Title
Food and Fuel Polyculture: A Sustainable Option for Developing World Communities

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Publication Date
2006-04-01

Food and Fuel Polyculture

A Sustainable Option for Developing World Communities

by

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A capstone project submitted in partial fulfillment of the
requirements for the degree of:

Master of Advanced Studies, Marine Biodiversity & Conservation

Scripps Institution of Oceanography, University of California, San Diego

2007

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Food and Fuel Polyculture

A Sustainable Option for Developing World Communities

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December, 2006

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INTRODUCTION

World Population a Coastal Problem

Currently the world's human population is concentrated on the coast with estimates ranging from 40-60% of this population living within 100km of the coastline (figure 1) (Cohen et al., 1997). As of 2006 world population has moved past 6.5 billion with an expected increase of 40% by 2050 (UN ESA, 2001; UN ESA, 2004). This equates to approximately 2.6 billion additional people by 2050 for a total of approximately 9.1 billion souls living on and consuming resources on Earth. Ninety five percent of current human population growth is concentrated in the developing world and this trend is expected to continue through this century. Further the growth in and migration to coastal regions is expected to increase over the coming decades (Cohen et al., 1997; UN ESA, 2004).

Using the above estimates conservatively, by 2050 it is likely over 6.4 billion people will live within 100km of the world's coastline. This is just shy of the world's current total population concentrated within 100km of the coast. Given that 95% of this projected increase in human population will be in the developing world, the majority of this mass of people will be concentrated in tropical and subtropical regions with much of the growth adjoined to tropical marine ecosystems (figure 1). Further, a large portion of this growth arguably will be concentrated in and around marine biodiversity hotspots, as well as linked terrestrial centers of biodiversity (Roberts et al., 2002). During this same period the world's coastal population is undergoing significant expansion, the standard of living is also expected to increase significantly in the developing world where the vast majority of this population growth is expected to occur. Over the coming decades the combination of exploding population and substantial increases in standard of living will lead to a significant increase in the demand for energy and protein (i.e.

food fish) by the world's tropical and subtropical coastal population (UN ESA, 2001; UN ESA, 2004).

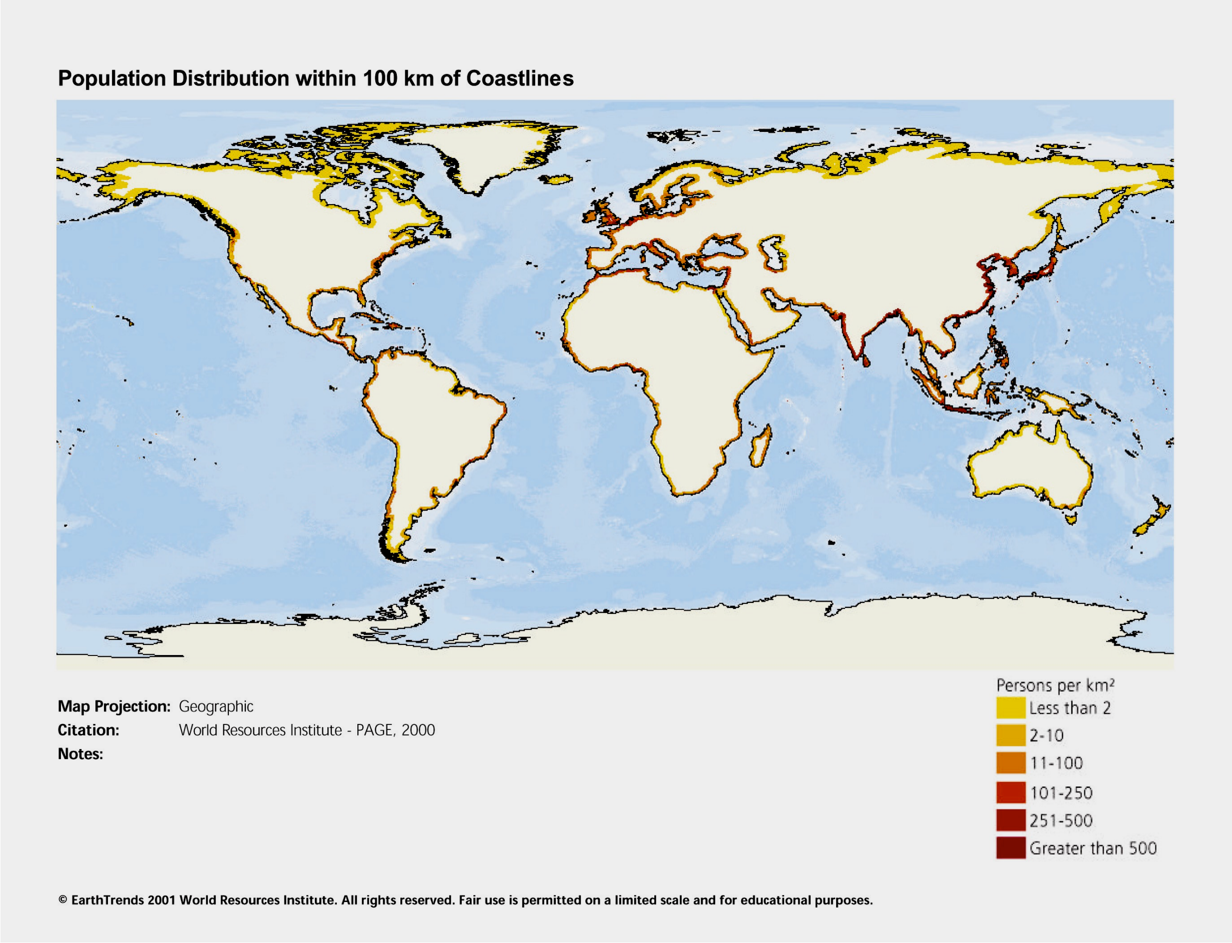

Figure 1 Population distribution within 100km of the coastline as of 2000 (EarthTrends 2001, World Resource Institute).

World Fisheries Peaked and Overexploited

The production from world marine capture fisheries has remained essentially flat at about 80 million tones since the mid 1980's. World inland capture fisheries have increased only slightly over the same period (figure 2.) (UN FAO, 2004; UN FAO 2005). At the same time world fishing effort over the last 20 years has increased significantly and in many cases this effort now targets species that would not have been considered commercially viable in the past as many traditional stocks are overexploited to the point of commercial extinction (UN FAO, 2005). Clearly the production of world capture based fisheries has peaked and continued overexploitation arguably will lead to even lower production in the future. Aquaculture will be key to meeting future world demand for fisheries products and reducing fishing pressure on the world's aquatic ecosystems. And, arguably is the only long-term viable option for increasing fisheries production. The data clearly demonstrates this trend, as aquaculture production has provided the only significant increase in world fisheries production over the past 20 years (figure 2): the same period capture based fisheries have remained flat.

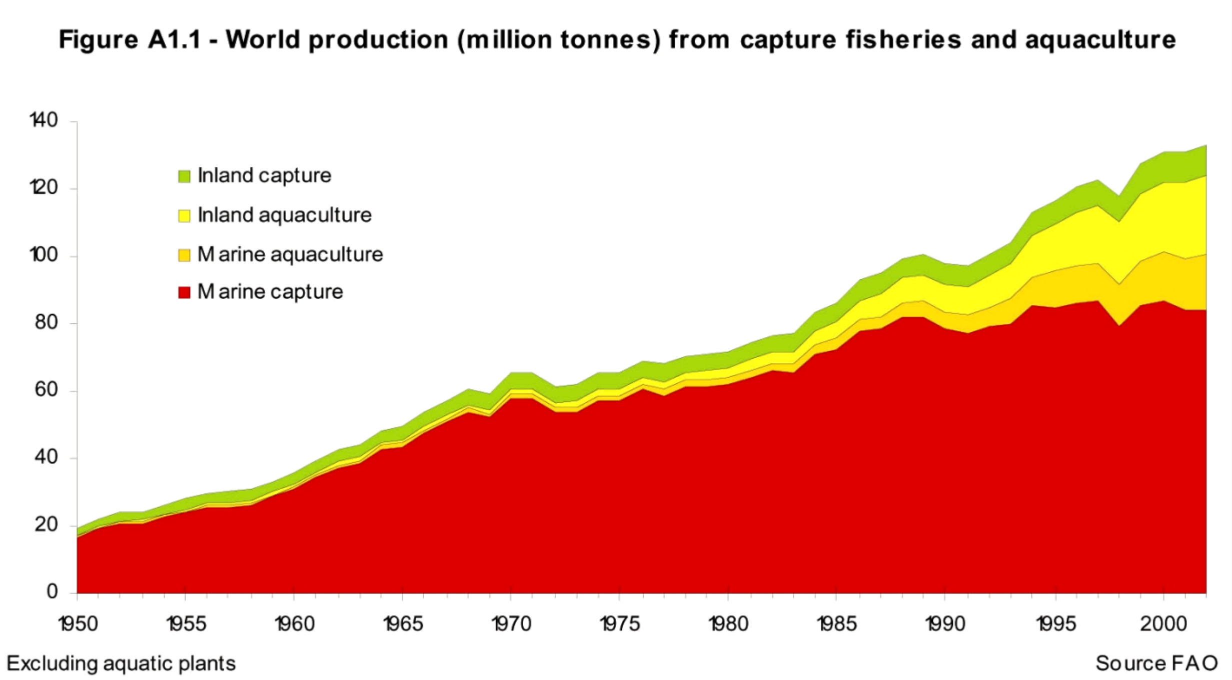

Figure 2 World production (million tones) from capture fisheries and aquaculture. (UN FAO, 2005).

Risk and Opportunity in Tropical Marine Systems

While in the long-term aquaculture offers a positive alternative to capture based fisheries, current practice are not sustainable. Of the negative externalities produced by nearly all current aquaculture operations nutrient-rich waste streams, discharged into the surround aquatic environment, are generally the most significant problem. This issue likely has the largest negative impact in naturally oligotrophic environments such as most tropical and subtropical marine systems. This in combination with warm sunny conditions equates to a heightened risk to these environments from aquaculture derived nutrients. Tropical marine systems are at risk of significant ecological destabilization even from relatively minor inputs of nutrients such as nitrogen, phosphorous and sugars from aquaculture activities (Das et al., 2004; Beman et a., 2005; Gyllenhammar & Hakanson 2005; Morand & Merceron, 2005). On the other hand, these same factors –consistent high levels of sunlight, warm water, and an aquaculture supplied nutrient stream– can be harnessed to create an algal culture system to remove nutrients from aquaculture waste water, and at the same time produce animal feeds, fertilizers and biofuels.

FOOD AND FUEL POLYCULTURE

Essence of Proposal

With the right system in place, nutrients in aquaculture waste water are not "waste" but a valuable commodity. The mechanism proposed by this paper to achieve this outcome is essentially a polyculture system with an output of food, and an additional output of biofuels. The system would utilize algal culture for biofuel production as a mechanism to remediate nutrient rich aquaculture waste streams. A food and fuel polyculture (FFP) operation would capture the negative externality (cost) of nutrient discharge into the environment and convert it to a net benefit for the polyculture enterprise, as well as a positive externality (benefit) to the surrounding community and ecosystem (Costa-Pierce, 2002; Fei, 2004; Angel et al., 2005).

The primary external inputs to a FFP system would be solar energy, water and nutrients in the form of animal feeds and fertilizers. The system would provide food and work in the form of energy for electricity, transportation, etc. to the associated human population while having no significant output into the surrounding ecosystem other than clean water (figure 3). Nutrient loads in the waste water from the agriculture and aquaculture activities would be removed and utilized by the algal culture system to produce biofuels. The system's carbon footprint would be essentially net neutral, as the same amount CO_2 produced through the combustion of biofuels to produce energy by the system would be taken up by subsequent crops of algae for biofuels (Gao K., McKinley, 1994; Benemann et al., 2003). Admittedly this is a simplistic analysis of what in application will undoubtedly have other possible unintended impacts on the surrounding ecosystem, such as escape of domesticated stock and/or pathogens from the polyculture operation. With good polyculture facility design and management, and careful plant and animal stock selection the majority of such issue can be virtually eliminated.

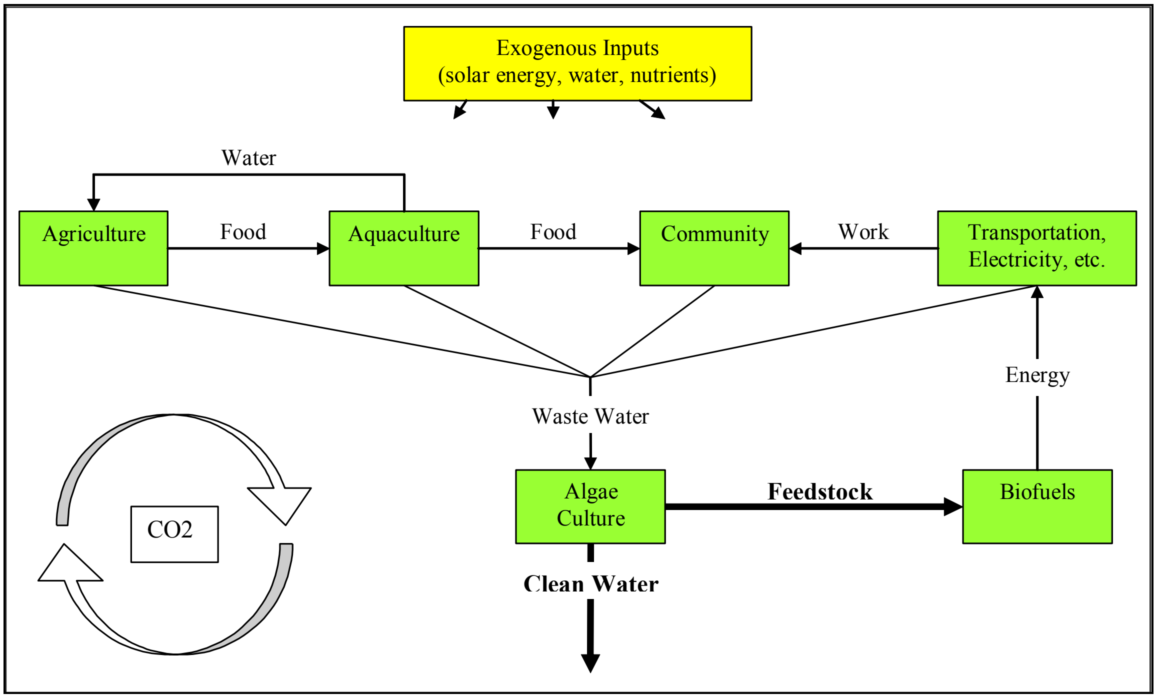

Figure 3 Flow diagram representing primary links between components of a food and fuel polyculture (FFP) system.

Quick Look at Algae to Biofuel

Algal culture can produce biodiesel, ethanol and methane, and may in the future be capable of producing hydrogen (Melis & Happe, 2001; Prince & Kheshgi, 2005). The product of biodiesel, ethanol and methane through algal culture is similar to current terrestrial production of biofuels, but algal culture offers a number of advantages over the current agricultural feedstocks used for biofuels such as corn and soybeans. The main advantage being most algae species are significantly more energetically efficient than any terrestrial plant species. Microalgae are particular efficient, with many species conservatively 10-20 times more energetically efficient than terrestrial plants (Sheehan et al., 1998).

Figure 4 provides a simplified overview of the biofuel production process for algae as a feedstock to produce biodiesel, ethanol and methane. Biodiesel production is the simplest and least energy intensive of the three. Oil (primarily triacylglycerols) derived from algal culture is combined with 10-14% alcohol by volume (typically ethanol or methanol) and a catalyst (typically sodium or potassium hydroxide) in a simple reactor. The catalyst initiates a chemical process known as transesterification in which the glycerin in the oil drops out and is replaced by the alcohol. The resulting product is an ethyl or methyl ester (biodiesel) and crude glycerin. The reaction occurs efficiently at relatively low temperatures: 110-120 °F (43-49 °C). Ethanol is produced through yeast based fermentation of algae derived starches and sugars. The fermentation process is simple and non energy intensive, but distillation requires large amounts of energy to heat the fermented product in the distillation process. Methane is produced through digestion of algae derived organic matter by methanogenic microbes. The digestion process is moderately simple and can produce heat energy as a byproduct, but for methane to be usable as a fuel it must either be compressed or liquefied which is energy intensive and mechanically technical. All three of the above biofuel production processes have some waste and/or co-product issues, all of which can be resolved if taken into consideration upfront as part of system design process.

Biodiesel
Algae Culture → Algae Oil (+ Alcohol) → Processor = Biodiesel

Ethanol
Algae → Algae Starch/Sugar → Fermentation → Distillation = Ethanol

Methane
Algae → Algae Organic Matter → Digester → Compress = Natural Gas (CNG/LNG)

(Moderate energy and/or storage intensive or technical process)
(High energy and/or storage intensive or technical process)

Figure 4 Simplified biofuel production process for algae feedstock to biodiesel, ethanol and methane.

Focus on Biodiesel

While the production of biodiesel, ethanol and methane can all be incorporated into the biofuel part of a FFP system, from this point forward the focus will be on biodiesel. In most cases the production of biodiesel will be the more appropriate option in developing world locations. Biodiesel offers the advantage of a simple low-tech refining process, relatively low energy input and easy and safe storage, handling and transport when compared to ethanol and methane. The glycerin "waste" from processing can be utilized to produce soaps, fertilizers and in some cases a component in animal feeds (Tyson, 2005). One possible problem with biodiesel is long-term storage in warm humid environments, but this can be overcome either by closely matching production to use or with biocides added to reduce microbial degradation of the fuel if long-term storage is necessary. Biodiesel also offers wide application as a fuel for transport, farm equipment, manufacturing machinery and electric generation. Electric generation is an important consideration in developing world locations. While ethanol and methane can be utilized for electric generation, diesel-electric generation is the worldwide standard for power generation at all levels below large-scale developed world power-grids. From power generation for a small to medium sized developing world community to backup power for large building in the developed world, diesel-electric generators are the most well developed and common method for electric power generation (Figure 5).

Figure 5 Left, diesel-electric generator providing local electric power for a small community. Center, typical mobile diesel-electric generator for backup and emergency power. Right, diesel-electric generator fabricated from an old railroad utility cart. (Google Images: http://images.google.com/)

Food and Fuel Polyculture System

Species and crops utilized in a FFP system can and will vary widely depending on the location of the operation, available resources, and the needs of the organization operating the facility and associated community. The FFP approach allows each operation to be tailored to local circumstances and in most cases carefully fitting the facility design and the animal and plant species under culture to local environmental and social circumstances will be necessary to realize the full potential of the FFP approach. In general a FFP system will incorporate fish ponds rearing a finfish or shellfish product. The nutrient-rich water from the fish ponds then flows into an agricultural product. Possible options include a food algae crop, a water intensive crop such as rice, or a hydroponic system which can incorporate a wide variety of traditional terrestrial agricultural crops. The waste water from all crops then flows into algae ponds designed specifically for algal culture for biofuel production. Algae are then harvested from these ponds and in the case of biodiesel production algae oil is extracted from the crop and converted to fuel. The remaining algal material is then utilized in animal feeds, fertilizers, or for the production of other biofuels. Waste water leaving a FFP system should be quite nutrient-poor and have a low pathogen load "clean" (Figure 6).

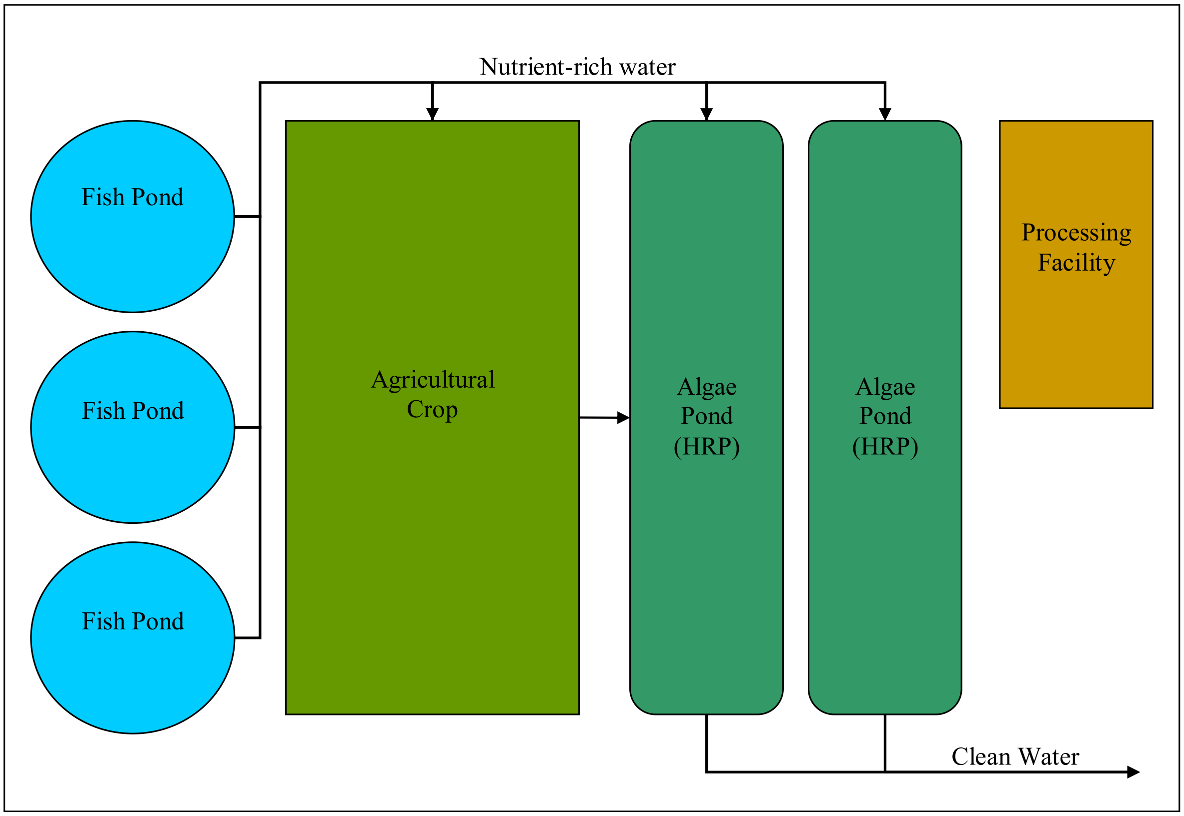

Figure 6 Food and Fuel Polyculture (FFP) system overview incorporating High Rate Ponds (HRPs).

Based on the most current research results the High Rate Pond (HRP) design seems to be the best performing large-scale algae culture system for the species of algae tested as candidates for biofuel production to date (Sheehan et al., 1998; Huntley & Redalje; 2007). It has been used effectively for both microalgae and macroalgae production. Typical design is a large oval raceway with a center divider. Water flow is maintained in the HRP via a paddlewheel and CO2 is injected in the case of high-density culture operations. HRPs are typically shallow (10-30cm) in the case of microalgae culture and deeper (1m +) in the case of macroalgae culture (Figure 7).

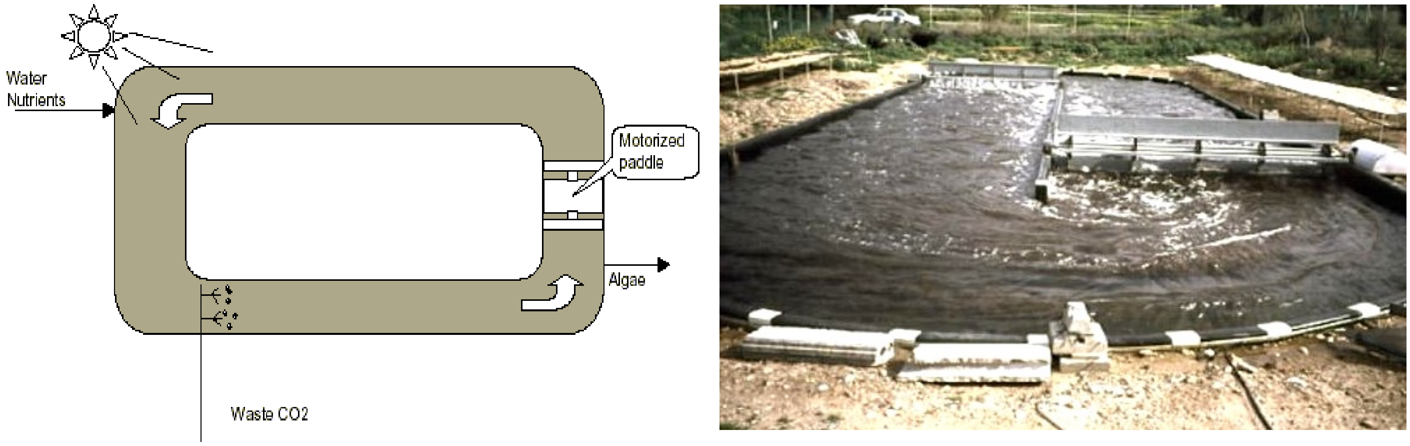

Figure 7 Left, general design of a High Rate Pond (HRP) (Sheehan et al., 1998). Right, HRP in operation (Google Images: http://images.google.com).

DOES THE WORLD HAVE ENOUGH ROOM?

Rough Estimates from Available Solar Energy Calculation

The major, and I would argue reasonable, assumption this estimate hinges upon is easily achieving a 1% photosynthetic available radiation (PAR) efficiency from algae under cultivation. PAR efficiencies of 2% and above have been reported for Miscanthus (Clifton-Brown et al., 2001). Large scale algal culture in early pond systems have achieved 10% PAR efficiencies and relatively long-term trials under laboratory conditions have reported greater than 20% PAR efficiencies with microalgae (Sheehan et al., 1998). Given a moderate level of investment in refining current algal culture technology directed at biofuel production, PAR efficiencies of 2% should easily be achievable at a commercial production level and in the near future 10% PAR efficiencies may be commercially achievable.

The following calculation is designed to be conservative. It uses a 1% PAR efficiency and does not consider any of the earth's ocean surfaces as usable for biofuel algal culture.

- The Sun delivers 120,000 terawatts (TW) to the earth's surface annually
- The earth's surface is approximately 28% land area (149,000,000 km^2)
- Earth's human population currently uses 13 TW annually
- Current human population is approximately 6.5 million

120,000 TW (from sun) * 28% (earth land area) * 1% (PAR efficiency) = 336 TW available

13 TW (needed) / 336 TW (available) = 3.86% available land

3.86% (available land) * 149,000,000 km^2 (earth land area) = 5,750,000 km^2 or 575 million ha

575 million ha (needed land) / 6.5 billion people = 0.088 ha per person

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Given the above, a rough but reasonable estimate for the land needed to produce enough biofuels too meet the energy demands of the current world population is approximately 0.088 ha per person or less than a quarter of an acre per person. Bump PAR efficiencies up to a reasonable 2% and the above figure is cut in half—approximately 1/10 of an acre (0.044 ha) per capita to provide the world's energy needs through biofuels begins too seem very reasonable. If you bring PAR efficiencies up to arguably achievable levels of 5-10% and/or utilize ocean surface area, the concern of large-scale biofuel production through algal culture competing for space with terrestrial food crops quickly evaporates.

STATE OF ALGAE TO BIOFUELS

Microalgae to Biofuels

Aquatic Species Program (ASP), NREL, DOE

From 1978 to 1996 the US Department of Energy's National Renewable Energy Laboratory ran the Aquatic Species Program (ASP). The main focus of this program was the production of biodiesel from high lipid-content algae grown in ponds, utilizing waste CO_2 from coal fired power plants (Sheehan et al., 1998). In the early years of the ASP program a collection of over 3,000 oil producing strains of organisms (primarily microalgae) was amassed from samples taken from sites in the west, northwest and southwest continental US, and Hawaii. After screening and characterization efforts the collection was reduced to around 300 promising species, mostly green algae and diatoms. The collection is now housed at the University of Hawaii and is available to researchers (Sheehan et al., 1998). At the height of the ASP program much of the work was focused on the physiology and biochemistry of algae as it related to improving oil production in algal organisms—particularly nutrient deficiency as a trigger for increased oil production (Sheehan et al., 1998). While the ASP program found contradicting results using nutrient deficiency culture techniques, their work clearly provided the foundation for more recent work which has demonstrated the utility of nutrient deficiency as a mechanism to increase oil content in algal cells (see: Dempster and Sommerfeld, 1998; Yamaberi et al., 1998; Peng et al., 2000; Miao and Wu, 2003; Huntley and Redalje, 2007) The latter years of the ASP program were mostly focused on molecular biology and genetic engineering techniques for improved oil production in microalgae, and the development of large-scale algae production systems. This work was a major factor in refining the design of the High Rate Pond (HRP) system currently used by a number of commercial ventures for the production of Spirulina (*Arthrospira sp.*) and other commercial algae species, and the algal culture system suggested for food and fuel polyculture in this paper.

The majority of public research conducted during the period the Aquatic Species Program was active was either directly part of the program or contract work funded through the ASP. The program's basic conclusion was microalgae production of biodiesel was technically feasible but economically unfeasible. The program concluded the factors effecting cost the most were biological, and not engineering related. Even with favorable assumptions of biological productivity, their projected costs for biodiesel were two times higher than petroleum diesel fuel costs at the time (Sheehan et al., 1998). At the time this conclusion was made oil was at approximately $25 per barrel. The program was closed by the US Department of Energy in 1996, but a number of the researcher involved continued to work in the area of energy production through the culture of microorganisms.

Recent R&D work

After the closure of the Aquatic Species Program the majority of public research work on microalgae for biodiesel production shifted to academic institutions—mostly in the US, Japan, Israel, and more recently China. The vast majority of this work has been high-tech in nature and only really appropriate for further development and application in industrialized nations. The focus of this recent work is split to opposite ends of the spectrum. The majority of the work is narrowly focused on lab-scale research on the characteristics of individual microalgae species – such as lipid profiles– or oil extraction and processing techniques (see: Dempster and Sommerfeld, 1998; Yamaberi et al., 1998; Peng et al., 2000; Sawayama et al., 1999; Keffer & Kleinheinz, 2002; Miao & Wu, 2003; Miao & Wu, 2006). A much smaller collection of work has focused on rough calculations of the economics and engineering of utilizing microalgae for biofuel production as a method to replace large portions of the world's energy needs—such as replacing all petroleum used by the US for transportation (see: Briggs, 2004; Huntley & Redalje, 2007). Through an extensive literature search I was unable to find any public research work moving towards application of algae culture for biofuel production to small or medium scale ideas/projects. Though it does appear that some research at this level is being conducted in the private sector, but results –for obvious reasons– have not been published.

Future microalgae R&D needs: hurdles to application

A primary hurdle encounter culturing microalgae outside of a lab environment –particularly large-scale production in open ponds– are problems with species dominance and predation. Indigenous species of algae frequently will out-compete domesticated species under culture replacing a crop of high-lipid algae with an unusable product. Similarly zooplankton predators can invade a pond system and consume a significant portion of the target species under culture. This has been a significant issue for all research work on large-scale production of microalgae for biofuels (Sheehan et al., 1998; Huntley & Redalje, 2007). Huntley and Redalje (2007) discuss the use a two part culture system that seems to address the problem of species dominance and predation effectively. In their system a permanent colony of the algae under culture are maintained in a closed photobioreactor at high densities. The colony in the photobioreactor is used to inoculate grow-out ponds with an algae harvest cycle of 3-4 days. This method advances target algae species growth in the grow-out pond which allows harvest to occur before problems of species dominance and predation can take hold. This appears to be a major advance in large-scale microalgae production.

Other difficulties with large-scale culture of microalgae for biofuel production include problems maintaining suspension in the water column of the grow-out pond, difficulties with harvesting and extraction of lipids, DO supersaturation, and photoinhibition where algal cells collect more solar energy than can be utilized in photosynthesis causing damage to the cell (Sheehan et al., 1998). A further hurdle to application to the FFP system is the generally technical nature of current large-scale microalgae culture systems for biofuels. Example, most designs utilize CO2 injection to achieve maximum production per given area and to stabilize pH. Some, like the two part culture system described above, incorporate large lab like components in the facility.

I would argue that microalgae culture for biofuel production holds great promise for the industrialized world, but in the short-term it is likely too technically and engineering intensive for the food and fuel polyculture concept. Long-term, as the culture technology develops and matures, microalgae for biofuels could be retooled for use in small to medium scale projects in the developing world.

Algae for Food and Fuel Polyculture

Macroalgae likely best candidate

Given the current state of algae culture technology, I would argue that large-scale macroalgae culture for the production of biofuels offers a number of significant advantages over microalgae culture and is likely the best candidate for the food and fuel polyculture concept. The polyculture system remains basically the same. With the only major addition being attachment structures in the High Rate Pond system such as float or rope attachments similar to what is currently already in wide commercial use (Figure 8). Macroalgae culture technology is well established at the commercial level and grown commercially in many parts of the world. Japan has produced around a half million tons annually of *Porphyra, Undaria* and *Laminaria sp.* for decades (Gao and McKinley, 1994). Culture difficulties such as maintaining target species dominance within the grow-out pond and predation by unwanted organisms are greatly reduced in macroalgae culture when compared to microalgae. Macroalgae harvesting can be accomplished through simple hand or mechanical means, and extraction of lipids would likely be very similar to the techniques used with terrestrial grain crops such as soybeans. In the case of application to a FFP system, the macroalgae component could be designed with the goal of efficient moderate intensity production as apposed to maximum productivity. This would replace the need for CO2 injection with a simpler aeration system, and should eliminate the problems of DO supersaturation and photo inhibition.

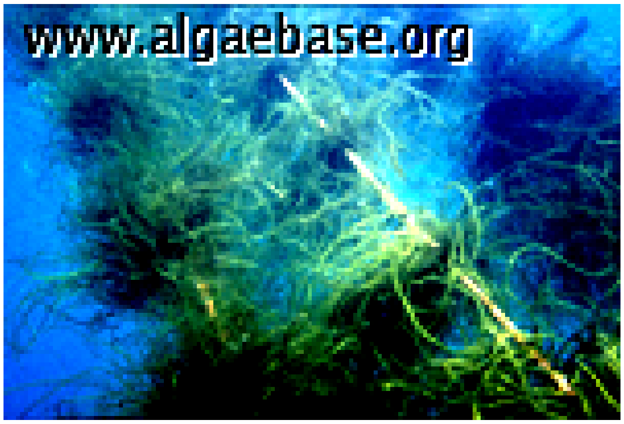

Figure 8 *Gracilaria sp* growing on a rope-culture system (www.algaebase.org).

While a few reviews of the potential for macroalgae to biofuels have been published (see: Chynoweth et al., 1987; Calvin & Taylor, 1989; Gao & McKinley, 1994), actual research work on macroalgae culture for biofuel production appears to be completely lacking. This leaves two major questions unanswered regarding utilization of macroalgae culture in a FFP system. First, are achievable PAR efficiencies under culture at least close to that of microalgae? At first glance, I would argue macroalgae PAR efficiencies for some species are high enough to fit in the FFP system. Example, Gao and Mckinley (1994) projected the production of *Laminaria japonica* on an annualized basis to be 6.5 times the maximum projected yield for sugarcane on an areal basis. Second, what are the oil and sugar profiles of species with acceptable PAR efficiencies? At this time I am unable to find any published work detailing oil or sugar profiles of macroalgae.

FOOD AND FUEL AS A CONSERVATION TOOL

Two Distinct Opportunities

The food and fuel polyculture concept offers two distinct opportunities as a conservation tool. First, human generated nutrient-rich waste streams pose a significant threat to aquatic ecosystems around the world. Remediation of nutrient-rich waste streams is inherent to the FFP system—the concept values agriculture and aquaculture “waste” as a commodity to be captured and converted into fuel. The conservation action of reducing discharge of nutrient-rich waste should occur with little or no political/economic input. Second, production of world capture based fisheries has peaked and continued overexploitation likely will lead to even lower production in the future. Aquaculture will be key to meeting future world demand for fisheries products and reducing fishing pressure on the world’s aquatic ecosystems. Reduction of fishing pressure on local ecosystems is an opportunity presented within the FFP concept, but NOT inherent to the concept. Reducing the "need" to fish by increasing available aquaculture derived food and materials does not necessarily equal reduced fishing pressure. Political/economic input will likely be needed to achieve the conservation goal of reduced fishing pressure as an outcome of implementing a FFP project.

To achieve the full potential of the food and fuel polyculture concept a project will need to:
1) Establish clear links between development and conservation. 2) Acknowledge trade-offs from the start and with all parties involved. 3) Work toward specific goals with specific time frames.

4) Employ adaptive management techniques—learn from doing as part of an "experimental design". 5) Projects with conservation and development goals must help local people do something they want in order to be successful. (see: McShane & Wells, 2004)

NEXT STEPS FOR FOOD AND FUEL POLYCULTURE

I would argue that new research paths in algae culture for biofuel production need to be followed in order to achieve results for application in the near-term. Maximum solar conversion (PAR) efficiency are likely not necessary for commercial success with algae culture for biofuels—particularly in the case of food and fuel polyculture systems. A focus on simple easily applied culture techniques may yield a similar cost/benefit ratio per unit invested compared to employing the latest intensive technology to achieve maximum yield. Research and development efforts should be refocused toward small to medium scale ideas and projects with an emphasis on applied, relatively low-tech systems. The overwhelming majority of past and current work pertaining to algae culture for biofuel production is concentrated on microalgae. Microalgae holds great promises and this work should continue, but active work with macroalgae for biofuel production should be initiated and receive at minimum a similar level of effort. Screening of potential macroalgae candidate species for biofuel production, and developing technology transfer from current commercial algae farming operations for use in FFP systems are strongly recommended starting points. The concept of food and fuel polyculture is in its infancy, but with moderate investments in research to further develop the system's components, the concept can play a role in providing food and energy to the world's population while at the same time helping to conserve valuable natural resources— particularly those in at risk aquatic ecosystems.

ACKNOWLEDGEMENTS

I would like to thank my Capstone Advisory Committee –Nancy Knowlton (chair), Clark Gibson, B. Greg Mitchell, and Dale Squires– for all of their help and guidance with my work on the FFP concept. And, the class of 2006 MAS students and CMBC faculty for their input.

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