**Chapter** 4

# UNCONVENTIONAL BIOMASS PRODUCTION

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TABLES



FIGURE

# Chapter 4
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## Introduction

A number of unconventional approaches to biomass energy production have been proposed. Several nontraditional crops that produce vegetable oils, hydrocarbons, and other chemicals or cellulosic material are under investigation. Both freshwater and saltwater plants are being considered, and various other approaches to biomass fuel production are being examined. A common feature to all of these approaches is that the full potential of individual plants proposed as fuel-producers cannot be fully assessed without further R&D. A description of some general plant characteristics, however, can aid in comparing the various possible types of energy crops.

The general aspects of farming, plant growth, and the efficiency of photosynthesis are considered in chapter 3. Since future crop yields will depend on these factors and on the development of hybrids for energy production, the possibilities for genetic improvements are considered here. Following this, crop yields and various unconventional bioenergy crops and approaches to farming them are discussed.

## Genetics

There are two major areas of genetics. The first, which plant breeders have used most effectively to date is the classical Mendelian approach (introduced by Gregor Mendel in the 19th century). It involves selecting and cross-breeding those plants with desired characteristics (e.g., biomass yield, grain yield, pest resistance). The process is continued through each succeeding generation until a hybrid, or particularly favorable strain, is isolated. Strains with unique and desirable properties are often crossbred to produce hybrids that outperform the parents. Hybrid corn is an example. This technique is limited, however, by the variability of characteristics that exist naturally in plants or mutations that occur spontaneously during breeding. One can isolate the best, but one cannot produce better than nature provides.

The second approach to genetics, molecular genetics, is a recent development that involves manipulating the genetic code more or less directly. Three types of potential advances from molecular genetics can be distinguished: 1 ) improvements in the efficiency or rate of biological conversion processes (e.g., fermentation, anaerobic digestion), 2) introducing specific characteristics into specialized cells such as the ability to produce insulin,[1] and 3) improvements in photosynthetic efficiency, plant growth, and crop yields. The complexity of the tasks increases greatly as one goes from 1) to 3), as described below.

The first type involves subjecting single cells to chemicals or radiation that cause mutations in the cells' genes. The way these mutations occur is not well understood and the effects are generally unpredictable. The result is to increase the diversity of cell types over what occurs naturally; and in favorable cases one may produce a cell that performs a particular function "better" than naturally occurring cells. This method has been applied successfully to the production of antibiotics, in biological conversion processes,[2] and in increasing the tolerance of plants to certain diseases; but it is generally a "hit and miss" proposition.

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[1] A Elrich, et al , Science, VOl 196, p. 1313, 1977

[2] For example, see G H E inert and R. Katzen, "Chemicals From Biomass by Improved Enzyme Technology, " presented at the *Biomass as a Non-Fossil Fuel Source,* ACS/CSJ Joint Chemical Congress, Honolulu, Hawaii, April 1979

The second type involves identifying the genes responsible for a particular function in one cell and transferring these genes to another cell. This transfer does not always require a detailed knowledge of how the gene produces the desired characteristic. One can draw from the pool of naturally occurring characteristics, but the conceptual link between the gene and the characteristic must be relatively direct.

The third type probably would involve altering a complex set of interdependent processes in the plant. Although some plant physiologists believe that some improvements in photosynthetic yield can be achieved by suppressing processes like photorespiration (a type of plant respiration that occurs only in the presence of light), this belief is highly controversial among specialists in the field. It is generally believed that the processes involved in plant growth and photosynthesis and their relation to specific genes are too subtle and poorly understood at present to know what biochemical processes should or can be altered to improve plant growth and crop yields.

Some additional near- to mid-term advances are likely in the area of biological conversion processes and with gene transfers in the area of synthesizing high-value chemicals, like insulin, that would be either impractical or impossible to synthesize by other means. The complexity of plant growth and photosynthetic efficiency, however, reduces the chances of improving ‘these characteristics in plants through molecular genetics in the near future. Although the possibility cannot be precluded that a scientist will alter a crucial process in plant growth despite the lack of knowledge, there are few grounds for predicting that this will occur before the fundamental biochemical processes involved in plant growth and photosynthesis and the way that environmental factors limit them are better understood. There is a great deal of controversy surrounding this subject, but most arguments— both pro and con– are based on intuition rather than demonstrated fact.

## Crop Yields

Current knowledge and theories of plant growth do not enable one to predict the crop yields that can be achieved with unconventional crops. Nevertheless, because of the importance of biomass yields in determining the economics of production, it is important to have an idea of the approximate magnitude of the yields of various options that may be possible.

To this end, corn – a highly successful example of crop development– is used as the basis for these estimates. Corn has the highest photosynthetic efficiency of any plant cultivated over large areas of the United States. As discussed in chapter 3, an optimistic estimate for average corn grain yields would be about 140 bu/acre (3.9 tons of grain/acre) by 2000. Many farmers routinely exceed this yield, as do experimental plot yields. This number, however, is quite optimistic for average yields from cultivation on millions of acres of average U.S. cropland. Furthermore, since cropland that could be devoted to energy crops is generally of poorer quality than average cropland, using this as a basis for estimates may be overstating the potential.

A yield of 140 bu/acre for corn corresponds to a photosynthetic efficiency of about 1.2 percent over its 120-day growing season. Perennial crops, however, probably will have somewhat lower efficiencies during the cold weather at the beginning and end of their growing seasons. Consequently, it is assumed that perennials can achieve an average photosynthetic efficiency of 1.0 percent. With these assumptions, and the others stated below, the following yields may be possible.

- Dry matter yield.— With an 8-month growing season in the Midwest, biomass production could yield 15 ton/acre-yr of dry plant matter. For the Gulf Coast (12-month growing season), the yields could reach 21 ton/acre-yr.

- Grain yields.– Based on corn yields, average grain production from some plants could yield 3.9 ton/acre-yr.
- Sugar yields.– Good sugar crops are 40- to 45-percent sugar on a dry weight basis (e.g., sugarcane, sweet sorghum). In the Midwest, sugar crops will probably be annual crops leading to possible yields of 4 tons of sugar/acre-yr. Along the Gulf Coast, there is a longer season. Current average sugar yields are 4 ton/acre-yr. As with corn, the yields could conceivably be increased by 40 percent to 5.6 ton/acre-yr.
- Aquatic plant yields.– Estimates for water-based plants are more difficult to derive, since there is considerably less experience and applicable information. Water plants have a continuous supply of water and are never water stressed. For maximum productivity, nutrients and carbon dioxide (CO,) (for submerged plants) would be added to the water and could be available continuously at near-optimum levels. The water would prevent rapid changes in temperature. All of these factors favor plant growth, and if other problems with cultivating aquatic plants can be solved, yields may be quite high (see "Aquiculture" and "Mariculture"). Nevertheless the uncertainty is too great to make a meaningful comparison with the land-based plants. As with other plants, experimental yields will probably not be representative of commercially achievable yields.
- Yields in greenhouses.– Yields in greenhouses are also very uncertain, due to a lack of sufficient data and potential problems such as fungal attacks on plants, root rot, and other problems with extremely humid environments. If these and other problems are solved, then crop yields approaching those estimated for the milder climates may be achieved.
- Vegetable **oil or hydrocarbon yields. –** In addition to solid material, plant biomass includes oils. New seed oil crops typically contain 10-to 15-percent vegetable oil, and in sunflowers the oil comprises up to 50 percent of the seed weight.[3] Assuming that plants which are 50-percent seed contain seeds that are 50-percent oil, the oil content may reach 25 percent of the total plant weight.

  Assuming the biochemical reaction producing the oil is 75 percent as efficient as that which produces cellulose, then for 1-percent photosynthetic efficiency the oil production would be 16 bbl/acre-yr for a plant that is 25-percent oil. For an oil-producing reaction that is 50 percent as efficient as the reaction that results in cellulose, the yield would be 12 bbl/acre-yr.

  Plant material stored as hydrocarbons has also been proposed as a source of liquid fuels. Eucalyptus trees and milkweed, for example, contain up to 12-percent hydrocarbons. Assuming that this content could be doubled, the same yields as for oil crops would apply.
- Arid land crop yields.– Another important and sometimes limiting factor in biomass production is water. Generally plants will grow well without irrigation in areas of the United States where the rainfall is 20 to 30 inches or more. For high biomass-producing crops in relatively humid climates (like the Midwest), the minimum water necessary for plant growth in open fields is about 200 weights of water for 1 weight of plant growth. There has been interest, however, in plants that can grow under more arid conditions. In desert regions with very low humidities, requirements are more typically 1,000 weights or more of water per 1 weight of plant growth. (Some plants survive for long periods of time without water, but they do not grow. ) Assuming the 1,000:1 figure, the maximum plant growth that could be expected in a region with 5 inches of rain and no irrigation is 0.6 ton/acre-yr. Oil yields would be correspondingly low or less than 1 bbl/acre-yr.
- **Natural systems. —** In addition to agriculture, there has also been interest in using biomass produced by plants in their natural state. In

[3] D. Gilpin, S Schwarzkopf, j. Norlyn, and R. M. Sachs, "Energy From Agriculture– Unconventional Crops," University of California at Davis, contractor report to OTA, March 1979.

the natural state, most of the nutrients are returned to the soil as the leaves drop off or the plant dies and decays. Harvesting of some of the biomass removes some of the nutrients, although animal excretions and the natural breakdown of minerals in the soil provide new nutrients. The rate of replenishment varies considerably from area to area, however, and this determines the rate that biomass could be removed from natural systems without depleting the soil.

The potential growth of biomass in continuously harvested natural systems has apparently not been studied. (Forestlands are an exception, although the emphasis there has been on the production of commercial timber rather than on total biomass.) It has been estimated, however, that some natural wetlands produce more than 5 ton/acre-yr of growth, and that 11.4 million acres of rangeland produce more than **2.5** ton/acre-yr.[4] While no estimates for the production of natural systems can be given, they will certainly permit less harvestable growth than intensively managed systems on comparable soil.

In evaluating the possible yields for biomass production, all of the yield estimates here should be treated with extreme caution. None of these yields has been achieved under large-scale cultivation (i. e., mill ions of acres) and the estimates for oil-producing plants are particularly uncertain. Experimental plot yields, on the other hand, exceed these yields for many plants.

Moreover, several factors operate to prevent average yields from reaching these estimates for large-scale production of biomass. The most important are the less than ideal soils of most potential cropland and the fundamental limitations of plant genetics with current knowledge. On the other hand, management practices improve with time and increased costs for farm products may eventually justify more extensive management practices, such as additional fertilizers, extensive soil treatment, and expanded irrigation. *

Each plant is, to a certain extent, a special case. The experience with large-scale cultivation of crops is limited to a few food, animal feed, fiber, and chemical crops. Many plant scientists argue that maximum food production implies maximum biomass production. However, few genetic and development programs have been specifically aimed at maximizing biomss output for crops suitable to large areas of the United States.

These contradictory factors mean that the potential for biomass production is uncertain. And the uncertainty of the estimated yields is judged to be at least 50 percent. Consequently, the yields could easily vary anywhere from 0.5 to 1.5 times the numbers reported.

It is highly unlikely, however, that average U.S. yields for corn will exceed 140 bu/acre before 2000, and perhaps not after then. And corn is one of the best biomass producers for the U.S. climate known to man. Consequently, the numbers reported represent reasonable limits in terms of what is known today. Any large-scale production of biomass that significantly exceeds these yields would represent a major breakthrough. Estimates that are based on projected yields significantly exceeding those in table 36 either: 1) are limited to the relatively small acreage of the best U.S. soils,

**Table 36.–Optimistic Future Average Crop Yields for Plants Under Large-Scale Production[a]**

| Region | Product | Plausible average yield[b] (ton/acre-yr) |
|---|---|---|
| Midwest | Dry plant matter | 15 |
| Gulf Coast | Dry plant matter | 21 |
| Midwest | Sugar | 4 |
| Gulf Coast | Sugar | 5.6 |
| Midwest | Grain | 3.9 |
| Midwest | Vegetable oil or hydrocarbons | 1.7- 2.2 (12 -16 bbl) |
| Area with 5 inches rainfall per year and no irrigation. . . . . . . . . . . | Dry plant matter | 0.6 |
| Area with 5 inches rainfall per year and no irrigation. . . . . . . . . | Vegetable oil or hydrocarbons | 0.1 (0.7 bbl) |

[a]In this context, large-scale production means cultivation on millions of acres of average U S cropland

[b]Estimated uncertainty ± 50 percent

SOURCE Office of Technology Assessment

*"An Assessment of the Forest and Range Land Situation in the United States, " Forest Service, U S Department of Agriculture, review draft, 1979

• It is unclear whether Irrigation will be socially acceptable for energy production or whether the necessary water will be available

2) rely on technologies that do not now exist and are not anticipated in the near future, or **3)** require extensive management practices that are not likely to be cost effective unless there are dramatic increases in the prices for farm commodities,

## Unconventional Land= Based Crops

A large number of plants not now grown commercially in the United States are potentially energy crop candidates. Some are relatively high biomass producers and others could provide a source of a variety of chemicals that could be used as fuel or as chemical feedstocks. Unlike conventional crops, these crops could be considered primarily for their value as fuel. (However, see also ch. 10.)

Assessing and comparing potential yields for the unconventional crops from literature reports are extremely difficult, since these reports often do not give dry yields, the plants often are grown on unspecified soils and in different climates, and the water and nutrient inputs often are not given. Furthermore, it is a well-known fact that experimental plot yields are larger than those achieved with large-scale commercial cultivation. For these reasons, the yields reported below should be treated with extreme skepticism. Comparative cultivation experiments and crop development will be needed in the various regions and soil types in order to establish which crops are, in fact, suitable or superior for bioenergy production. In broad terms, the categories include: 1 ) lignocellulose, 2) vegetable oil and hydrocarbon, and **3)** starch and sugar crops. Each group is considered briefly below, and an incomplete list of candidate bioenergy crops is shown in table 37.

**Table 37.–incomplete List of Candidate Unconventional Bioenergy Crops[a]**

| | |
|---|---|
| ***Lignocellulose crops*** | |
| American sycamore | Red alder |
| Bermuda grass | Russian thistle |
| Big bluestem | Salt cedar |
| Gum tree (eucalyptus) | Sudan grass |
| Kenaf | Switchgrass |
| Napier grass | Tamarix |
| Poplar | Tall fescue |
| Reed canarygrass | |
| ***Vegetable oil and hydrocarbon crops*** | |
| Crambe | Milkweed |
| Guayule | Mole plant (euphorbia) |
| Gum tree (eucalyptus) | Safflower |
| Jojoba | Turnip rape |
| ***Starch and sugar crops*** | |
| Buffalo gourd | Kudzu vine |
| Chicory | Sweet potatoes |
| Fodderbeets | Sweet sorghum |
| Jerusalem artichoke | |

[a]Some of these crops are produced commercially today on a limited scale, but not for their energy value

SOURCE D Gilpin, S Schwarzkopf, J Norlyn, and R M Sachs, "Energy From Agriculture—Unconventional Crops, " University of California at Davis, contractor report to OTA. March 1979, S Barber, et al , "The Potential of Producing Energy From Agriculture, " Purdue University, contractor report to OTA, and J S Bethel, et al , "Energy From Wood, " University of Washington, contractor report to OTA

### Lignocellulose Crops

Various species of hardwood trees (e.g., red alder, hybrid poplar) and grasses (e. g., kenaf, Bermuda grass, Sudan grass, big bluestem) are candidates for crops grown primarily for their high dry matter yields (lignocellulose crops).

Theoretically, one would expect perennial crops (like trees and some grasses) to be superior biomass producers to annual crops, since the perennials develop their leaf cover sooner in the spring and do not need to generate a complete root system each year. One would also expect grasses to be superior biomass producers to trees because of their larger leaf area per acre of ground, * but considerable attention has been focused on trees, since the technologies for using wood are more advanced. Experimental plot yields for short-rotation trees are **5** to 20 ton/acre-yr.[5] Yields of as much as 10 to 15 ton/acre-yr may be achieved for large-scale cultivation of some of these crops in good soil (see "Crop Yields" section) but are likely to be 6 to 10 ton/acre-yr in poorer soils. Since farming costs could be similar to corn, this could result in biomass for about $20 to $50/ton.

"Thereby reducing light saturation, which lowers photosynthetic efficiency

[5]Gilpin, et al , op cit

The trees would typically be grown for 6 to 10 years before harvest, while the grasses would be harvested several times a year. With fewer harvests for the trees, each harvest could be considerably more expensive and consume more energy than grass harvests without unfavorably affecting the economics or net energy balance. However, tree crops would require that the land be dedicated to the crop for several years and converting the land to other uses would be more expensive, due to the developed root system. Also, if a disease were to kill the crop, reestablishing a tree crop would be more expensive. Both trees and some grasses are perennial crops and, consequently, would require fewer herbicides and would reduce erosion on erosion-prone land as compared to annual crops. Grasses, having a more complete soil cover, would be more effective in preventing soil erosion.

## Vegetable Oil and Hydrocarbon Crops

Vegetable oils and hydrocarbons are chemically quite different from petroleum oil. Nevertheless, most vegetable oils and hydrocarbons can be burned and might prove to be a substitute for fuel oils or, with refining, for other liquid fuels. However, appropriate methods for extracting the oil from the plant and for refining the oil are not well defined at present.

A number of edible and inedible vegetable oils are currently produced commercially.[6] In addition, unconventional crops such as gum tree (eucalyptus), mole plant (euphorbias), guayule, milkweed, and others could be used as vegetable oil and hydrocarbon crops (or for natural rubber). The maximum current yields of commercial oil plants are in the range of 100 to 200 gal/acre (2.5 to 5 bbl) of vegetable oil and/or hydrocarbon. Reports of 10 bbl/acre (420 gal) for euphorbia were apparently based on measurements of plants on the edge of a field, which were 1.5 times larger than interior plants. Also, in some cases, 16 months of growth were used to obtain "annual" yields, [7]

The theory of hydrocarbon and vegetable oil production in plants is not adequate to predict possible yields. However, from other considerations ("Crop Yields" section) there may be a significant potential for improvement. Furthermore, some of these crops (e. g., guayule) may do well on land where there is slightly less water available than would be needed for conventional crops. [8] Others, such as milkweed, can be grown with brackish water which would be unusable for conventional food crops. [9] Comparative tests under comparable conditions will be necessary to determine which plants show the most promise for energy production.

Because of the higher prices that can be paid for chemicals and natural rubber, the fact that these products are economic in some cases does not in any way imply that energy production from vegetable oil and hydrocarbon plants will be economic. Some proponents of hydrocarbon plant development have failed to distinguish between these end uses, a fact that has led to considerable confusion and misunderstanding.

Critics of the development of vegetable oil and hydrocarbon plants for energy argue that the production of these products by plants is considerably less efficient than normal chemical synthesis (e.g., to produce methanol or ethanol from dry plant matter). They also point out that the plant often must be subjected to stress (drought or cold) to produce hydrocarbons, and this lowers the photosynthetic efficiency. Consequently, they contend that the high yields being predicted (e.g., 26 bbl/acre[10]), will not be achieved in the foreseeable future.

At present, however, the theory of and experience with these types of plants is inadequate to make a meaningful judgment.

[6] *Agricultural Statistics* (Washington, D. C.: U.S. Department of Agriculture, 1978).

[7] Gilpin, et al., op. cit.

[8] K. E. Foster, et al., "A Sociotechnical Survey of Guayule Rubber Commercialization, " Office of Arid Land Studies, University of Arizona, Tucson, Ariz., prepared for the National Science Foundation under grant PRA 78-11632, April 1979.

[9] W. H, Bollinger, Plant Resources Institute, Salt Lake City, Utah, private communication, 1980.

[10] J D. Johnson and C. W Hinman, "Oils and Rubber From Arid Land Plants," Science, VOl 280, p. 460,1980.

## Starch and Sugar Crops

Starch and sugar crops are of interest since they can be used to produce ethanol with commercial technology. Current corn grain yields can be processed into about 260 gal of ethanol per acre cultivated and sugar beets (usually irrigated) can produce about 350 gal/acre, on the average. Irrigated corn, however, would match the sugar beet yield. Furthermore, experimental plot yields for corn produce about 430 gal/acre-yr and record yields exceed 850 gal/acre. In addition to the conventional starch and sugar crops, several other plants have been proposed as ethanol feedstocks including sweet sorghum and Jerusalem artichokes.

Experimental plot yields for sweet sorghum could be processed into about 400 gal of ethanol per acre year. Furthermore, this crop produces large quantities of residues that are suitable for use as a distillery boiler fuel. The yields for large-scale cultivation, however, are still unknown, and concern has been expressed that droughts during parts of the growing season could reduce sugar yields significantly.

Experimental plot yields for Jerusalem artichokes have produced about twice the sugar yields of sugar beets under the same growing conditions in Canada. Whether this result can be applied to other regions is not known. Jerusalem artichoke, like the sugar beet, is a root crop. Harvesting it, therefore, causes extensive soil disturbance which increases the chances of soil erosion.

[11] Gilpin, et al , op cit

Other plants such as fodderbeets, sweet potatoes, and Kudzu vine are also potential ethanol crops. Comparative studies are necessary to determine which crops are best in each soil type and region of the United States. As was emphasized in chapter 3, this comparison should include the displacement of other crops that can be achieved by the byproducts of ethanol production. This factor tends to favor grains, but other possibilities do exist. [12]

## General Aspects

Intensive cultivation of unconventional crops may cost about the same as corn, or $200 to $400/acre-yr in the Midwest. These costs, together with the yield estimates given above, allow an approximate comparison of the costs for various unconventional land crops, which is shown in table 38. Since the exact cultivation needs have not been established, a more detailed comparison is not warranted at this time. These costs estimates, however, show that unconventional crops may be economic energy sources. The ultimate costs will depend to a large extent on the yields that can actually be attained with intensive management and the success of developing crops that can be cultivated on land that is poorly suited to food production.

The crops that are now grown in U.S. agriculture were selected for properties that are unre-

[12] R Carlson, B Commoner, D Freedman, and R Scott, "Interim Report on Possible Energy Production Alternatives in Crop-Livestock Agriculture," Center for the Biology of Natural Systems, Washington University, St Louis, Mo , Jan. 4, 1979

**Table 38.-Optimistic Cost Estimates for Unconventional Crops[a]**

| Product | Ultimate fuel | Yield of ultimate fuel per acre cultivated | | Contribution of feedstock to fuel cost[b] | |
|---|---|---|---|---|---|
| Dry plant matter | Combustible dry matter | 15 ton | (195 $10^6$ Btu) | $20/ton | ($1 .53/ $10^6$ Btu) |
| Dry plant matter | Methanol | 1,500 gal[c] | (95 $10^6$ Btu) | $0.20/gal | ($3.15/$10^6$ Btu) |
| Dry plant matter | Ethanol | 1,300 gal[d] | (107 $10^6$ Btu) | $0.23/gal | ($2.80/$10^6$ Btu) |
| Grain | Ethanol | 364 gal | (31 $10^6$ Btu) | $0.82/gal[e] | ($9.89/$10^6$ Btu) |
| Sugar (Midwest) | Ethanol | 540 gal | (46 $10^6$ Btu) | $0.56/gal | ($6.50/$10^6$ Btu) |
| Vegetable oil or hydrocarbon crop | Vegetable oil or hydrocarbon | 504-670 gal | (63-84 $10^6$ Btu) | $0.45-$0.60/gal | ($3.60-$4.70/$10^6$ Btu) |

[a] Based on yields in table 36
[b] Assuming $300/acre cultivation and harvest costs, does not include conversion costs
[c] Assuming yields of 100 gal/ton of biomass
[d] Assumes yields of 85 gal/ton of biomass
[e] Does not include by product credit for distillers' grain If byproduct Credits Included, the situation becomes more complex as described in ch 3, in the section on "Energy Potential From Conventional Crops" The byproduct credit would reduce the costs by roughly one-third

SOURCE Office of Technology Assessment

lated to energy. It 'is likely, therefore, that other plants will prove to be superior to conventional crops for energy production. Beyond the yields of these crops, properties like insensitivity to poor soils, multiple products (e.g., vegetable oil, sugar, and/or starch plus dry plant herbage) displacement of other crops with crop byproducts (e. g., corn distillery byproduct), the energy requirements to cultivate the crop, the energy needed to convert it into a form that can be stored (especially for sugar and starch crops), tolerance to adverse weather conditions, ease of harvesting and conversion to fuels, and the environmental impacts of growing the crop are all factors that should be considered when choosing energy crops. In short, analyses of the net premium fuels displacement per new acre cultivated (as was done for various conventional crops in ch. 3), the cost, and the environmental impacts are needed to compare the options. Due to the diversity of U.S. soils and climates, different crops will no doubt prove to be superior in different regions. Many of the possible unconventional crops appear promising, but the ultimate decisions will have to come from experiment and experience. (Typically it requires 10 to 20 years to develop a new crop.) Nevertheless, some general aspects of plants can be expected to hold for the unconventional crops.

Root plants (e.g., Jerusalem artichokes, sugar beets, potatoes, sweet potatoes) will cause the most soil erosion. Annual crops will be next, and perennial grasses can virtually eliminate soil erosion.

Soil structure and climate are dominant features controlling plant growth and these can be controlled by man only to a very limited extent. Plants vary as to their sensitivity to these factors and to the presence of nutrient solubilizing mycorrhizae in the soil,[13] but yields will decrease on going to poor soils and climates. Crops grown in arid climates without irrigation or an underground supply of water will give low yields; and social resistance to using water for energy production in the West could preclude irrigated energy crops, although some people maintain that this resistance will not extend to crops.

Finally, any crop that grows very well in an area without inputs from man is likely to spread and become a weed problem.

[13] J. M. Trappe and R. D. Fogel, "Ecosystematic Functions of Mycorrhizae," reproduced from *Range Sci. Dep Sci.*, series No, 26, Colorado State University, Fort Collins, by U S. Department of Agriculture.

## Aquiculture

Aquatic plants comprise a diversity of types, from the single-celled microalgae to the large marsh plants such as cattails and even some trees such as mangroves. Considerable interest exists in the cultivation of many different aquatic plants as energy sources. Examples are the production of cattails in the extensive marshes of Minnesota, the cultivation of water hyacinths on wastewaters in Mississippi or Florida, and the establishment in the Southwest of large-scale brackish water ponds for microalgal production of chemical feedstocks. OTA has prepared a detailed review of the potential of fresh and brackish water aquiculture systems for energy production.[14] The general conclusions were that the production of aquatic biomass has near-term potential in conjunction with wastewater treatment and high-value chemicals production. However, the development of large-scale "energy farms" based on aquatic plants is less promising at present, from both an economic or a resource potential viewpoint. Nevertheless, aquatic plants have certain unique attributes, the key one being high achievable biomass production rates

[14] J. Benemann, "Energy From Aquiculture Biomass Systems: Fresh and Brackish Water Aquatic Plants, " Ecoenergetics, Inc , Vacaville, Cal if , contractor report to OTA, April 1979

which justify continued research on a variety of approaches to the development of aquaculture energy systems.

Higher aquatic plants growing in or on water are not, as a rule, water limited — a common and natural state of land plants. Thus, they are capable of higher rates of photosynthesis by keeping their stomata (plant pores) open longer than land plants* thereby, increasing $CO_2$ absorption. Thus, plants such as the water hyacinth and cattails exhibit very high rates of biomass production, often exceeding 20 ton/acre-yr. This high productivity is achieved, however, by evaporation of large amounts of water, exceeding by a factor of two to four that transpired by land plants. Thus, cultivation of water plants can only be considered where ample supplies of water exist or where the systems are covered, such as in greenhouse structures.

Some aquatic plants, however, do not exhibit very high biomass production rates. For example, the common duckweed (Lemna sp.) covers a water surface very rapidly; however, once this is achieved, further growth in the vertical direction is minimal. Thus, the productivity of such plants is relatively low when compared to plants such as water hyacinths and marsh plants which extend their shoots up to several feet into the air. Indeed, the high leaf area index (the ratio of the total leaf area to the ground area), sometimes exceeding 10, of these plants, accounts, along with high transpiration rates, for their high productivity.

Another type of aquatic plant that exhibits relatively low productivity is the salt marsh plant Spartina, which does not produce as much biomass as its freshwater analogues such as Typha (cattails) or Phragmites (bullrush). The high salt concentration tolerated by Spartina also results in a decrease of transpiration and productivity. Even among the freshwater marsh plants, biomass productivities are limited by both the seasonal growth patterns of the plants in the temperate climate of the United States and the large fraction of biomass present in the root system which may be difficult to recover. The submerged aquatic plants such as the notorious weed Hydrilla, are also not remarkable for their biomass productivity. Adaptation to the light-poor environment frequently encountered below the water surface has made these plants poor performers at the high light intensities that would be the norm in a biomass production system.

Finally, the case of the microalgae must be considered. Being completely submerged they also are subject to significant light losses by reflection from the water surface (at low solar angles) and scattering of light. More importantly, in a mixed algal pond, the cells near the surface tend to absorb more light than they can use in photosynthesis, resulting in a significant waste of solar energy. However, if a microalgal production system is designed to enhance mixing, then rapid adjustment by the algae occurs, thus overcoming, to some extent, the handicap inherent in inefficient sunlight absorption by microalgal cultures. Therefore, microalgal cultures could be considered in a biomass production system. A review of the rather sparse productivity data available, together with consideration of the basic photosynthetic processes involved, suggest that green algae and diatoms are promising candidates for mass cultivation, probably with achievable production rates of at least 20 ton/acre-yr, with blue-green algae, particularly the nitrogen-fixing species, considerably less productive.

It must be noted that the available data on aquatic plant productivity are too limited to allow confident extrapolations to large-scale systems. Most available data are based on natural systems where nutrient limitations may have depressed productivity or small-scale, short-term experimental systems where edge effects and other errors may have increased productivity. Actual yearly biomass production rates in sufficiently large-scale managed systems must be considered uncertain for any aquatic plant, particularly if factors such as stand establishment, pest control, optimal fertilizer supply, and harvesting strategy are concerned. Thus, to a considerable extent, assess-

'Somata are closed to conserve water, but this also prevents carbon dioxide from entering the leaf

''Ibid

**ing the potential of aquatic plants in energy farming, like that of other unconventional crops, involves** more uncertainty than specific detailed knowledge.

Among the uncertainties are the economics of the production system, including the harvesting of the plants. Detailed economic analyses are not available; those that have been carried out are based on too many optimistic assumptions to be credible or useful. Of course each type of plant will require a different cultivation and harvesting system. However, in all cases, these appear to be significantly more expensive per acre in both capital and operations than the costs of terrestrial plants. This increased cost per acre can only be justified by an increased biomass production rate or a specific, higher valued product. Because the productivity and economics of aquatic plants are, to a large degree, unknown, the potential for aquatic plant biomass energy farming is in doubt.

One approach to improve the economics of such systems is to combine the biomass energy system with a wastewater treatment function. As aquatic plants are in intimate contact with water, they can perform a number of very important waste treatment functions—oxygen production (by microalgae) which allows bacterial breakdown of wastes, settling and filtration of suspended solids, uptake of organics and heavy metals, and, perhaps most importantly, uptake of the key nutrients that cause pollution. The relatively high concentrations of nitrogen and phosphorus in aquatic plants (e.g., about 10 percent nitrogen and 1 percent phosphorus in microalgae and 3 percent nitrogen and 0.3 percent phosphorus in water hyacinths), makes these plants particularly useful in nutrient removal from wastewaters. Research in wastewater aquiculture is well advanced, although some critical problems remain to be elucidated, and several large demonstration projects are being initiated throughout the United States. For example, water hyacinths are being used in wastewater treatment plants in Coral Gables and Walt Disney World, Fla., in projects which involve fuel recovery by anaerobic digestion of the biomass. Microalgal ponds have been used for several decades in many wastewater treatment systems throughout the United States. More stringent water quality standards are resulting in a need for better microalgal harvesting technology and presenting an opportunity for fuel recovery from the harvested microalgae. Several projects throughout the United States have demonstrated the beneficial effects of marsh plants in wastewater. treatment. In all cases, wastewater aquiculture appears more economical and less energy intensive than conventional technologies.[16] However, the total potential impact of wastewater aquiculture on U.S. energy supplies, even when making favorable market penetration assumptions, is minimal — about 0.05 to 0.10 Quad/yr.[17]

For aquatic plants to make a more significant contribution to U.S. energy resources, other types of aquatic biomass energy systems must be developed. One alternative is the conversion to fuel of aquatic plants already harvested from natural, unmanaged stands. Examples are water hyacinth weeds removed by mechanical harvesters from channels in Florida and other southern States and cattails or bullrushes cut periodically in natural marshes in Minnesota or South Carolina to improve wildfowl habitats. However, the infrequent occurrence of such harvests, the small biomass quantities involved, and transportation difficulties make energy recovery from such sources essentially impractical. The conversion, if practiced, of natural marsh systems to large-scale managed (planted, fertilized, harvested) plantations will present significant ecological problems and, even if these are ameliorated or overcome, opposition by environmental groups. Nonetheless, large areas of marshes do exist in the United States and they, in the long term, may become resources that could be exploited on a multipurpose and sustained yield basis like the national forests. In the near term, however, the technology for aquatic plant biomass energy systems must be developed with presently unused or "margin-

"'Ibid
[17]Ibid
[18]Ibid.

al" land and water resources. In addition, relatively high-value biomass energy products, specifically chemicals and liquid fuels, should be produced by such systems. Examples of such systems include the production of alcohol fuels from cattails (either by hydrolysis of the areal parts or directly from the starches stored in the roots) or the production of hydrocarbon fuels and specialty chemicals from microalgae.

Microalgae are known to produce a variety of useful chemicals. However, the development of such production technology is only just now beginning, and the potential resource base (land, water, nutrients) available for such systems is not yet quantified. Thus, the future contribution to U.S. fuel supplies of aquatic plant biomass energy systems cannot be predicted. However, sufficient possibilities and promise exist to warrant further R&D efforts.

# Mariculture

This section describes problems and opportunities associated with developing future ocean farms which might use the giant kelp (macrocysts) as a future biomass energy source. Other macroalgae have also been proposed as potential marine biomass crops. By examining the possibilities of kelp and also noting other proposals, OTA hopes to illustrate the status of this technology in general, its future potential, the problems involved, and the Federal role in this segment of alternative energy research.

Macroalgae are harvested around the world. About 2 million wet metric tonnes are now cut annually, and estimates are that the total potential worldwide crop is 10 times this much—about 20 million wet tonnes.[19]

In recent decades seaweed cultivation has rapidly become more successful and has substantially added to annual harvest figures. For example, as of 1970 there were 130,000 acres of sea surface under cultivation in Japan, about 25,000 acres in The Peoples Republic of China, and additional acreage in Taiwan, Korea, the Philippines, and elsewhere. None of the current annual world harvest is being used for energy production.

In the United States, where wild seaweed beds have been harvested for many years, the possibility is beginning to be studied of increasing production through ocean farm cultivation techniques. A small test farm has been installed along the California coast.[20]

Large ocean kelp farms could theoretically supply significant quantities of natural gas (methane). Linked to a methane production system, for example, and assuming serious technical problems are solved, a l-million-acre kelp farm could produce enough gas to supply 1 percent of current U.S. gas needs.

It would be no easy matter to farm such vast tracts of ocean. Much still needs to be learned about macroalgae cultivation. But serious research is reducing the areas of ignorance and seaweed may some day become a biomass producer.

Algae are among the simplest and most primitive **of** plants. The larger macroscopic algae are commonly referred to as seaweeds or macroalgae. Large seaweeds are the dominant plant in most shallow coastal waters including those off California and Mexico, where they attach themselves to rocks or some other hard substrate under water.

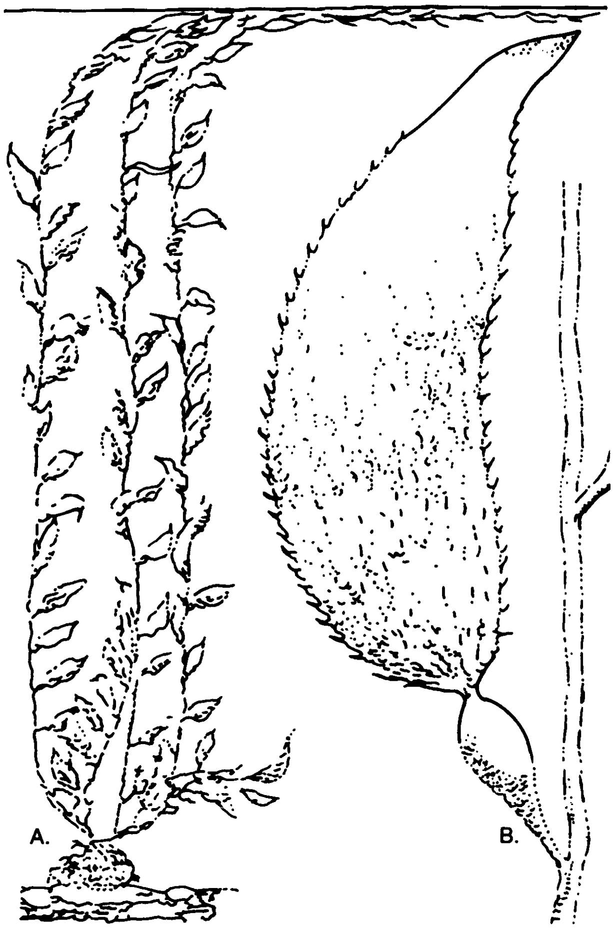
To date, the seaweeds apparently most adaptable to human cultivation are the red and the brown algae. People have eaten red algae varieties for thousands of years, especially in countries such as Japan and China.

[19] G Michanek, Seaweed *Resources of the Ocean,* U.N. Food and Agriculture Organization, Rome, 1975,

[20] A. Flowers, statement before the House of Representatives Committee on Merchant Marines and Fisheries, Subcommittee on Oceanography, p. 18, committee report serial No. 95-4, June *7,1978.*

The brown algae group includes the giant kelp *Macrocystis* (figure 13), already harvested in the United States from wild and semicultivated beds and considered at present as the best candidate for intensive cultivation off California and as a possible fuel producer.[21]

Figure 13.—Macrocystis Pyrifera




(A: 1/64 natural size; B: 1/4 natural size.) The Giant Kelp is shown in the left part of the plate in a natural pose with the long leafy stipes rising to the sea surface from the massive holdfast. On the right is one of the leaf-like fronds showing the gas-filled float bladder at its base and the distinctive teeth along the margin (Anon. 1954).

SOURCE: Velco, Inc.

Kelp may grow in length as much as 2 ft/day or increase its weight by 5 percent per day under optimum conditions. The plants form natural beds up to 3 miles wide and several miles long in southern California. This kelp is now harvested and put to a variety of uses, principally in the food-processing industry. Fuels have never been produced from kelp except in minute quantities as part of research testing.[22]

Unfortunately, there is no consensus among the experts who have made projections as to the potential of ocean energy farms. Their estimated costs vary widely and are based on such very sparse data that they cannot be used to either support or reject ocean farm proposals. Estimates of production rates vary by factors of as much as 100. Better experimental data and more complete biological engineering tests will allow for better estimates in the future. The estimates used here lie approximately in the middle of responsible optimistic and pessimistic projections for a 400,000-hectare (1 million acre) ocean kelp farm:

- average productivity = 20 dry ash free (DAF) tons per acre per year, and
- average annual energy produced = **0.2** Quad (1 percent of U.S. gas consumption of 20 Quads/y r).

Such a system, if built, would provide the equivalent in energy supply of one large LNG-importing plant such as the one located at Cove Point, Md. It would, of course, be a domestic rather than an imported fuel, however.

Experiments are underway into the best laboratory-reared seaweed farms. Eventually, some researchers hope to produce a "pedigreed" kelp bred specifically for high methane production, fast growth, and hardiness.

A key problem faced by potential ocean kelp farmers is to deliver enough nutrients to the plants to fertilize them. This is because, while the deep waters of the ocean contain many necessary nutrients, surface water is often as devoid of nourishment as a desert is

[21] Neushal, et al., "Biomass Production Through the Cultivation of Macroalgae in the Sea," p 100, Neushul Mariculture, Inc, for OTA, Oct 6, 1978

[22] M. Neushal, "The Domestication of the Giant Kelp, *Macrocystis* as a Marine Plant Biomass Producer," presented at the *Marine Biomass of the Pacific Northwest Coast Symposium,* Oregon State University, Mar. 3,1977

devoid of water. One fertilizing technique being tried is artificial upwelling of seawater, which involves pumping nutrient-rich, deep ocean water to the surface to benefit the kelp plants.[23]

Current research on marine plants can be divided into two categories.

The first category, funded by several Federal agencies to a total of about $1 million in 1979, generally includes research projects aimed at a better understanding of marine plants, their cultivation, and potential new uses of the plants.

The other "category" is actually just one project: the Marine Biomass Research Program jointly funded by the Gas Research Institute (GRI) and the Department of Energy (DOE), which has funded over $9 million of directed research as of 1979.

This ongoing marine biomass project includes a test farm off California. The farm began artificial upwelling experiments late in 1978, but was forced to suspend operations in early 1979 due to storm damage. This prototype is meant to provide biological information and research clues needed to operate much larger culture farms. It also aims at experimental work into cultivation of giant kelp on moored structures in the open ocean. The test farm, may lead to the actual operation of a full-scale ocean farm.

There is considerable difficulty at this time in evaluating the appropriateness of the Marine Biomass Research Program because little has been produced. It is important that research results on the cultivation of kelp on ocean farms be reported in a comprehensive way and subjected to critical review if a future large program is to be justified.

Kelp and other seaweeds are potentially a highly productive source of biomass for fuels. Estimates can vary drastically as to what may be possible for future large ocean farms, but OTA's evaluation of a hypothetical ocean kelp farm indicates productiveness could range from a low value of 6 DAF ton/acre-yr to a high value of 30. In comparison, this country's average corn harvest is 6 DAF ton/acre-yr and Hawaiian sugarcane averages 14 DAF ton/acre-yr.

OTA estimates that if about 1 million acres were ever farmed, the gross energy production could amount to 0.2 Quad. This is equal to approximately 1 percent of current U.S. natural gas consumption. These production estimates should be treated with caution since there are no ocean kelp energy farms and nobody has ever planted and harvested a macroalgae energy crop.

Actual gross energy production from such a huge hypothetical ocean kelp plantation has been projected by other researchers to range from 10 times OTA's estimate to only one-tenth that figure. The entire project might simply prove impossible, others caution. Years of experiments will be necessary before any projections can be confirmed.

There is even less data to draw on in estimating net energy possibilities. In a report prepared for DOE by the Dynatech R&D Corp., net energy outputs were estimated to range anywhere from a negative number to about 70 percent of crop energy.[24]

Much of the technology to construct present concepts of open ocean farms is already well known. Similar platforms, structures, and moorings have been built for the offshore oil industry and the existing seaweed industry uses mechanical harvesting techniques.

Less certain areas of ocean farm engineering at present include nutrient distribution, dispersion characteristics of upwelled water, and specific configuration of the structure to which kelp plants will be attached. A major problem for cultivated kelp beds may be to supply an ocean farm with proper nutrients in correct quantities. The extreme difficulties of noting the delicate balance of nutrients found in a natural environment and reproducing this in a cultivated one are well known to researchers.

[24] Dynatech R&D Co , "Cost Analysis of Aquatic Biomass Systems," prepared for the Department of Energy, contract No HCP/ET-400-78/1

Test farms will upwell deep ocean water to supply kelp with proper nutrients. Reservations about this procedure are twofold among skeptics. They worry that deep water could become stagnant under the farms, or that, once upwelled, the water would dilute too rapidly and sink again.

As previously mentioned, this country's major ocean biomass project is jointly supported by CR I and DOE. The project may become the most heavily funded biomass program of the 1980'S, with grants projected to grow to over $50 million yearly by 1983. Plans for this project have been developed mainly by GRI, although regular DOE approval for phases of the project is mandatory.[25]

GRI estimates imply that ocean kelp farming could be a commercially viable project for this country. The Institute's fuel production cost estimates for methane generation from kelp range from $3 to $6/million Btu.

The previously mentioned Dynatech report on fuels from marine biomass comes to a different conclusion. Its estimates range from $7/million Btu up to several hundreds of dollars per million Btu, should productivity prove low and design costs high.

Some critics of the GRI marine biomass program contend that there is not enough data available to justify the level of expenditures for the biological test farm.

Critics have stated that the open ocean test farm is an inappropriate and perhaps premature step in a long, logical process of developing future deep sea operations. Considerations which may be overlooked by this test farm approach include:

- the need for better information on kelp growth and productivity and limiting factors in natural beds;
- the need for additional basic research into nutrients and productivity (much research is also needed on plant diseases, predators, and water movement and quality);
- the possibility of developing shallow water kelp farms either in areas of natural upwelling or in conjunction with other fertilizing techniques (see ch. 10);
- hard data on net energy expectations is lacking; and
- no plans are being readied at present as alternatives to fertilization by upwelling.

Since plans for future ocean biomass farms call for the use of millions of acres of ocean surface, there will be conflicts with other traditional users. The dedication of large areas of open ocean surface for a single commercial purpose such as this is unprecedented. It would require complex, special regulation after review of current local, national, and international laws.

Even though the ocean space within the 200-mile zone surrounding the United States is 1½ billion acres, conflicts can be expected with such traditional ocean users as commercial shipping, the navy, commercial and sport fishing, offshore oil and gas operation, and recreational boating. To date, no detailed investigation of legal or institutional approaches to resolving conflicts has been accomplished. This issue will need analysis prior to any large-scale initiative in ocean farming, and will have a major impact on feasibility, productivity, and cost of marine biomass in the future. Analyses of specific sites and siting problems will be crucial to the ocean question.

OTA has found that Federal research programs directed toward energy problems have not been adequately coordinated with similar research directed toward production of food, chemicals, or other products.

Much research is needed to develop any suitable marine plant culture regardless of whether the end product is food or fuel. Such basic research could be better supported and coordinated by all interested agencies. Programs supported by Sea Grant and the National Science Foundation have tended to focus on basic biological efforts or food production goals while DOE programs are focused on pri-

[25]General Electric Co., briefing, "Energy From Marine Biomass Project, Program Review, " for the Gas Research Institute, Newport Beach, Cal if., March 1978.

mary fuel production. Since DOE now has the major funds available for seaweed research, the tendency has been to create programs focused on fuel production. The encouragement of further diversity in existing seaweed research efforts is essential to a long-term improvement in the knowledge and capability of developing future marine plant culture programs.

One approach to conducting a systematic program for developing ocean farms would be to expand research in natural seaweed beds and shallow water farms prior to experiments in deepwater, open ocean farms. This possibility would mean coordination of several existing research efforts; expanding some, developing some new ones, and generally integrating many efforts focused on basic biological questions and food production as well as energy production.

# Other Unconventional Approaches

There are several other unconventional approaches to biomass production. Because of the complexity of plant growth, it is likely that many approaches will be tried and fail. However, this complexity also gives rise to significant possibilities. While all unconventional approaches cannot be covered here, a few are discussed below.

## Multiple Cropping

Multiple cropping consists of growing two or more crops on the same acreage in a year. Growing winter wheat on land that produced a summer crop is one example. The winter wheat can delay spring planting, so its use is applicable only for land where certain summer crops are to be grown. However, this is basically a conventional approach.

The unconventional multiple cropping consists of growing more than one summer crop on an acreage by harvesting the first crop before it matures or developing species that mature rapidly. Since starches, sugars, vegetable oils, and hydrocarbons are generally produced in the greatest quantities in mature plants, this approach would probably reduce the overall yields of these products. Also, the time between the harvest of the first crop and the development of a full leaf cover in the second crop will be a time when sunlight is not captured by the plants as effectively as it could. Consequently, this approach would also be expected to reduce the total biomass yields.

## Chemical Inoculation

By subjecting some plants to herbicides like paraquat or 2,4-D, hydrocarbon or vegetable oil production can sometimes be increased. These chemicals block certain biochemical pathways, thus promoting greater production of other products. Preliminary results with guayule, for example, indicate that 2,4-D may cause a doubling of the natural rubber content of this plant.[26] While it is too soon to assess this approach, it may prove to be an effective way of improving yields of these products.

## Energy Farms

Energy farms have been proposed[27] as a means of providing a reliable supply of large quantities of biomass for large conversion facilities located on or near the farm. The basic idea is to have a large tract of land (tens

[26] Gilpin, et al., op. cit.

[27] See, e.g., G. Szego, "Design, Operation, and Economics of the Energy Plantation," *Proceedings Conference on Capturing the Sun Through Bioconversion* (Washington Center for Metropolitan Studies, 1976); G.C. Szego and C C Kemp, "Energy Forests and Fuel Plantations," *Chemtech*, p. 275, May 1973; and *Silviculture Biomass farms* (McLean, Va.: MITRE Corp., 1977).

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of thousands of acres) dedicated to growing the biomass feedstock for a nearby conversion facility. Although this is technically possible, a number of practical and economic considerations probably will limit investment in energy farms. Moreover, this approach ignores the effect that bioenergy production has on related sectors. Some of the more important of these points are:

- **Land. –** The land available for energy farms has often been estimated to be several hundred million acres.[28,29] OTA's analysis, however, indicates that considerably less land is available for biomass production (see ch. 3). Furthermore, there would be practical difficulties with buying large contiguous tracts of the size needed for large conversion facilities (tens to hundreds of thousands of acres).

  If cultivation on very poor or arid land proves to be feasible or if irrigation for energy production is socially acceptable and the water is available, then these limitations could be somewhat less severe than they appear to be at present.
- **Crop yields.–** Estimates of future yields from short-rotation tree farms have been as high as 30 ton/acre-yr,[30] which OTA considers to be highly unrealistic. Yields of 6 to 10 ton/acre-yr are more realistic for the poorer soil that could be available for energy farms.
- **Initial investment.–** If short-rotation trees are used as the energy crop, there would be a 6- to 10-year leadtime before the first harvest could be made. This would be prohibitively long for many investors. Grasses, however, would reduce the leadtime to a fraction of a year. In either case, the cost of acquiring the land would increase the initial investment substantially.
- **Risk.—** Using short-rotation trees as the energy crop would give yields that are less sensitive to weather than grass because the growth would be averaged over several years. A pest infestation, however, could destroy the entire crop in which an average of 3 to 5 years' cultivation had been invested, and this could be financially disastrous. If grass is the energy crop, or the time between tree harvests is reduced, the loss from a pest infestation would be considerably less, but the yields would fluctuate more from year to year, making it necessary to rely on outside sources of biomass in years with low harvests or to sell surpluses in years with bumper harvests.
- **Competition with other uses for the land. –** Because of the uncertainty about future cropland needs for food production, it would be unwise to assume that tens of millions of acres could be devoted to a conversion facility for 30 years without affecting the price of farmland and thus food.
- **Preclusion of nonenergy benefits. -**OTA's analysis indicates that bioenergy harvests, if properly integrated into nonenergy sectors, can provide benefits beyond the energy, such as increased growth of timber suitable for paper and lumber. Attempting to isolate bioenergy production from these other sectors would preclude some of the potential benefits.

Although none of these factors is insurmountable, taken together they make energy farms appear considerably less attractive than numerous other bioenergy options. Particularly because of the risk and the initial investment, it is more likely that bioenergy crops will be grown as one of the many crop choices available to farmers, rather than on large tracts dedicated solely to energy production. There is, however, no technical reason why energy farms cannot be constructed.

## Biophotolysis

Biophotolysis is generally defined as the process by which certain microscopic algae can produce hydrogen (and oxygen) from water and sunlight. Two distinct mechanisms are known by which microalgae can carry out biophotolysis: 1) through a "hydrogenase" en-

[28] Szego, op. cit.
[29] *Silviculture Biomass Farms*, op. cit.
[30] J. A Allich, Jr., and R E Inman, "Effective Utilization of Solar Energy to Produce Clear Fuel, " Stanford Research Institute, final report No NSF/RANN/SE/GI38723/FR/2 , 1974

zyme (biological catalyst) which is activated or induced by keeping the microalgae in the dark without oxygen for a period of time; or 2) through the "nitrogenase" (nitrogen-fixing) enzyme which normally allows some types of microalgae (the "blue-green" algae) to fix atmospheric nitrogen to ammonia but which also can be used to produce hydrogen by keeping the algae under an inert atmosphere such as argon gas.

In the case of biophotolysis with hydrogenase the key problem is that when simultaneous oxygen production occurs, the hydrogenase enzyme reaction is strongly inhibited and the enzyme itself inactivated. Although it was recently demonstrated that simultaneous production of oxygen and hydrogen does occur in such algae,[31] it is uncertain whether it will be possible to sustain such a reaction in a practical system. This difficulty has led to proposals for separation of the reactions either by developing an algal system which alternates oxygen and hydrogen production, (possibly on a day-night cycle) or by developing a two-stage process. Such systems are still at the conceptual stage, although considerable knowledge exists about the basic mechanisms involved.

Somewhat better developed is a biophotolysis process based on nitrogen-fixing blue-green algae. I n these algae the oxygen-evolving reactions of photosynthesis are separated from the oxygen-sensitive nitrogenase reaction by their segregation into two cell types — the photosynthetic vegetative cells and the nitrogen-fixing heterocysts. Heterocysts receive the chemicals necessary to produce hydrogen from vegetative cells but are protected from oxygen by their heavy cell wall and active respiration. Using cultures of such algae from which nitrogen gas was removed, a sustained biophotolysis reaction was demonstrated: about 0.2 to 0.5 percent of incident solar energy was converted to hydrogen gas over a l-month period. However, significant problems stil exist in the development of a practical system —1 O times higher conversion efficiencies must be achieved, a goal which may not be reached due to the high energy consumption of the nitrogenase reaction. Also, the mixture of hydrogen and oxygen generated by such a system may be expensive to separate.

Whichever biophotolysis mechanisms or processes are eventually demonstrated to be capable of efficient and sustained solar energy conversion to hydrogen fuel from water, they must take place in a very low-cost conversion system. The development of an engineered biophotolysis conversion unit must meet stringent capital and operational cost goals. As biophotolysis will be limited by the basic processes of photosynthesis— probably no more than 3 to 4 percent of total solar energy conversion to hydrogen fuel —this sets an upper limit to the allowable costs of the conversion unit. In principle, the algal culture—the catalyst which converts sunlight and water to hydrogen and oxygen–can be produced very cheaply; however, the required "hardware" to contain the algal culture and trap the hydrogen produced may be relatively expensive.

Biophotolysis is still in the early stages of development. No particular mechanism, converter design, or algal strain appears to be inherently superior at this stage. Claims that near-term practical applications are possible, that genetic engineering or strain selection can result in a "super" algae, or that biophotolysis is inherently more promising than other biomass energy options are presently not warranted. A relatively long-term (10 to 20 years) basic and applied research effort will be required before the practical possibilities of biophotolysis are established.

## Inducing Nitrogen Fixation in Plants

The biological process of nitrogen fixation, the conversion of nitrogen gas (not a fertilizer) to ammonia (a fertilizer) has only been found to occur in bacteria and the related blue-green algae. These primitive organisms maintain the ecological nitrogen cycle by replacing nitrogen lost through various natural processes. The capability for nitrogen fixation expressed by many plants (soybeans, alfalfa, peas) is due solely to their ability to live in a symbiotic

[31] E Greenbaum, *Bioengineering* **Biotechnology Symposium, VOl 9, in press**

association with certain bacteria (of the genus *Rhizobia),* which form the characteristic "root nodules." A certain fraction of the photosynthetic products of these plants are transferred to the roots where they are used (as "fuel") by the bacteria to fix nitrogen to ammonia which is then sent (in bound form) to the protein synthesizing parts of the plant.

This process is, in principle, energy intensive, with each nitrogen atom (fixed) reducing the biomass production by several carbon atoms (about 2 to 3).[32] In practice, significant inefficiencies in the process are often noted, most particularly the recent discovery that some *Rhizobia* bacteria in root nodules waste a large fraction of the "fuel" supplied by the plant in the form of hydrogen gas.[33] By using *Rhizobia* strains that can effectively recycle the hydrogen gas, this loss may be overcome.

Although biological nitrogen fixation can substitute, to a large extent, for the fossil-fuel-derived nitrogen fertilizers currently used in agriculture, the tradeoff may be an overall reduction in biomass yields. In an era of decreasing fossil fuel availability, such a tradeoff may be desirable, particularly as the price of commercial fertilizers is a limiting economic factor in many biomass production proposals. However, nutrient recycling could be preferable to de novo production, as it probably would be less costly and energy intensive. Alternatively to biological nitrogen fixation, thermochemical conversions of biomass to synthesis gas and their catalytic conversion to ammonia are feasible. Whether this is more favorable both in terms of economics and energy efficiency is uncertain.

A number of scientists have proposed that, through genetic engineering, they could transfer the nitrogen-fixing genes directly to the plant. However, such proposals face technical barriers. For example, the nitrogen-fixing reaction is extremely oxygen sensitive and is unlikely to be able to take place in the highly oxygen-rich environment of a plant leaf. In principle, there would only be a relatively minor advantage for a plant to directly fix nitrogen rather than do so symbiotically. Much more basic knowledge in many areas of plant physiology, genetics, biochemistry, etc., as well as developments in genetic engineering and plant tissue culture will be required before the potential for practical applications of such concepts can be evaluated.

## Greenhouses

It is well known that increasing the $CO_2$ concentration **in the air results** in significantly improved plant growth for some plants. Depending on the specific plant and the specific conditions of the experiments, **a 50-to 200-percent increase in biomass production has been noted. Greenhouses have the additional advantages of providing a "controlled environment"** where pest control, water supply, and fertilization can be better managed, resulting in potentially high yields. The higher temperature in greenhouses allows extended growing seasons in temperate climates. Greenhouse agriculture is rapidly expanding thoughout the world to meet the demands of affluent countries for out-of-season vegetables and horticultural products. However, the high cost of greenhouse agriculture and its high energy consumption make production of staple **crops unfeasible and proposals for biomass energy** production unrealistic at present. Although significantly lower cost greenhouse technology is feasible in principle, biomass production costs in Arizona, for example, would still be 10 times as expensive as open-field biomass crops grown in the Midwest.[34] A significant inflation in farm commodity, farmland, and water prices could make greenhouse systems more attractive. At present and in the foreseeable future, however, greenhouses do not appear economically feasible for bioenergy production.

[32] K. T Shanmugan, F. O'Gara, K. Andersen, and P C. Valentine, "Biological Nitrogen Fixation," *Ann. Rev. Plant Physiol. 29,* p. *263,1978.*

[33] Ibid.

[34] L. H. de Bivort, T. B. Taylor, and M. Fontés, "An Assessment of Controlled Environment Agriculture Technology, " report by the International Research and Technology Corp. to the National Science Foundation, February 1978.