In this connection, although high levels of productivity are usually attributed to virtually all kinds of freshwater macrophytes, particularly the nuisance species, actual yield data for most of them are either lacking entirely or surrounded by such uncertainty as to be virtually worthless. As a result, to be completely objective the analyses referred to above have had to postulate such a wide range of possible yields as to make the final conclusions meaningless. The need for basic data on the annual productivity of some representative freshwater macrophytes therefore appeared to us to be a prerequisite for any further consideration of their potential use.

Primary production of three species of freshwater macrophytes:

Three freshwater macrophytes were grown in artificial culture systems at the Harbor Branch Foundation aquaculture facility in Fort Pierce, Florida during 1977-78. These were the floating species water hyacinth (<u>Eichhornia crassipes</u>) and duckweed (<u>Lemna minor</u>) and the submerged, normally rooted species <u>Hydrilla verticillata</u>, sometimes known as "Florida <u>Elodea</u>". <u>Eichhornia</u> has long been a serious nuisance in Florida, choking canals and water ways throughout the State. <u>Hydrilla</u> is a more recent invader, but has taken over and completely obstructed many of the larger lakes and rivers in the State during the past decade and is now generally considered a more serious problem than water hyacinths. Because of its small size, duckweed is not a serious threat to Florida's waterways and their uses, but the tiny plant is ubiquitous and grows in ponds, ditches, canals and other quiet water areas.

The above plants were grown out-of-doors in PVC-lined earthen ponds 30 m^2 in area, and in concrete vaults 1.75 m^2 in area, in a medium of enriched well water, which was circulated through the cultures. Growth of the plants was measured as the increase in weight per unit area and time, determined by direct weighing. Consistent wet weight values were obtained by draining the plants for specific time intervals. At each weighing, a plant sample was removed, weighed, dried for 48 hours at 60°C and reweighed. From that relationship, productivity was calculated and expressed as mean grams dry weight/ m^2.day for the growth period in question.

The water hyacinths in the culture unit were grown in Vexar-mesh cages ranging in size from 1.0 to 2.3 m^2. At intervals of approximately one week, the cages with the contained plants were lifted from the water using a hand rope winch and suspended from an A-frame over the culture, with a spring scale between the end of the line and the Vexar cage. The culture was allowed to drain for four minutes and weighed. Individual plants were removed to return the population to its starting density (i.e., at the time of the previous weighing and harvest), and the cage was returned to the water.

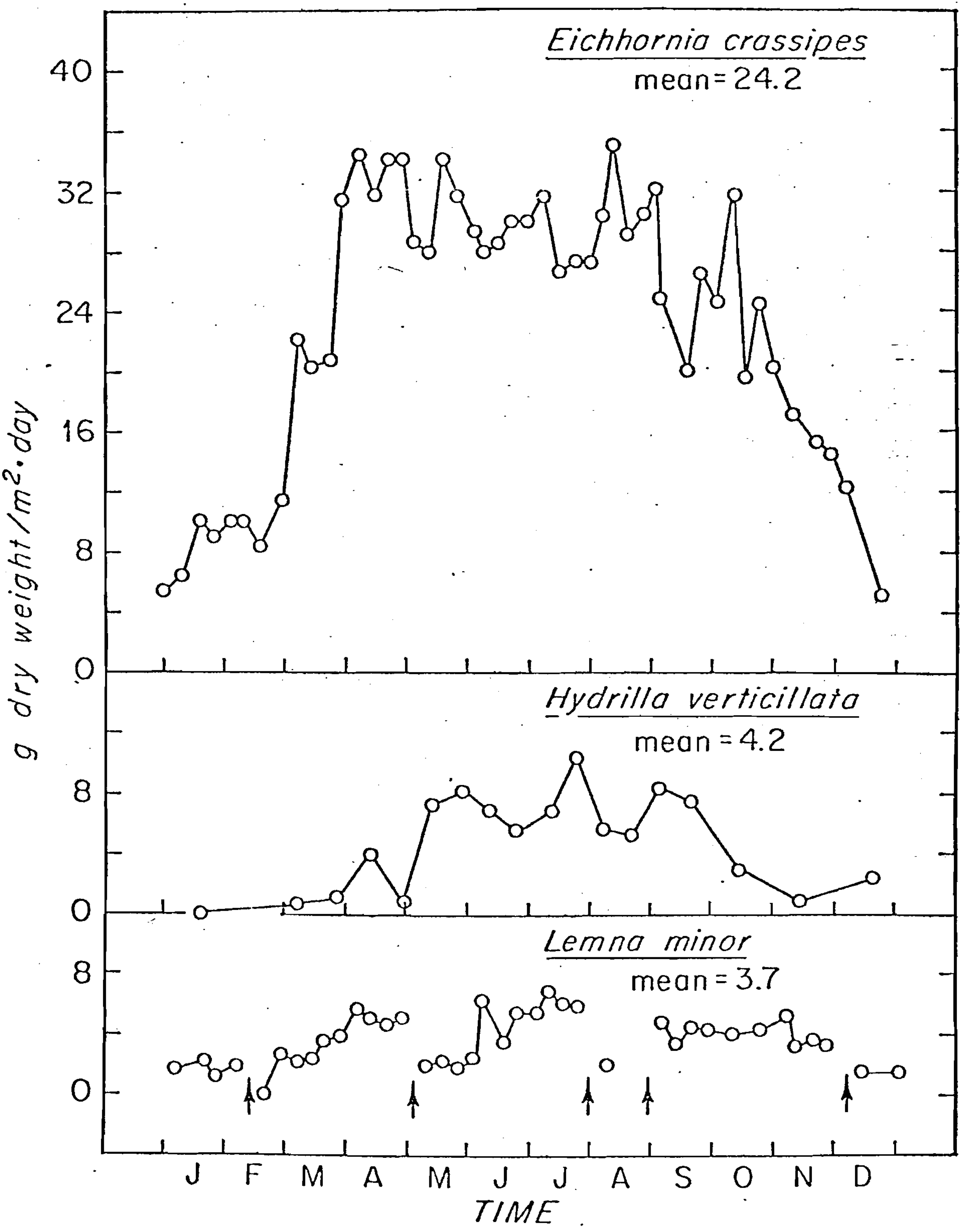
Duckweed was grown in ponds and vaults with the plants covering the entire water surface. Each week, the plants were netted from the water, transferred in handfuls to a dry container (allowing excess water to drain), weighed by balance or spring scale, harvested back to their starting density, and returned to the water.

Since Hydrilla is found rooted to the bottom in natural stands, it initially appeared impossible to weigh the plants without destroying the culture. After unsuccessful attempts to grown Hydrilla in a free-floating fashion, it was discovered that apical sections of the plants would grow when woven through a Vexar-mesh screen suspended above the pond bottom. The Vexar screens and attached plants were then periodically removed, at intervals of one to two weeks, allowed to drain for 10 minutes, weighed, and returned to the water. Subsequent experiments proved that growth of Hydrilla attached to Vexar-screening in this way was virtually identical to that of plants rooted in sand or rich mud substrate, indicating that they obtained adequate nutrients from the enriched water alone (DeBusk et al., in press).

Unlike water hyacinth and duckweed, which can reproduce by budding off new plants, Hydrilla grows vegetatively from apical meristems which concentrate near the water surface in dense mats. New growth is generally harvested by cutting off sections of the individual plants some distance below these growing tips. However, this was found to arrest further growth for periods of 10 days to two weeks until new meristematic growth tips were regenerated. In practice, this means that harvested (cut) Hydrilla does not grow about half the time, a situation that would lead to serious underestimates of the growth potential of the species. Hydrilla was therefore not harvested back at all during the year that its growth was monitored, although it was recognized that the culture probably exceeded its optimal density for growth during part of the year.

The optimal culture conditions for growth of the three species, including composition and concentration of nutrients, residence time of the enriched water in the cultures, density of biomass at which the water hyacinths and duckweed were maintained by harvesting, and other factors, were all determined experimentally and are described by DeBusk et al. (in press). Once these conditions were established, the plants were grown continuously and their productivity monitored for a complete year.

Annual yields of duckweed, water hyacinth, and Hydrilla are shown in Fig. 1 (DeBusk et al., in press), each point representing mean daily productivity over periods of one to several weeks (depending upon season and growth rate). The annual daily means for the three species were 3.7, 24.2 and 4.2 g dry wt/m^2.day (equivalent to 13.5, 88.3 and 15.3 dry metric tons/hectare.year respectively). The productivity of both duckweed and water hyacinths in the culture units in Fort Pierce averaged about three times the yields of the same plants as monitored in nearby, highly euthrophic natural environments (DeBusk et al., in press), presumably due to the controlled circulation and enrichment of water.


Eichhornia crassipes
mean = 24.2
Hydrilla verticillata
mean = 4.2
Lemna minor
mean = 3.7
g dry weight/m²·day
40
32
24
16
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Among the limted data for water hyacinth production in Florida are those of Lugo et al. (unpublished ms.) for a natural stand in a small, polluted pond near Gainesville. From CO_2 gas exchange measurements made in isolated chambers over 24-hour periods throughout the year, they found a net annual production of 4200 g carbon/m^2. This is roughly equivalent to 23 g organic or 28 g total dry wt/m^2.day on an average, which is within 10% of the annual mean obtained at Harbor Branch Foundation.

For the past several years B. C. Wolverton and his colleagues at the NASA Laboratories, Bay St. Louis, Mississippi, have been evaluating the performance of water hyacinths and other macrophytes for advanced wastewater treatment. Wolverton has projected a yield of 154 m tons/ha.year over the seven-month season that the plant grows at that location (Wolverton and McDonald, 1978). However, his estimate is apparently based on specific growth rate measurements (percent increase/day) made in one series of experiments and assumed or measured densities of the hyacinths made elsewhere. The close dependence of growth rate on density (DeBusk et al., in press) means that plant productivity cannot be reliably estimated from separate measurements of growth rate and density.

Hillman and Culley (1978) similarly discuss the high productivity of duckweeds in terms of specific growth rate, citing several other publications that use the same criterion (e.g., g/g.day), and stating, "Thus, it is reasonable to conclude from these figures that duckweeds can grow at least twice as fast as other higher plants." In addition to discussing specific growth rates, Hillman and Culley cite an unpublished master's thesis reporting a mean annual yield for duckweeds (species not given) of 7.85, with a maximum of 9.8, dry tons/acre.year (19.6 and 24.5 t/ha.year respectively). These are slightly higher but comparable to the yield of Lemna minor at Harbor Branch Foundation (13.5 t/ha.year).

Conclusions:

Annual yields of the three aquatic species are shown in Table 1 compared with those of the most productive agricultural crops. Duckweed and Hydrilla are not outstanding in this ranking, but are about on a par with several of the temperate terrestrial species. Water hyacinth, however, tops them all and must go on record as one of the most productive plants on earth.

Westlake (1963) predicted the high productivity of water hyacinths, stating: "It seems possible that about 150 metric tons of organic matter per hectare per year might be attained in a good climate if Eichhornia crassipes could be grown so that the young plants always dominated and the water surface was always completely covered, without much exceeding the density which would begin to severely decrease the net efficiency because of self-shading effects." Experiments at Fort Pierce showed conclusively the need to maintain the hyacinths at their optimal density by routine harvesting (DeBusk et al., in press). A yield of 150 organic tons/ha.year would be equivalent to a sustained daily production of 41 g/m^2.day organic or 50 g/m^2.day total dry weight (82% organic). Short-term yields at Fort Pierce did approach that figure on a few occasions and it is conceivable that annual production of a carefully-managed crop in the tropics could come close to Westlake's figure. But central Florida is semi-tropical and growth of <u>Eichhornia</u> is accordingly severely depressed in winter (see Fig. 1), with the emergent vegetation sometimes being killed back completely during winter freezes. Thus the reported yield of 88.3 t/ha.year would seem to represent something close to the maximum potential for the species in the continental United States.

Using that yield, it may be estimated that a 1000-hectare water hyacinth energy farm in southern United States could produce on the order of 10^{12} BTU of methane per year, assuming an energy content of some 20 million BTU per dry ton of plant biomass, half of which would be recoverable by anaerobic digestion (Christopher and Hobson, 1976). Also assuming that the hyacinth biomass is roughly 2.5% nitrogen (Boyd and Scarsbrook, 1975), the above yield would remove all of the nitrogen from the wastewater from a city of about 700,000. Other nutrients would be removed in proportion, providing both a source of fertilizer for the energy farm and an advanced wastewater treatment system for the neighboring community.

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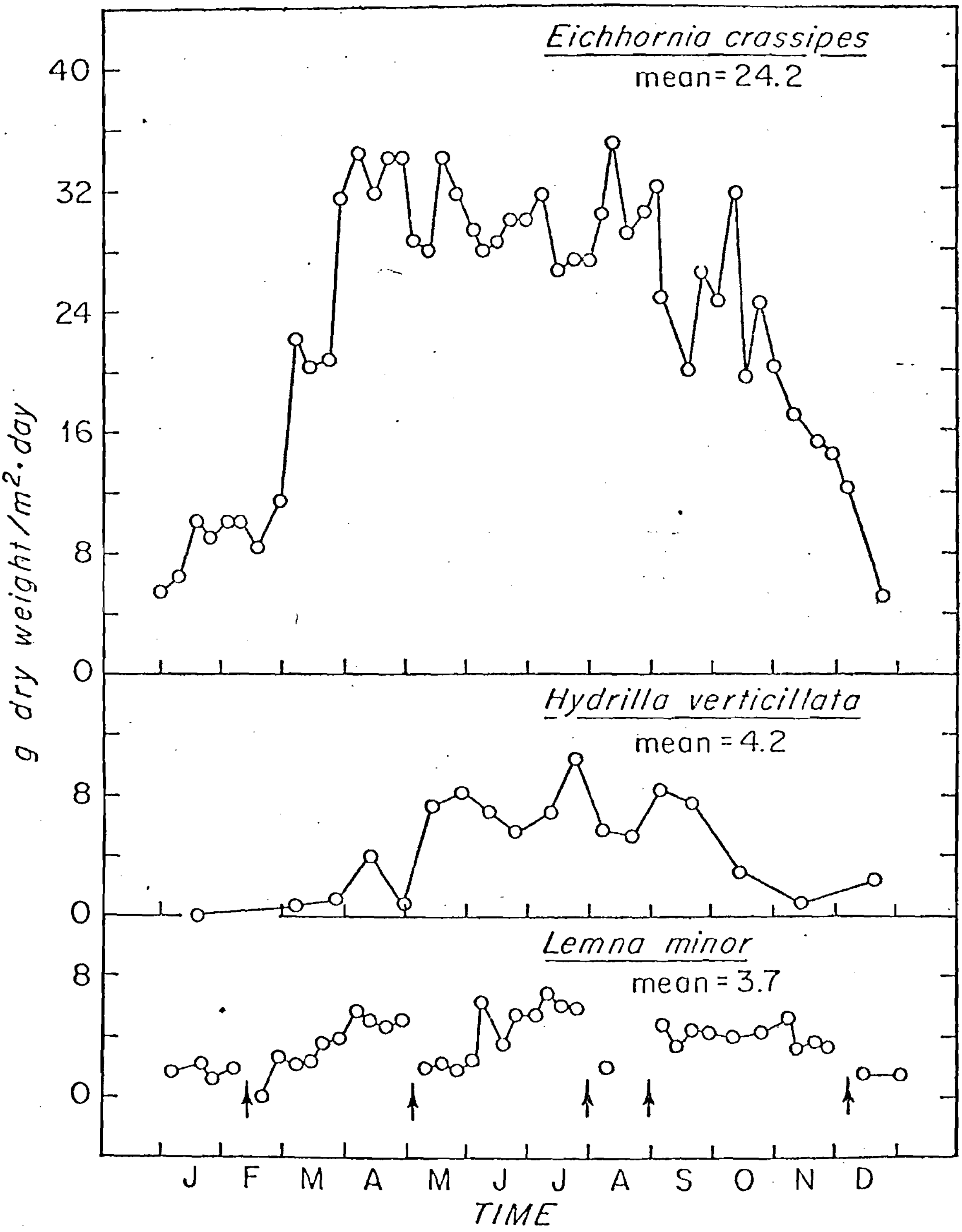
Figure legend:

Fig. 1. Annual yields of water hyacinth (Eichhornia crassipes) duckweed (Lemna minor) and Hydrilla verticillata at Fort Pierce, Florida (DeBusk et al., In press). Arrows in Lemna figure indicate times when culture became overgrown with epiphytic algae or was blown out of pond by high winds and had to be restarted.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mean = 24.2
Hydrilla verticillata
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g dry weight / m^2 · day
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32
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