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TROPICAL MACROALGAL CULTIVATION FOR BIOCONVERSION TO METHANE

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ABSTRACT

Several concepts have been developed for tropical marine biomass cultivation for bioconversion to methane. These concepts take advantage of Florida's large areas of relatively shallow water. One concept, tidal flat seaweed farms, uses currently available macroalgal candidates (Gracilaria, Ulva) and at biomass yields of 12-25 dry ash free tons/hectare-year can provide delivered low feedstock costs of \$40-25/DAFT, or on an energy basis, \$3.60-2.30/G joule, respectively. These biomass yields are close to those achieved in commercial Gracilaria culture in Taiwan. Such systems would be constrained to nearshore waters of 0.5-1.5 m in depth, of which there are 190,000 hectares in northwestern Florida.

Concepts which would work in deeper waters (from 1.5-20 m depths) use floating seaweeds. Such biomass species would need to be produced by genetic breeding and hybridization, as there is not an adequate natural species available which also has high bioconversion rates. Such hybrids may be intrageneric ones of Sargassum, or Sargassum hybrids with other algae such as Macrocystis. A biotechnology approach could provide competitive feedstock costs with a large potential gas production, as there is approximately 1,900,000 hectares between 1.5-20 m depths in northwestern Florida.

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INTRODUCTION

Marine biomass cultivation for renewable energy has centered primarily on cultivation of cold water kelps on offshore structures, nearshore farms, and Chinese long line systems. The Harbor Branch Foundation, located in Florida, has been developing cultivation practices for tropical macroalgae as biomass resources. The initial efforts focused on determining maximum productivities of seaweeds, and later, cultivation practices for the red alga, Gracilaria tikvahiae, and the green alga, Ulva sp. These experiments were largely carried out in land based ponds or high intensity seaweed raceways (8,9,10). Later, the focus changed to "in the sea" cultivation of the brown algae, Sargassum spp. Sargassum, which can float on the sea surface like water hyacinths on lakes, has great appeal as engineering studies with various off-bottom kelp concepts have revealed that very high biomass yields are required to overcome the high capital costs. A floating seaweed could be contained in floating enclosures which are being developed at University of Florida for water hyacinth. Floating containment systems are already being used for commercial marine fish culture in Japan and Norway. The results of the research on Sargassum have been recently summarized (2,7). Economic analyses of water hyacinth cultivation (3,14) have been extrapolated to estimate cultivation costs of floating Sargassum (1).

Little attention has been paid to developing a viable concept for using Gracilaria or Ulva as a biomass resource. Gracilaria production can be sustained year round, and seasonal yields are closely correlated to seasonal light availability (9). However, the greatest limitation to high Gracilaria yields is water turnover rate in the culture system (8,11). Low water turnover rates lead to high increases in culture pH due to photosynthesis, which in turn reduces the availability of CO_2 (12). In commercial Gracilaria cultivation in Taiwan, the water turnover rate in ponds is on the order of once every 20 days, and results in biomass yields of 14 dry tons/hectare-year (ca. 9 dry ash free tons/hectare-year, Ref. 13). In high water turnover rate systems (10 or more exchanges/d), biomass yields can be as high as 150 dry tons/hectare-year (DT/HA-Y), and in small ponds receiving one to two exchanges per day, in the range of 25-50 DT/HA-Y (ca. 15-30 dry ash free tons/hectare-year, Ref. 10). It is therefore important that any concept for Gracilaria or Ulva biomass cultivation must include a means of providing sufficient water turnover to maintain reasonable biomass yields.

THE TIDAL FLAT FARM CONCEPT

Two concepts were initially explored, one of diking off ponds in shallow water and pumping water in and out, and the other of netting in shallow water areas and letting the tide and currents provide the water exchange. The first concept was quickly rejected as it requires energy

consuming pumps and expensive construction of dikes. The other concept, tidal flat farming, has great appeal as tides would provide one to two water exchanges per day, depending on the tidal cycle. In addition, construction methods and materials are fairly inexpensive. The concept involves enclosing areas of 1.5 m or less in depth, using netting supported by pilings. The seaweed would grow in the enclosure, and would be harvested daily by harvesting boats entering through boom gates. The seaweed would be shredded during harvesting and upon return to the dock facility, would be pumped out of the barges to the digester facility. In order to estimate potential economic feasibility of such a concept, a preliminary idealized farm and harvesting system has been costed out, using contractors' quotes or cost data from the engineering analysis of the Macrocystis (kelp) nearshore farm concept (4). Feedstock production costs have estimated at two different biomass yields of 12 and 25 dry ash free tons/hectare-year (DAFT/HA-Y). The lower end of these yields are close to those obtained in commercial scale cultivation (12 vs ca. 9 DAFT/HA-Y). The upper end was estimated based on biomass yields obtained in Florida in ponds receiving 1-2 exchanges/day (ca. 30 DAFT/HA-Y), and allowing for decreases due to loss, herbivory, and scale up effects on production.

The conceptual farm is circular, of 19 kms circumference, and 5344 hectares in area (based on best case of kelp economics). The enclosure is constructed of creosote pilings driven into the sediment every 5 meters, with a stainless steel cable joining the pilings at the top. One inch square nylon fish netting is secured to the cable and the pilings, with the weighted bottom buried in the sediment. Six floating boom gates allow access to the farm at various locations, depending on harvesting schedule, wind conditions, etc. There are 10 kms of drift seaweed fences within the farm, arranged to prevent all the biomass from concentrating in one location, and breaking through the net fence. These drift fences are constructed in a like manner as the farm perimeter. Capital costs are shown in the Table 1. In the event a circular farm is not feasible, a long rectanular farm, 1 km wide, would cost 15% more to construct.

Annual O&M for the farm consists of two components: farm maintenance and seaweed cultivation. The major cost estimated for farm maintenance is the replacement of all the netting every two years in a year round replacement operation. Replacement would be necessary due to biofouling of the netting and material degredation. Seaweed cultivation costs are primarily labor costs of farmers who must ensure that the seaweed does not pile up too heavily in select locations. The farmers are equipped with small boats to move seaweed mats around. Farmers will also be needed for weed and herbivore control. In addition, marine biologists must ensure the seaweed is adequately fertilized, and help plan harvesting operations. A nursery/laboratory has been included in the capital costs in the event that several species or clones are used over the course of a year, to maintain important clones and inocula, and for water chemistry. Possibly, germlings grown on vermiculite could be used for the large scale farm inoculations which would be involved (5).

The harvesting system for a tidal flat farm is fundamentally the same as the kelp system, specialized harvesters pumping kelp into barges. As the water depth is shallow (less then 1.5 m depth) all the equipment will be shallow draft (30 cm) with extra floatation via pontoons. The harvester will have a collection treadmill similar to a

TABLE 1. CAPITAL AND ANNUAL COSTS OF TIDAL FLAT FARM

CAPITAL COSTS

ITEM	NUMBER	COST
FARM		
Pilings, 5" diameter, 2.5 lb/ft[3] CCA treated. Installed cost.	8,448	$278,287
Piling - Cable connections	8,448	845
Cable, 1/2" diameter	130,000 ft.	76,700
Netting	18 bales	14,900
Net anchors		316,800
Net ties	90,133	2,700
Boom gates	6	30,000
Permits, etc.		50,000
Labor		104,000
Boat, equipment rentals, $300/d		37,500
		$ 911,732
15% Contingency		136,760
		$1,048,492
10% profit		104,849
		$1,153,341
4% engineering fee		46,134
Subtotal		$1,199,475
LAND BASED NURSERY/LABORATORY		
Laboratory, 1000 sq. ft.		$ 120,000
Greenhouses, 10,890 sq. ft.		217,800
Subtotal		$ 337,800
TOTAL (Farm and Lab-Nursery)	ca.	$1,538,000

ANNUAL COSTS

Farm Maintenance		
50% of netting		7,450
50% of ties		1,352
3 people, maintenance $8/hr(burdened)		49,920
		$ 58,722
Operations		
6 farmers, $8/hr(burdened)		$ 117,444
Lease		
$12.50/hectare, 5344 hectares		66,000
Subtotal, Farm O&M		$ 242,166
Nursery/Laboratory		
O & M, 3 people		$ 140,000
Fuel		$ 84,000
TOTAL O & M		$ 382,166
TOTAL FUEL		$ 84,000

kelp cutter, but the treadmill will not be fixed, rather be hinged. The seaweed will be piped to a towed barge after it is shredded by the harvester. For the 12 DAFT/HA-Y system, only one non-motorized barge is required. In the 25 DAFT/HA-Y system, motorized barges will be used, and the harvesting speed will have to increase to 1.5 kts. When the barge is full, it will return to the docks as an empty one is rotated in place. Crews from the empty barge will join the harvesting crew. The harvester will also spray digester effluent on the farm as a source of fertilizer. Digester effluent has been demonstrated as an effective fertilizer for *Gracilaria* (6), and recycling such effluents saves both disposal costs and fertilizer purchase. Harvesting will occur over 300 d, with 65 d allowed for inclement weather. Due to

TABLE 2. HARVESTING COSTS AT DIFFERENT BIOMASS YIELDS

FOR 12 DAFT/HA-Y Harvesting speed 1 kt			
Capital Costs			
1 Harvester at 1100 K			$1,100,000
1 Barge at 1000 K			1,000,000
2 Small boats at 10 K ea.			20,000
Dock			50,000
Pumps			200,000
Seaweed & effluent pipes to and from digester			2,000,000
			$4,370,000
		15% cont.	656,000
			$5,026,000
		10% profit	503,000
			$5,529,000
		4% eng fee	221,000
			$5,750,000
O & M			
Labor			
Harvesting		$ 1,408/d direct	
		535 38% fringe	
		582,912 for 300 days	
Maintenance		50,000 boat haul-outs & repairs	
2 Dock laborers		57,408	
		690,320	
	15% cont.	103,548	
		$793,868	
TOTAL O & M			$794,000
FUEL			$190,000
FOR 25 DAFT/HA-Y Harvesting speed 1.5 kts (8.3 h total harvesting time)			
Capital Costs			
1 harvester at 1100 K			$1,100,000
2 motorized barges at 1500 K			3,000,000
2 small boats at 10 K			20,000
Dock			100,000
Pumps			350,000
Pipes			3,000,000
			$7,570,000
		15% cont.	1,135,500
			$8,705,500
		10% profit	870,550
			$9,576,050
		+ 4% eng. fee	383,042
			$9,959,092
Annual Costs		ca.	10,000,000
O & M		$1,408/d harvester	
		285/d motorized barge	
		$1,693/d	
		643	
		$2,336/d	
		$700,800 300 d	
		75,000 boat haul outs	
		57,408 2 dock laborers	
		$833,208	
		114,981	
		$958,189	
TOTAL O & M		ca.	$960,000
FUEL			$230,000

insuffient data, it has not been possible to build calculations for seasonality into this study; therefore, yield has assumed to be constant throughout the year. Seasonal peaks in growth, which probably occur in spring and summer, will have to be accomodated by increasing harvest speed and incorporation of larger capacity barges. Several small boats are also provided for in this fleet for farm maintenance. At the dock, the seaweed is pumped from the barges through pipes to the bioconversion facility. Pipes also return digester effluent to the barges for recycling on the farm. Table 2 details these costs.

Feedstock Costs and Cost Sensitivities

The total capital, O & M, and fuel costs, as well as delivered feedstock costs are shown in Table 3. Feedstock costs on an energy basis for the 12 DAFT/HA-Y yields are $3.60/G joule and for 25 DAFT/HA-Y, $2.30/G joule, assuming methane yields of 5.5 SCF/lb V.S. added and 85% net methane production after digester heating requirements are met. Recent bioassays of Harbor Branch Foundation *Gracilaria* clones by the Institute of Gas Technology have indicated a methane yields of 6-7.5 SCF/lb V.S. added. Feedstock costs on a weight basis for this system range from $40-25/dry ash free ton, respectively. By comparison, feedstock costs for nearshore *Macrocystis* are $80/DAFT at 25/DAFT/HA-Y; for *Sargassum* in floating farms, $71/DAFT at 25 DAFT/HA-Y; and for *Laminaria* raised on long line farms, $132/DAFT at 38 DAFT/HA-Y (1). Typically, these other macroalgal systems require biomass yields in the range of 38-50 DAFT/HA-Y in order to be price competitive, with the exception of *Laminaria*, which must be cultured on cost-prohibitive long line farms. When costs sensitivities for both capital and operating costs were performed at the two different biomass yields, the effect was only significant at low biomass yields of 12 DAFT/HA-Y when O&M costs increased by a million dollars. The greatest cost unknowns in the system are the final farm configuration (site specific), and total lengths of drift seaweed fences required in the farm. In the 25 DAFT/HA-Y system, if the farm is located more than 6 kms from the dock or is rectangular in shape, an additional harvester may be required.

Biological Constraints

The tidal flat farm concept is an untested approach to seaweed farming and as such, will encounter a number of constraints with regards to potential biomass yields. Key problems will be weed species which foul the biomass crop itself, cutting down substantially on production, and the impact of marine herbivores such as amphipods. Current, chemical control technologies for these pests are not well developed, and it may be necessary to develop selective algicides and herbivore control agents. Alternatively, co-culture of important carnivorous fish may provide herbivore control (and a significant economic co-product). Current speeds will also affect the choice of the biomass crop. In confined bays and estuaries, with low water movement, *Ulva* sp. may be better suited as it is well adapted to such water movement, while *Gracilaria* would be best suited suited for areas with stonger currents and greater water exchange. Perhaps most important, however, will be the seaweeds' interactions with the substrate. As the seaweed tumbles and moves across the bottom, a fine particulate substrate can cover the thalli. With wave and wind action,

Table 3. SUMMARY OF COSTS BY BIOMASS YIELD

Feedstock Costs		
DAFT/HA-Y	12	25
Capital	$7,288,000	$11,538,000
O & M	1,176,000	1,342,000
Fuel	274,000	314,000
G joule/year*	6.17×10^5	1.23×10^6
$/G joule**	3.60	2.30
$/DAFT	40	25
Sensitivities ($/G joule)		
+$1million Capital	4.10	2.46
+$100,000 O & M	4.14	2.48
+$1million O & M	5.63	3.22

*based on 85% net methane production from the conversion facility.

**based on 5.5 SCF/LB V.S. ADDED

the seaweed can actually be buried in the sediments, greatly reducing farm productivity. The Taiwanese *Gracilaria* farmers prefer ponds lined with coarse sand (13). Coarse material is less likely to get stirred up by wave and wind action, or to cover the thalli. Should seaweed-sediment actions prove to be deleterious, it may prove useful to engineer several small boats to constantly stir up the sediment and release buried seaweed.

RESOURCE BASE

Florida is rapidly growing state, which will inevitably lead to problems of recreational water use versus seaweed farming. In analyzing locations best suited for seaweed to energy farms, it was felt that the area between Tarpon Springs and Pensacola would incur the least conflicting use. This area is north of the "cold front line" and is less attractive from a recreational and living perspective to immigrants. The area is primarily used by fishermen. In this area, subtidal bottom lands between 0.5-1.5 m depths encompass 190,000 hectares, after elimination of shipping lands, state and federal parks and preserves, oyster fishing and rearing areas, and areas where seaweed does not naturally occur. This analysis has not yet taken into consideration substrate types, annual changes in water chemistry, physical properties and flow, or socio-political restrictions, hence the available area may be further restricted. It should be realized that this large area is only one tenth that which is available in the depth ranges of 1.5-20 m (1,900,000 hectares), hence use of this area would result in far greater gas supplies. Nonetheless, the tidal flat farm concept could make a significant contribution to regional gas needs.

RECOMMENDATIONS

While sustained culture of pelagic, floating Sargassum has been recently accomplished, and resulted in biomass yields of 9-12 g dry wt/m^2-d from small (1-2 m^2) enclosures (2), the technology for Sargassum culture is still not as well developed as for Gracilaria or Macrocystis. In addition, all the Sargassum species tested to date have shown poor bioconversion performance compared to other seaweeds. A floating crop approach may not be the only way to effectively use deep water areas. More recent economic analyses of bottom anchored, canopy forming species such as Macrocystis, in depths of 9-15 meters, have indicated that cost effective gas may be produced at reasonable yields of 38 DAFT/HA-Y. While Sargassum can form a canopy in shallow water, it does not achieve the depth range of Macrocystis (possibly due to a less efficient translocation system?). Plant breeding could potentially improve Sargassum yields, composition for conversion, and develop the plant for either pelagic cultivation or as a canopy species, or perhaps somatic hybrids of Sargassum-Macrocystis could provide valuable biomass crops. It is obvious that this approach involves long term research in the areas of genetics, biotechnology, and algal physiology, including studies of translocation processes, biochemical composition, carbon fixation, and plant growth regulators. Understanding the adaptive role of variable morphologies under different environments can also help guide the breeding and biotechnology research. Such long term research, rather than cultivation trails and scale up, is appropriate given the recent decline in worldwide oil prices.

The tidal flat farm concept needs to be tested in field trials and scale up studies to learn more about large scale cultivation technology. While there is little interest in scaling up biomass systems at the moment, Florida's regional energy planners should realize there is greater certainty that this approach can be commercialized than offshore seaweed cultivation. Should regional energy demands ever necessitate an engineering and scale up approach to solve immediate problems, this technology could be developed most quickly. The tidal flat farm also has great appeal for use in the Caribbean islands or Central America, as it could be part of a polyculture system with fish, leading to a high value export product and local energy. A long term, more basic research effort would also benefit this concept, possibly through development of new marine biomass clones and cultivars. Biotechnological research such as somatic hybridization could lead to herbicide resistant strains as a byproduct of the researchs' experimental design which incorporates such resistance in plant lines to aid in selection of new hybrids. These herbicide resistant Gracilaria or Ulva clones would facilitate weed control on tidal flat farms.

Marine biomass represents a real energy option for Florida. The tidal flat farm concept provides a fairly low risk approach which can help ensure marine biomass technology is implemented when regional biomass based energy becomes price competitive. Should it be possible to develop the higher risk offshore marine biomass technology, Florida may become an energy exporting state. A well planned, long term investment in the genetics, biotechnology, and physiology of Florida's tropical seaweeds could lead to major benefits for the energy business of this state.

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DISCUSSION

M. Neushul, U. of California — Have you considered the possibility of other crops on that vast area of submerged land off the coast of Florida?

Bird — We looked at the sea grasses at one time in the early part of the Florida Marine Biomass program, but we only looked at the sea grasses that are native to Florida. The three native species have low biomass yields and productivities, so we eliminated them early. They're very slow growers compared to Gracilaria. There's a possibility that these could also be bred, and their yields improved quite dramatically through classical breeding and used as a biomass crop for the very shallow areas.

FUELS FROM MICROALGAE: AN ASSESSMENT OF TECHNOLOGY REQUIREMENTS

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ABSTRACT

The Aquatic Species Program (ASP), field managed for the U. S. Department of Energy (DOE) by the Solar Energy Research Institute (SERI), seeks to develop the technology for production of liquid fuels from aquatic plants, primarily microscopic algae. As part of this program, an extensive technology evaluation was performed to determine the extent to which microalgae might replace conventional petroleum-based liquid fuels by the early 21st century, as well as to delineate the critical research areas and issues that must be resolved before such replacements could occur. Several aspects of the overall technology evaluation are discussed in this paper. Two critical methodological decisions were made in the performance of this work: (1) that the multivariate nature of technology evaluation precludes the reduction of alternative configurations to a single-valued measure of worth; and, (2) that the technology evaluation team must reconcile the perspective of the scientists with that of the decision makers. Therefore, the approach chosen includes the development of a series of detailed technology configurations, and attempts to present the results and requirements of these options as dispassionately as possible. The result of such an approach is to turn the data over to the decision makers, allowing them to seek their own expert consensus on the likelihood of success of each technology configuration.

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