MICROALGAE SYSTEMS FOR BIOFIXATION OF CO_2 AND MITIGATION OF GREENHOUSE GASES

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SUMMARY

There is growing evidence that global warming could become a major environmental problem during the 21st century. The precautionary principle commands preventive action, at both national and international levels, to minimize this potential threat. Many near-term, relatively inexpensive, mitigation options are available. In addition, long-term research is required to evaluate and develop advanced countermeasures, in the eventuality that they may be required. The utilization of power plant CO_2 and its recycling into renewable fuels by microalgae cultures provides both near- and longer-term R&D opportunities to develop novel greenhouse gas mitigation technologies.

Microalgae production is an expanding industry worldwide, with two major commercial systems in the U.S., producing *Spirulina* biomass in large ponds, and several dozen microalgae operations around the world, some of which produce *Dunaliella salina* and *Chlorella*, all used as food supplements. Commercial *Spirulina* biomass production costs are high, over \$5,000/ton of dry algal biomass, well over an order of magnitude higher than acceptable for renewable fuels production and greenhouse gas mitigation. Microalgae are also used in the U.S. and other countries in wastewater treatment, though in such systems the algal biomass is usually not harvested. This paper briefly reviews the current state-of-the-art and the R&D needs required to achieve the low biomass production costs required for microalgae fuel production and greenhouse gas mitigation.

The concept of CO_2 utilization and fuel production by microalgae cultures ("biofixation") was first proposed over four decades ago and has been the subject of several engineering-feasibility studies over the years. These analyses were based on the same type of cultivation system used by most commercial operations: open raceway ponds mixed with paddle wheels. For low cost biomass production very large growth ponds, up to 10 ha, would be required, vs. the typically less than 0.5 ha ponds presently used in most commercial systems. Also, biomass production ponds would not be lined with plastic liners, due to excessive costs. It should be noted that at least one U.S. producer operates large (>2 ha) unlined ponds, and similar ponds are used in wastewater treatment. Thus the basic process design on which large-scale microalgae biomass production technology could be based is already established.

This paper briefly update the prior cost analyses of such a process, specifically for the mitigation of CO_2 emissions from power plants by producing microalgae fuels (vegetable oil for biodiesel and byproduct methane gas). Both direct flue-gas utilization near the power plant and remote use of CO_2 captured from flue gas and piped to the algal ponds were analyzed. In the case of remote

applications, the purification and delivery of the CO_2 is a major process cost. With direct flue-gas utilization, the flue gas piping from the power plant to the ponds and the gas transfer system into the ponds become major cost issues. Overall these alternative CO_2 sources result in comparable costs, though the flue-gas utilization system is limited to about 30% of the total plant CO_2 outputs because flue gas can not be stored and the algal ponds use less CO_2 in winter and none at night. With biomass productivities thought to be achievable in the near-term with current technology, a cost of \$50/t CO_2 mitigated was projected, while a doubling of productivities (to near maximum theoretically achievable) reduces costs to \$20/MT CO_2. CO_2 mitigation costs are very sensitive to the value of the algal oil and methane fuels produced from the biomass. Land requirements depend on the type of power plant, with a conventional coal power plant requiring 6 ha per MW capacity for the highest productivity case.

The engineering analyses on which these costs analyses were based did not identify any major apparent engineering limitation to pond scales and designs. However, the major performance objectives in large-scale microalgae production remain to be demonstrated: algal species control, low-cost biomass harvesting (by settling), production of biomass with a high content of fermentable substrates or oils, and, most fundamentally, the achievement of very high productivities. Such stand-alone microalgae CO_2 biofixation and fuel production systems require long-term R&D. Near-term R&D priorities are to develop and demonstrate CO_2 utilization and greenhouse gas reductions with microalgal wastewater treatment systems. Such systems have the additional benefit of reducing other greenhouse gases, methane and nitrous oxide. The inherent appeal of CO_2 utilization, rather than disposal, the synergisms with wastewater treatment, the possibility of co-production of higher value products and the potential for world-wide applications, all argue for an expanded R&D effort and the need for international collaboration in this area.

1. INTRODUCTION TO MICROALGAE CULTIVATION

Microalgae are microscopic plants that typically grow suspended in a liquid medium (planktonic growth), although attached growth is also common. The planktonic microalgae are the focus of mass culture work. These range from unicells to colonies and filaments of up to a few hundred cells. Microalgae include the prokaryotic cyanobacteria (like *Spirulina*) and eucaryotic green algae (e.g. *Chlorella*), diatoms, red algae, and others. There are thousands of species, only a fraction having been studied in any detail, and less than a handful cultured successfully in mass cultures.

Microalgae mass cultures have been studied for almost 50 years, starting in the late 40's as a potential source of low-cost human food protein, a major concern at the time (Burlew, 1953). Concerns about water pollution starting in the 1950's focused interest in the use of microalgae in wastewater treatment (Oswald and Golueke, 1960). Many small to medium sized wastewater treatment plants now use algal ponds, although in only a few cases is the algal biomass produced actually harvested. During the 1960's microalgae were investigated for atmosphere regeneration in space vehicles. The perception during the 1970's that fossil fuels would soon run out, made microalgae culture of interest in renewable fuels production R&D. Commercial interest in high value nutritional products, led, during the 1980's, to the commercial development of a microalgae industry in the U.S., in California and Hawaii, as well as around the world. Starting in the early 1990's the threat of global warming focused attention on microalgae as a method for CO_2 utilization (Benemann, 1993). Here the concept is to use microalgae to convert solar energy and fossil CO_2 to a renewable fuel that replaces fossil fuels, thereby reducing fossil CO_2 emissions into the atmosphere.

The interest in microalgae is essentially two-fold:

1. They are thought to have very high productivities, compared to higher plants.
2. Their cultivation requires an enriched CO_2 source, such as power plant flue gas.

However, arguments for microalgae culture in CO_2 utilization must be based on the relative costs of such processes, rather than on maximum productivity arguments or the utilization of power plant CO_2, per se. Growing higher plant biomass on atmospheric CO_2 for use as fuel , is just as valid an approach to greenhouse gas mitigation as direct utilization of power plant CO_2 with microalgae.

2. HISTORY OF MICROALGAE MASS CULTURE

The first efforts to mass culture microalgae were initiated in the U.S. almost fifty years ago (Burlew, 1953), mainly because of the perception that microalgae were very fast growing plants. However, high growth rates are not synonymous with high productivity (still a commonly held, though mistaken, belief). And microalgae cultivation proved to be difficult and expensive, from the maintenance of cultures and high cost of the closed cultivation vessels ("photobioreactors"), to the harvesting and processing of these single celled organisms. However, this initial work, to which many of the early pioneers in this field contributed - Myers, Kok, Tamiya, Krauss, and others - outlined most of the problems still being addressed today: CO_2 supply, harvesting, species control, reactor design, the effect of turbulence on productivity, etc. Most of this early work concentrated on the unicellular green alga *Chlorella*, which had been a favorite for laboratory studies of photosynthesis since the 1920's.

It was in Japan that the first commercial production systems for microalgae were developed: During the 1960's several *Chlorella* cultivation facilities were established, using circular ponds, to produce a dried algal powder, sold as a "health food". Currently *Chlorella* is produced by some ten plants in Japan and Taiwan, with a 300 t/y Japanese-owned plant established in Indonesia in 1995 and a large closed tubular photobioreactor plant recently started-up in Germany. *Chlorella* cultivation is difficult, mainly due to contamination problems and the need for expensive centrifuges to harvest these cells.

The next commercial algal production system was for *Spirulina*, a filamentous blue-green alga that has been a traditional food source both in Mexico and Africa. Production was initiated in the 1970's near Mexico City, at a carbonate evaporation pond (these algae favor high concentrations of carbonate), and during the 1980's in the U.S., with one plant each operating in California and Hawaii. *Spirulina* is used primarily as food supplement (nutriceutical), with some applications as a specialty aquaculture feed and food coloring. In 1993 the Mexican plant closed, but the slack in supply was soon more than made up with expansion of the U.S. operations and the entry of many smaller facilities in China, India and elsewhere. Current world production is estimated at some 1,500 – 2,000 tons per annum, with somewhat over 50 hectares of total production area. Most systems use paddle wheel mixed, raceway type ponds, typically some 0.2-0.5 hectares, though the plant in S. California operates several larger ponds. U.S. plant-gate production costs for Spirulina can be estimated at about $5,000/mt.

Most recently commercialized was the production of green alga *Dunaliella salina*. Some strains of *Dunaliella salina*, growing at high salinities, produce high levels of beta-carotene, used as a food colorant and vitamin/antioxidant food supplement. Two plants are operating in Australia, based on extensive (up to 100 ha each) ponds, with one plant of about 10 ha using raceway ponds in Israel, and a smaller system in India. Other microalgal products of commercial interest include pharmaceuticals, animal and aquaculture feeds, in particular astaxanthin from *Haematococcus pluvialis,* fine chemicals, soil conditioners, and fertilizers, among others. However, these products are currently produced either only small scales or are still at a R&D stage, and would not have a significant impact in greenhouse gas mitigation. Microalgae ponds are also used by many municipalities and industries for wastewater treatment. However, in such ponds no effort is made to control the algal species or productivity, and, with few exceptions (e.g. Sunnyvale, California), the algal biomass is generally not harvested.

Microalgae can be grown not only in light and with CO_2 (autotrophic growth), but also in dark fermenters using sugars for both energy and C sources (heterotrophic growth). Recently, two U.S. companies have developed commercial products for the human and animal nutrition markets based on heterotrophic microalgae production. However, for CO_2 utilization this technology is not applicable, and, thus, here only the autotrophic, sunlight, cultivation is considered.

For the past two decades the U.S. Department of Energy (DOE), has supported microalgae R&D for the production of liquid (vegetable oils, biodiesel) and gaseous (methane and hydrogen) fuels and, more recently, also for CO_2 mitigation (Sheehan et al., 1998, Benemann, 2000). In Japan, a major program (estimated budget 1990 - 2000 about $250 million) was initiated a decade ago to develop microalgae biotechnology for CO_2 mitigation, but ended recently. Below, an overview of the issues in microalgae CO_2 utilization and greenhouse gas mitigation is presented, starting with a brief introduction to the basics of microalgae culture.

3. MICROALGAE CULTURE FUNDAMENTALS

The growth requirements of microalgae are similar to those of higher plants - light, water, carbon dioxide, and inorganic nutrients. Unlike higher plant cultivation, in microalgae cultures nutrients (including CO_2) and water can be relatively easily maintained at or near optimal levels, so that productivity is limited only by the amount of sunlight available and the genetic and biochemical capabilities of the algae. Environmental factors, such as pH, salinity and temperature, among others, can, within limits, be more readily managed in algal than in higher plant culture. The hydraulic nature of microalgae cultivation permits near continuous production, allowing microalgae cultures, in principle, to approach the limits of photosynthetic solar energy conversion efficiencies.

A central issue in microalgae cultivation are the "photobioreactors", the vessels in which the algae are cultivated. These can range from simple, unmixed (except by wind and hydraulic dilution), earthen ponds, to highly complex enclosed reactors. The diffuse nature of sunlight, requires that any photobioreactor must cover large surface areas. A major design parameter of photobioreactors is depth, which should be as shallow as possible. Productivity will be maximized, for given environmental conditions, at some optimal algal concentration per unit area (not volume). Thus, by minimizing depth, volume is reduced, and cell concentration maximized. This reduces overall liquid handling, and, perhaps most important, harvesting effort, whose cost primarily depends on the volume, not biomass, processed.

Different algal reactors use different operating depths: raceway ponds 10 - 30 cm; tubular reactors 1 - 5 cm; thin flat plate reactors 2 - 5 cm; and shallow cascade systems < 1 cm, for examples. However, very shallow reactors exhibit severe engineering limitations, from the outgassing of CO_2, to large temperature fluctuations, to, in particular, inability to scale-up such systems beyond very small unit sizes (typically <100 m^2) because of hydraulic slope limitations. Other considerations in choosing a photobioreactor design include species control, O_2 build-up, and most important, overall capital and operating costs.

The most commonly used, and potentially lowest overall cost, cultivation systems are the raceway, paddle wheel mixed ponds (Oswald, 1988). These optimize, to the extent possible, performance and costs. However, most microalgae strains cannot be easily maintained in open ponds - they are overrun by other algae or are eliminated by grazers. Indeed, as stated above, currently only a few algal species are grown in open pond cultures, *Spirulina* and *Dunaliella*, which require a highly selective chemical environment (high bicarbonate or high salinity, respectively), and *Chlorella*, which is subject to frequent contamination and requires production of massive (and expensive) starter cultures (inoculum). The problem of contamination and grazing is a central one in microalgae culture, as or even more important than productivity and harvesting.

4. ALTERNATIVE MICROALGAE MASS CULTURE SYSTEMS

The relative advantages, applications and costs of various types of open and closed photobioreactors designs are a matter of active research and debate. As mentioned, closed photobioreactors, have inherent problems of gas exchange (Weissman et al., 1988), in addition to high capital and operating costs. They find applications in specialty (high value) chemicals production and, in the context of large-scale algal cultures, for the production of inoculum. For the purposes CO_2 utilization and fuel production, only open pond reactors are plausible.

Four basic open pond designs are currently used in microalgae production:
1. Deeper (30 to 100 cm), unmixed (except by wind circulation), ponds;
2. Shallow (1- 2 cm) "cascade" type systems;
3. Circular ponds, mechanically mixed from a central pivot; and
4. Paddle wheel mixed, shallow (10 - 30 cm deep) raceway pond designs.

The deeper, unmixed ponds are used in wastewater treatment and were used in Mexico for *Spirulina* production. Productivities in such unmixed ponds are very low and CO_2 fertilization is not practical. Cascade systems, developed in Czechoslovakia (a 1 ha production unit was operating in Bulgaria), are very expensive, and exhibit large temperature fluctuation and high CO_2 outgassing. Circular ponds, used in *Chlorella* production in the Far East, exhibit poor hydraulics and their maximum unit size is limited to about 2,000 m^2. They are also expensive, in part due to the complexity of the central pivot mixing system. Thus, only the raceway, paddle wheel mixed ponds, which can be easily scaled-up are plausible candidates for consideration in low-cost algal biomass production.

As mentioned above, current commercial microalgae production is very expensive, at least $5,000/mt, with worldwide production being only about 3,000 – 4,000 tons/year for all three commercially produced microalgae species. Greenhouse gas mitigation ultimately requires millions of tons per year of biomass production, and production cost reductions of well over one order of magnitude. Economics of scale, larger growth ponds and systems, will result in major, but by themselves not sufficient, cost reductions. The fundamental issue, addressed below, is whether, through improved process designs and algal strain development, cheaper, more stable and much higher productivity cultivation processes can be achieved. These, along with the development of lower cost harvesting and processing technologies and favorable siting may allow sufficient cost reductions to consider such systems for fuel production and greenhouse gas mitigation.

5. PRIOR FEASIBILITY ANALYSES AND COST ESTIMATES

Several prior engineering feasibility and cost analysis (Benemann et al., 1982, Weissman and Goebel, 1987, for examples only) suggested that it may be feasible to consider large-scale microalgae cultures for energy production. That is, that it may be possible to achieve both low costs and high productivities for large-scale optimized systems. Table 1 presents a composite summary (updated to 1995 $) of the economics developed in the prior studies, Table 2 the land area needs for CO_2 utilization and Table 3 presents a more detailed cost breakdown. The analysis was for a conceptual almost thousand hectare system directly utilizing flue gas from a large coal-fired power plant, for production of an algal biomass with a high vegetable oil-content, for conversion to biodiesel fuels (though the conversion to biodiesel process is not included in the cost estimates)

TABLE 1. SUMMARY OF MICROALGAE. CAPITAL AND OPERATING COSTS (Based on Benemann et al., 1982; Weissman and Goebel, 1987, see also Benemann, 1993).

PRODUCTIVITY ASSUMED: (ash-free dry weight)	Currently Projected	Maximum Theoretical
Average Daily g/m2/day	30	60
Annual mt/ha/yr	109	218
Barrels of oil/ha-year	380	760
CO2 Fixed into Biomass mt/ha-yr	240	480
CAPITAL COSTS ($/ha):		
Ponds (earthworks, CO_2 sumps, mixing)	23,800	32,600
Harvesting (settling ponds, centrifuges)	12,500	17,000
System-wide Costs (water, CO_2 supply, etc.)	26,700	38,000
Processing (oil extraction, digestion)	10,000	20,000
Engineering, Contingencies (25% of above)	18,000	26,900
TOTAL CAPITAL COSTS ($/ha)	91,000	134,500
OPERATING COSTS ($/ha/yr):		
Operating Costs (Power, nutrients, labor, etc.)	9,850	15,300
Annualized Capital Costs (0.2x Total Capital)	18,200	26,900
Credit for methane ($3/MJ + CO2 credit)	- 2,800	- 5,600
Credit for oil produced (@$35/barrel)	-13,300	-26,600
Net Operating Costs $/ha/yr	11,950	10,000
CO_2 Mitigation Costs ($/mtCO2fixed into oil)	50	21

TABLE 2. LAND REQUIREMENTS FOR ALGAE CO_2 UTILIZATION

Assumptions: 30% CO_2 average annual CO_2 utilization
1,000 MW power plant, 0.88 kgCO_2/kWh (coal fired).
Composition: 50% lipid, 25% carbohydrate, 25% protein.
Heat of Combustion: 7.5 Kcal/g (60% C in biomass).
Avg. Annual Solar Insolation: 500 Langleys, 45% visible.
Production: 1.05 x 106 mt/yr biomass; 3.7 x 106/yr barrels oil.

Annual Productivity mt/ha/yr	109	219
Lipid fuels barrels/ha/yr	380	760
Solar Conversion Efficiency (appx.)	5	10
Fixation C mt/ha/yr	66	131
LAND AREA REQUIREMENTS:		
,000 Ha required growth ponds area	9.6	4.8
,000 Ha total area (ponds x 1.25)	12	6

TABLE 3. DETAILED SYSTEM CAPITAL AND OPERATING COSTS
Benemann, 1993, based on Benemann et al., 1982 and Weissman and Goebel, 1987

	PRODUCTIVITY ASSUMPTION	
CAPITAL COSTS ($/ha)	30 g/m2/d	60 g/m2/d
Growth Ponds:		
1. Grading, earth works	5,000	5,000
2. Walls (perimeter, central, etc.)	4,500	4,500
3. CO_2 Sumps @ $2,400/ea, require 2/4	4,800	9,600
4. Mixing System (Paddle Wheels)	5,000	5,000
5. Carbonation System (@$2,000/sump)	4,000	8,000
6. Instrumentation (Miscellaneous)	500	500
7. Primary Harvesting(Settling Ponds)	8,000	8,000
8. Secondary Harvesting(centrifuges)	4,500	9,000
Subtotal	36,300	49,600
System-wide Costs		
9. Water Storage and Distribution	4,600	4,600
10. CO_2 Delivery Pipe to Module	13,300	21,600
11. CO_2 Distribution System to Ponds	4,000	6,500
12. Nutrient Supply System	800	800
13. Buildings, Roads, Drainage, etc.	1,500	1,500
14. Electrical, Machinery	2,500	3,000
15. Extraction Process Equipment	6,000	12,000
16. Anaerobic Digestion System	4,000	8,000
Subtotal	36,700	58,000
Other Capital Cost Factors		
17. Engineering (10% of total above)	7,300	10,750
18. Contingencies (15% of 1-18)	10,700	16,150
Subtotal	18,000	26,900
CAPITAL COSTS TOTAL ($/ha)	91,000	134,500
19. Biomass Production t/ha/yr	109	218
20. Capital Costs $/t-yr	834	620
21. Barrels of Oil/y (@ 3.5 bar./t)	380	760
22. CAPITAL COSTS $/Barrel/y	240	180
OPERATING COSTS ($/ha/yr)		
23. Power (mixing, harvest., misc.)	1,500	2,000
24. CO_2 (flue gas) blower power	1,600	3,200
25. Nutrients (N, P, Fe - 50% recycle)	1,250	2,500
26. Maintenance (3% of total Capital)	2,730	4,100
27. Labor	2,600	3,500
28. Operating Costs Subtotal	9,680	15,300
29. Credit for methane (+ CO2 credits)	- 2,800	- 5,600
30. NET OPERATING COSTS $/ha/yr	6,880	10,700
COSTS $/BARREL OF ALGAE OIL:		
33. Net Operating Costs	18	14
34. CO_2 Mitigation Credits ($16/tCO2)	-10	-10
35. Annualized Capital Costs (0.2 x Capital)	51	35
36. TOTAL COSTS $/BARREL	59	39

Note that in the mitigation costs are very sensitive to the projected prices of oil and methane. This analysis suggests that with reasonable assumptions about the price of the oil, or value of CO_2 mitigation, such a process would be economically feasible. However, this is only true for the higher productivity assumption, which is considered a theoretical maximum, not likely to be fully achieved in practice. These tables demonstrate the sensitivity of such a process to productivity, suggesting a strong but not linear effect, as may be expected.

This analysis is a composite of the prior studies. Thus, Weissman and Goebel (1987) estimated substantially higher capital and operating costs in some categories than Benemann et al., 1982, and vice-versa. For example, the construction of the ponds (leveling, earthworks, walls and berms) was seven-fold more expensive in the 1987 than in the 1982 study. The rather expensive rock pond liner and concrete block construction for the walls and berms in the 1987 study, vs. simple earthworks in the 1982 report, account for these differences. By contrast CO_2 supply and transfer systems were four times more expensive in the 1982 vs. the 1987 analysis, explained by the high costs of transportation and use of flue gas in the 1982, vs. pure CO_2 in the 1987, study. In the present cost estimate the rock liner was dispensed with and simple earthworks used for the berms, with some costs added for embankment protection. A 1.5 km large diameter pipe delivered flue gas from the power plant to the ponds. Other costs were interpolated between the studies. It should be noted that the cost of flue gas delivery to the ponds and gas transfer into the culture is rather comparable to the cost of CO2 capture from the power plant and delivery to the algal ponds, though in this case the ponds can be sited remotely. Another difference between the two cases is that flue gas can not be stored at night, and thus a flue gas system would be able to use only about 30% of total CO_2 outputs from the power plant, compared to close to 60% for the concentrated CO_2 case.

The major difference with the earlier studies are the productivity assumptions. The 1987 report already assumed over a 50% higher the productivity (on a C basis) (30 g/m^2/d, and lipid content of 50%) than the 1982 report. This was in part due to the results of the intervening research with small and large outdoor ponds, providing a better measure of the achievable production (Weissman and Tillett, 1989, 1992). This estimate is used as the "Currently Projected" case in Tables 1 and 2, with twice this productivity, the "Maximum Theoretical", also cost-estimated to assess the effect of productivity on costs, though such an extremely high productivity could be reasonably expected to be only approached, not fully reached, with long-term R&D.

Even with high productivity projections and very favorable design and cost assumptions, the costs for CO_2 mitigation and fuels production with microalgae cultures still will likely approach $100/t C-$CO_2$. Although perhaps not more so than some other CO_2 mitigation options, such as CO_2 recovery and ocean disposal, these are still very high costs, suggesting the need for further process improvements, if possible, and alternative approaches.

6. MICROALGAE CO_2 MITIGATION R&D ISSUES

Many aspects of large-scale microalgae production are uncertain and speculative, and require further analysis and, most importantly, R&D, to achieve the highly productive and low cost systems that could make significant contributions to greenhouse gas reductions. Major subjects requiring R&D include:

- Application of commercial designs to low cost algal mass cultures.
- Wastewater treatment systems potential for CO_2 utilization.
- Fundamental aspects of microalgal productivity.
- Algal species control and culture stability
- Microalgae harvesting technologies for low cost production.
- Production of algal fuel.
- Large-scale culture systems engineering designs and operations.

- Resource potential and greenhouse gas mitigation impacts.

Here a brief discussion of these R&D issues is presented.

Commercial Microalgae Mass Culture Systems. The commercial raceway pond systems currently operating in the U.S. provide a foundation for the vision of large-scale, low cost, microalgae systems. The fact that such systems already exist, albeit at a smaller scale and with much higher costs then required for fuel production and CO_2 utilization, allows for some optimism about the long-term goals. An important issue is to verify the present engineering designs and cost estimates for large-scale systems and determine if further cost reductions are possible. Closed photobioreactors are too expensive (both capital and operating) to be directly useful in such applications, though small units will likely be used for inoculum production purposes.

Microalgae Waste Water Treatment Systems. Several municipal wastewater treatment facilities in the U.S. use the Advanced Integrated Ponding System developed at the University of California Berkeley uses similar paddle wheel mixed raceway ponds used in commercial microalgae production (Green et al., 1994). Similarly, the Partitioned Aquaculture System developed at Clemson University uses such ponds in aquaculture waste treatment (Brune et al., 2000). Microalgae wastewater treatment - municipal industrial, agricultural and aquacultural - represents the most likely and plausible pathway to developing and implementing low-cost microalgae CO_2 utilization / fuel production technologies in the near-term. In such systems costs are mainly covered by waste treatment credits, allowing operation at much smaller scales and lower productivities. The supplementation of CO_2 to the algal cultures would greatly increase biomass outputs and allow additional fuel production. Waste treatment systems also reduce fossil energy inputs compared to conventional treatment alternatives and reduce secondary greenhouse gas emissions (methane, nitrous oxide). Indeed, these factors are often more important in the overall greenhouse gas mitigation balance than the additional CO_2 utilization and biomass fuel production. Waste treatment processes are a high priority for future R&D in this field.

Fundamental Aspects of Microalgal Productivity. Productivities achieved with outdoor microalgae cultivation systems have been, at best, about 3 – 4 % of total solar energy converted into biomass (higher heating value), with commercial or waste treatment systems considerably lower. A 5% efficiency is extrapolated as being achievable with current technology, based on reasonable (though still favorable) assumptions. Such efficiencies are well below the 10% projected from theoretical models for photosynthesis and observed in laboratory cultures under low light intensities. A major factor that limits productivities in pond cultures is light saturation: more photons are captured by the photosynthetic apparatus under full sunlight than it can use. Light saturation could be overcome by reducing the light harvesting pigment content in algal cells, in principle doubling, or more, overall productivities (Benemann, 1990; Melis et al., 1999). Initial work in Japan has demonstrated an almost 50% productivity increase in continuous high-light laboratory cultures with a reduced pigment mutant (Nakajima et al., 2000). A high priority in future R&D is the demonstration of the feasibility of this approach to productivity maximization in actual outdoor cultures. Indeed, the feasibility analysis and economic projections in Tables 1 – 3 are based on the assumption that it will, indeed, be possible to overcome most of the light saturation effect and achieve much higher productivities.

Species Control and Culture Stability. Most algal strains, are difficult to maintain in large-scale cultures, becoming easily contaminated with invading species, subject to grazing and other biological upsets. Indeed, genetically improving strains for high productivity will result in the invasion and contamination problems becoming even more difficult. Production of large amounts of inoculum will be too expensive and not sufficient by itself to deal with this problem. There are, however, techniques that may allow maintenance of stable cultures for sufficient periods, such as management of nutrients and selective environments. Eventually, of course, starter cultures (inoculum) will need to be produced. Culture maintenance and stability is a central R&D issue in this field.

Harvesting. The microscopic nature and dilute culture of microalgae, makes harvesting a major technical and cost issue. Microalgae harvesting has been the subject of a large number of studies. Potentially the lowest-cost process is bioflocculation, in which the algae spontaneously flocculate and settle, allowing simple gravity sedimentation to concentrate the biomass. Bioflocculation is often observed in nature, and has been demonstrated experimentally in waste treatment processes (Benemann et al., 1980). One important observation is that nitrogen limited algal cultures exhibit bioflocculation. However, such processes are presently mainly observational, lacking theoretical foundation.

Fuels from Microalgae. The objective of microalgae culture for CO_2 mitigation is to convert the microalgal biomass to fossil fuel substitutes. Due to their relatively higher value, liquid fuels, such as ethanol or biodiesel, are generally preferred over gaseous or solid fuels (biogas or dried algal biomass). Production of ethanol or biodiesel requires that algal biomass high in fermentable carbohydrates or vegetable oils, respectively. Another alternative is the alga *Botryococcus braunii*, which produces large amounts (often some 50% of total biomass) of pure hydrocarbons, suitable for direct use as fuels (Wake and Hillel, 1980). How to produce algal biomass high in such constituents, without contamination or sacrificing overall productivity is a central research goals in this field. Considerable work has also been carried out in microalgal hydrogen production, but that field has not advanced significantly from an applied perspective, and faces even greater basic and applied R&D challenges than microalgae renewable fuel production and CO_2 utilization (Benemann, 2000). One possible approach is anaerobic dark hydrogen fermentations of algal biomass, either using their endogenous hydrogenase enzyme system or by exogenous bacterial fermentations. In this case little CO_2 would be required, as it could be recycled in the process.

Resource Potentials. Some prior resource assessments of the potential of microalgae for CO_2 mitigation in the U.S. Southwest suggested that as much as 10% of U.S. fossil fuel supplies could be produced by microalgae (see review in Sheehan et al., 1998). However, these only considered single factors, such as land or brackish water availability, neglecting other limitations such as climate or CO_2 sources. Thus, these were much too optimistic. A resource assessment based on a limited penetration of domestic wastewater treatment markets would conclude that microalgae systems have a very minor potential for greenhouse gas mitigation in the U.S., less than 0.1% of emissions. However, by including industrial, agricultural and aquacultural applications, as well as other greenhouse gases, more significant impacts can be projected. Also, microalgae systems for CO2 mitigation may find applications in solving environmental problems in large-scale nutrient removal and brackish water management. And, of course, the global potential for microalgae technologies in would be much larger than in the U.S., or most developed countries. Assessments of the regional and global potential of microalgae technologies for environmental protection and greenhouse gas mitigation are required.

7. CONCLUSIONS

Justifications for R&D of microalgae CO_2 utilization and greenhouse gas mitigation include: the relatively modest R&D efforts required, the existing research base for this technology, the relatively rapid progress that can be projected with these fast-growing organisms, and the benefit of this R&D environmental protection generally. Near-term R&D priorities include the development and demonstration of microalgae wastewater treatment processes that utilize CO_2 and produce fuels. Longer-term R&D will be required on increasing microalgae productivities, culture stabilities and low-cost harvesting. Demonstration of achievable productivities in year-round operations at favorable sites would be a goal of these efforts.

In conclusion, the use of microalgae in wastewater treatment would be a likely initial application for CO_2 utilization and greenhouse gas mitigation by microalgae technologies. The major advantage of such a scheme is that most of the costs of biomass production and energy recovery would be covered by the wastewater treatment function, allowing cost-effective systems at a relatively small scale. Also, such applications would reduce other greenhouse gases, such as methane and nitrous oxide, compared to conventional technologies used presently. Such an approach would also provide a starting point for commercial applications and a basis for the long-term development of larger-scale microalgae systems devoted primarily to energy production and greenhouse gas mitigation. The cost-estimates presented above demonstrate both the potential and the challenges of the latter approach: the need for very low cost and very high productivity systems. Considerable applied and even basic R&D will be required to achieve practical applications for microalgae greenhouse gas mitigation, suggesting the need for an international cooperative R&D network.

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