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The Controlled Eutrophication Process: Using Microalgae for CO_2 Utilization and Agricultural Fertilizer Recycling.

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ABSTRACT

In 1960, Oswald and Golueke [1] presented a conceptual techno-economic analysis, "The Biological Transformation of Solar Energy", proposing the use of large-scale raceway ponds to cultivate microalgal on wastewater nutrients and then to anaerobically ferment the algal biomass to methane fuel. The methane was to be converted into electricity, with the CO_2-containing flue gas recycled to the ponds to support algal production. Over the past forty years a great deal of research has been carried out on this and similar concepts for microalgae fuels production and CO_2 utilization. However, major technical challenges have limited the practical application of this technology: the difficulties of maintaining selected algal species in large-scale production systems, the lower-than anticipated biomass productivities and methane yields, and the high costs of harvesting the algal biomass and of the overall process. These limitations can, however, be overcome by applying such processes where additional economic benefits, such as wastewater treatment or nutrient recovery, are available and where relatively large systems (> 100 hectares) can be deployed, allowing economics of scale.

One such site is the Salton Sea in Southern California, into which over 10,000 tons of nitrogen and phosphate fertilizers are discharged annually by three small rivers draining large tracts of irrigated agriculture. Removal of nutrients from these inflows is required to avoid eutrophication of this large (some 900 km^2), shallow, inland sea, with resulting massive algal blooms, fish kills and other environmental impacts. Nutrient capture could be accomplished with some 1,000 hectares of algal pond systems, with the algal biomass harvested and converted into fuels and the residual sludge recycled to agriculture for its fertilizer value. A techno-economic analysis of this process, based on nutrient removal defraying a fraction of the costs, suggests that such a process could mitigate several hundred thousand tons of fossil CO_2 emissions at below $10/ton of CO_2-C equivalent.

INTRODUCTION - MICROALGAE APPLICATIONS IN ENVIRONMENTAL PROTECTION.

Microalgae ponds have been utilized for several decades for the treatment of municipal and other wastewaters, with the microalgae mainly providing dissolved oxygen for bacterial decomposition of the organic wastes [2]. The major limitations in this technology are the relatively low loadings that can be applied per unit area-time, increasing land area requirements, and the high cost of removing the algal cells from the pond effluents, using chemical flocculation or other means. High-rate ponds, with channels and mechanically mixed, were introduced a half century ago [3], and allow much higher loadings than the standard unmixed "facultative" ponds. However, high rate ponds also exhibit higher algal cell densities,

making algae removal, harvesting, a requirement for wide-scale applications. Paddle wheel-mixing provides a controllable and flexible mixing regime than pumps, and allows managing the pond culture to promote algal cells that tend to flocculate and settle [4]. However, it has not been possible to demonstrate such a "bioflocculation" processes with the high reliability required for algal harvesting in municipal wastewater treatment. Thus, in current designs, high rate ponds are followed by large settling or "maturation" ponds, and often the effluents from the ponds are used for irrigation, ground water recharge, or similar applications. Development of more intensive, smaller footprint, microalgae wastewater treatment processes based on high rate pond technology and low-cost algal harvesting remains an R&D challenge. One process that accomplishes this goal is the Partitioned Aquaculture System (PAS) [5, 6, 7], being applied as the "Controlled Eutrophication Process" at the Salton Sea, as described more fully below.
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Microalgae have also been used extensively studied in other environmental applications. The removal of heavy metals from wastewaters has been extensively studied and some actual applications with immobilized algae were reported, though these could not compete commercially with ion exchange resins [8]. The removal of residual nutrients from wastewaters, so-called "tertiary treatment", specifically N and P, has also been studied with a variety of processes, from attached algal cultures to controlled algalculture in cooling reservoirs [9, 10]. Microalgae are excellent for nutrient removal processes, as they exhibit high contents of N and P, about 10 and 1% respectively on a dry weight basis, several-fold that of higher plants. Also, microalgae cultures are able to reduce residual concentrations of these nutrients to vanishingly low levels and allow for a significant variability in N:P ratios, from about 3 to 30 N for each P, on a weight basis, depending on limiting nutrient.

Finally, microalgae cultures have been proposed for some years as a method for fixation of CO_2 and production of biofuels, of interest in greenhouse gas mitigation. The first conceptual development of this idea was by Oswald and Golueke in 1960 [1] who described a large-scale system with dozens of large (40 hectare) high rate ponds, with the algae grown, the biomass harvested by a simple flocculation-settling step, and the concentrated algal sludge anaerobically digested to produce biogas (methane and CO_2). The biogas would be used to generate electricity and the flue gas CO_2, along with the nutrients in the digester effluent, used to grow more algae. Make-up water and nutrients (C, N, P, etc.) would be provided from wastewaters. A preliminary engineering-cost analysis suggested power production costs similar to those projected for nuclear energy. A more detailed, study-level, design and engineering analysis of this concept was carried out by Benemann et al. in 1978 [11], who concluded that with favorable assumptions (low-cost harvesting, high productivities), such systems could produce biogas competitively with then projected fossil fuel prices.

Since the early 1980's, the U.S. R&D effort in microalgae biofuels production has centered on the DOE-sponsored "Aquatic Species Program", which aimed at producing algal oils for production of biodiesel (see review in [12]). As part of this effort, several rather more detailed engineering design and cost analysis studies were carried out, during the 1980's [13, 14], again with many favorable assumptions in particular very high productivities. A quarter hectare pilot plant operated in New Mexico [15], demonstrating the feasibility of outdoor microalgae cultivation on saline waters and efficient CO_2 capture. The relatively long-term nature of the R&D required for such dedicated energy production processes, among other factors, led to the wind-down of the Aquatic Species Program in the mid 1990's. In Japan a very much larger government-sponsored program, involving many private companies, on microalgae biofixation of CO_2 was carried out during the 1990's. This program focused on mainly closed photobioreactors, including optical fiber systems, for fixation of CO_2 and co-production of high value products [16]. Currently in the U.S. similar concepts are being developed with U.S. Dept. of Energy support [17, 18]. In Japan, also during the 1990's, electric utility companies carried out additional R&D programs, including cultivation of microalgae on seawater and actual power plant flue gas CO_2 in small ponds inside greenhouses [19], as well as projects on biological H_2 production by fermentation of microalgae biomass [20]. Microalgae biofixation R&D continues in Japan, though at a lower level of intensity [21, 22, 23]. Most recently an "International Network on Microalgae Biofixation of CO_2 and Greenhouse Gas Abatement" was formed, to foment and coordinate R&D activities in his field [See Pedroni et al, in These Proceedings).

Microalgae biofixation of CO_2 and greenhouse gas abatement requires open pond systems and must include other co-products or services, such as wastewater treatment or fertilizer recycling. One example is the use of microalgae to remove N and P from agricultural drainage waters, such as at the Salton Sea, described herein.

AGRICULTURAL DRAINAGE WATERS - THE SALTON SEA

Irrigation in desert or semi-desert environments often leads to soil salinity problems, due to surface evaporation, requiring drainage of the fields, thereby producing so-called agricultural drainage waters, high in salts and nutrients, principally N, P and K. In Southern California, agricultural drainage systems used in the Coachella and Imperial valleys drain into the large, about 900 km2, below sea-level Salton Sea. The modern Salton began with the accidental flooding of the Salton sink in 1904 with Colorado River water with a TDS of 300 ppm. The Sea has no natural outlet and today serves as a “dumping ground” for irrigation return water, surface flow and wastewater discharges. Consequently over the years the Salton Sea has continued to increase in salinity (today ~ 46 ppt), and fertilizer nutrients concentration (such as N, P) as well as a variety of heavy metal burdens. The major sources of inflow to the Sea are the Alamo (45%), New (45%) and White Water (10%) Rivers. Surface inflow to the Salton Sea from the Imperial and Coachella Valley irrigation return water and runoff range from 1 to 1.5 billion m^3 per year, mainly through the Alamo and New Rivers in the south, with a smaller (< 10% of total) inflow from the White Water in the north. As the Sea has increased in salt content, it has seen a transition of ecosystems from freshwater to brackish, now reaching the tolerance limits of most fish. Proposed solutions to these salinity increases include evaporative ponds, spray systems, desalinization plants and pumping Seawater to the Gulf of California. Evaporative ponds requires diking some 10–20% of the Sea, the other options are very expensive and energy consuming.

One management plan is to install dikes within the sea near the freshwater inputs, creating fresh to brackish ecological zones ("ecotones", Figure 1), where fisheries and wildlife could prosper, with the center of the sea continuing to increase in salinity. However, accumulation of N and P levels presently create hyper-eutrophic conditions which results in severe fluctuations in dissolved oxygen concentrations, leading to massive fish kills, something not remedied by the proposed salinity control measures alone. To reduce the nutrient loads on the lake, an adaptation of the PAS, Partitioned Aquaculture Systems [6, 7], is proposed, sited near the three main inlets to the Sea (see "PAS" in Figure 1). This "Controlled Eutrophication Process" concept is similar to the conventional PAS, with algae grown in typical high-rate ponds (raceway, paddlewheel mixed), with the algal culture passed through separate zones containing planktivorous fish, such as Tilapia, which convert the algal biomass to settleable solids (feces and pseudo-feces). This is easily removed by sedimentation and recycled on land as organic fertilizer, possibly after anaerobic digestion to produce methane gas. To remove most inflowing nutrients, at least 100,000 metric tons annually of algal biomass would need to be produced, on over 1,000 hectares of algal ponds, while co-producing large amounts of fish, probably best suitable for animal feeds. Development of this process has been initiated at Kent SeaTech, Inc., with two 3,000 m^2 high-rate pond ASP systems located next to the White Water River. In the longer-term if may be of interest to develop systems in which fuels are the major, even if not exclusive, product. These are discussed next.

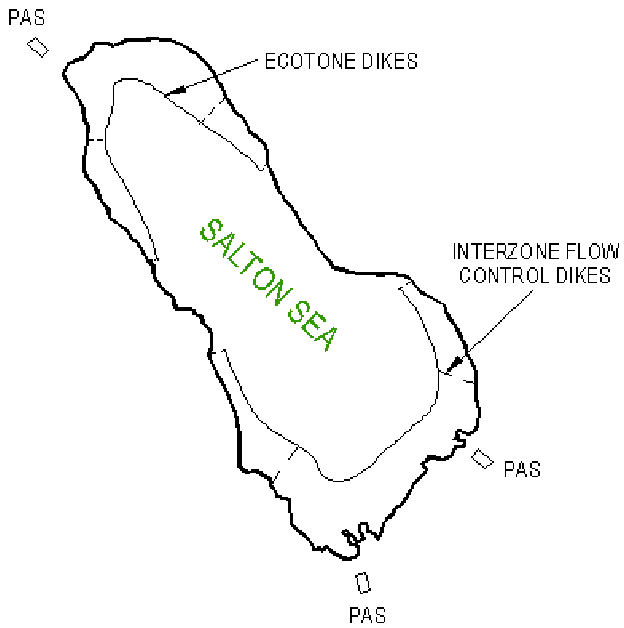

Figure 1. Salton Sea, appx. 900 km2, showing proposed dikes creating fresh/brackish ecotones and PAS units (over 1 % of total sea surface area) for high rate pond recovery of wasted nutrients and fish production.

MICROALGAL BIOMASS SYSTEMS FOR FUEL PRODUCTION.

As discussed earlier, extensive work has been carried out on microalgae biomass production systems, including potential applications to the Salton Sea. Indeed, pioneering work in the 1960's and 70's already anticipated the establishment of large-scale algal ponds at or even in the Salton Sea, for nutrient (nitrate) removal and salinity control, with the algal ponds serving a dual function in salt evaporation and algal biomass production [24]. This early work demonstrated the rudiments of this technological approach, including the ability of the algal cultures to grow well on drainage waters and remove most nitrate. In later work, the Salton Sea featured in several engineering cost analyses studies [11, 13], particularly a study carried out [14] that developed cost estimates for a pilot-scale facility on the shores of the Salton Sea and also for large-scale microalgae-to-fuels plants. The latter analysis was generic and directed to the production of algal oils for liquid transportation fuels (biodiesel). The costs of extracting and converting such fuels makes the alternative, production of methane (biogas) from the algal cells for on-site power generation. An initial cost estimate is presented below, based on a recently updated study [25].

The basic design of a large-scale (400 ha of ponds; 500 ha, total area) algal biomass production process is rather similar to that of current commercial algal production systems, such as the *Spirulina* producing Earthrise Co. plant located on the South shore of the Salton Sea, only larger. Instead of the typical 0. 3 to 0.5 hectare ponds used for *Spirulina* culture, the individual growth ponds would be about twenty-fold larger, some 8 hectares, and would not be lined with plastic, but have dirt bottoms. Unlined ponds have been demonstrated in both the PAS process and in pilot plant-scale algal biomass production systems (see above). Large (>4 ha) unlined ponds are also used in same *Spirulina* production and wastewater treatment, suggesting that this technology can, indeed, be scaled-up. Large unlined, paddlewheel-mixed, ponds are of simple design and low cost, with some $5,000 per hectare of growth pond area for the site clearing and pond levees, and another $5,000/ha for paddle wheels. Actually, the cost of the CO_2 supply system (including piping, diffusers, sumps, control system) is the more costly, about $10,000, assuming sumps suitable for the transfer of flue gas from a small powerplant operating with biogas from the digestion of the algae, and supplemental natural gas. To these must be added a harvesting system, assumed to be a simple flocculation-settling pond, whose design is based on the flocculation time and settling velocity of the algal biomass. Making reasonable assumptions, a cost of some $7,000 /ha for the harvesting process was derived. Another $3,000/ha must be added for the anaerobic digestion process, which would be a simple covered lagoon, as used in California and elsewhere for animal manures. Finally $5,000/ha is estimated for infrastructure, including buildings, electrical, roads and another $5,000 for engineering and contingencies. This assumes that water, nutrients and waste disposal (blow-down) would be provided by the Salton Sea or its tributaries, and that no centrifugation is used in harvesting. (Centrifugation was used in earlier studies, including for oil extraction). The total capital investment in such a process would be some $40,000 per hectare, significantly lower than prior estimates for algal-oil production processes, in part due to lack centrifuges [25].

Operating costs would be, essentially, for the power consumed in the process (see below) and labor (about $3,000/ha), with a $1,000 /ha allowance for chemicals (such as flocculants to aid in harvesting) and other consumables, plus the fixed capital charges (taxes, maintenance, insurance, depreciation and return on investment), at 20% of total investment, for a total operating cost of some $12,000/ha per year. Assuming an average productivity of 33 g/m^2/day, or 120 mt/ha-yr (a lower productivity than assumed in some studies), the cost of algal production would be some $100/mt of dry biomass. Against this would need to be compared power outputs and consumption. For the present process, using flue gas from a natural gas power plant as the CO_2 source, the main energy input ("parasitic power consumption") is for the flue gas transfer from the power plant into the ponds, about two-thirds of the appx. 100 kWhr/ha-day required, vs. some 300 kWh/ha-day of gross power output (assuming a yield of 1,000 kWhr/MT algal biomass), for a net of 200 kWhr/ha-day (670 kWhr/MT of biomass net), or, at $100/MT of biomass, some $0.15/kWhr for the fuel (biogas) input to the power plant. This is about a factor of two to three-fold higher than current costs for fossil fuels. This analysis could be made more favorable, by changing some assumptions, for example the distance between the power plant and the algal ponds, reducing parasitic power consumption, or the achievable productivity. However, such savings would likely be balanced by other factors minimized or overlooked in such a very generic and initial estimates. The greater potential is to combine such algal-fuel production systems with co-products and processes that can cover some of the costs of algal fuels. Such as proposed above as the Controlled Eutrophication Process for nutrient removal, also discussed next.

CONCLUSIONS: MICROALGAE PROCESSES FOR GREENHOUSE GAS ABATEMENT.

The very brief and general analysis presented above is quite favorable in most respects, and provides the lowest plausible cost that can be projected for microalgae biomass production. It assumes very favorable sites and technological developments in strain improvements, cultivation processes, biomass productivities, harvesting and processing (see Pedroni, et al., 2002, These Proceedings, for a discussion of R&D needs). Indeed, the above projected cost of only $100/MT is far below current costs of commercial algal biomass production, of at least $5,000/MT (estimated plant-gate cost for producing dried *Spirulina* by Earthrise Farms, Inc.). This great disparity between current reality and future projections can be ascribed to many factors: the great differences in scale (a factor of over ten for the individual growth ponds as well as the plant overall), the greatly simplified process (in particular simpler harvesting and no drying), no cost for the nutrients, water or CO_2, and three-fold higher productivities (33 $g/m^2/day$) than for current commercial *Spirulina* production, and almost 50% higher than projected for the PAS process. Achieving such low costs and high productivities will require a substantial R&D effort and success. For dedicated algal-fuel production systems even higher productivities would be required. Although very high productivities may be achievable through genetic manipulation of microalgae [26, 27]; those approaches still have to be brought out of the laboratory into outdoor pond cultures.

In the meantime, and for most site-specific cases, microalgae processes for fuel production and greenhouse gas mitigation will require to be a component of other processes, such as nutrient removal, aquaculture waste treatment (the PAS), both (the Controlled Eutrophication Process), or large volume co-products, such as animal feeds or chemicals. A currently commercial example of the latter is the co-production of ethanol fuels and animal feed (distillers dried grain) in corn-to-ethanol processes. Indeed, a similar process could be contemplated for conversion of high-starch algal biomass to ethanol and animal feeds, which could be economically competitive with corn ethanol, depending on externalities (e.g. ethanol fuel subsidies). Another example is the co-production of fish in the case of the Controlled Eutrophication Process for nutrient removal from the Salton Sea. Indeed, in this case the value of both co-products, the fish biomass and of the nutrient removal from the agricultural drainage waters, add value to the overall process. It is at present difficult to estimate these benefits, or the trade-offs required. For example, fish co-production may result in lower methane yields from the system, and the markets for such animal feeds need to be developed.

The nutrients recovered from the agricultural drainage waters, and contained in the residues of the digested algal biomass, could have a premium value as an organic fertilizer, highly desirable in organic farming. Indeed, it may be possible to establish actual nitrogen fertilizer production processes based on nitrogen-fixing cyanobacteria, if the resulting fertilizers have particularly high value. More broadly, municipal wastewater treatment, particularly for tertiary treatment (nutrient removal) provides a significant opportunity for development of such microalgae processes, with the value of water cleaned-up a major consideration. Indeed, the value of the recoverable water resources produced by microalgae waste treatment processes could exceed the value of the fuels, fertilizers, and all other products combined. The difficulty resides in the highly site-specific nature of such processes, which requires site-specific analyses. Site-specific studies are also required to address the seasonal variability of such processes, which can result in a three-fold or greater difference in productivity between summer and winter. Wastewater treatment processes, such as tertiary treatment, must accommodate these swings, requiring both seasonal performance objectives and operations.

The one major co-product not yet discussed from an economic perspective is greenhouse gas mitigation. It must be first recognized that the mere fixation of CO_2 into algal biomass does not represent, by itself, a greenhouse gas abatement process. That occurs only when this fixed CO_2 is converted to a biofuels that replace a fossil fuel. It should be noted that at most half, and more typically one third, of the CO_2 fixed into algal biomass is actually contained in a final fuel product. However, there are additional, and often much more important, mechanisms by which microalgae systems reduce greenhouse gas emissions: reductions in fossil energy inputs and secondary greenhouse gases (CH_4 and nitrous N_2O) emissions during wastewater treatment, compared to conventional processes [28, 29]; from the recycling of nutrients (in particular nitrogen fertilizers), and the reduction in the energy intensity of other co-products, such as animal protein or feeds. Indeed, until the competitive economics of greenhouse gas abatement are better established, such an analysis is difficult. However, from the above example of a methane production –nutrient removal process at the Salton Sea, a greenhouse gas mitigation credit of $10/MT CO_2 abated (at the high end of current projections for such credits), would contribute sufficiently to this process to support its economic viability.

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