The Controlled Eutrophication Process; Microalgae for Biofuels Production and Fertilizer Recycling at the Salton Sea, California

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Abstract

A potential site for a large-scale integrated microalgae CO_2 biofixation process is the Salton Sea in Southern California. This large (350 mile^2), shallow, inland lake receives about 10,000 tons of nitrogen and phosphorous per year from agricultural drainage waters and other sources, resulting in massive algal blooms, fish kills and other negative environmental impacts. The "Partitioned Aquaculture System" (PAS), developed at Clemson University, integrates microalgae biofixation of CO_2 with fish aquaculture promoting a high rate of harvestable algae and fish production. An adaptation of the PAS, the "Controlled Eutrophication Process" (CEP), is currently being evaluated by Kent SeaTech Corp in cooperation with Clemson University, in two ¾-acre (3,000 m^2) ponds to obtain field data quantifying and demonstrating algal and fish productivity, algal harvestability, and waste N and P recovery in this innovative high rate culture facility designed for by-product recovery. Nutrient inputs currently eutrophying the Salton Sea may be recovered using 4,000 acres of CEP units producing an algal sludge that may be blended with waste paper to be fermented into methane gas fueling 20 MW of exportable electricity generation capacity, biofertilizer production, and 20,000 tons of fish biomass, while abating as much as 200,000 tons of greenhouse gases, all while generating a cash flow of nearly $20,000,000 per year. Extrapolating CEP treatment applied to 10% of US concentrated animal feeding operations manure nitrogen and phosphorus production on 300,000 acres of land could potentially yield the equivalent of 50% of current US seafood flesh demand while reducing GHG emission by over 8 MMTC/yr. The integration of GHG mitigation with nutrient recovery and recycle, along with fish aquaculture and algal biomass recovery/utilization encourages environmental mitigation services as a social benefit of a profit driven enterprise. Application of the PAS/CEP technology offers potential for demonstration of large-scale microalgae culture for integrated environmental mitigation related to reclamation of municipal solid waste, waste nutrient recovery, and GHG reduction.

Introduction

The objective of Clemson University's Partitioned Aquaculture System (PAS) research program has been to stimulate the development of a sustainable aquaculture industry by providing technology that allows increased aquaculture production while reducing or eliminating the environmental impact of aquaculture, and simultaneously increasing the profitability of such operations. The PAS technology has been under development at Clemson University for the past 12 years (patented Brune et. al. 2001). The basic concept of the PAS is to partition conventional pond fish culture into distinct physical/chemical/biological processes linked together by a homogenous water velocity field. This physical separation of the fish culture ponds from algal production and water purification, allows separate optimization of these processes and thus, maximizes overall system performance. In the initial work on the PAS, algal productivities of 6 to 12 gm C/m^2/day were sustained throughout the growing season as opposed to 1-3 gm C/m^2/day in conventional ponds (Brune 1995; Drapcho 2000). This results in a greatly increased fish output per unit production area, a reduction in feed inputs and aeration power consumption, and elimination of wastewater discharge, compared to conventional aquaculture production systems.

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Central to the success of the PAS is the homogenous water velocity field, provided by a low speed, low head, feedback controlled, paddlewheels. Thus the PAS is essentially a high rate algal pond, such as studied and developed by Oswald (1988) and colleagues (Benemann et al., 1980) for many years at the University of California for municipal wastewater treatment and used by most algal production companies. However, paddlewheel mixed algal growth ponds have not been previously used in aquaculture production. Such systems provide enhanced interfacial gas exchange rates, maximizes algal productivity, and CO_2 consumption, minimizes waste solids settling, and allow for harvesting of excess algal solids, thus improving water quality and providing a potential source of biomass for renewable energy.

The PAS design includes three main components: the algal channels, the fish raceways (separated from the algal ponds with coarse screens, allowing free-flow of water while restraining the fish), and a settling sump, to capture and concentrate settleable solids (fish wastes and algal flocs) for removal from the system. The removal of excess algal solids can also be managed with populations of filter-feeding fish. The PAS process allows for semi-independent control and management of the algal production ponds and the finfish and filter-feeding raceways optimizing the environmental conditions for each component and maximizing the waste treatment and algal feed production potential. This in turn reduces feed inputs and power requirements for aeration, and maximizes waste treatment capacity. Finally, the separation of the different process functions, and maximization of algal biomass production, results in, not only increasing fish production, but also in providing the potential for waste CO_2 utilization, and for harvest and conversion of algal biomass for production of renewable power.

The use of a PAS process results in a substantial reduction in atmospheric emissions, water pollutants and other environmental impacts associated with external feed inputs. Energy inputs into operation of a PAS are reduced in comparison to conventional systems, as a result of the reduction in aeration requirements, due to the separation of the algal and fish production processes, and the increased O_2 production in the algal channels. Paddlewheel mixing is a very energy efficient process. Many other advantages can be listed for such high-rate algal pond systems in aquaculture, including more predictable management of pond physico-chemical parameters (e.g., D.O., pH, NH_3, etc.), control of dominating algal species (avoidance of undesirable off-flavor producing cyanobacteria) and avoidance of algal bloom “crashes”, which can quickly deplete O_2 levels in the ponds. Most important, this technology is of overall lower unit cost and higher productivity than conventional processes, the key factor in its future widespread implementation, and therefore potential for reduction of aquacultural environmental impact.

The Controlled Eutrophication Process

Kent SeaTech and Clemson University have conducted extensive research, development, and demonstrations involving the application of the PAS for concentrating and removing nutrients from wastewater streams. This modification of the PAS is described as the Controlled Eutrophication Process (CEP), in which dense populations of single-celled algae are cultivated in high-rate algal ponds and then are removed (harvested) by a variety of methods prior to water flow exiting the system (Figures 1,2,3). The Controlled Eutrophication Process represents the water treatment portions of the patented Partitioned Aquaculture System (PAS) developed at Clemson University. In joint research, Kent SeaTech and Clemson have proved the technical and economic feasibility of using CEP technology to reduce nutrient concentrations from aquaculture effluent.

Figure 1. Algal harvesting belt installed in 1/3 acre PAS/CEP unit.

Figure 2. Algal concentrate delivery from harvesting belt.

Figure 3. Algal concentrate obtained from harvesting belt.

The Salton Sea and the Controlled Eutrophication Process

A. Eutrophication of the Salton Sea in Southern California

The Salton Sea is a large inland lake (365 square miles) that is 227 feet below sea level, has no outlet, and has been accumulating salt and nutrients from stormwater, treated sewage, industrial waste discharges, and agricultural drainage for nearly 100 years. Over geologic time, the Salton Basin and Lake Cahuilla have been periodically flooded due to natural diversions of the Colorado River, but after each diversion ceased, the area became a dry lake bed. More recently, as the region developed and large scale agricultural irrigation and municipal and industrial waste streams from the U.S. and Mexico were created, the Sea has become a permanent body of water, with evaporative losses approximately equal to tributary inflows. The buildup of salts and nutrients from agricultural, municipal, and industrial discharges from the Imperial and Coachella valleys has led to the development of an inland hypereutrophic, hypersaline lake.

As the Sea has increased in salt content, it has seen a transition of ecosystems from freshwater to brackish to salt tolerant organisms. A variety of solutions have been proposed for management of water quality within the Salton Sea. These range from evaporative ponds/spraying systems to concentrate salts, to pumping of water for discharge to the Gulf of California. However, reducing the salinity will not resolve one of the most serious water quality problems in the Salton Sea; the high nutrient loads that are causing eutrophication. The large-scale algae blooms, cyclic low oxygen levels, massive fish mortalities, and frequent odor problems that are caused by eutrophication represent major water quality problems that must be addressed. A recent proposal to the Salton Sea Authority has suggested the establishment of freshwater impoundment zones within the existing Sea perimeter near the major freshwater river inflow areas (Figure 4).

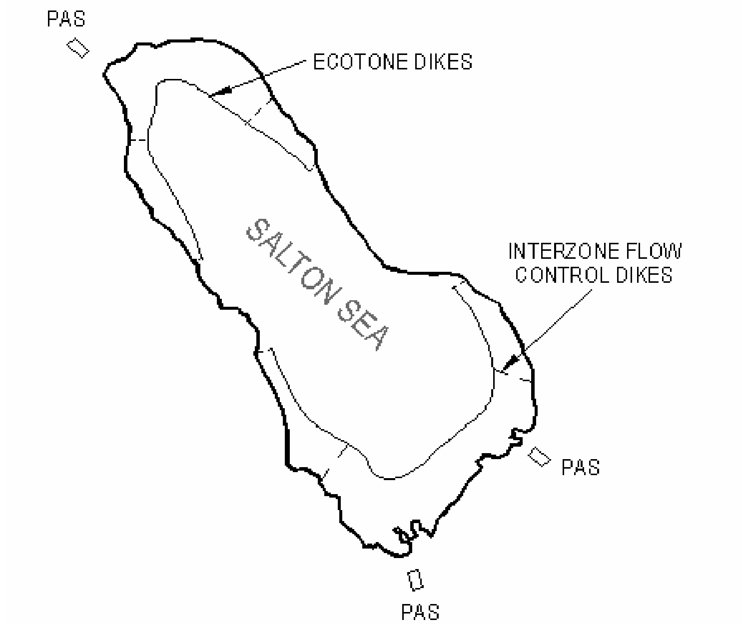

Figure 4. The Salton Sea showing proposed dikes creating fresh/brackish ecotones and PAS/CEP units (1 % of total surface area) for high rate recovery of waste nutrients. As the Sea continues toward a supersaline environment that would be inhospitable to most freshwater and brackish organisms, this freshwater habitat would continue to support fish and the fish-eating birds. Whether the freshwater impoundment zone concept is eventually implemented or not, lowering the amount of nutrients flowing into the Sea through its tributaries is of paramount importance in improving and maintaining acceptable water quality conditions within the sea.

The principal tributaries to the Sea (the Alamo, New, and Whitewater Rivers) contain 0.19 to 1.47 mg/L of total phosphorus at N/P ratios of 4.6 to 39.6. Phosphorus is considered to be the limiting phyto-nutrient in the Sea. The high algal growth potential of the Salton Sea caused by high levels of nutrients results in frequent wide-spread, high density algal blooms. Senescence of these blooms often leads to catastrophic low dissolved oxygen events, triggering massive and unacceptable fish mortalities and odor problems. A cost-effective solution to this problem is required. Accordingly, the Salton Sea Authority and the U.S. Bureau of Reclamation are seeking to develop appropriate technologies to mitigate and restore Salton Sea water quality.

B. CEP Application for Remediation of the Salton Sea

CEP units will be configured differently from the design used in aquaculture wastewater treatment (as in the case of the PAS). In the aquaculture system, no water is discharged to the environment and the filter-feeding fish are held in the water of the algal growth basin with equilibrium algal cell concentrations typically not exceeding 50-60 mg/L VS. However, in the CEP application, water flow through the system will provide hydraulic retention times as short as 1.0 day. The algal standing crop will be sustained at values ranging from 80-160 mg/L as dry weight volatile solids (VS). The algae-laden discharge from the treatment zone will be passed over high densities of confined filter-feeders and through algal sedimentation chambers/zones with a controlled retention time, resulting in a steady state algal cell density of 20-30 mg/L providing for near maximum uptake rate by the filter feeder biomass (figure 5). With this CEP flow configuration, 75 to 90% of the algae-bound N and P will be removed without the need for flocculant addition. The remaining 20-30 mg/L of algal biomass will be removed with low-level metal salt flocculant addition in a final polishing basin (Figure 4). In this way, the flocculant demand to achieve >90% N and P removal will be only 10-25 % of the mass required for direct flocculation of river water nutrient load.

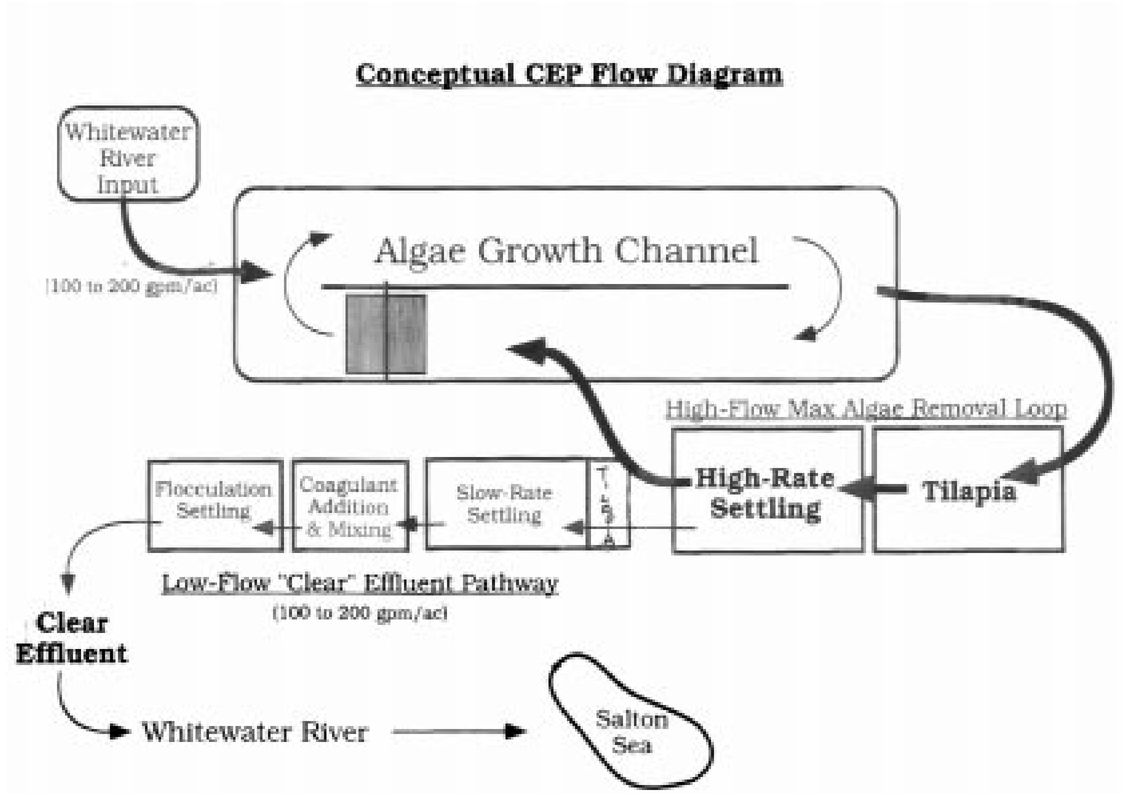

Figure 5. Experimental Controlled Eutrophication Process (CEP) Flow Diagram. Shown are the high rate ponds receiving nutrient rich river water inputs, followed by the main tilapia production ponds, in which the algal biomass is converted into fish biomass, fecal pellets and algal flocs, the latter removed in the sedimentation tanks. Most of the flow is re-circulated through the high rate ponds with a portion of the treated effluent discharged through a smaller tilapia culture, followed by slower sedimentation and final polishing of the effluent with chemical coagulants and settling of the flocs. The output is a purified effluent low in nutrients that would be returned to the river and Salton Sea.

C. Full-Scale CEP Application for Salton Sea Nutrient Remediation

Effective management of the current nutrient loading to the Salton Sea will require several thousand acres of large-scale CEP systems. Each individual CEP unit will likely be between 10 to 100 acres in size, operating at two feet of water depth (three foot high earthen levees), with 100-300 foot wide CEP channels constructed with their long axis parallel to the fall of the land to minimize levee construction. Adjacent units would use common earthen levees, stair-cased to match the elevation fall. Although additional studies are required to accurately estimate the full-scale construction and operational costs at the Salton Sea, pilot-scale PAS systems at Clemson University, which utilize the CEP technology suggest capital construction costs of approximately $15,000-$25,000 per acre

The need for nutrient management on such a large scale provides an opportunity to utilize and recycle waste nutrients within a private enterprise while providing a public environmental service. Conversion of nutrients to algal biomass and subsequent conversion of a portion of the algal biomass to valuable fish biomass would result in marketable byproducts mitigating a substantial portion of the operational costs involved in treating the Salton Sea inflows. The algal biomass harvested from these systems could also be used directly as an organic supplement and fertilizer for local farms, without production of biogas fuel.

Micoalgal 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 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. 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 nitrates. In later work, the Salton Sea featured in several engineering cost analyses, in particular a study that developed cost estimates for a pilot-scale facility and large-scale microalgae fuels plants on the shores of the Salton Sea. The latter analysis was generic and directed to the production of algal oils for liquid transportation fuels (biodiesel). The relatively high costs of extracting and converting such fuels makes the alternative, production of methane (biogas) from the algal cells for on-site power generation more attractive.

A. Improved Biogas Production with Algae/Waste Paper Co-digestion

The solar energy stored in photosynthetic (algal) biomass may be captured as methane through anaerobic digestion. This concept was originally proposed over 40 years ago by Oswald and Golueke (1960). In their paper the integrated processes of large-scale raceway cultivation of microalgae and wastewater treatment, followed by fermentation of algal biomass to methane fuel was first proposed. However, Golueke et al (1957) found that methane production from algal biomass at 35°C, 30 days HRT and a loading rate of 1.5 g VS/l day averaged only 260 cm^3 per gram of volatile solids, or 390 cm^3 per liter of digester volume per day. This low level of energy recovery from the fermentation of algal biomass alone is not energetically or economically favorable. Chen and Oswald found the heat pretreatment of algal sludge at 100 °C for 8 hours could improve the efficiency of methane fermentation to a maximum of 33%. However, the increase in methane energy recovery would not off-set the energy input for the heat pretreatment.

Recently studies at Clemson University were directed at improving the digestability and fuel recovery from algal biomass by combining the algal sludge with waste paper. Algal sludge was harvested from the Partition Aquaculture System at Clemson University. The algal sludge ranged from 2% volatile solids content, harvested with metal salts induced flocculation to 6% volatile solids content when harvested using filter feeding fish as a harvest and concentrating technique. The species of dominate algae in the sludge would vary by season, however the bulk of algal biomass was composed of *Scenedesmus sp*. or *Chlorella sp*. Waste paper was collected from recycle bins of the Department of Computer and Information Technology labs at Clemson University. The waste paper collected from the DCIT computer lab was originally used for laser printers and one side was printed on most of waste paper. The paper was cut using a shredder or scissor into 0.5×1 cm pieces before blending with algal sludge.

B. Algal and paper co-digestion at fixed algal sludge loading of 2 g VS/l day

Algal sludge can be harvested using metal salts, however this produces a reduced VS solids content in the concentrated sludge limiting the VS contribution from algae biomass to 2 gm VS/l day. For this reason it was necessary to investigate the effect of loading the digester with varying amounts of paper at a fixed amount of algal sludge loading. The composition at each loading rate for co-digestion at 10 days HRT is given in Table 1.

Co-digestion of these mixtures resulted in a maximum methane production rate at a loading rate of 5 g VS/l day and 60% paper fraction (C/N=22.6/1). VFA concentration increased from 1300 mg/l (at 2 g algal VS/l day) to a maximum of 6200 mg/l (at 5 g paper + 2 g algal VS/l day). TAN concentration was observed to decrease from 589 mg/l to less than 200 mg/l.

Table 1. Observed methane production, VFA, TAN and C/N ratio in co-digestion of algal sludge and waste paper at fixed algal loading rate of 2 g VS/l day and 10 days HRT.

Loading g VS/l d	Paper g VS/l d	Algal sludge g VS/l day	CH_4 ml/l d	VFA mg/l	TAN mg/l	Alk×1000 mg/l	C/N	5N NaOH ml/l day
2	0	2	180±34	1305±147	589±86	4.6±0.35	6.7	0
3	1	2	823±16	3780±458	541±2	4.7±0.2	13.3	0
4	2	2	1170±75	3912±1290	524±24	5.4±0	18	0
5	3	2	1607±17	5220±855	396±8	4.3±0.4	22.6	0.25
6	4	2	856±40	6228±685	175±7	4.3±0.3	27.2	1.5

Anaerobic co-digestion of waste paper with algal sludge produced a dramatic increase in methane production rate from less than 200 cm^3 CH_4/l day (at 2 g VS/l day, 100% algal loading) to over 1600 cm^3 CH_4/l day (at 5 g VS/l day, 60% paper fraction; Figure 6). Methane yield was seen to increase from less than 100 cm^3/g VS loaded to 325 cm^3/g VS loaded. The digestion process appears to benefit from the combination of reduced ammonia concentration under low C/N ratio feedstock loading (under algae loading alone) and added ammonia under high C/N feeding (under paper alone feeding) and increased cellulase activity under conditions of the combined algae/paper loading The observed optimal C/N ratio ranged from 18/1 at a loading rate of 4 g VS/l-day (50% algae/paper mix) to 22.6/1 at a loading rate of 5 g/l-day (60% paper). Cellulase activity was observed to increase 3-fold with paper addition.

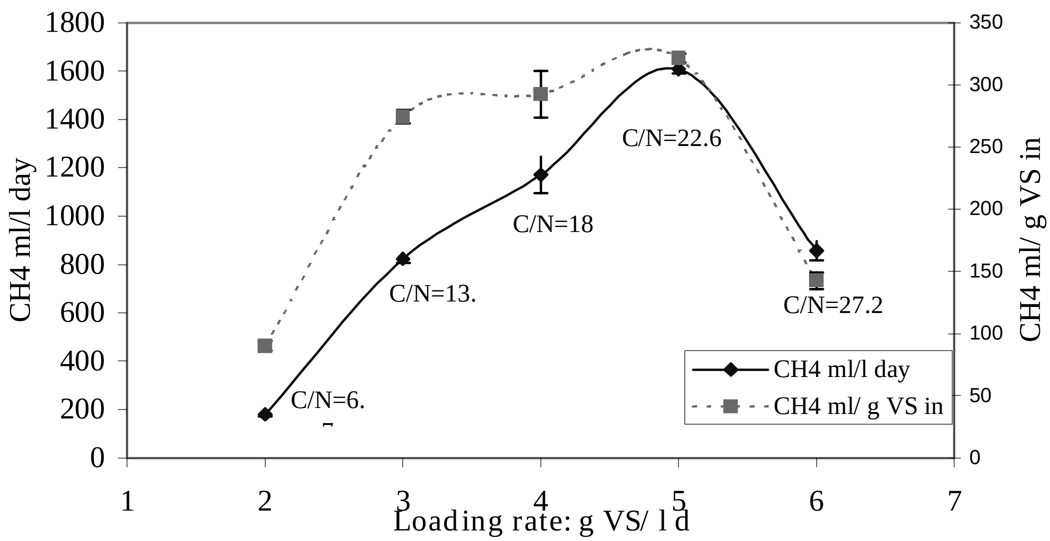

Figure 6. Observed methane production vs loading rate at fixed algal loading of 2 g VS/l and varying paper fractions at 10 days HRT.

CEP for By-Product Recovery and Greenhouse Gas Abatement

We estimate that recovery of 22.5 tons (at 9 mg/l) of nitrogen and 2.5 tons of phosphorous (at 0.9 mg/l) per day from the discharges to the Salton Sea, (the combined flows of the New and Alamo Rivers) will require approximately 4000 acres of CEP water surface area, growing algae biomass at an average of 7.6 g C/m^2 day (15.2 g VS/m^2 day). This daily algae biomass production rate of 270 tons VS /day will be combined with an equal mass of MSW paper and fed to a digester of 98 million gallons in volume (at a loading rate of 5 gm VS/liter day). The digester will produce 20 MW of energy (at 1.6 liter CH_4 per liter of reactor volume per day). The algal biomass will be recovered using filter feeding fish which will also produce a fish biomass of 40 million lbs per year (10,000 lb/acre). The CO_2 required to recarbonate the algae ponds may be recovered from the digester flue gas providing 100% of the carbon requirements of the algal reactors. The nitrogen and phosphorus recovered from the surface water discharge to the sea will be concentrated approximately 40 times in the digester effluent to be returned to farmers which will further reduce the nutrient loading to the sea by decreasing the amount of commercial fertilizer purchased to be used in the valley (Figure 7).

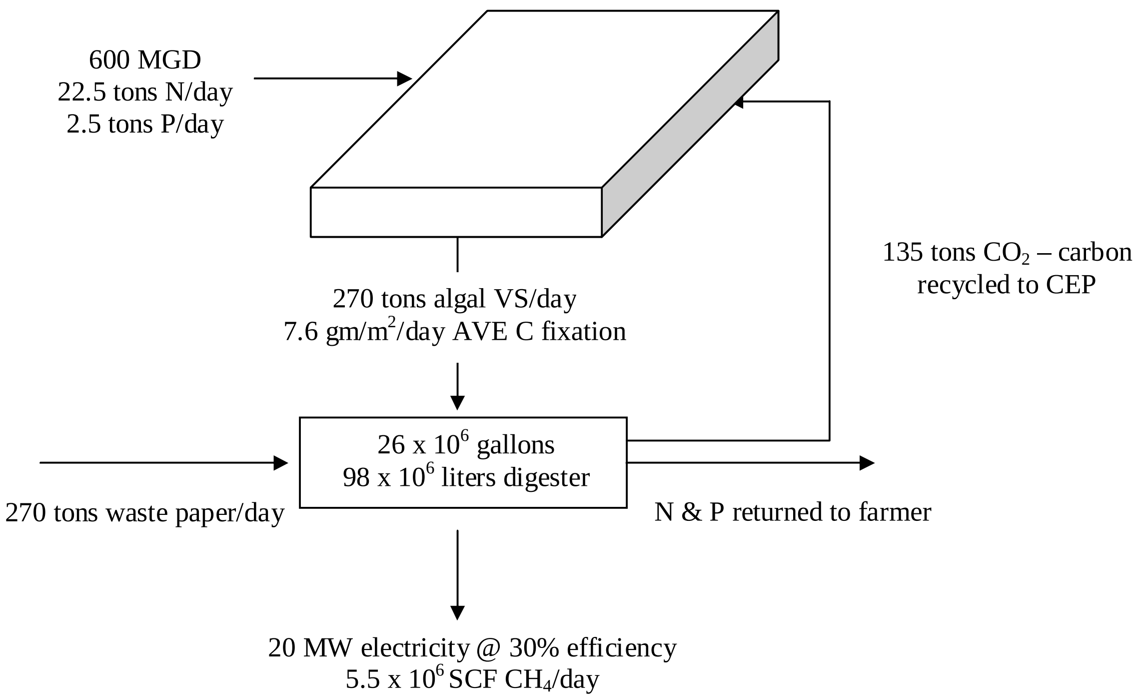

Figure 7. Projected materials and energy balance on CEP for recovery of waste nutrients to the Salton Sea.

A preliminary cost analysis of the CEP recovery process suggests that the recovered fish flesh will produce an income of $6,000,000 per year (at $0.15/lb), (or potentially five times more income if the flesh could be sold as food as opposed to feed). The fertilizer value would be approximately $3,285,000 per year, with energy producing an income of $10,100,000 per year, yielding a net income of approximately $19,385,000 per year. Ongoing research is directed at refining and improving our net operating cost estimates for the 4000 acres of CEP which we currently place at between $20,000,000 to $40,000,000 per year.

Table 2. Income Generation from By-product Recovery.

Product	**Income $/yr**
Fish meal (@ 15¢/lb)	$ 6,000,000
Energy (@ $5/10^6 BTU, 5¢/Kw-hr)	$10,100,000
Nitrogen Fertilizer (@ 20¢/lb)	$ 3,285,000
TOTAL	$19,385,000

In addition to the reduction in waste nutrient loading to the Salton Sea the CEP process will reduce fossil fuel usage, commercial fertilizer purchases and produce valuable fish flesh protein produce from solar energy. We estimate that this solar energy recovery and associated fossil fuel replacement, recycle and reuse of crop nutrients and production of fish flesh will result in a reduction in associated GHG production by as much as 100,000 to 200,000 tons per year (as carbon, Brune, et al, 1999)

Recently, Brune et al (1999) examined the widespread application of controlled eutrophication systems for management of manure and surface waters associated with concentrated animal feeding operations (CAFOS) and the associated benefits of mitigation of nutrient enrichment of public waters, as well as reduced greenhouse gas emissions through improved manure management reducing CH_4 and NO_2 release. The Southern states with highest potential for nitrogen enrichment of surface water, also provide high levels of solar radiation and air temperature; conditions best suited for high rate photosynthetic systems. In addition to local adverse nutrient enrichment impacts, poor manure management contributes significantly to US greenhouse gas emissions. The US is currently responsible for 27% of global GHG emissions. Anaerobic processes contribute 16% of total US GHG emissions. Current US agricultural manure management practices contribute 35% of US anaerobic processes GHG emission. Worldwide current manure management practices contribute over 200 MMTC/yr to the GHG pool.

It was estimated that CEP treatment of 10% of US AG CAFO manure nitrogen and phosphorus on 300,000 acres of land could potentially yield the equivalent of 50% of current US seafood flesh demand while reducing GHG emission by over 8 MMTC/yr. At current US corn production on 400 million acres, with US corn production averaging 80 bu/acre, the total nitrogen assimilation capacity of CEP units treating the equivalent of 10% of US CAFOS manure would correspond to 16-32% of US annual corn nitrogen fertilizer equivalence. The integration of GHG mitigation with nutrient removal and recycle, along with fish aquaculture and algal biomass recovery/utilization encourages environmental mitigation services as a social benefit of a profit driven enterprise. Application of the PAS/CEP technology offers potential for demonstration of large-scale microalgae culture for integrated environmental mitigation related to reclamation of municipal solid waste, waste nutrient recovery, and GHG reduction.

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