biological methods for trapping solar energy is slow. This suggests that the economic and other advantages of using photosynthesis have not been widely accepted. The case for photosynthesis would be strengthened if LP and other by-products were fully exploited. There is already well financed research in Berkeley and Madison (USA) on large-scale equipment suitable for this job; the most pressing need is for research on the species most suitable for it.

The future of leaf protein in the context of appropriate technology

Research on the production of edible LP on a small-scale for local use is in an almost exactly inverse position. We know many suitable sources of LP, and there is good reason to think that its practical exploitation would have a more immediate effect on the welfare of more people than an increase in the energy supply would have. But there is no simple, robust, and economical unit on the market with which it can be made: nor is there properly financed work on the design of such a unit. Until this work is done, LP will be thought of as an interesting possibility rather than as a recognized food.

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Algae and water plants as energy converters

In H.A. Wilcox' paper the concept of raising seaweeds on huge structures ('ocean farms') is presented and the use of this biomass for food, fibers, fertilizers, methane and other products is described.
The basic problems of collecting energy from the sun through microalgae are discussed by S. Aaronson and Z. Dubinsky. Applications of this technique may be suited for sewage purification plants or in saline ponds in the tropics or subtropics. Many products, such as pharmaceutics and chemical raw materials can be gained from phototrophic microorganisms. Furthermore, the cells can be used to eliminate toxic or polluting compounds.
A similar study is made by C. Santillan as he presents the particular case of *Spirulina* in Mexico, a protein source depended upon the Aztecs already centuries ago.
The paper by T.G. Tornabene reviews the potential that microorganisms have for producing lipids and hydrocarbons and the use of these as fuels.
The special case of the oil alga *Botryococcus braunii* is examined by R. Bachofen. Considerable basic research is still required before it will be possible to induce the state, as is occasionally found in nature, wherein 85% of the dry weight of the algal cells is hydrocarbons.
In the alga *Dunaliella* the main product of photosynthesis is glycerol. A. Ben-Amotz et al. discuss the biological glycerol production from CO_2 with sunlight in ponds. As a raw material for the chemical industry this seems to be a promising alternative for the future.

The ocean as a supplier of food and energy

by Howard A. Wilcox

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Summary. This paper presents the concept of raising seaweeds and other valuable organisms with the aid of huge structures ('ocean farms') emplaced in the surface waters of the open oceans. Potential advantages from and difficulties to be expected in realizing the associated technologies are briefly set forth. Much of the published literature pertaining to the concept is referenced and summarized. Wave-powered upwelling of cool, nutrient-rich waters through vertical pipes extending to depths of 100-300 m is indicated as desirable. Technologies are outlined for using the harvested seaweeds to create foods and other valuable products such as animal feeds, fertilizers, fibers, plastics, synthetic natural gas (methane), and alcohol and gasoline fuels. Results from site selection studies and economic analyses are given. It appears that dynamically positioned farms orbiting with the surface current patterns typically found on the ocean will be most cost-effective. The general conclusion is stated that open ocean farming will become economically more feasible as the cheaper fossil fuels and food producing lands of the earth become increasingly consumed in the course of the next century.

The possibility of cultivating crops of vegetation on the vast areas of the open ocean, a possibility apparently first suggested (in 1968) by this author, has gripped the imaginations of a growing number of technicians and planners throughout the world. If successfully realized, this technology would enable the planet's oceans to become a huge new source of feeds, foods, fuels, and chemicals - fixed carbon and fixed nitrogen - for the benefit of humanity. Moreover, the resulting great oceanic aquacultural enterprise would supplement rather than be competitive with the already existing land based sources of these vital goods for all the world's peoples.

In late 1972, the US Navy initiated an experimental program to explore the ocean farm concept[1], and in 1977, the project was shifted to the management aegis of the General Electric Company, which continues to direct the program to this date.

The concept of open ocean aquaculture is grounded on the following combination of facts:

1. The rate of receipt of solar energy on the surface of the earth is huge, being more than 10,000 times greater than our present use rate of all other forms of energy.
2. The flow of solar energy is naturally maintained and highly reliable in both the technical and the political sense.
3. Most of the solar energy received by the surface of the earth is absorbed by the upper layers of the oceans because the oceans cover some 70% of the earth's surface area and possess relatively low average reflectivities.
4. Man's use of the earth's currently received solar energy need not upset the net balance of the planet's carbon dioxide, oxygen, water, and energy flow cycles, as calculated on a global average basis over time spans of a few months.
5. The sun is the only known energy source available for the large scale photosynthetic production of vegetation.
6. Vegetation can be converted by known technology into foods, fertilizers, fibers, plastics[2], synthetic natural gas (methane)[3], synthetic liquid fuels such as ethanol, methanol, and gasoline[4], etc. Indeed, vegetation is the only practically renewable source of such products that is available today.
7. Although nearly all areas of the surface waters of the major oceans are 'biological deserts' because they are almost devoid of the nitrate and phosphate compounds required for the growth of vegetation, ocean waters below depths of 100-300 m generally contain these nutrient materials at relatively high average concentrations[5], and these waters stand at a gravitational potential energy deficit relative to the surface of only about 3000 J per ton of water[6].
8. Plants immersed in the ocean can be highly efficient photosynthesizers[7] and are generally immune to the 2 main hazards of land farming, namely, drought and frost; yet, thus far, we have brought only a very small fraction of the ocean's area under systematic cultivation[8].
9. Most of the vegetation producing areas of the world's dry land surface have already been exploited[9], and the ocean appears to possess 5-10 times more 'potentially arable' area than the land.

Up until now, 3 primary problems have prevented farming of the open oceans: 1. the natural bottom is so far down in most places that the sunlight cannot reach it, thus preventing the reproduction and growth of attached seaweeds; 2. the natural surface waters are (as mentioned above) almost devoid of some of the nutrients required for the growth of plant life; 3. the hazards of storms at sea have seemed insurmountable. Potential answers to these problems are: 1. emplace an open-work mesh of stout plastic lines some 15-30 m down from the ocean's surface, thus giving the seaweeds a substrate for attachment regardless of the depth of the natural ocean bottom; 2. extend the intake pipes of wave or wind powered pumps vertically down from the surface zone some 100-300 m in order to create artificial unwelling of the cool, nutrient rich deeper waters; 3. apply modern ocean engineering techniques plus judicious siting of the farm systems in order to withstand stresses from, and to reduce encounter frequencies with, the marine storms that cannot be avoided.

The major question for this concept at present concerns its economic feasibility, but the issue is more one of 'when' rather than 'whether' the concept will eventually pay off. As the world's population increases and as its vegetation and energy producing potentials are progressively diminished, there will necessarily be an improvement in the economic feasibility of ocean farming as compared to land farming or other methods of utilizing the energy- and food-producing powers of the sun.

Growing and harvesting the seaweeds

Figure 1 shows one concept which has been under

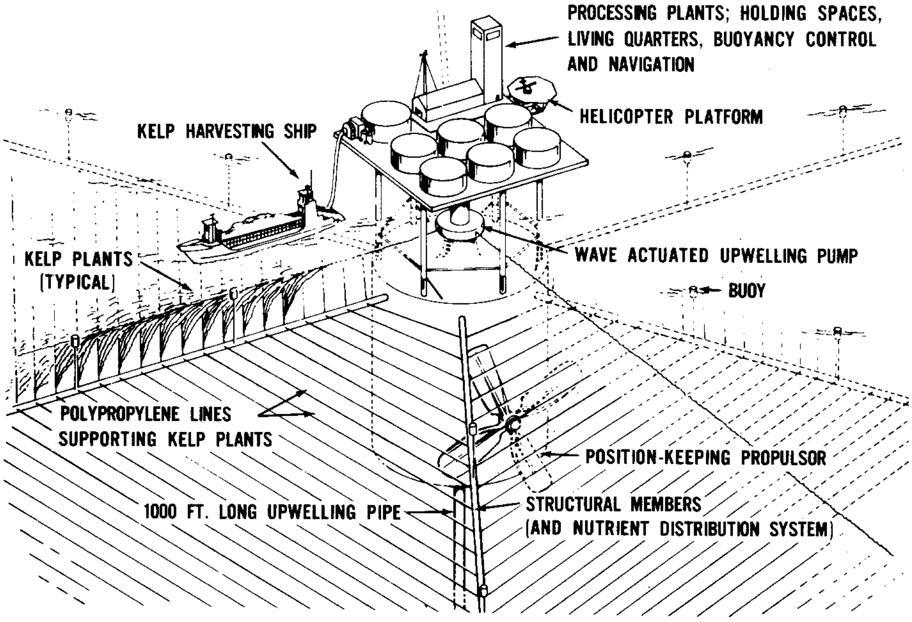

Figure 1. Conceptual design. 400-ha ocean food and energy farm unit.

study since 1973[10]. In this system the passing waves would cause floats to rise and fall, and these floats would be connected to lift pumps in upwelling pipes so as to force cool, nutrient laden water from the deeps to the surface zone. There the seaweeds - the giant California kelp *Macrocystis pyrifera* (fig. 2) - would use these nutrients plus high value photons from the sun to weld carbon dioxide and water drawn from the surrounding ocean into the kinds of energy-bearing molecules that form the basis of the entire world's food chain, namely, carbohydrates and proteins. The seaweeds would be attached by their 'holdfasts' to the mesh of plastic lines shown in figure 1, and they would be periodically harvested (coppiced), as they are today in California coastal waters, by ships bearing large clippers which cut the seaweed fronds at a level 1 or 2 m beneath the ocean's surface[11]. After each harvesting the seaweeds would continue to grow, thus replacing the previously cut fronds in readiness for a subsequent harvest. If a few plants were to be lost, natural recruitment of juveniles from neighboring plants would replace them, so planting of the farm is expected to be required only once.

Figure 3 shows the general flow of materials in this ocean farm system. All the carbon, oxygen, and other atoms involved would simply be recycled, going from the farm system's input point on the left into the products on the right and then returning around the system back to its input point again. High value photons would enter the system shown in figure 3 at the left, and low value photons (infrared radiation) would leave the system at the right.

Each hectare of cultivated ocean is expected to yield some 700-800 tonnes of whole seaweed (fresh weight basis) per year. This translates to a conversion efficiency relative to the incident solar energy of about 2%[12]. At first there was a fear in some quarters that the deep ocean waters might contain compounds toxic or otherwise inimical to the growth of kelp, but work by Prof. Wheeler J. North in 1976[13] demonstrated that there need be no anxiety in this regard. Indeed, his research work showed growth rate stimulation of juvenile kelp plants by flowing mixtures of waters drawn from the surface and from several hundred meters of depth, in both the Atlantic and the Pacific

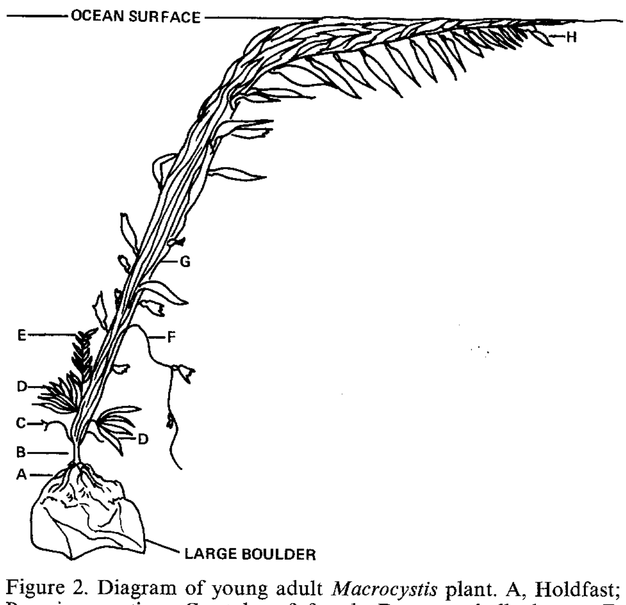

Figure 2. Diagram of young adult *Macrocystis* plant. A, Holdfast; B, primary stipe; C, stubs of frond; D, sporophyll cluster; E, juvenile frond; F, senile frond; G, stipe bundle; H, apical meristem. No root involved - plant takes all nutrient direct from surrounding water.

oceans, in approximate accordance with the following table:

Mix ratio (% deep/% surface)	Growth rate (% per day)
100/0	15.1
50/50	19.3
10/90	17.5
5/95	12.2
0/100	9.5
Control plant in flowing bay water at Corona del Mar, California	7.9

The upwelling of cool, nutrient-laden water (probably at about 10 °C) from the deeps is expected to make it possible for ocean farms to operate successfully even in the warmest waters of the tropics.

Kelp stands naturally shelter and support abundant faunal communities[14]. Hence the ocean farm system will be expected to encompass the harvesting of its fin fish, and it will probably include also the culturing of oysters and other organisms in order to utilize to the greatest possible extent the phytoplankton whose growth will inevitably be accelerated by the upwellings it produces.

Foods, feeds, and other products

Whole *Macrocystis pyrifera* has been used in experimental feeding trials with sheep, abalone, fish, chickens, and fly larvae[15]. Results from tests at the University of California at Davis showed sheep digestion efficiencies of some 58% of the organic matter in the dried kelp - about the same as for the basal ration composed of alfalfa hay, oat hay, barley and sodium phosphate. Juvenile abalone showed 10% conversion efficiencies, considered on a fresh weight of kelp to fresh weight of abalone basis. Experiments with the fish, chickens and fly larvae did not produce positive results.

Figure 4 shows a schematic processing diagram for producing methane gas and other desirable products

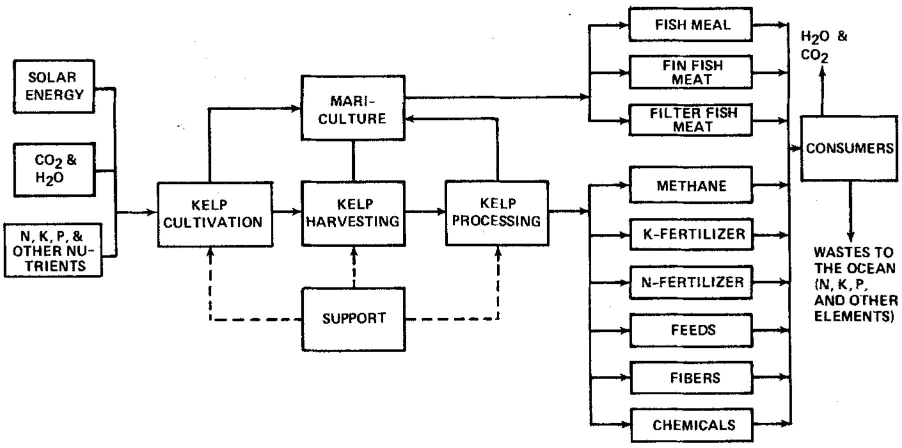

Figure 3. Ocean farm project; flow chart.

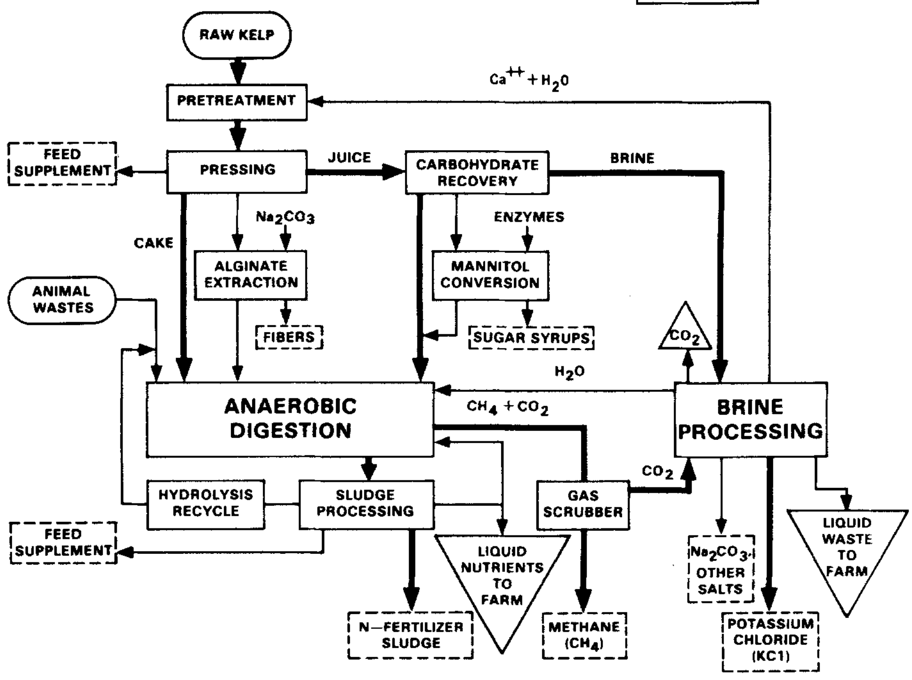

Figure 4. Ocean farm project; process chart for production of methane and other products.

from kelp[16]. Energy conversion efficiencies of about 50% have already been achieved with anaerobic digesters operating on a whole kelp feedstock to produce methane[17], and it is believed that efficiencies in the 60–80% range can probably be achieved for this process.

Site selection

It appears that optimal sites for future ocean farms will be in 3 relatively storm-free latitude bands: a) about 25 °N to about 40 °N of the equator, b) a similar zone south of the equator, and c) about 15 °S to about 15 °N of the equator[18].

Economics

Because of the high costs of deep ocean mooring lines, most of the commercially practical ocean farms of the future (not the small, experimental units of today) will probably need to be dynamically positioned by fuel powered propulsors (see figure 1). This holds true even for areas where the natural bottom is only 300 m or so beneath the surface. More than 90% of the ocean is more than 300 m deep[19]. However, if suitable arrangements can be worked out among the various ocean-owning nations - perhaps by the paying of appropriate rental fees for use of one another's waters - so that large ocean farms may move predominantly with the circulating currents which exist naturally on the ocean's surface, then the costs of ocean farming will be dramatically reduced (probably by as much as 20–40-fold) compared to the expenses that will be entailed if the farms are required to remain anchored over specified locations on the ocean floor below.

Assuming that such dynamically positioned farms can be emplaced and operated to produce kelp at the rate previously stated (corresponding to 2% conversion efficiency relative to the incident solar energy), economic studies[20] have showed that an ocean farm system using some 40,000 ha of ocean will be able to produce some 620 million m^3 of methane per year at a cost ranging from a low of about US$0.08 to a high of about US$0.25 per m^3. The range of costs given depends mainly on the assumptions used for food and byproduct credit values, distances to coasts, etc. (All dollar values are for the year 1975.) These studies also showed that 1. large systems of area 8000 ha or more, are required to be economically feasible, 2. oceanic structures will probably cost less than US$7000 per ha, 3. harvesting ship costs will probably amount to about US$3300 per ha of cultivated ocean, and 4. associated on-shore processing facility investment costs will amount to about US$4000 per ha of cultivated ocean area.

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