Algal Turf Scrubbing: Cleaning Surface Waters with Solar Energy while Producing a Biofuel

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As human populations have expanded, Earth's atmosphere and natural waters have become dumps for agricultural and industrial wastes. Remediation methods of the last half century have been largely unsuccessful. In many US watersheds, surface waters are eutrophic, and coastal water bodies, such as the Chesapeake Bay and the Gulf of Mexico, have become increasingly hypoxic. The algal turf scrubber (ATS) is an engineered system for flowing pulsed wastewaters over sloping surfaces with attached, naturally seeded filamentous algae. This treatment has been demonstrated for tertiary sewage, farm wastes, streams, and large aquaculture systems; rates as large as 40 million to 80 million liters per day (lpd) are routine. Whole-river-cleaning systems of 12 billion lpd are in development. The algal biomass, produced at rates 5 to 10 times those of other types of land-based agriculture, can be fermented, and significant research and development efforts to produce ethanol, butanol, and methane are under way. Unlike with algal photobioreactor systems, the cost of producing biofuels from the cleaning of wastewaters by ATS can be quite low.

Keywords: algae, biofuel, ecological engineering, nitrogen, phosphorus

There is a growing need for low-cost technologies to improve water quality in degraded aquatic ecosystems. Ecological engineering offers an approach to managing this problem through the development of controlled ecosystems designed specifically for water treatment (Mitsch and Jørgensen 1989, 2004, Kangas 2004). Ecologically engineered systems use the free energies from nature as a subsidy, along with some inputs from human technology, to provide less costly solutions to certain environmental problems than conventional designs powered by fossil fuel–based energies. Free energies include the "natural machineries" that are the products of evolution, along with natural energy inputs of sunlight, wind, and rain. Well-known examples of ecologically engineered systems are treatment wetlands (Kadlec and Knight 1996) and bioengineered vegetation used for erosion control (Schiechtl and Stern 1997). The main trade-off in these systems is that they require large areas of land for implementation because they are driven by solar energy. Therefore, these systems are effective alternatives in rural settings where land is available, but they are less applicable in urban settings where land costs are high. In this article, we describe an ecologically engineered, algae-based system (the algal turf scrubber, or ATS™).

In recent years, great attention has been devoted to the use of algae to produce biofuels (Chisti 2007); it has been known for many decades that nutraceutical production can be of great value (Constantine 1978, Lembi and Waaland 1988, Radmer 1996). However, aquatic algae have greater photosynthetic potential than higher-trophic-level plants, and algae are also capable of using solar energy to facilitate nutrient removal (of nitrogen [N], phosphorus [P], carbon dioxide) and injecting oxygen into degraded waters (Beneman and Oswald 1996). The greatest opportunities for algal cultures lie in combined wastewater cleanup and biofuel and nutraceutical production. In this article, we introduce the ATS process, which has been researched and developed for many years, scaled up to multiacre levels, and is now ready for use at the watershed scale.

ATS: A biomimicry of coral reef primary production

Since the studies of Odum and Odum (1955) at Enewetak Atoll, it has been thought that tropical coral reefs in low-nutrient seas could actually be highly productive. Odum and Odum suggested that small attached and boring algae were the principal source of this productivity. Following an extensive yearlong analysis of coral reefs on St. Croix in the Caribbean in the late 1970s, Adey and Steneck (1985) demonstrated that primary productivity values 5 to 10 times higher than those of terrestrial forests and agriculture were routine and were limited primarily by the amount of available light. The primary source of the productivity-driving photosynthesis was the dense, biodiverse turf of filamentous algae that covered roughly 40% of the reefs' carbonate surfaces. Experimental screens established at many reef sites across the eastern Caribbean demonstrated mean algal turf productivities of 5 to 20 grams (g) per square meter (m^2) per day (all productivity values reported in this article reflect dry weight; figure 1; Adey 1987). The researchers involved in this fieldwork showed that

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Figure 1. Algal screens floating in a coral reef environment in the eastern Caribbean Sea.

the oscillating motion (surge) created by trade-wind wave action was a principal factor driving high productivity (Carpenter et al. 1991, Adey and Loveland 2007).

During the 1980s and 1990s, the principal elements of this algal-turf-driven, high coral-reef primary productivity were ecologically engineered to create a device called an ATS (Adey 1983; see also the parallel work by Sladeckova et al. 1983 and Vymazal 1989). Integrating water flow and surge with high light intensity and frequent harvest, ATS units achieved high levels of primary productivity and were used to control water quality in a considerable variety of enclosed microcosms and mesocosms of coral reefs, estuaries, and rocky shores (reviewed by Adey and Loveland 2007). Early work on ATS involved designing pulsing hydraulic systems to mimic the wave energy found in coastal systems. However, because freshwater attached algae behave similarly to marine algal systems (Mulholland et al. 1994, 1995), freshwater ATS were also developed (Adey and Loveland 2007). The original wild ecosystems (coral reefs) that ATS "mimicked" were very-low-nutrient, light-limited systems. However, later in the 1980s, small ATS units were employed on high-nutrient source waters of raw sewage and chicken manure, and they were both quite successful at removing nitrogen, phosphorus, and biological oxygen demand (Adey and Loveland 2007) and produced even higher levels of harvest production. Beginning in the early 1990s, a scaling-up process of ATS units was initiated for both large-scale finfish aquaculture and wastewater treatment. One of the authors (WHA) (eventually) obtained a series of six patents that would potentially bring venture capital into the scaling-up process (US patents 4,333,263; 4,966,096; 5,097,795; 5,715,774; 5,778,823; and 5,851,398). Landscape-scale ATS systems have been built as large as 3 hectares (ha) in dimension and as great as 150 million liters per day (lpd) in capacity; a set of ATS units for whole-river amelioration of 11 billion lpd is now in final engineering design.

The ATS system consists of an attached algal community, which takes the form of a "turf," growing on screens in a shallow trough or basin (referred to as a *raceway*) through which water is pumped. The algal community provides water treatment by the uptake of inorganic compounds and release of dissolved oxygen through photosynthesis. Water is pumped from a body of water onto the raceway, and algae remove the nutrients through biological uptake and produce oxygen as the water flows down the raceway. At the end of the raceway, water is released back into the water body, with a lower nutrient concentration and a higher dissolved oxygen concentration than when it was pumped onto the raceway. The nutrients that have been removed, or "scrubbed," from the water body are stored in the biomass of the algae growing on the screen. The algae are harvested approximately once per week during the growing season, thus removing nutrients from the waterway in the algal biomass. Harvesting is important because it rejuvenates the community and leads to higher growth rates; harvesting also prevents or reduces the potential effects of invertebrate micrograzers. In fact, biomass production rates of ATS are among the highest of any recorded values for natural or managed ecosystems (Adey and Loveland 2007). Because of the fast growth rate of algae on ATS, this technology can remove nutrients and produce oxygen at a high rate. Design features of ATS include the flow rate of water, the slope of the raceway, the loading rate of nutrients in the water, and the type of screen used to grow algae.

Landscape-scale ATS systems

The scale-up of ATS systems for sewage treatment began in the mid 1990s with a tertiary wastewater unit in Patterson, California (Craggs et al. 1996). The algae-growing surface in this case was an inclined, textured surface of high-density polyethylene (a soil-bed liner) 150 m long and 7 m wide (figure 2). Secondary wastewater from the city's sewage

Figure 2. Pilot-scale ATS tertiary wastewater treatment system in Patterson, California. See Craggs and colleagues (1996).

plant flowed over this surface in a series of pulses, with flows varying between 445,000 and 890,000 lpd. A wide variety of chemical, physical, and biotic operational parameters were analyzed, and the algal biomass was mechanically vacuum harvested at one- to two-week intervals, depending on the season. Harvest production (including trapped organic particulates) in June and July typically ranged from 50 to 60 g per m^2 per day. In December and January, because of the extremely foggy conditions of the Central Valley, algal productivity was 8 to 12 g per m^2 per day. The yearly mean of algal production was 35 g per m^2 per day. The ash-free dry weights were 40% to 50% of the total dry weight.

From the percentage of nutrients in the harvested solids (3.1% N and 2.1% P) and the yearly mean productivity of 35 g per m^2 per day, the yearly mean removal rates of N and P in the Patterson pilot plant were determined to be 1.1 ± 0.5 and 0.7 ± 0.2 g per m^2 per day, respectively. The yearly mean concentration of nutrients in the incoming wastewater was 5 milligrams (mg) per liter (L) total N and 3 mg per L total P. Higher concentrations of nutrients in influent water can lead to even higher removal rates. Mean removal rates of more than 4 g N per m^2 per day were achieved on a stream-treatment ATS in Arkansas; this unit was placed several hundred meters downstream from a municipal treatment plant outlet (Adey 2010).

On sunny days, the pH of the ATS effluent at Patterson reached 10 or higher; at pH values of 8.0 to 10, much of the P in the water column was precipitated as calcium hydroxyapatite into the algal mat. Not all dissolved P is removed from the water column because of partial resolution at lower nighttime pH values. Precipitation into the algal biomass of numerous divalent and trivalent cations (Ca^+, Mg^+, Al^+, Fe^+, etc.) also occurs with phosphates, and probably with carbonates as anions. The system thus acted as a partial deionizer as well as a nutrient sink.

Non-point-source nutrient removal

In 1991, a pilot-scale ATS floway (15 m long, 0.75 m wide; Adey et al. 1993) was tested for six months on a sugar farm in the Florida Everglades. The algae self-seeded from the source drainage canal and included species of the genera *Cladophora*, *Spirogyra*, *Enteromorpha*, and *Stigeoclonium,* as well as a variety of filamentous diatoms such as *Eunotia* and *Melosira* (figure 3). A weekly harvest interval of the algal biomass and vacuum harvesting with a standard shop wet-vacuum was employed. The source water in this experiment had total P concentrations of 0.04 to 0.05 mg per L. Mean dry algal production levels ranged from 33 to 39 g per m^2 per day, with lower rates occurring in the winter and higher rates in the late spring. The mean P content of harvested biomass ranged from 0.3% to 0.4%. During the spring (a period of average solar intensity and low nutrient supply), the calculated total P removal rate ranged from 0.1 to 0.14 g P per m^2 per day.

Beginning in 2002, HydroMentia, Inc., of Ocala, Florida, began building 18-million- to 110-million-lpd ATS units for nutrient scrubbing of agricultural non-point-source wastewaters (streams, canals, and lakes) throughout south Florida. Because these units are modular, with single modules ranging from 3 million to 93 million lpd, any size is potentially possible. Funded by the South Florida Water Management District, a 1-ha ATS system was also built and operated for two years to test the economics of the process. This S-154 unit was used to clean stormwater from a canal just north of Lake Okeechobee in Florida (figure 4). The target nutrient in this case was P, and the stormwater was ultimately derived from agricultural activities, primarily cattle production.

A plot of P removal, compared with P loading for ATS and with the storm-treatment-area-constructed wetlands—the latter extensively developed in the northern Everglades of south Florida—is shown in figure 5. As is shown in the figure, P removal is a function of loading rate (i.e., flow rate and P concentrations). The highest P removal rates in the S-154 system were derived from the most heavily loaded set of experiments (i.e., increased flow rates). These rates were

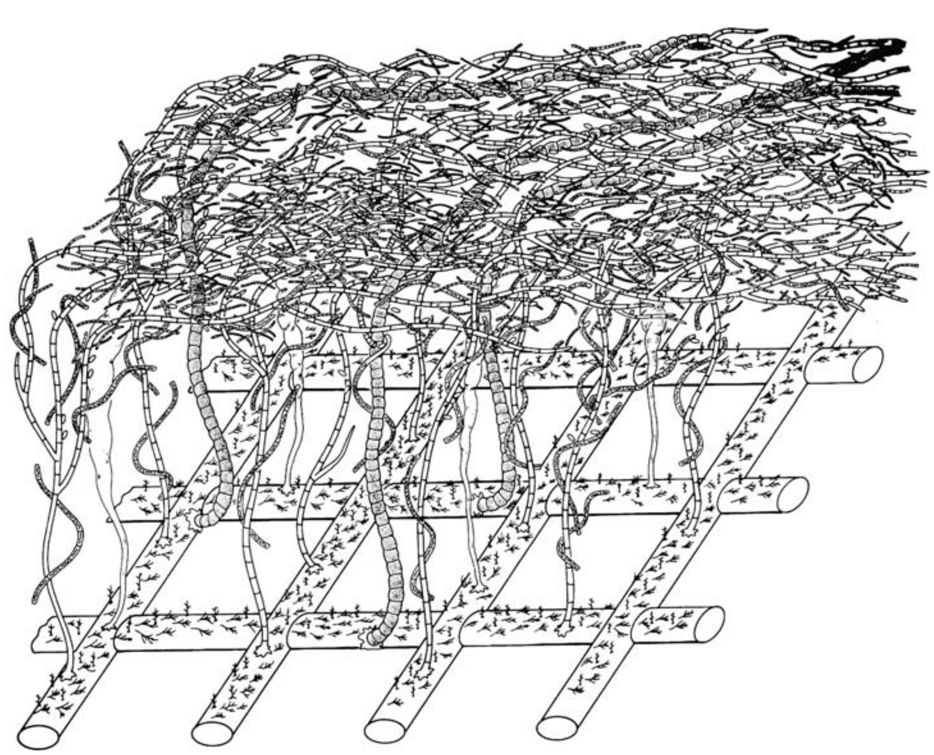

Figure 3. Algae on screen from Everglades 1991 study. Reprinted from Adey and colleagues (1993).

Figure 4. Aerial view of S-154 algal turf scrubber in central Florida. Photograph: Courtesy of HydroMentia, Inc.

exceeded only by the Patterson ATS system described above. ATS removal capability is roughly two orders of magnitude greater than that of the managed wetlands in the same region.

Nutrient removal with ATS from concentration animal sources

Extensive studies at the US Department of Agriculture's research facility in Beltsville, Maryland, have documented ATS algal productivity and nutrient recovery values using dairy and swine manure effluents. Initial studies using small indoor ATS units (1 m^2) and different loading rates of dairy manure effluents demonstrated that algal productivity and nutrient content values of the resulting biomass grew with increasing loading rate up to maximums of about 20 g per m^2 per day (10% ash content) and 7% N and 1.5% P (Wilkie and Mulbry 2002, Kebede-Westhead et al. 2003, 2004). More recent studies using outdoor, pilot-scale ATS raceways and

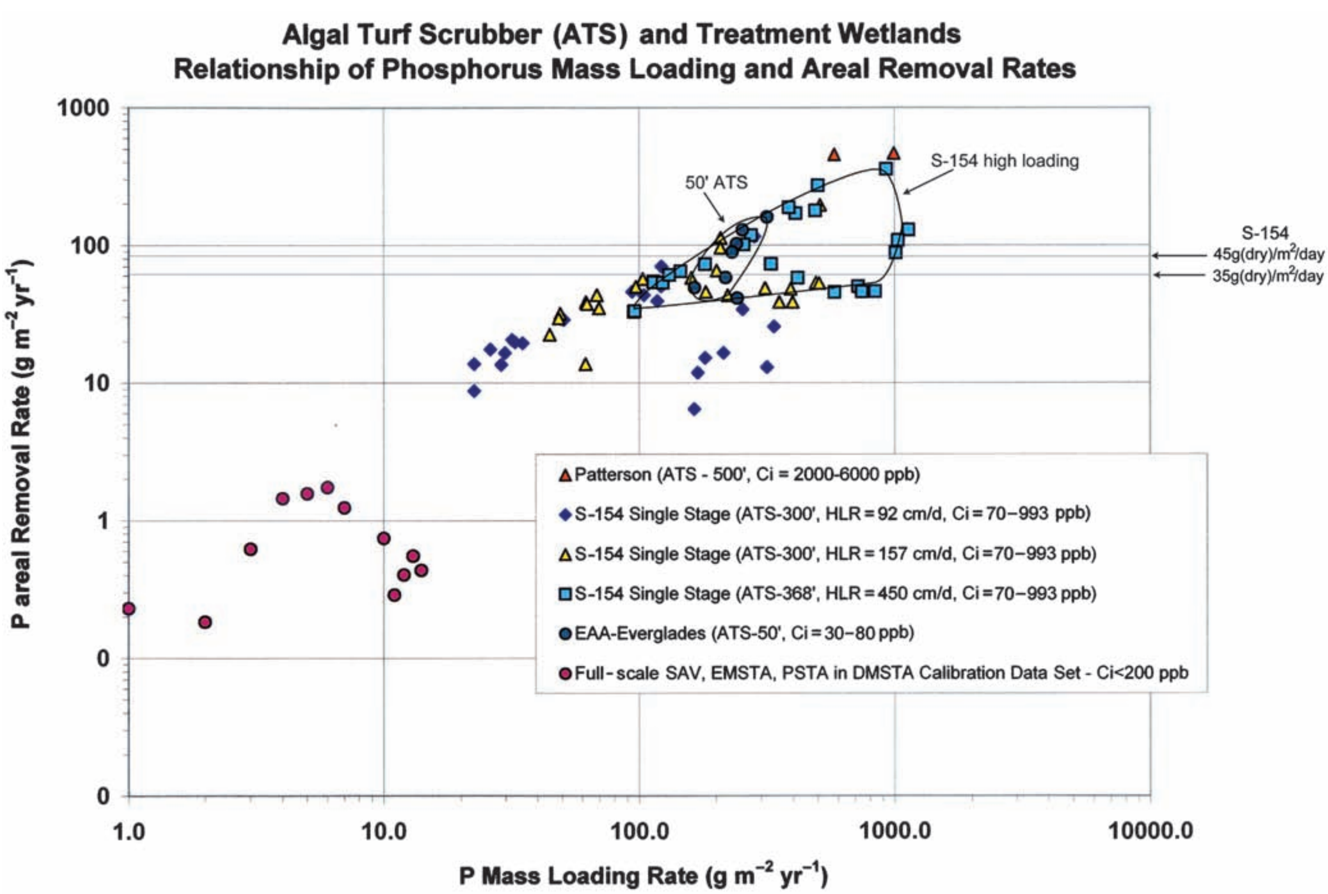

Figure 5. Plot of phosphorus (P) removal (in grams per square meter per year) against loading (in grams per square meter per year) comparison of algal turf scrubbing and storm treatment areas (STAs) with biomass production. In the figure, Patterson refers to the central California tertiary treatment system described by Craggs and colleagues (1996); EAA-Everglades is a farm canal treatment unit described by Adey and colleagues (1993); S-154 is a two-acre natural stream treatment unit referenced by Sano and colleagues (2005) and shown in figure 4. The remaining information is derived from South Florida Water Management Unit reports on STA constructed wetlands. EMSTA, PSTA, and DMSTA are code names for different STA types. Abbreviations: Ci, total phosphorus concentration; cm/d, centimeters per day; HLR, hydraulic loading rate; ppb, parts per billion; SAV, submerged aquatic vegetation. This diagram was compiled by and provided with the courtesy of HydroMentia, Inc.

dairy manure effluents yielded weekly productivities ranging from 5 to 25 g per m^2 per day and averaged about 10 g per m^2 per day during a 270-day growing season (April to December) from 2001 to 2006. At loading rates up to 1 g total N per m^2 per day, recovery of input N and P in the algal biomass was 80% to 100%. However, at higher loading rates (up to 2.5 g N per m^2 per day), recovery of input N and P in the biomass decreased to 40% to 60% (Mulbry et al. 2008a).

Greenhouse studies using dried algae from manure treatment demonstrated that plants grown in potting mixes amended with algae were equivalent in mass and nutrient content to plants grown with an equivalent amount (on an N-availability basis) of a commercially available fertilizer (Mulbry et al. 2006). Dried algae is an excellent alternative to inorganic fertilizers in that it contains no ammonia-N or nitrate-N that can leach into groundwater or be carried away by rainfall at the time of application. Instead, when applied to the surface of or lightly incorporated into the soil, the dried algae breaks down as seedlings grow. About 25% to 33% of algal N becomes plant available within 21 days after application. Extensive analyses of the algal biomass from multiple manure effluent experiments showed that it does not contain heavy metals at concentrations that would limit its use as a fertilizer or animal feed supplement (Mulbry et al. 2006). An economic analysis of a farm-scale ATS system for treating dairy manure concluded that it would be very expensive on a per-animal basis but very competitive with other accepted but less well-documented agricultural best-management practices (Pizarro et al. 2006, Mulbry et al. 2008a).

Nutrient removal from rivers

A large part of the nutrients invested in agricultural production, whether through farm run-off or subsurface drainage, eventually reaches major rivers, where it joins with uncaptured N and P from sewage plants. ATS systems can be applied to US rivers, where total N and P concentrations typically range from 1 to 5 mg per L and 0.1 to 0.6 mg per L, respectively. An 11-billion-lpd engineering plan to clean the entire Suwannee River in Florida of excess nutrients has been designed, and test units are in operation. It is anticipated that in the central United States, ATS systems would develop a mean yearly algal biomass production rate of 35 g per m^2 per day. Although extensive field test studies are needed, it seems likely that the north-to-south range of yearly algal production in ATS units used to clean rivers in the United States would be about 25 to 45 g per m^2 per day.

During the late 1980s, it was determined that agriculturally derived nutrients, principally P, were seriously affecting the Florida Everglades. In the search for a landscape-scale technology for removing that P from farm run-off, the South Florida Water Management District screened two-dozen technologies and selected nine for further study. Managed, constructed wetlands were eventually selected as the most suitable technology after a decadelong comparison. In an economic analysis published in 2005, Sano and colleagues, reporting for the Institute of Food and Agricultural Sciences of the University of Florida, normalized data from the S-154 ATS test plant as a 23-ha facility over a 50-year operation. It was determined that such an ATS system could remove P for $24 per kg. The ATS cost, per unit of P removed, was about one-third of the least expensive equivalent constructed wetlands module.

In late 2005, the engineering firm Hazen and Sawyer, of Hollywood, Florida, revaluated the S-154 data, with and without pumping and algal harvesting costs. They evaluated several scenarios for the algal biomass, including "giving it away." Using the data for 0.5 mg per L P influent concentration and including one-half pumping costs (for river floodplain operation) and a discount rate of 5.375%, the firm's figures provide a cost of $28 per kilogram P. Assuming this number (Florida construction and labor costs) to be higher than the US average and allowing for a broad range of value in the algal biomass, including energy value, the basic nutrient scrubbing task was accomplished for $24 per kg (with N removed at the same time, for the dollars already invested). Therefore, N and P were removed at a cost of approximately $1.50 and $22.40 per kg, respectively. When the production of the ATS plant is normalized for the lower light and temperatures in the center of the country (e.g., in St. Louis, Missouri), the cost is roughly 20% of the average cost of nutrient removal as it was published by the Chesapeake Bay Commission in 2004 (CBC 2004). Because these analyses attributed all costs to P, the relative costs of the two nutrients are distributed according to the CBC mean proportions.

Bioenergy: Solar energy capture using photosynthetic systems

Given the consequences of carbon release and global warming, the need for renewable energy supplies and especially liquid fuels for transportation has become widely accepted. Although many types of renewable energy are being implemented, including solar, wind, and geothermal, it is widely recognized that biofuels are also a necessary part of developing greater energy self-sufficiency (Tyner 2008). The US short-term answer has been corn ethanol, with the longer-term addition of cellulosic fuels from switchgrass and wood chips. However, as was discussed in a review by Rotman (2008), corn ethanol is probably not economically or energetically viable over the long run; cellulosic ethanol is still in the research phase. Optimistic forecasts predict meaningful production in five years, whereas pessimistic forecasts predict that it may not be economical, suggesting that meeting our national biofuel targets will require further technological breakthroughs.

One answer to the energy dilemma has been microalgal production (Ryan 2009). Experimentally, algal biomass production values can be 7 to 30 times greater than agricultural production values, especially when driven by carbon dioxide from power plant stack gases (Huntley and Redalje 2007, Wang et al. 2008). Some commercial entities have reported 7500 to 22,500 L of biofuel per ha per year in pilot plant operation (Chisti 2007). This compares with 75 to 975 L of biofuel per ha per year for agricultural products from soy to palm. Although there has been clear exaggeration about biofuel yields from algal production (Waltz 2009), this is an active area of renewable energy research.

There are two general approaches to industrial algal production. The oldest and most developed technology is mass culture of suspended algae in open raceways or ponds. This technology is relatively inexpensive (compared with photobioreactors) and is highly productive (up to 30 g dry weight per m^2 per day; Goh 1986, Benemann and Oswald 1996, Olguin 2003, Craggs et al. 2003). This approach was pioneered for wastewater treatment by Oswald and coworkers at the University of California, Berkeley, and has been extensively developed in central California. Three algae-based municipal wastewater treatment plants are currently operating in California. The oldest has been in continuous operation for more than 20 years (Oswald 1995, 2003). Clarens and colleagues (2010) conducted a life-cycle analysis using data from the literature for an open-pond algal production system. They found that the algae-to-energy pathway is most favorable when nutrients in wastewater effluents are used in place of commercial fertilizers.

More widely promoted in recent years has been the closed photobioreactor concept, in which selected or genetically engineered monocultures of algae are grown in an interconnected array of clear tubes or bags (Carvalho et al. 2006, Ugwu et al. 2008). Such algal culture is carried out in greenhouses, using a wide range of proprietary technologies to optimize photosynthesis. Greenfuels Technologies has reported a three-month mean rate of production of 98 g per m^2 per day in a pilot operation linked to an Arizona Public Service power plant. On 12 December 2007, Vertigro Joint Venture issued a press release reporting a three-month average algal production in a pilot photobioreactor at El Paso, Texas, of 102 metric tons per ha per year (138 g per m^2 per day). Although the economics of such operations remain largely unknown, the infrastructure required clearly suggests very high costs if the key environmental and culturally pristine conditions requisite to high production are to be met. Recent estimates of algal biomass production costs for photo bioreactors are about $3.50 per kg (Chisti 2007). Although carbon dioxide sequestration is clearly a favorable feature of this methodology, carbon capture can be only a minor economic element in such a high-cost endeavor. Extensive life-cycle analyses will also have to be performed to determine the net value of fossil carbon kept from the atmosphere per unit of energy produced. Finally, it seems problematic that large volumes of complex wastewater could be efficiently used in a system requiring precision and sterile conditions for production; this suggests that large-scale wastewater treatment is unlikely to be a significant part of any photobioreactor equation.

Biofuels potential of ATS

Tertiary treatment of average domestic secondary wastewater and treatment of moderately eutrophic rivers by ATS in midlatitudes would produce on the order of 18 metric tons (dry weight) of algal biomass per ha per year. This algal biomass would result from treating about 3.7 million lpd per acre of secondary sewage effluent or 18 million lpd per acre of river water, as was indicated by the ATS studies cited above. For the typical large-river nutrient range of 0.1 to 0.6 mg per L of P (with P as an indicator of total nutrient spectrum), the algal biomass produced is likely to be dominated by green algae but to be rich in diatoms. All algal cells have phospholipid membranes and a small amount of oil that can be converted to biodiesel. Diatoms store food in oils, and therefore tend to have higher oil content (some of the "high oil" algae utilized in the US Department of Energy studies of the 1990s were diatoms; Sheehan et al. 1998. Oil extraction of ATS algae has been demonstrated by Midwest Research Institute researchers, who used algal biomass from HydroMentia's Taylor Creek Plant in the Lake Okeechobee watershed. Although it is possible to convert oils from ATS algae into biodiesel, in this article we focus on biofuels from fermentation processes rather than from oil extraction; this is because of the relatively low concentrations of fatty acids in the ATS algae (Mulbry et al. 2008b, 2010) and the relatively higher economic value that might come from conversion of algal oils into nutraceuticals, such as omega-3 fatty acids (Adey 2010).

In 1998, the chemist David Ramey improved the 90-year-old acetone-butanol-ethanol industrial fermentation. Ramey (1998) used two separate species of the anaerobic bacteria *Clostridium* in a two-step fermentation process, followed by a physical concentration process that produced a 90% butanol product plus hydrogen gas as a byproduct. In a 2004 report to the US Department of Energy, he described a continuous production plant of 185 L per week from corn and dairy wastes and proposed plans for expansion to multimillion-gallon production. Researchers from the University of Western Michigan have analyzed the Taylor Creek algal biomass and produced a preliminary plan for

Table 1. Biofuel production from ATS algae and corn, assuming biomass yields of 20.5 and 1.3 dry metric tons per hectare per year, respectively.

Biomass production	ATS algae	Corn
Percentage carbohydrate	25	35
Carbohydrates available, tons per hectare	5.1	0.5
Percentage fermented	90	90
Carbohydrates used, tons per hectare per year	4.6	0.4
Fermentation efficiency (carbon into fuel)	51	51
Fuel produced, tons per hectare per year	2.4	0.2
Potential ethanol production, liters per hectare per year	2790	242
Potential butanol production	2718	238

Note: ATS, algal turf scrubber

producing butanol (from carbohydrates) from the algal product (table 1). Using the current cost data for a 580-ha, 11-billion-lpd ATS system designed to clean the Suwannee River in Florida, and applying that study to a similar plant in the center of the country, we calculated that the algal biomass substrate available for energy conversion would cost about $0.75 per kg. This compares with recent estimates to produce microalgal biomass using photobioreactors of $3.50 per kg (Chisti 2007), as was noted above.

Although the photobioreactor biomass is estimated to have higher oil content than ATS algal biomass, and therefore to have lower refining costs, the ultimate price of the biofuel produced by the two methods is likely to be about the same: between $1.60 and $2.70 per L ($6 to $10 per gallon). Therefore, growing algae using ATS solely to produce energy—even at large, efficiently operated facilities on river floodplains where pumping costs and energy input are minimal—is not likely to be a profit-making endeavor and would be highly sensitive to the price of crude oil. On the other hand, ATS algae provide a much larger potential for bioenergy supply than corn and soy because of their high productivity. In addition, the value in the nutrient removal process, given as credits or bankable dollars—even at a fraction of the cost of current removal in the Chesapeake Bay watershed, for example—would cover the cost of construction, operations, and maintenance, and still leave a significant profit margin. The recovered oil and butanol would be byproducts available at the cost of refining, very likely at 20% to 30% of current fuel prices. Because the processed biomass would produce a balanced fertilizer, this would provide an additional return. Perhaps most important, the energy product would have little sensitivity to the global price of crude oil.

Conclusions

The use of ATS for water quality improvement is an established practice (Adey and Loveland 2007). ATS was developed through ecological engineering techniques and has been studied for more than 30 years. Commercialization of the technology is under way by HydroMentia, Inc., which is currently building and operating ATS on the hectare scale in Florida. Use of ATS for water quality improvement represents a kind of "nutrient farming" (Hey 2002, Hey et al. 2005), with clean water as a primary output. Values from byproducts of the biomass of algae grown on ATS need to be developed, but these will accrue in addition to water quality improvement values. When scaled up for application to whole watersheds, ATS will generate further value as the basis for a "green economy" with jobs for people who would build and operate the systems and the spin-off businesses that would make use of the algal biomass.

Research to improve the performance of ATS is continuing. Productivity of algae grown on ATS is primarily limited by the interaction of sunlight and temperature, because nutrient-rich waters are used for operating the system. Inputs from industrial power plants (carbon dioxide–rich flue gas and heated water from cooling use) are being tested for their potential to stimulate algal growth on ATS. A recent testing of a three-dimensional screen also indicated increased algal growth as a result of the larger surface area for attachment and support of algal species. Finally, variations on the original floating screens are being developed and tested, which would extend the application of the technology to open-water locations. Because of its modular and flexible design, ATS can be installed in a number of rural settings to utilize wastewaters or polluted water from rivers, lakes, and coasts for multiple benefits.

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