ALGAL TURF SCRUBBERS: CLEANING WATER WHILE CAPTURING SOLAR ENERGY

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EXECUTIVE SUMMARY

Algal Turfs and Algal Turf Scrubbers (ATS)

Algal Turfs are biodiverse communities of unicellular to filamentous algae of all major algal phyla. Algal Turf Scrubbers (ATS) are bioengineered ecosystems dominated by algal turfs. They clean water to very high quality, and remove CO2 from the atmosphere by capturing solar energy at rates 10 times that of agriculture and 50 times that of forestry.

ATS was invented at the Smithsonian Institution, by scientist, Walter Adey in the 1980s as a tool for controlling water quality in highly diverse model ecosystems. The technology received extensive R&D for aquacultural, municipal, and industrial water cleaning by Dr. Adey, using venture capital, through the 1990s. Later, HydroMentia, Inc., of Ocala, Florida, engineered ATS to landscape scale of 20-50 Mgpd (it is important to note that this is a modular system, capable of expanding to any size.) A 2005 independent study of ATS, by the South Florida Water Management District and the IFAS Institute of the University of Florida, certified ATS as 5-100 times more cost efficient at removing nutrients from Everglades canal waters than the next competitor, the STA, a managed marsh system. ATS and STA were the final contestants in a 15-year study of nine technologies, and ATS was the only technology that created a useable byproduct.

Water Quality and Energy Independence

ATS systems are capable of removing N and P from surface waters in the mid latitude US at $0.60/kg and $10.60/kg respectively, and independently producing an energy product consisting of biodiesel and Butanol. Since they are controlled ecosystems, using local algae, ATS does not suffer the major disadvantages of agricultural crops, which for maximum efficiency require fertilizers, herbicides and pesticides. ATS removes CO2 from water and the atmosphere, and can be configured to remove CO2 from power plant stack gases. As a normal part of operations, ATS removes heavy metals, break down toxic hydrocarbons, and oxygenates treated waters.

The Competition

Many technologies are under development for solving the U.S.'s energy dependency. Some, like artificial photosynthesis require major technological breakthroughs; others, like agricultural crops, i.e., bioenergy, require intensive application. Switchgrass, a new hope for solving these problems, requires much more R&D and great land area. There are also microalgal techniques that require genetic engineering of single species of special characteristics. All of these techniques have environmental consequences that are potentially very significant. All are monocultural and agro-industrial by their nature, unlike ATS, which uses a biodiverse ecosystem of local organisms.

CHALLENGES

Population growth, modernization, globalization, and the subsequent burden and stress they continue to place on the planet have created immense socioeconomic, health, and environmental challenges for society. Unfortunately, solutions receive different priorities depending on the scientist, NGO, or governmental agency in charge; efforts toward one solution are often piecemeal and only mildly effective, and unfortunately, often exacerbate other problems. As an example, current energy solutions are multifold, with solutions ranging from a combination of nuclear, coal, natural gas, oil, and recently biofuels. All however present numerous problems: nuclear has the problem of safety and security concerns; oil and natural gas have issues of over demand, supply, accessibility, and pollutant release; and coal, although readily and cheaply abundant, places an immense burden on the environment due to mining effects, and the release of carbon dioxide and other harmful pollutants. Assuming that sustainable solutions are even approached, all of those on the table today involve methodologies that will have serious impacts on the atmosphere, water quality, and biodiversity.

Biofuels are strong contenders to overcome some of the problems of fossil fuels; yet approaches that use corn, soy, require excessive land and rely heavily on fertilization. This would place a tremendous burden on food-cropland, streams, rivers, and coastal waters, and would lead to eutrophication, organic chemical toxicity and a decline in biodiversity. Switchgrass still requires decades of R&D. The problems are as numerous as the solutions. The key is to find solutions that have multiple benefits: they must be economically competitive and biological in nature, but ultimately lead to environmental restoration.

THE SOLUTION

What is an algal turf?

Algal turfs are communities of organisms dominated by aggregations of unicellular to branched filamentous algae and cyanobacteria (blue-green algae). They are attached to hard substrates, rock, wood or plant stems. Most major groups of algae provide species that occur in turfs: green algae in fresh waters, brown and red algae in marine waters and diatoms and blue greens universally. In addition, they support numerous epiphytes and enmeshed algal unicells, and like grasslands and lawns, are often maintained by fish and invertebrate grazers in the face of competition by larger algae. It is likely that there are tens of thousands to hundreds of thousands of algal species that can form algal turfs. While algae provide algal turf's primary structure, by definition, these are biodiverse communities containing numerous protozoans and small invertebrates. They are sometimes referred to by other names e.g.: periphyton, aufwuchs, algal mats, and biofilms.

Why algal turfs are so productive

Given strong current, surge or wave action, sunlight and regular grazing, algal turfs can be highly efficient at capturing solar energy. Most individual cells of algal turfs are photosynthetic; however, the extraordinary level of efficiency of algal turfs is also partly the result of high levels of mixing; flowing water, forced against cells by surge, greatly increases chemical exchange. In addition, photosynthesis in most higher plant and planktonic algal cells is biochemically inhibited in full sunlight, especially at high temperatures. Rarely are water temperatures as high in aquatic situations as in terrestrial environments, and of course, the typical problem of terrestrial plants: water loss, stomate closure and CO2 cut off does not occur. Most important, however, because of the back and forth swashing of filaments in wave surge, individual cells receive flashing light and no cells are fully shaded by others. This allows a very high level of light capture, and typically, as measured by oxygen release, there is no inhibition even in full tropical summer sun at mid day. Equally important, a very high proportion of light energy captured is transferred to chemical storage as added biomass.

For many of the same reasons, algal turfs are only very weakly inhibited by low nutrient levels. Individual cells are able to uptake carbon, nitrogen and phosphorus at fractions of ppb levels. Since the water film adjacent to each cell cannot be exhausted of nutrients in a surge and flow environment, relatively high levels of productivity occur even at very low nutrient concentrations.

For decades, the dream of microalgae, planktonic algae grown in large vats or even ponds, for food, biochemicals and more recently bioenergy, has lived on. Because it is difficult to efficiently achieve high productivity levels and to harvest planktonic algae, intensive searches for unique species, and more recently to alter species by biotechnology, have been undertaken to solve these problems. However, at the end of a major bioenergy project at the U.S. Department of Energy (DOE) in the 1990's, it was concluded that their greatest difficulties lay in trying to maintain a monoculture - algal weeds are everywhere. As biodiverse ecosystems, algal turfs are not subject to these serious problems.

ALGAL TURF SCRUBBERS

An Algal Turf Scrubber is applied biomimicry—an ecologically engineered, algal turf dominated, mini-ecosystem. An individual Algal Turf Scrubber is a sloping plastic membrane surface, square meters to hectares in dimension, and has a rough surface or is overlain by a mesh screen of several millimeters in pore size. A thin layer of water (1-2 cm thick) is pulsed across the screen. Algal spores from the waters being treated settle quickly on the screens and grow rapidly, taking up nutrients and carbon dioxide as they grow.

Depending upon season and temperature, the resulting algal turf must be harvested every 5-15 days to maintain high levels of productivity. Given this regime, Algal Turf Scrubbers are considerably more productive than terrestrial crops. Traditional crop production during the summer in the United States is 2-4 grams dry weight/m^2/day. Switchgrass, given intense fertilization, can be higher than corn and soy, but year-round production in the central U.S. is only 3-6g/m^2/day. Unlike algal turfs, switchgrass provides tough stalks that require specialized, and, as yet unproven at industrial scale, enzyme breakdown. Algal turfs have less recalcitrant fibers and no lignin, and are more easily refined than even corn and soy--at the same levels of light, they can photosynthesize and produce new tissue at roughly 10 times that of typical crops (and 50 times that of forests.) Moreover, in central to southern areas of the country, Algal Turf Scrubbers can be operated year round.

Algal turf scrubbers do not require fertilization; they operate at high production levels on waste nutrients. Even if nutrient levels on the major river systems on which operation is planned were to be reduced to pre-Columbian levels, production would remain moderately high because of the great efficiency of nutrient capture. Fish are the primary grazers of algal turfs, but they cannot function in the thin water layer of the scrubber. There are micrograzers of algal turfs such as chironomid larvae, but they are naturally kept in check by frequent harvest, and the dense bird populations that flock to large scrubbers. Diseases are not destructive because of the high diversity of algal turfs; individual species come and go to little effect.

MATURE TECHNOLOGY

The above information is supported by dozens of experimental studies and hundreds of years of operational time (i.e., multiple ATS over 25 years of operation). Moreover, ATS systems have received over 15 years of research and development testing followed by a ten-year history of pilot plant construction and operation for water quality control. This not only includes ATS systems for water treatment, but also for aquaculture. Two full-scale plants of tens of millions of gallons per day were operated for finfish production in Florida and Texas (one for over ten years) with great technical success. Finally in 2005, the University of Florida provided proof of concept with respect to the economic viability of ATS. This study reported on a one hectare ATS pilot system, normalized to a 56-acre, 50-year operation, and was funded and monitored by the South Florida Water Management District and the IFAS Institute of the University of Florida.

THE COMPETITION

Terrestrial Plants: Corn and soy are currently cultivated to produce gasohol, biodiesel, and methane. To achieve even moderate productivity, they require fertilization and often treatment with herbicides and pesticides. Diseases can become serious hazards in these extensive monocultures. Even with best management practices, nutrients and toxic compounds will find their way into already highly overburdened lakes, rivers and coastal waters. Most of the production of these plants in temperate zones occurs in summer, with die off or aestivation in winter.

Microalgae: Most of the algal production work for the last half-century has been carried out on plankton (i.e., in large vats or ponds). These “microalgae” systems have a disadvantage in that the cells are free in the water column. The cells move with the water and are difficult to “mix”; being unattached, they carry their local water film with them and that film acts as a barrier to metabolite exchange; shading and light inhibition are difficult to avoid. Moreover, harvest is difficult, in the past requiring expensive centrifugation. There are newer methods of precipitation for microalgae, but they require chemical treatment and a sludge that must be managed. These are batch processes requiring continual management.

For the last decade, considerable effort has been expended to improve microalgal production by searching for and culturing specialized species and by genetically altering species to provide greater solar capture or more desirable storage products. However, these types of approaches have two major drawbacks: the basic problems of invasive species and monoculture.

In terms of biomimicry, ATS systems are like membranes at the cellular level. Efficiency is likely to be greater, given the same solar input and driving energy, on an ATS, than in a pond or vat. Also, ATS systems are communities and ecosystems; they employ local pre-existing species; since the biodiversity is high, diseases are not a factor in long-term production. None of the primary challenges of modern agriculture: herbicides, pesticides, fertilizers, soil depletion, drought and diseases are significant factors with ATS.

It is our belief that not only are ATS systems economically more competitive than microalgal pond systems, they are easier to maintain, require less energy and land for production, and produce more useable biomass than competitors. More importantly, the Algal Turf Scrubber is based on a biodiverse ecosystem, not a monoculture, and therefore has the advantage of being “local”, stable, and sustainable.

ENVIRONMENTAL BENEFITS OF ALGAL TURF SCRUBBERS

ATS systems, through the process of cleaning water, produce multiple environmental and social benefits. The ultimate result is clean, healthy water, as well as restored waterways. This is accomplished in several ways:

Environmental Benefits

As in most photosynthesis, algal turfs abundantly release oxygen; in ATS systems, oxygen is dissolved into the overflowing water. It is not unusual for water flowing off an ATS plant in the afternoon to be highly supersaturated. In waters needing extensive bioremediation, such as the Chesapeake Bay and the Gulf of Mexico, large ATS plants would have a significant and immediate impact on downstream dead zones.

Nitrogen and Phosphorous

ATS systems are well known for their abilities to “scrub” nitrogen and phosphorus. Their lack of sensitivity to nutrient concentration, until extremely low levels are achieved, provides the ability to accomplish high water purity. Equally important, when high biomass production is desired, it is unlikely that fertilization will ever be required, except for the most specialized of uses.

Carbon Dioxide

In some fresh waters, mostly those of moderate quality and higher pH, readily available CO2 in the water can be exhausted during the afternoon, as pH in water flowing down a large ATS is driven to over 10, affecting productivity. A simple solution to this problem is to link CO2 in power plant stack gases to large-scale ATS systems. While this can be done with today's technology, an insertion process under development would greatly improve transfer efficiency, and would increase the CO2 scrubbing aspects of ATS from simple atmospheric carbon removal to pre-atmospheric, industrial removal. Theoretically, ATS systems, at very large scale, are capable of not only blocking power plant release of CO2 to the atmosphere but of significant draw down of existing atmospheric CO2.

Heavy Metals

It has been known for a half century that algal cell walls adsorb heavy metals, and it is a characteristic of ATS phytoremediation, that heavy metals are removed from treated waters and sequestered into the algal biomass. This is an added value of ATS water cleaning, especially in waters with an industrial or urban component.

Toxic Organics

Combined with solar ultraviolet, ATS systems with high oxygen supersaturation break down entrained hydrocarbons. There is an extensive general research literature on this process, and a single ATS research study in the late 1990's demonstrated that when combined with artificial ultraviolet, ATS systems have considerable capability of breaking down a variety of chlorinated hydrocarbons. Additional research is necessary in this area, as a single study, even with a considerable laboratory support, cannot provide the basis for systems engineering; however, it is likely that if ATS is carried out at very large scale to produce bioenergy, it will significantly reduce toxic hydrocarbons in aquatic environments and ultimately the ocean.

BYPRODUCT POTENTIAL OF ALGAL TURF SCRUBBERS

In addition to the environmental benefits of ATS systems, there is a large potential for valuable byproduct use and reuse to create new economic opportunities. The key to realizing the full potential of Algal Turf Scrubbers lies in approaching solutions from a whole-systems perspective. Using ATS interconnected to other existing technologies, such as fermentation systems or anaerobic digesters, the potential for byproduct reuse increases dramatically. Not only do you get clean water and nutrient removal, you have the potential to sequester industrial CO2, develop new sources of renewable energy, and create new sources of fertilization and animal feed. This is accomplished by re-imagining how value is defined and produced. Trapped within the confines of one technology or solution, it is naturally impossible to extend past the core competency of any technology to create more abundant value. However, like nature, when connected to other technologies, emergent qualities in the system produce a cascade effect. One waste or byproduct becomes the input for another byproduct. In this way, we can wring every amount of value out of the system, while simultaneously eliminating waste and improving the environment. It is a win-win-win situation.

Biodiesel and Energy Production

Bioenergy, as biodiesel, gasohol and methane from corn, soy and waste biomass, has become an important component of U.S. energy use. However, bioenergy remains at only a few percent of total U.S. requirements, and the most optimistic estimates would put it in the maximum range of 15-20% of imported oil (see e.g., Lovins et al,

2004. Winning the Oil Endgame). The primary difficulty with agricultural bioenergy is that at current corn, soy, switchgrass levels of productivity, to match imported oil, all the agricultural land in the U.S. would be required. That could perhaps be cut in half with extremely intensive culture, but the fertilizers and pesticides required to do that would provide an ecological disaster. At an MIT seminar in 2005 on the U.S. energy crisis and its relationship to global warming, the participants could ascribe only a minor role to bioenergy and suggested nuclear as the only, but admittedly difficult option. On the other hand, some major organizations, such as NRDC, support a bioenergy option.

The U.S. Department of Energy (DOE) funded a number of projects to use microalgae for oil production in the 1990's. Being planktonic, systems of moderate productivity and low economic efficiency, they were not competitive at then existing prices, but they did provide the basis for understanding the conversion of algal biomass to biofuels – mostly either biodiesel or methane. An analysis of the algal product from the S-154 test facility (www.hydromentia.com) provided 55% volatile solids of dry weight, which is more favorable for direct energy conversion than the algae of the DOE study. The likely range based on IFAS economics is $0.85-$1.00/gal FOB at an ATS-plant. At roughly $40/bbl, this is highly competitive with fossil fuels today. When coupled with potential nitrogen and phosphorous credits, the economic potential becomes compelling, with costs below $0.40-$0.50 cents a gallon.

This is an area where economic research is required – namely what is the cheapest way to convert ATS algal turf to a useable energy product? Microalgae researchers usually settle on methane, though many are searching for species high in oil, or genetically engineered species, to achieve greater productivity. ATS scrubbing of moderate nutrient waters, tend to produce a biomass that is rich in diatoms (which carry their storage products as oil), and diatoms were probably the source of most petroleum. This is likely to tip the scale to a biodiesel product, though several other options are also viable.

ATS SYSTEM ENGINEERING

During the period from 1980-1991, ATS analysis consisted primarily of basic laboratory research on bench scale to greenhouse-scale systems treating waters ranging from highly oligotrophic model ecosystems to highly loaded aquaculture, chicken manure and raw sewage. Some of this work continued through the 1990's, adding toxic chlorinated hydrocarbon breakdown and extending to treating mesocosm systems of several million gallons. This research was mostly carried out by Walter Adey's Ecological Systems Technology, Inc. and the S.I.'s Marine Systems Laboratory and appeared in many publications – see Bibliography.

Beginning in the early 1990's, ATS analysis expanded to small, pilot field systems, ranging from a Florida Everglades agriculture water treatment system, to secondary and tertiary treatment of sewage at high and low ammonium levels, to finfish aquaculture ranging up to 500,000 gpd. This began the engineering phase as it related to design for maximum efficiency. Most of this work was carried out by Aquatic BioEnhancement Systems, Inc.

In the late 1990's and through to the present day, formal engineering to maximize efficiency of the ATS process was undertaken by the engineering staff of

HydroMentia, Inc. HydroMentia has designed, constructed and operated several full-scale systems ranging up to 40Mgpd for aquaculture, agricultural and municipal non-point source treatment. A number of lake and stream treatment systems are currently under construction. Based on an engineering report for one of those systems, written for the South Florida Water Management District (SFWMD), an economic analysis was prepared by the IFAS Institute of the University of Florida (http://edis.ifas.ufl.edu/FE576). Note that ATS are sometimes called Managed Aquatic Plant Systems (MAPS).

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