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LAND-BASED CULTIVATION OF SEAWEEDS: AN ASSESSMENT OF THEIR POTENTIAL YIELDS FOR "ENERGY FARMING"

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In Florida, there has been considerable effort since 1976 by John Ryther and his colleagues, primarily at the Harbor Branch Foundation, near Fort Pierce, to assess the potential of seaweeds as a source of biomass for conversion into methane. This effort was funded, in sequence, by the Energy Research and Development Authority, the Solar Energy Research Institute. Presently, the project is being reorganized as part of the Gas Research Institute/Institute of Food and Agricultural Sciences "Methane from Biomass and Waste Program." This latter program is looking at the potential of a number of different types of biomass (e.g., trees, agricultural crops and wastes, freshwater plants, seaweeds), with the goal of developing a comprehensive alternative energy program, based on renewable biomass, for the state of Florida.

This chapter is a summary of the experimental seaweed cultivation that has taken place in Florida as part of this work. In particular, the development of one species (Gracilaria tikvahiae) as a potential energy crop will be traced through several levels of experimentation.

Production of Biomass

The most important criterion that determines the potential of a species to serve as an "energy crop" is a rapid and sustained production of biomass (i.e., yield). Additional considerations are ease of cultivation, complexity of life cycle, and the simultaneous production of other economically important materials (e.g., phycocolloids). For any given geographical area, the best species, in regard to yield, will be determined by the local climate (i.e., light and temperature conditions). Thus it is important that the native flora of the area be "screened" for the presence of fast-growing species that are most suitable to local environmental conditions. It is highly unlikely that fast-growing exotic species will ever be introduced into new areas for large-scale *in situ* cultivation because of concerns over their impact on the local ecosystem, as demonstrated by man's unintentional introduction of exotic seaweed, such as *Sargassum muticum* and *Codium fragile*.

Accordingly, the first step in the research program at the

Harbor Branch Foundation was to measure the potential yields of local seaweeds in small outdoor tanks called "screening troughs" (Figure 4.1) (see list at end of chapter). Of over 55 species that were examined in these troughs, the best performer, on the basis of sustained yields, was the red seaweed _Gracilaria tikvahiae_ (Figure 4.2), which had an annual average of 35 g dry weight $\cdot m^{-2} \cdot day^{-1}$, which is equivalent to an annual yield of 128 dry metric tons $\cdot ha^{-1} \cdot yr^{-1}$. Other species, particularly green seaweeds such as _Enteromorpha_, _Chaetomorpha_, and _Ulva_, could grow faster than _Gracilaria_ for short periods, but high yields were not sustained for very long. The yield of _Gracilaria_ in these screening troughs is among the highest for any plants in the world under any conditions. Of course, these data represent what is possible under rather idealistic conditions; they demonstrate the potential of _Gracilaria_ to produce biomass, but they are probably not attainable on a commercial level, at least in the near future. It is important to note that the method of cultivation employed on this small scale was very energy-intensive, i.e. large amounts of flowing seawater and aeration were required, and could not be practically employed for the commercial cultivation of _Gracilaria_ for the purpose of bioconversion because of an unfavorable net energy balance.

Gracilaria has been grown in larger tanks than these screening troughs. In one configuration (Figure 4.3), _Gracilaria_ has been successfully grown for several years, with an average productivity of 22 to 25 g dry weight $\cdot m^{-2} \cdot day^{-1}$ (80 to 91 dry metric tons $\cdot ha^{-1} \cdot yr^{-1}$). Most of the research has involved one particular clone ("ORCA") of _G. tikvahiae_ that was first isolated in December 1977. From an initial weight of a few grams, many tons of this clone have been grown at the Harbor Branch facility. During this time, the clone has not reproduced sexually; rather it propagates itself vegetatively, reproducing only through fragmentation. The use of such a sterile clone is useful because, once a desirable clone is selected, it can be maintained, without changes in its genetic makeup, for long periods.

This energy-intensive tank culture has been successfully scaled up to tanks having a surface area of 29 square meters and a volume of 24,000 liters without any decrease in the above yield. Additional research has indicated that aeration and seawater flow can be reduced without significant losses in yield, but probably not to a point where this method would be economically viable for the production of methane. However, it is possible that this type of culture could be successfully employed if _Gracilaria_ were to be cultivated for the production of agar, an expensive phycocolloid that has many commercial applications, primarily in the food and drug industries.

While additional research continues on minimizing energy inputs into this type of tank culture, there have also been some attempts to grow _Gracilaria_ in what may be considered a non-intensive type of culture, PVC-lined earthen ponds (Figure 4.4). These ponds varied in size from 10 to 20 m^2, in depth from 0.4 to 0.8 square meter, and had volumes up to 25,000 liters. In most

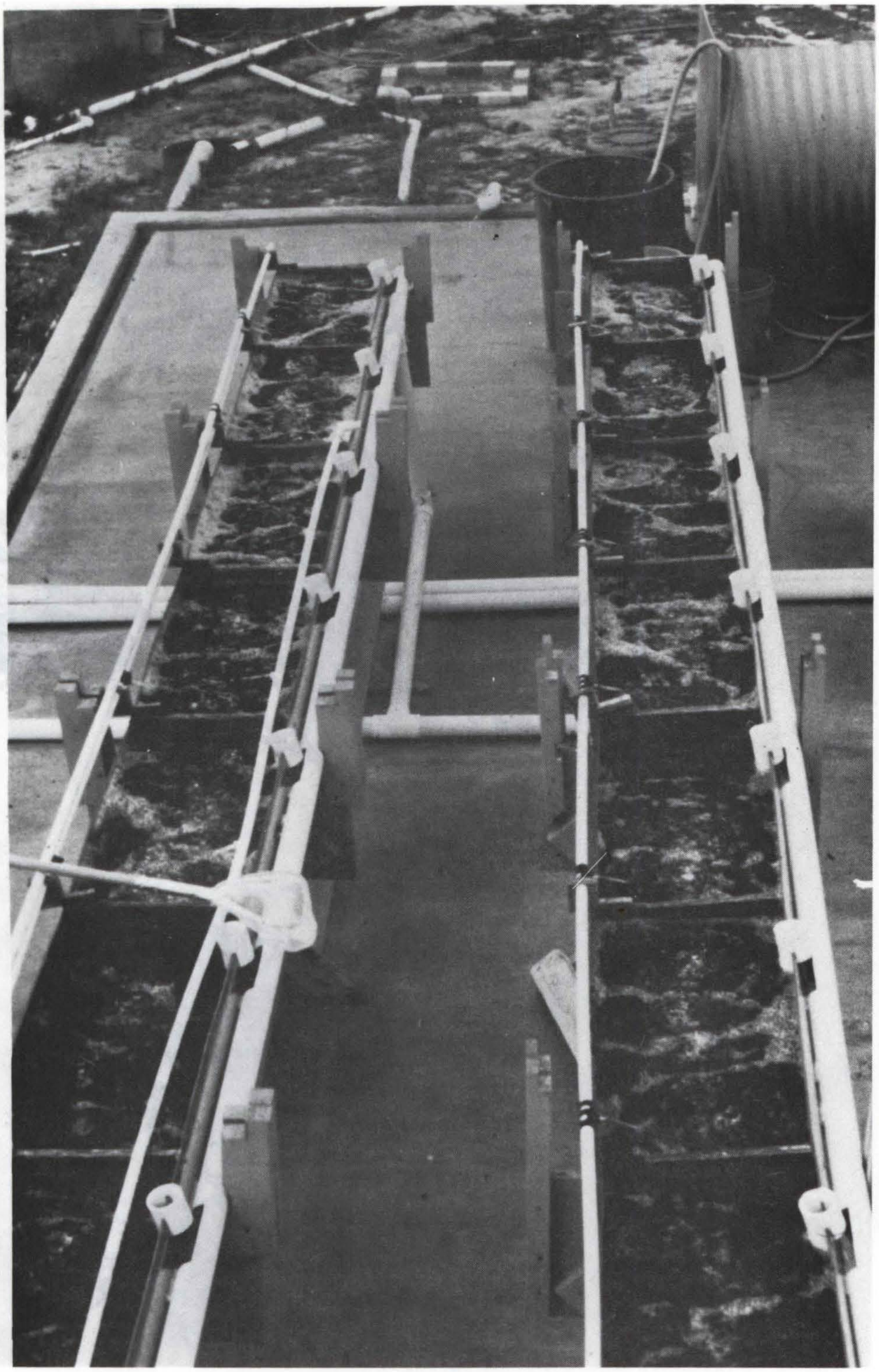

FIGURE 4.1 "Screening troughs" used in the screening of seaweeds at the Harbor Branch Foundation (These tanks were constructed from PVC pipe and sectioned into small [55 liters] chambers. Seaweeds were heavily aerated and received over 20 culture-volume exchanges per day of enriched seawater.)

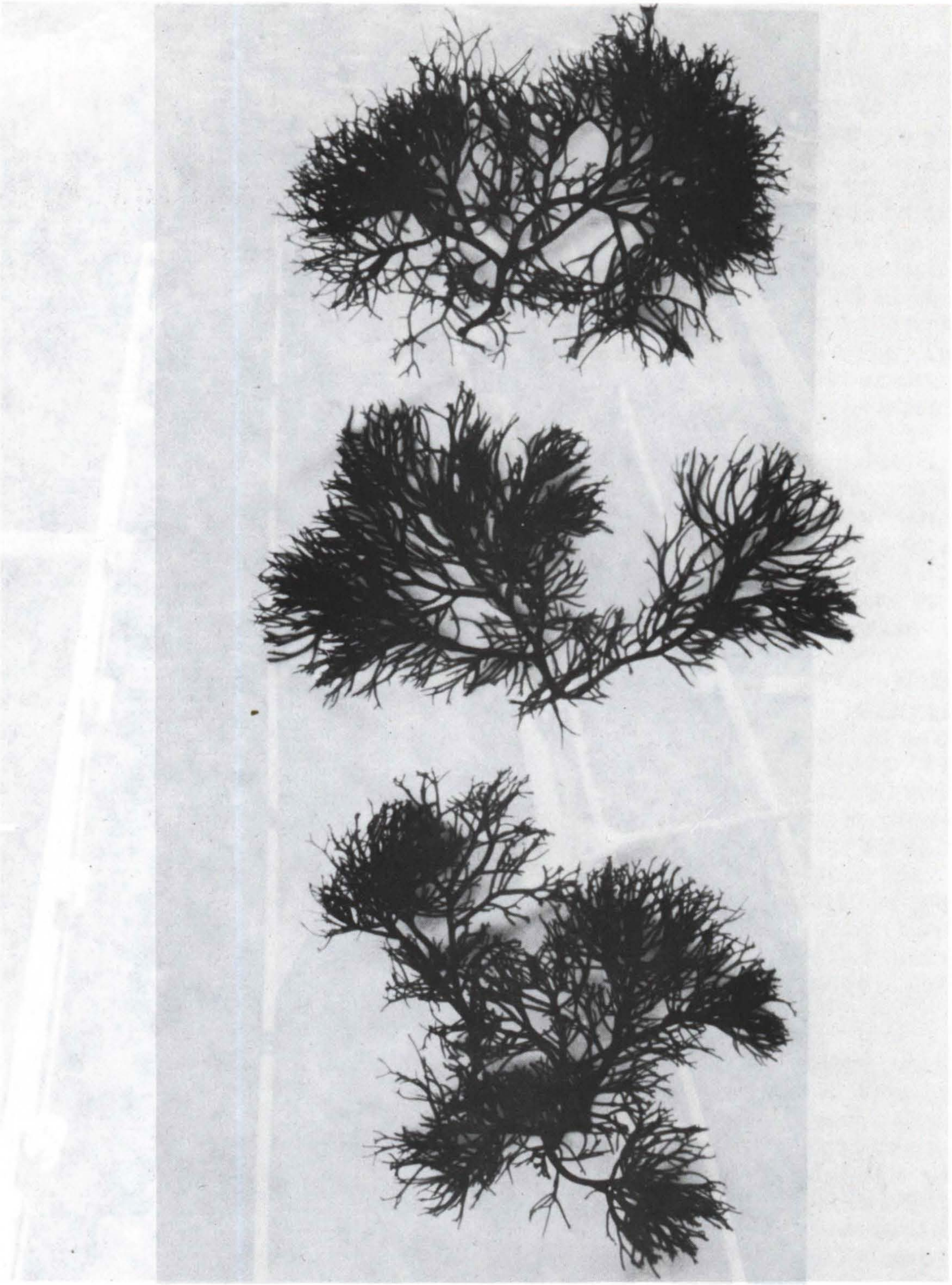

FIGURE 4.2 Gracilaria tikvahiae (the most successful species during screening trials conducted in 1976-1977 in tanks like those in Figure 8.1)

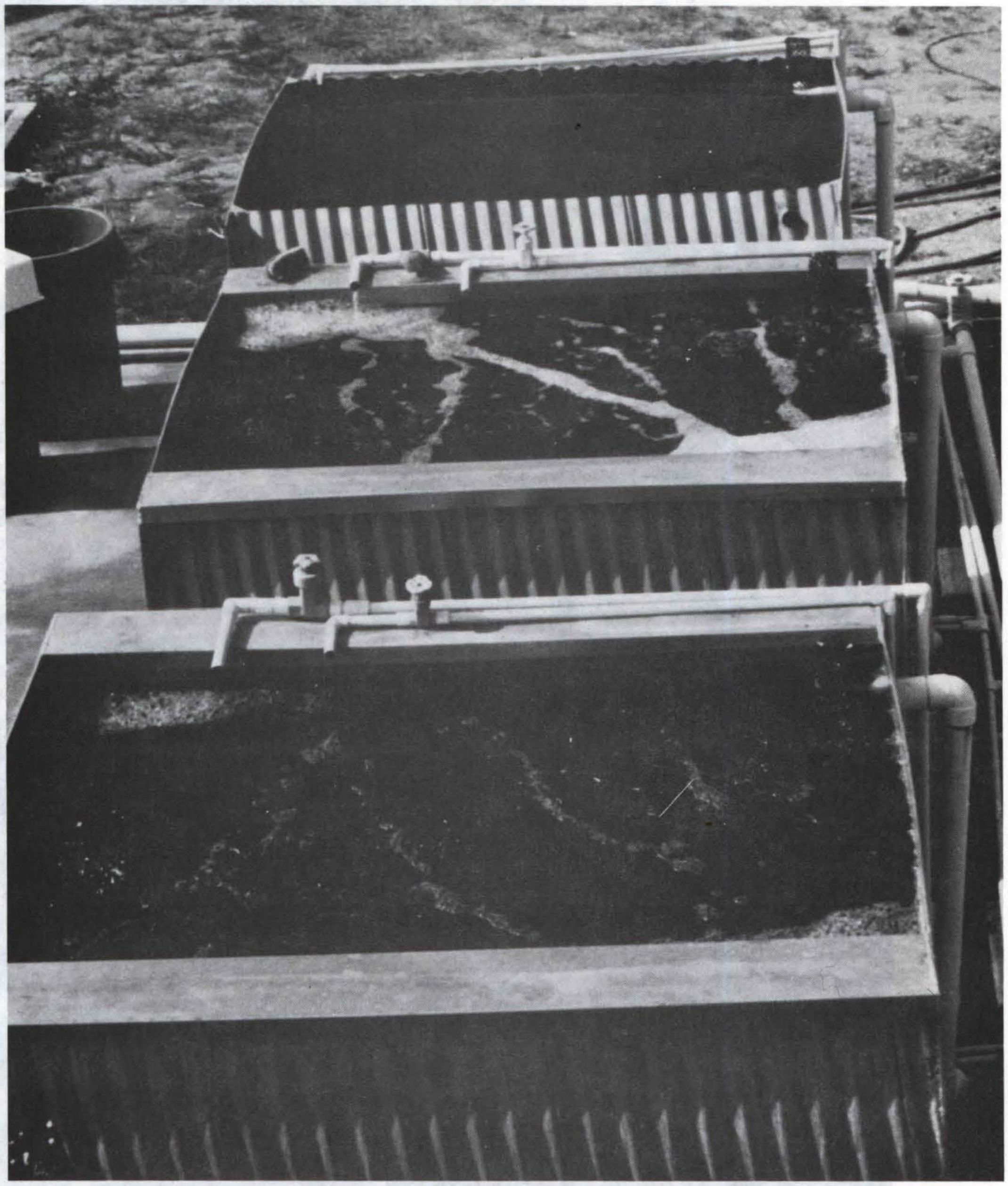

FIGURE 4.3 Tanks for Gracilaria cultivation, constructed from aluminum culvert pipe (Typical flow rates were 4 volume exchanges/day [volume was 2,600 liters]. Heavy aeration was used to keep the plants in continuous suspension. Similarly constructed tanks have been used with volumes up to 24,000 liters.)

FIGURE 4.4 PVC-lined earthen ponds, used to provide a less intensive mode of cultivation (Bottom area ranged from 10 to 20 m2, depths were 0.4 to 0.8 m, and volumes were 5,000 to 25,000 liters. Typically no aeration was employed and flow rates were 2 volume exchanges/day.)

cases, Gracilaria was scattered, unattached, along the bottom of the ponds. Initially, no aeration was employed, and the exchange of seawater was relatively low (2 volume turnovers/day). Yields in this type of "bottom culture" were significantly lower than in the energy-intensive method and usually ranged from 5 to 8 g dry weight$\cdot$m$^{-2}\cdot$day^{-1} (18 to 29 dry metric tons$\cdot$ha$^{-1}\cdot$yr^{-1}). Besides this considerable reduction in yield compared to the more intensive cultivation, other problems were encountered that were primarily associated with a reduction in water motion. The most serious of these was the growth of diatom mats on the sides of the ponds. These mats eventually detached from the liners, became entrapped in the seaweed, and floated Gracilaria to the surface, where, without agitation, surface temperatures reached 40°C in the summer. Such a high temperature is lethal to Gracilaria. In addition, once Gracilaria was floating, it was quite susceptible to being blown to one end of the pond by even moderate winds. The resulting heterogeneous distribution of seaweed further reduced yields--during the day, part of the pond was overcrowded with seaweed, causing much self-shading, while the rest of the pond was empty; thus, light energy, the ultimate limiting factor for seaweed growth, was squandered in the system. Also, at night, the dense patches of seaweeds became quite anaerobic. These problems could be alleviated by applying low levels of aeration to the ponds, specifically, enough aeration to circulate water around the seaweed without moving the plants themselves. In so doing, thermal stratification was eliminated, diatoms and other potential fouling organisms were more readily washed out of the pond, the distribution of Gracilaria within the pond was fairly homogeneous, and anaerobic conditions were avoided. Consequently, yields of Gracilaria in such ponds were approximately twice that of completely unaerated ponds. While this is a considerable improvement, these yields were still only about half of the energy-intensive mode of cultivation. While actual net energy balances have not yet been determined, this type of cultivation ("bottom culture" with minimum aeration) may be a good compromise between the two extremes, especially if aeration need not be applied continuously (e.g., only summer days).

The beneficial effects of aeration for seaweeds can be attributed to the following: (1) it increases photosynthetic efficiency, by rotating the seaweeds in such a way that they are able to maximize the absorbance of light rather than having a high amount of self-shading; (2) it increases nutrient uptake rates, by reducing diffusion boundary layers; (3) it increases the availability of metabolic gases (carbon dioxide, oxygen), both by reducing diffusion boundary layers and direct enhancement from the airline; and (4) it flushes out competing algal cells and spores, thereby reducing the epiphyte problem. While the effects of aeration are clearly beneficial to seaweeds being cultivated in land-based systems, it appears that its requirement is partly an artifact of the culture configuration; seaweeds in situ derive the same benefits as above from water movement (i.e., currents).

"Bottom culture" was also studied, on what may be considered a pilot scale, in a 0.1-hectare (0.25-acre) pond (Figure 4.5). This pond was twice stocked with several tons of Gracilaria. Each time cultures were sustained for only 6 months, during the cooler months of the year. Mean productivity was ca. 7 g dry weight $\cdot m^{-2} \cdot day^{-1}$. In both years, growth stopped with the advent of warm summer temperatures. No aeration was employed in this pond. Serious problems were also encountered with grazing by amphipods. At present, no further work with this pond is planned. Research is concentrated on minimizing the amount of aeration and seawater flow required to grow Gracilaria and is being conducted in tanks.

Prospects

Clearly, there is a considerable amount of data that indicates that at least one seaweed, Gracilaria tikvahiae, has the potential to be an energy crop in a mariculture system. In addition, there are several other species under study in Florida that show promise. All of these seaweeds are readily digestible, with favorable methane production characteristics. Furthermore, with the utilization of digester residues as a replacement for conventional fertilizer and proper nutrient management, the problem of providing a relatively inexpensive fertilizer to a seaweed farm appears solvable.

The major limitation of this research is that it is land based; almost certainly, such a system will not have large-scale application for the purpose of bioconversion. Although it is possible that some small-scale applications are feasible if they are tied to other products/services (e.g., sewage treatment, polyculture systems, phycocolloid production), any significant energy farm will be located in open water. Thus, in order to test this whole concept, experimental seaweed farms will have to be deployed in situ.

While such a deployment is not immediately planned for the Florida project, it remains a long-term goal. The design of such a farm needs to be planned with considerable input from both biologists and engineers. It is important that the biology of the species involved is understood as fully as possible, especially in areas of environmental regulation of growth and reproduction, selection of fast-growing strains, and defining nutrient and harvesting strategies. Studies of possible locations for seaweed farms need to be made, with an emphasis on selecting a site that is most conducive to seaweed growth yet has minimal impact on the local environment and on other users of this resource. Given the biological and site constraints, engineers need to design appropriate structures that will survive the harshness of the ocean environment and yet be harmonious with the plants under cultivation. A well-engineered structure has no value if it does not provide a favorable environment for seaweed growth. Forums between biologists and engineers such as this workshop in New York are needed to form the symbiosis of biology and technology that will be required for the successful development of commercial seaweed farms.

FIGURE 4.5 A 0.1-hectare (0.25-acre) pond used as a demonstration for nonintensive cultivation of Gracilaria (This PVC-lined pond had walls made of concrete blocks and a sand bottom.)

Whether or not energy farming will be viable in the foreseeable future is unknown. A rational decision can only be made after considerable experimentation and the development of a pilot-scale seaweed farm in situ. The uncertainty of fossil fuel reserves, including their costs and continued availability, prevent any meaningful economic projection at this time. At present, it appears that there is enough potential in seaweeds to serve as an alternative source of energy to merit further study. If successful, marine energy farms will help fulfill one of man's oldest dreams: to farm and harvest the sea.

Acknowledgements

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