ABSTRACT

Title of Document: ECONOMIC ANALYSIS OF ALTERNATIVE APPLICATIONS OF AN ALGAL PRODUCTION SYSTEM

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A variety of different best management practices are being studied to reduce nutrient pollution in the Chesapeake Bay. The algal turf scrubber™ (ATS) effectively removes nutrients from Bay waters in experimental trials but there is no large-scale applications in the Chesapeake Bay watershed. The purpose of this project was to conduct an economic analysis of the ATS technology to determine the feasibility for nutrient removal across the Bay landscape. Baseline data for the analysis were extrapolated from several small-scale experimental trials of the ATS. The analysis included scaled costs along with benefits from nutrient trading credits, bio-product values of biofuel production, oxygen from photosynthesis and fertilizer value of nutrients taken up in algal growth. Six operating scenarios were analyzed through various cost analyses. The results indicate that the ATS technology can be economically viable under certain conditions and can be complementary to other best management practices for restoration of water quality in the Bay.

ECONOMIC ANALYSIS OF ALTERNATIVE APPLICATIONS OF AN ALGAL PRODUCTION SYSTEM

By

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Chapter 1 : Technology and Market Background

1.1 Technology

The algal turf scrubber (ATS) system is an ecologically engineered water improvement technology (the Algal Turf Scrubber is a trademark registered to the Hydromentia Corporation of Ocala, Florida) (Adey and Loveland, 2007). Ecological engineering is the use and control of natural ecological systems to solve environmental problems (Kangas, 2004). Based on Walter Adey's coral reef studies, this technology is a biomimicry of algal turfs found on the coral reef crest (Adey & Goertemiller, 1987; Adey et al., 2011). Adey found that high light intensity in conjunction with the energy rich surge created by waves created an environment for the highest rates of production in the Biosphere.

The coral reef model was then simulated by the creation of the ATS as a method of wastewater treatment. The ATS takes advantage of the high primary production rate of algae in a controlled system to help solve water quality issues. The ATS is composed of a native algal community that grows attached on screens, depicted in Figure 1.1. The system is comprised of an algal covered raceway over which nutrient rich water is pumped.

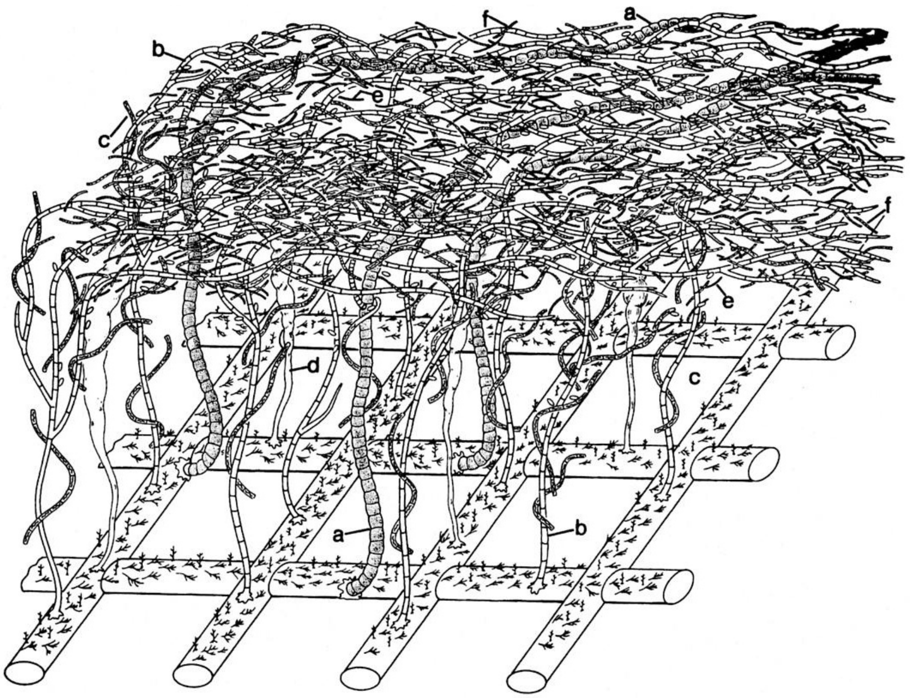

Figure 1.1 Algae grown attached on screen from Everglades study. Reprinted from Adey et al. (1993).

A systems diagram of the inputs, processes, and outputs of the technology are shown in Figure 1.2. As the water flows over the algal community, the waster is stripped of its nutrient contents, which are incorporated into the algal biomass.

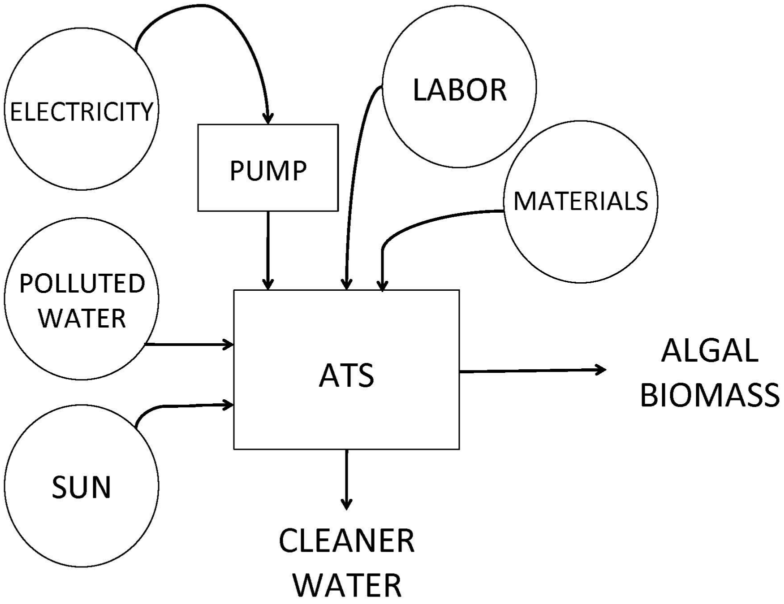

Figure 1.2 Systems diagram. Modeled after coral reefs, the algal turf scrubber inputs include light, polluted water, electricity to run a water pump, and labor to harvest the biomass. Algal biomass as well as nutrient reduced but oxygen rich water are byproducts.

Figure 1.3 shows an ATS unit prototype that encapsulates all the features of high primary productions discovered in Adey's coral reef study. The unit includes a source of light, screens in which algae may adhere to, and a tipping bucket to simulate the energy rich wave surge.

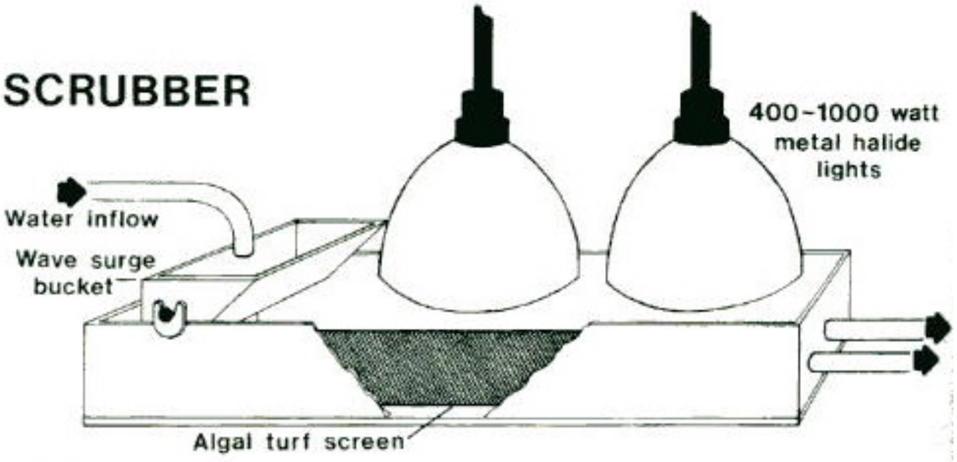

Figure 1.3 Small algal turf scrubber unit (Adey and Loveland, 1998).

The algae perform the ecosystem service of removing nitrogen, phosphorous, and other nutrients from the water and releasing dissolved oxygen (DO) through photosynthesis. The post “scrubbed” water is then added back to the water source with an increased DO concentration, helping to mitigate hypoxic zones. The ATS delivers these ecosystem services on a variety of scales: small scale depicted in Figure 1.3, the pilot scale experimental system in an agricultural setting in Figure 1.4, or the industrial scale managed by HydroMentia, Inc., of Ocala Florida in Figure 1.4.

Figure 1.4 Different scale ATS systems. The system on the left shows an industrial-scaled ATS at 1 hectare in Florida and able to process 10 million gallons per day (HydroMentia Inc., n.d.). Picture courtesy of HydroMentia, Inc. The system on the right is a solar-based system constructed on a farm near Bridgetown, Maryland with dimensions of 6 meters wide and 50 meters long.

In addition to the construction of ATS systems at a variety of scales, the technology has been thoroughly vetted over the last decade through a plethora of publications. Table 1.1 shows a comparison of ATS studies throughout the Chesapeake Bay region. Additionally, algal growth rates, nutrient uptake rates, source water condition, and other parameters in different studies have been provided as one-page summaries in Appendix A as an overview of the literature surrounding the ATS.

Table 1.1 Comparison of algal turf scrubber studies from around the Chesapeake Bay region. All studies from outdoor raceways that operated for at least one annual cycle.

System location	water treated	growing season	flow rate	productivity	nutrient content	
		months	L/min/m	$g/m^2/day$	(% N)	(% P)
Lancaster, PA[1]	Susquehanna River	8	173	12.9	2.5	0.3
Beltsville, MD[2]	dairy manure	9	93	~10	5.9	0.8
Bridgetown, MD[3]	ag drainage ditch	9	35 (day) 14 (night)	<5	2.0	0.3
Baltimore, MD[4]	urban harbor	12	190	7.2	3.2	0.1
Gloucester, VA[5]	York River	12	100	~20	1.3	0.2
Reedville, VA[6]	Great Wicomico River	12	125	15.4 (2D screen) 39.6-47.7 (3D screen)	2.5	0.2

[1] Kangas et al. 2009

[2] Mulbry et al. 2008

[3] Kangas & Mulbry 2012

[4] May et al. 2013

[5] Canuel & Duffey 2011

[6] Adey et al. 2013

1.2 Services

1.2.1 Nutrient Uptake

Ecosystem services are the processes provided by natural ecosystems as well as the species that they are comprised of, sustain human life (Daily, 1997). One such ecosystem service provided by the ATS is wastewater treatment. The high productivity and nutrient removal rates observed by the ATS were employed in a number of wastewater remediation projects. A study by Craggs et al., (1996) found that a controlled stream mesocosm through the format of an ATS was successful at reducing nutrients in secondary sewage to tertiary sewage levels. Adey et al., (1993) found that phosphorus reduction via an ATS in the Florida Everglades at a rate of 140 mg/m^2/day or 511 kg/ha/year was 100-250 times the phosphorus removal rate of comparable wetlands. This technology was also employed to effectively treat dairy manure effluent at costs comparable to upgrading existing water treatment plants (Mulbry et al., 2008). These highly efficient levels of nutrient reduction set the stage for approval as a Best Management Practice (BMP) for nutrient reduction and nutrient credit generation in the Chesapeake Bay region. In addition, the nutrients removed may be recycled as fertilizer.

1.2.2 Dissolved Oxygen Replacement

The ATS not only removes nutrients from wastewater but also performs the ecosystem service of increasing DO via photosynthesis into the water (Benemann & Oswald, 1996). This addition of DO is unique to the ATS, compared to other wastewater treatment processes that must incur additional costs to aerate.

The poor water quality of the Chesapeake Bay can in part be attributed to eutrophication, out of control algal growth, and eventually the formation of hypoxic zones. According to the Maryland Department of Natural Resources (2013) these zones occur when waterways are loaded with high amounts of nutrients from both point sources (sewage or industrial plants) and non point sources (stormwater or agricultural runoff). This high nutrient concentration allows for the uncontrolled growth of algae in the form of blooms. The decomposition of these blooms by bacteria requires a large amount of oxygen, which leaves zones depleted of DO and uninhabitable by other organisms.

Thus, as a technology that has the potential to significantly improve the water quality of the Chesapeake Bay, part of the non-market value of improved water quality via increased DO concentration was determined through valuing the DO injected by the ATS. The replacement value may be used to determine the value of a service the ecosystem contributes by determining the replacement cost of the next best alternative (Heal, 2000). In this case, the value was calculated using the replacement value by replacing the ATS with an aerator.

1.3 Products

1.3.1 Biofuel

In addition to the wastewater treatment element of the ATS this system also produces a valuable algal biomass that may be used as a feedstock for biofuel production. The United States consumes 140 billion gallons of automotive fuel every year (Ryan, 2009). At this current rate of consumption, in addition to the inevitable reach of peak oil, the need of a new form of sustainable energy has become apparent. For example, in 2005 the United States oil production hit a production cap at about 75 million barrels per day (Murray & King, 2012). Prior to 2005, oil production was able to keep up with demand. While most research concerning algal biofuel focuses on its potential for biodiesel, other fuels of interest in the United States include ethanol and butanol.

There are definite advantages in using algae as a feedstock for biofuel over first generation biofuel feedstocks, such as corn. Firstly, growing algae does not displace arable cropland that can be used for food production (Ferrel & Sarinsky-Reed, 2010). Secondly, some inputs required for corn, such as fertilizer and premium cropland are not necessary for the growth of algal biomass. In addition, the ATS actually utilizes and cleans wastewater caused by run-off from crops like corn. Lastly, a system such as the ATS is harvested once a week over the course of a 9-month growing season while corn is only harvested once. This gives algae a greater biofuel production potential due to higher biomass accumulation over the course of a growing season. However, algae as a feedstock is not nearly as established a biofuel feedstock in the marketplace as its first generation rivals.

Due to the high carbohydrate and relatively low oil content of ATS algae, as characterized by Mulbry et al. (2008a) the focus of this analysis will be on the fermentation of algal biomass to produce biofuels rather than extraction of oils. However, it should be noted that it is possible to convert oils from ATS into biodiesel and research is underway to convert ATS algae into biodiesel via pyrolysis.

Currently, research efforts are focused on the conversion of algae into butanol through innovative processes at the University of Arkansas under the direction of Jamie Hestekin. Using a modified acetone butanol ethanol (ABE) fermentation process, Hestekin is able to show greater conversion efficiencies of algae to butanol at lower costs. These results are at the bench scale, conversion rates and costs are scaled up for the purpose of this feasibility study.

Figure 1.5 shows a simple schematic of the conversion of algal biomass to biobutanol. Compared to the traditional ABE method, this method involves adding an additional step in the fermentation process instead of going straight to butanol production. This in turn creates a more attractive carbon and energy balance when compared to traditional butanol conversion.

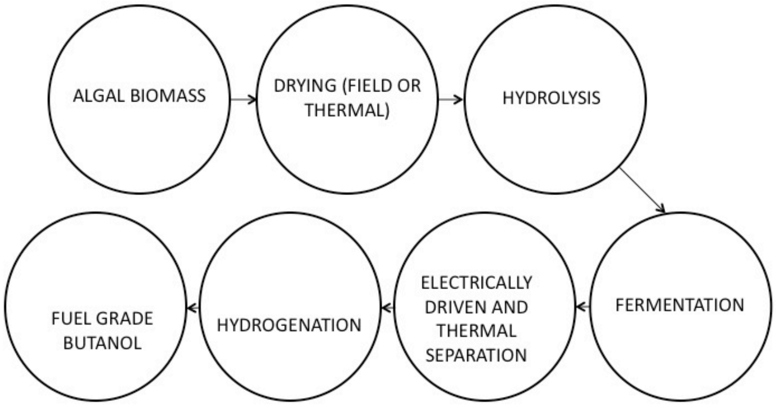

Figure 1.5 Overview of algal biomass conversion to fuel grade butanol.

1.3.2 Fertilizer

The recovery of nutrients before they are lost to the bay is a challenge faced by agriculturalists. Precipitation causes nutrients to run off the land and into local waterways, thus contributing to nutrient loading and decreased water quality. Also, another problem is the loss of nitrogen to the atmosphere due to denitrification. Thus, closing the nutrient cycle through uptake by an ATS could serve two purposes. First, it could allow farmers to comply with Total Maximum Daily Loads (TMDLs) by meeting their baseline nutrient reduction requirements and generate nutrient trading credits for reductions beyond the baseline. Secondly, the algae produced from agricultural run-off could then be recycled and used as slow-release soil amendments to avoid volatilization.

Algal biomass from ATS systems have been extensively studied as slow release fertilizers (Mulbry et al., 2006; Mulbry et al., 2005). In these studies, the ATS was used to recycle manure nutrients from raw manure effluent as well as anaerobically digested manure. The biomass produced from these manure inputs was added as soil amendments to grow crops. In the Mulbry et al., (2006) study, results demonstrated that corn grown using algal biomass as its nutrient source was equal to fertilizer in its ability to supply nutrients to corn seedlings as a slow release fertilizer. The corn in this study was grown in a growth chamber in order to compare plant growth and nutrient uptake to conventional fertilization efforts and therefore longer-term field studies are necessary to assess yields under conventional large-scale crop conditions. However, the preliminary success of biofertilizers from ATS treatment is encouraging as another possible revenue stream for the system. Therefore, the value of algal biofertilizer will be assessed from a cost avoided standpoint.

1.4 Green Jobs

One advantage of a system such as the ATS is the creation of "green" jobs while also improving water quality. These jobs are termed as "green" due to the fact that they drive water quality improvement as well as renewable energy through biofuels. The installation of an ATS would require one manager and two laborers working 40 hours/week for two weeks at a rate of $60 and $15/hour, respectively. The manager would be responsible for the design, siting, and engineering specifications required for an ATS and would thus require intimate knowledge of ATS technology. Once the scrubber is installed, the system would only require one laborer working 20 hours/week at a rate of $15/hour to maintain and harvest the system, which would run 270 days per year in the Chesapeake Bay region due to growing season constraints. The ATS would be harvested manually by brushing or scraping the algae off the screens, thus rejuvenating the algal population.

1.5 Intellectual Property

The Algal Turf Scrubber ™ is a trademark registered to HydroMentia, Inc., of Ocala, Florida. Inventor Walter H. Adey of The Smithsonian Institution of Washington, D.C. patented the ATS on June 8, 1982. Table 1.2 shows a select list of the patented ATS technology to show this technology has been thoroughly vetted.

Table 1.2 List of select patents for ATS technology.

Title	**Patent Number**	**Date of Patent**
"Algal Turf Scrubber"	4,333,263	June 8, 1982
"Water Purification System and Apparatus"	5,097,795	March 24, 1992
"Animal Feedstocks Comprising Harvested Algal Turf and a Method of Preparing and Using the Same"	5,715,774	February 10, 1998
"Algal Turf Water Purification Method"	5,851,398	December 22, 1998
"Apparatus and Methods for Harvesting and Collecting Attached Algal Communities"	6,572,779 B1	June 3, 2003

1.6 Regulations

1.6.1 Total Maximum Daily Loads

In response to the Clean Water Act, which aims to make all waters of the United States “swimmable and fishable,” TMDLs established a pollution diet for the waterways of the Chesapeake Bay (EPA, 2010). The TMDL requirement span across the entire Chesapeake Bay Watershed (six states and Washington D.C.) and establishes the maximum amount, measured in pounds, of nitrogen, phosphorous, and sediment a waterway can receive. The Bay watershed is limited to a diet of 185.9 million pounds of nitrogen, 12.5 million pounds of phosphorous, and 6.45 billion pounds of sediment, representing a 25%, 24% and 20% reduction, respectively. Guidelines regarding how each state will meet their allocated pollution diet are described through Watershed Implementation Plans (WIPs).

1.6.2 Nutrient Trading

One method of facilitating nutrient reduction required by WIPs is through the generation of nutrient credits. Credits are generated by the installation of best management practices (BMPs) that go beyond the baseline nutrient reduction requirements mandated by TMDLs (MDE, 2011). Users who generate these credits may then sell them to regulated point sources, consumption buyers, and credit aggregators.

Maryland's Nutrient Trading Program began in 2008 with the introduction of a Maryland Department of the Environment (MDE) document that described the creation of a state nutrient trading program (MDE, 2011). The program today helps to facilitate trading between point sources, such as wastewater treatment plants, and nonpoint sources, such as farmers. The program is set up as a free market system in which buyers and sellers draw up their own contract that is then approved by the state. With this approach, the price of the nutrient credits is set in response to the market, not by the state. Market interfaces such as "mdnutrienttrading.org" and "thebaybank.org" have been launched to connect buyers and sellers.

The Maryland Department of Agriculture (MDA, 2013) lists six fundamental principles for nutrient trading in Maryland:

1) Before an agricultural nonpoint source may generate credits they must first meet baseline water quality requirements;
2) Agricultural credit generators must be in compliance with all local, state, and federal laws, regulations and programs before they may generate credits;
3) BMPs may not be funded by federal or state cost-share or mitigation banking programs and also generate nutrient credits;
4) The generation of credits cannot take out substantial portions of farm out of production;
5) Trades must result in a net decrease in loads. This is ensured by retiring 10 percent of agricultural credits sold in a trade and permanently applied toward TMDL goals; and
6) A BMP or agricultural reduction practice can only generate credits when it is installed or in operation.

While trades are still no trades in Maryland, Pennsylvania has contracted 56 trades to date with cost information on 31 trades (Pennvest, 2013). The Pennsylvania's ability to coordinate and close trades may be indicative of the nutrient trading potential throughout the Chesapeake Bay watershed, including Maryland. The ability to buy and sell nutrients generating by the ATS would greatly affect its positive cash-flow potential or even turn a profit while reducing nutrients.

1.6.3 Executive Order 13508

In 2009, the Obama administration approved an executive order calling for the protection and restoration of the Chesapeake Bay to further the efforts of the Clean Water Act of 1972 (Executive Order No. 13,508, 2009). The purpose of this order is to further efforts under the Clean Water Act to be led by the Federal Government. Part 3, Sec. 302 of the executive order cites "strengthening existing permit programs… establishing new, minimum standards of performance" and "implementing a compliance and enforcement strategy". It is this language that gives the EPA the authority to use existing permit programs as leverage to drive compliance. While the aforementioned TMDLs may be under voluntary compliance, the EPA does have the tools and authority to compel compliance by strengthening other permit programs, thus making voluntary TMDL compliance more cost-effective than stormwater noncompliance fines, for example. Therefore, regulated entities will still prefer to voluntarily comply with the TMDL regulation and will look for cost effective ways to reduce their pollution loads.

1.7 Critical Risk Factors: Competition

The ATS simultaneously competes in the renewable byproducts market (biofuel and fertilizer) as well as the nutrient reduction regulatory market. The uniqueness of this technology to compete both as a nutrient reducer and biofuel or biofertilizer generator makes this an attractive option for those interested in the environmental market. However, due to the opportunity cost of putting land out of commission and the dependence on electricity to run the pump, the sole use of the ATS as either a bio-products generator or water quality treatment is not economical.

Yet, when these two processes are concurrently capitalized upon, there is a real economic opportunity.

1.7.1 Other BMPs

Other agricultural BMPs include riparian buffers, wetland restoration, cover crops, oyster aquaculture and other structural and agronomic practices. A complete list of these BMPs may be found at the Maryland nutrient trading website (mdnutrienttrading.com). Included in this list is the ATS, which is considered to be an experimental practice that is up for official approval by the Maryland Department of Agriculture (MDA) in the summer of 2013. It is important to note that MDA does not encourage the conversion of productive farmland to the sole purpose of creating a nutrient credit bank and therefore those credits would not be approved for trading. While all of these BMPs are considered capable of reducing nutrients and generating credits, they do not included the additional revenue streams from the byproducts of these practices such as biofuels or biofertilizers.

1.7.2 Other Biofuels

The ethanol industry is well established and is primarily fed by government-subsidized corn (Tyner, 2008). According to the Renewable Fuels Association (2011), the ethanol industry has shown steady growth over the last decade, with an increase in the number of operating plants from 56 in 2001 to 204 plants in 2011. The Energy Policy Act of 2005 mandated a 7.5 billion gallons of renewable fuel standard by 2012, most of which is met by ethanol production. The purpose of mixing ethanol with gasoline is to increase the longevity of the oil we have now and to lessen our dependence on foreign oil. As it currently stands, 97% of the ethanol produced in the United States is made from corn (Ajanovic, 2011).

In contrast to ethanol, which is an established biofuel, an emerging biofuel of interest is butanol. Like ethanol, butanol is an oxygenate fuel made from biomass sugars and starch (Ryan, 2009). One advantage of butanol is its potential as a jet fuel blend stock, whereas ethanol is traditionally blended with gasoline (Guzman, 2010). According to Guzman, unlike ethanol, butanol has US approval to be blended up to 16% into gasoline versus 10% for ethanol, has 30% more energy per volume due to chemical composition, and can also be blended into diesel. In addition, many ethanol plants may be retrofitted to produce butanol. While butanol may not be as established as the ethanol market, the airline industry is a market that butanol may be competitive in.

1.7.3 Other Algal Production Methods: Open and Closed Ponds

Cited in the U.S. Department of Energy National Algal Biofuels Technology Roadmap (2010) by Ferrel and Sarisky-Reed, cultivating algae in open ponds is advantageous in a number of ways. Firstly, open pond algae cultivation is lower in capital costs when compared to closed photobioreactors (PBRs). Like the ATS, open pond systems are subject to environmental variables such as temperature and light exposure. When cultivating algae on a large scale it is common to prefer monocultures of designer species with high lipid content or other favorable genetic qualities. However, open pond operations are subject to invasion by other microorganism that take-away resources from the intended algal species. One benefit of the ATS in this regard is the allowance of self-seeding of native species onto the screens. Those algae that attach themselves onto the screen form a poly-culture community of different algal species that have evolved to survive under the natural environmental conditions of the area.

The closed pond PBR is the most expensive cultivation systems when compared to open pond and the ATS (U.S. DOE, 2010). The high cost of PBRs can be attributed to artificially supplying many of the system inputs that open pond reactors or the ATS take from nature for free. For example, indoor PBRs require artificial illumination whereas other forms of cultivation use solar radiation. However, the ability to control all inputs of the system offers an increased ability to maintain a monoculture of algae that is genetically designed for high biofuel yields (Ryan, 2009).

The closed and open pond systems both primarily focus on algae cultivation with nutrient removal as either an additional input cost or as a fortunate byproduct. Thus, these systems are driven by cost effective biofuel generation. The ATS is driven by just the opposite, cost-effective nutrient reduction. A side-by-side comparison of the ATS to these other algal cultivation techniques is not representative of the different drivers for algal production. Therefore, the ATS for biofuel production alone, such is the case for these other technologies, is not economical. However, this economic analysis will explore biofuel production in the context of regulatory compliance for nutrient reduction.

1.8 Objectives

In order to comply with federal and state regulations and improve the water quality of the Chesapeake Bay, there is a need for a BMP that is both cost-effective and capable of nutrient removal. This research explores the most cost efficient revenue streams for the ATS through different cost and production scenarios through the following objectives:

1) Calculate production quantities and costs for a 1-acre algal production system in order to determine revenue streams;
2) Determine capital and operations and maintenance costs for a 1-acre system for each scenario extrapolating from the Bridgetown System real cost data;
3) Perform a series of economic analyses for each scenario such as break-even, cash flow, benefit cost ratio, net present value, and sensitivity analysis; and
4) Compare the ATS in terms of nutrient reduction efficiency to cover crops.

The scenario approach was used to better understand where the ATS makes sense, relative to other BMPs in the Bay area. Economic feasibility is established by accounting for the costs and benefits of a system such as the ATS through different investment decision tools.

Chapter 2 : Economic Analysis

2.1 Analysis Assumptions

2.1.1 Financial vs. Economic

Traits of an economic analysis include: preclusion of taxes and subsidies and accounts for opportunity costs (Selvavinayagam, 1991). A financial analysis includes taxes and subsidies and opportunity costs are calculated by using local farm-gate prices. Due to the broad applicability of this technology, an economic analysis over a financial analysis was chosen. In order to use real numbers when possible, regional figures pertinent to Maryland or the Chesapeake Bay watershed were used for consistency, but prices for a particular farm were deemed unnecessary due to the broad nature of an economic analysis. The main point of this analysis is to determine if a revenue system such as this is at all feasible. Fine tuning and honing in on more precise numbers is outside the scope of this analysis. However, while the output numbers in this analysis may not be precise, they are accurate in terms of the economic viability.

2.1.2 ATS System Specifications

For the purpose of this analysis, a 1-acre ATS system will be used as a model for each scenario. The system will be approximately 40 meters (131 ft) wide and 100 meters (328 ft) long, to give a surface area of 1-acre. We assume a flow rate of 15 gallons/minute/foot of raceway and a growing season of 270 days (Kangas & Mulbry, 2012). The algal biomass will be air dried and therefore will not require a cost for drying.

2.1.3 Capital Cost Assumptions

Table 2.1 displays the assumptions used to calculate cost estimates for the ATS. The capital costs for the one unit acre sized system are based on real construction and materials costs from the Bridgetown system, shown in Figure 1.4 scaled up to one acre. The materials purchased in 2010 have been adjusted for inflation and are presented in 2012 USD. This data has been adapted and adjusted from the unpublished report from the Bridgetown Eastern Shore project entitled “Nutrient removal from agricultural drainage water using algal turf scrubbers operated using solar power” by Kangas and Mulbry (2012). In this analysis, the electrical source is grid power rather than solar.

Inflation was calculated using the change in average producer price index (PPI) for construction materials and components from 2010, when the materials were purchased, to 2012 (Bureau of Labor and Statistcs, 2013). The inflation rate was found to be 6.2% over the past two years and was multiplied by the 2010 prices to produce 2012 prices. Labor, land and grading are not included in the PPI for construction materials and components and were not adjusted for inflation.

Table 2.1 Capital cost estimates for algal turf scrubber per acre.

Item	**Notes**	**Cost (2010 US$)**	**Cost (2012 US$)**
Site preparation: grading compaction	1	$5,000	$5,000
Site preparation: labor	2	$7,200	$7,200
Water pump	3	$3,800	$4,035
Land cost	4	$0	$0
Liner and Installation	5	$15,400	$16,351
Surge boxes and plumbing	6	$4,000	$4,247
ATS screen	7	$3,200	$3,398
Subtotal		$38,600	$40,230
Engineering and contingencies (15% subtotal)	8	$5,790	$6,034
Total capital investment		$44,390	$46,264
Rounded ($100) total capital investment		$44,400	**$46,300**

Notes:

1) Cost of land preparation per acre (Kangas & Mulbry, 2012).
2) Estimated cost of one supervisor ($60/hr) and two laborers ($15/hr) for 40 hrs/week for 2 weeks; (Kangas & Mulbry, 2012).
3) Value based on one 18.5 kW pump delivering 15 gpm per foot of raceway and adjusted for inflation; (Kangas & Mulbry, 2012).
4) Average value of crop land in MD for 2010 and 2012 is $7,000 per acre but not included in the capital cost subtotal due to cost of doing business (NASS, 2012). Important to note that the average rental rate on the Eastern Shore, the location of the Bridgetown system, is $100/acre.
5) Value calculated using $0.35 per square foot of HDPE liner and adjusted for inflation.
6) Value calculated using siphon boxes (10 boxes at $300 each) and $1000 for plastic pipes and adjusted for inflation.

7) Value calculated using $0.07 per square foot for nylon netting and adjusted for inflation.
8) (Benemann & Oswald, 1996).

2.1.4 Operations and Maintenance Cost Assumptions

The main costs for yearly operations of maintenance are itemized and displayed in Table 2.2. The capital charge is calculated as the annual payment to pay off the capital costs at 3% interest over a 10-year period. The inclusion of the capital charge gives a total annual cost for the system at $32,200 per acre.

Table 2.2 Annual operations and maintenance cost estimates per acre using electricity from grid.

	Notes	Cost (2012 US$)
Capital charge	1	$5,424
Labor and overhead	2	$11,571
Electrical power for pumps	3	$15,201
Total annual costs		$32,196
Total Annual Cost rounded ($100)		**$32,200**
No capital charge		$26,772
Rounded ($100)		**$26,800**

Notes:
1) Capital charge of 0.11723 for A/P 3%, 10 (Stermole & Stermole, 2000).
2) Estimated cost of 1 laborer per week, 20 hrs/week at $15/hr for 39 weeks for a 270-day growing season.
3) Electricity based on 270 days, running 24 hours/day, 18.5 kw pump at rate of $0.1268/kwh average residential rate for Maryland December 2012 (EIA, 2013)

Figure 2.1 shows a breakdown of the annual costs by percentages. The electricity input is the greatest annual cost at nearly half of the cost, followed by labor at over a third of the cost and the capital charge rounding out at less than a fifth of the costs. Eliminating the need for electricity could cause a significant decrease in annual cost.

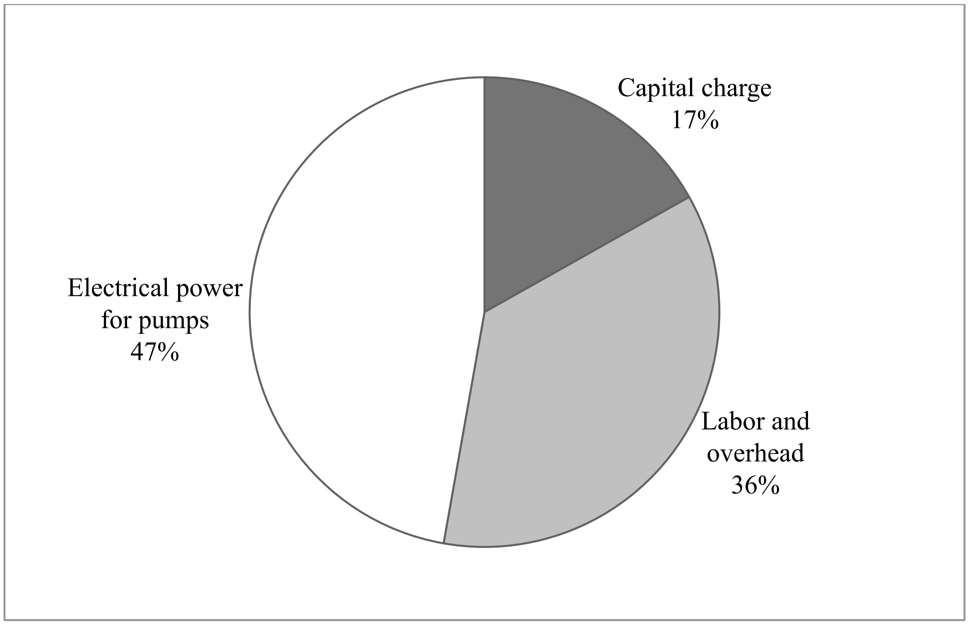

Figure 2.1 Breakdown of annual cost for 1-acre system.

2.1.5 Production Quantities Assumptions

Growth rate assumptions:

- Algal growth rates of 10, 20, and 30 dry g/m^2/day were examined to determine the uptake of nutrients as well as the total biomass produced.
- 10, 20, and 30 were chosen as growth rates because these are within the range of growth rates found in the literature, shown in Table 1.1.
- The low growth rates in Table 1.1 were due to problems outside of algal biophysical constraints, such as:

  - The Beltsville system was a recirculating system rather than a flow-through, which resulted in large herbivore eat outs.
  - The Bridgetown system did not receive enough water due to problems with battery storage to run the pump.
  - The Baltimore system was too far north and was limited by low temperature and low light intensity in the winter months, resulting in a low annual production average.

Nutrient content assumptions:

- A nitrogen content of 3% and a phosphorous content of 0.35% were assumed. These nutrient content percentages fall within the range of literature values for algae in general as well as those found in Table 1.1 (Azim & Asaeda, 2005; Borchardt, 1996; Vymazal, 1995).
- Nutrient removal was calculated by multiplying the biomass produced (dry grams/m^2/day) by the nutrient content of the biomass (% nutrient). This value was used to correspond to the pounds of nutrients available for trade or fertilizer.
- Unless otherwise specified, this analysis considers both N and P in nutrient quantities.

Growing season assumptions:

- A 270-day (9 month) growing season was assumed as denoted in Table 1.1, due to low temperatures and shorter days in the winter.
- Year-round systems have been put in place and this option will be further explored in the analysis.

Oxygen production assumptions:

- Average seasonal daily oxygen production rate of 5 grams/m^2/day for a growth rate of 14 grams/m^2/day used to determine annual DO production (Kangas et al., 2009).
- The algal DO production was assumed to have a linear relationship with growth rate and we were therefore able to assume DO production with varying growth rates.

Butanol production assumptions:

- A conversion rate of 15 gallons butanol per 2000 lb of algae was assumed to determine butanol production potential (Hestekin, personal communication, 2013).

A sensitivity analysis on the different growth rates was performed in order to determine the possible levels of revenue. A detailed explanation of these calculations is available in Appendix B. Table 2.3 provides annual production quantities at the previously mentioned growth rates in standard units while Table 2.4 provides the production quantities in metric units.

Table 2.3 Bio-product potential per year at different growth rates in English units.

Growth Rate	**Algal growth**	**Butanol**	**Nitrogen**	**Phosphorus**	**Dissolved Oxygen**
g/m^2/day	ton/acre/yr	gallons/acre/yr	lb/acre/yr	lb/acre/yr	ton/acre/yr
10	12	181	723	84	4
20	24	361	1445	169	9
30	36	542	2168	253	13

Table 2.4 Bio-product potential per year at different growth rates in metric units.

Growth Rate	**Algal growth**	**Butanol**	**Nitrogen**	**Phosphorus**	**Dissolved Oxygen**
$g/m^2/day$	kg/ha/yr	liter/ha/yr	kg/ha/yr	kg/ha/yr	kg/ha/yr
10	27000	1690	810	94	9643
20	54000	3380	1620	189	19286
30	81000	5070	2430	283	28939

2.2 Price Per Unit Assumptions

2.2.1 Butanol

From these different production quantities, revenue streams per year can be determined by multiplying the production units by a given monetary value. The butanol price calculation was based on a 1 million gallon/ year system (Hestekin, personal communication, 2013). The 1 million gallon/year system is based on the concept of a regional butanol plant that would receive algae from multiple farms. Upfront capital costs were estimated at $5 million dollars with operational costs at $3 million dollars per year. A 10-year capital straight-line depreciation period was used for the factory. A production cost per gallon of butanol was estimated using methods given in Anderson (2009) for estimating production costs of chemical plants. A detailed description of these calculations is given in Appendix B. These prices yielded a calculated production cost of approximately $3.50/gallon of butanol produced. According to the indicative chemical solvent price of approximately $7.00 and therefore a profit of $3.50 per gallon butanol if sold to a chemical company (ICIS, 2006). While butanol can be used as a biofuel, there is no concrete transportation market price for butanol, therefore for this analysis the chemical value is used.

2.2.2 Nutrient Trading Credits

Due to the lack of data on Maryland nutrient credit trades, Pennsylvania's credit trading history was used as a proxy. Pennsylvania was deemed an appropriate gauge of trading in Maryland because Pennsylvania is also in the Chesapeake Bay TMDL jurisdiction and faces similar regulatory drivers for water quality. Historical data regarding trades from 2006-2013 were available through PennVEST (Pennvest, 2013) and Pennsylvania's Department of Environmental Protection (Kasi, personal communication, 2013). Minimum, maximum, and average prices per pound of nitrogen and phosphorous were used as inputs into a sensitivity analysis to determine revenue flows based on different prices per pound. Data for Pennsylvania nutrient trading is available in Appendix C. Table 2.5 shows a sensitivity analysis of these values at different growth rates and the associated uptake of pounds per year for each nutrient.

Table 2.5 Sensitivity analysis varying nutrient credit prices and algal growth rates.

Nutrient trading levels	**Nutrient credit prices ($/lb)**	**Growth rate levels (g/m^2/day)**		
		10	20	30
Low N	$1.22	$882	$1,763	$2,645
Low P	$1.45	$122	$245	$367
Total		$1,004	$2,008	$3,012
Med N	$5.00	$3,613	$7,227	$10,840
Med P	$5.00	$422	$843	$1,265
Total		$4,035	$8,070	$12,105
High N	$15.00	$10,840	$21,680	$32,520
High P	$10.00	$843	$1,686	$2,529
Total		$11,683	$23,366	$35,049

For future reference in the analysis section of the thesis, Table 2.5 will be used to define levels of low (N $1.22/lb & P $1.45/lb), med (N & P $5.00/lb), and high (N $15.00/lb & P $10.00/lb) nutrient trading.

2.2.3 Fertilizer

The biofertilizer revenue determined by the price of each nutrient determined from the March 2012 fertilizer prices (USDA ERS, 2012). These calculations are provided in Appendix B. Calculations were based on a 3% nitrogen content and 0.35% phosphorus content nutrient uptake scaled to 1 acre on a per annum basis, the value of nitrogen was found to be $0.62/lb and phosphorus to be $0.74. Table 2.6 shows the yearly value of this byproduct in standard units and Table 2.7 shows the values in metric units.

2.2.4 Dissolved Oxygen

As previously mentioned, the injection of DO by the ATS does not have a current market value. However, due to the increase in water quality caused by the release of DO a replacement value was appropriated to the ecosystem service. A replacement value was deemed appropriate because there is no current market value for the service of injecting DO into waterways via photosynthesis (Heal, 2000). Two different aerator manufacturers (Triple Point Water and Kasco) were priced for an aerator that could service a 1 acre sized pond. The aerators were assumed to be on for 24 hours a day for a season of 270 days. Each aerator claimed to produce about 5 lb of oxygen per hour (Clearwater Habitats, 2013; Kasco Marine, 2013). Using the same electricity rate as the ATS of $0.1268/kwh average residential rate for Maryland

December 2012 (EIA, 2013), assumed product lifetime of 10-years, capital costs according to website and dealers, and a 15% annual maintenance cost based on replacing certain system components. The total annual production cost per pound of oxygen was found to be \$0.117 for Triple Point Water aerator and \$0.124 for Kasco, averaging out to \$0.12/ lb O_2. This valued was then multiplied by the total production of DO/year of the ATS to give this benefit a monetary value of about \$2000/acre/year or \$2300/ha/year, according to Table 2.6 and Table 2.7 at 20 $g/m^2/day$. However, because this service cannot be sold directly in the marketplace the value was not included in the revenue analysis. These calculations may be found in Appendix B.

2.2.5 Summary of production quantity values

The previously mentioned production prices per unit are given in Table 2.6 and Table 2.7 and are varied by growth rates of 10, 20, and 30 dry $g/m^2/day$.

Table 2.6 Monetary value of system benefits in English units.

Growth Rate	**Butanol**	**Nitrogen**	**Phosphorus**	**Dissolved Oxygen**
$g/m^2/day$	\$/acre/year	\$/acre/year	\$/acre/year	\$/acre/year
10	\$632	\$448	\$62	\$1,032
20	\$1,265	\$896	\$125	\$2,064
30	\$1,897	\$1,344	\$187	\$3,097

Table 2.7 Monetary value of system benefits in metric units.

Growth Rate	**Butanol**	**Nitrogen**	**Phosphorus**	**Dissolved Oxygen**
$g/m^2/day$	\$/ha/year	\$/ha/year	\$/ha/year	\$/ha/year
10	\$1,563	\$1,107	\$154	\$1,157
20	\$3,125	\$2,214	\$308	\$2,314
30	\$4,688	\$3,321	\$463	\$3,471

The values determined for the ecosystem goods and services provided by the ATS (butanol, fertilizer, dissolved oxygen, and nutrient credits) given in to Table 2.7 may not all have direct market values but a breakdown of each good or service's contribution to potential revenue is given in Figure 2.2.

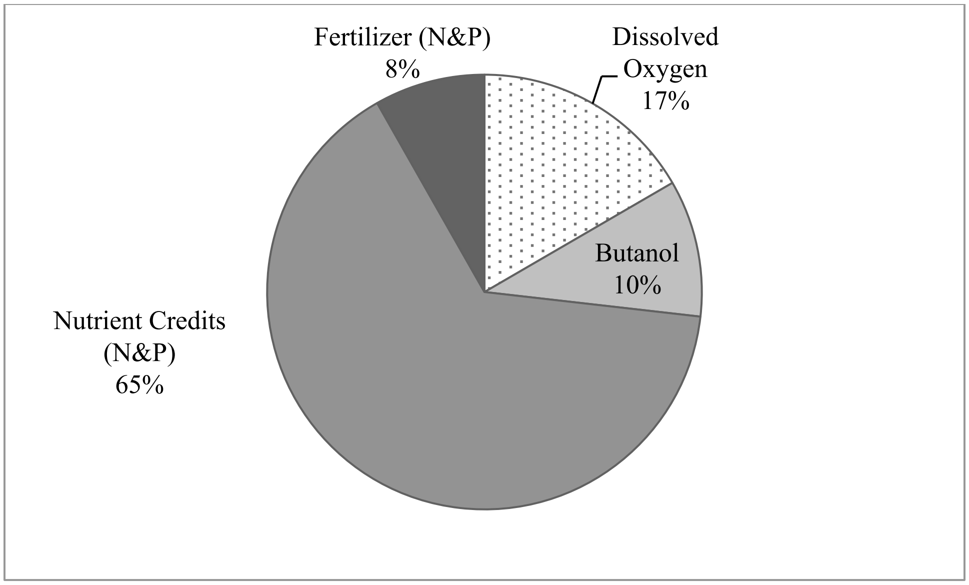

Figure 2.2 Breakdown of ATS ecosystem good and service contribution by monetary value at 20 $g/m^2/day$ and nutrient trading values of \$5/lb N and P per acre per year. The total value of all ecosystem goods and services determined to be \$14,300.

According to Figure 2.2, the majority of the possible revenue from ecosystem goods would come from nutrient credits from the reduction of nitrogen and phosphorus. Fertilizer, and butanol all hold similar monetary values where as dissolved oxygen is almost one-fifth of the contribution.

2.3 Analysis Methods

The economic analysis of this system takes two paths: using known nutrient credit values and finding the nutrient credit price for the system to break-even. The reason for these two different evaluations of revenue from nutrient trading credits is due to the fact that nutrient trading has not yet come online in Maryland and therefore data is lacking to perform a feasibility analysis with real dollars per pound numbers. Therefore, to compensate for this lack of data, we took the approach of using numbers from the Pennsylvania nutrient credit market to determine feasibility in addition to finding the break-even point of price per credit with known reduction efficiencies.

2.3.1 Costs

Each scenario begins with an analysis of capital, operational and maintenance, and opportunity costs, if applicable. These costs become the basis for the economic analysis.

2.3.2 Break-even

A breakeven analysis was performed to determine the level of sales in which total costs were compensated for (Stevens & Sherwood, 1982). The breakeven point for an annual nutrient credit price was determined for different growth rates. The formula:

$$PQ = CQ$$

was used to determine the breakeven point in which P is price, Q is quantity in terms of pounds (both N and P) reduced and C is the annual cost.

2.3.3 Cash flow and benefit/cost ratio

In order to determine the viability of this type of business concept, a cash flow analysis was performed. A cash flow describes the net inflow or outflow of money at a specific period in time, such as month or year (Stermole & Stermole, 2000). An inflow is money received, as revenue while an outflow is capital cost and operating expenses. The cash flow for a given period is therefore the inflows minus the outflows. A negative cash flow signifies that outflows exceed inflows and a positive cash flow is just the opposite. In general, a positive cash flow is desirable when evaluating a project. In this analysis, the following were assumed: 1) 10-year borrowing period; 2) 3% discount rate for farmers according to rates given to farmers that apply for the low interest loan for agricultural conservation (LILAC) (MDA, 2012); 3) 4% interest rate for businesses according to rates given for a commercial business loan for a large business in 2013 borrowing between $10,000 and $99,000 (Federal Reserve, 2013); 4) while butanol and fertilizer production are not technically mutually exclusive, assumed that the recovery of N and P from butanol production were not economic and therefore both revenue streams are not concurrently analyzed; 5) due to the nature of the scenario, the units will be in standard; and 6) units on a per acre per year basis.

In addition to the cash flow, all of the benefits (inflows) were divided by total costs (outflows) to determine a benefit/cost ratio. In general, favorable situations are defined when benefits exceed costs, which is given by a ratio >1.

2.3.4 Net Present Value

In order to take into account the time value of money, a net present value (NPV) analysis was employed. The NPV is the cumulative present value of all cash inflows and outflows over time, discounted at a particular rate for a specified period of time. Similar to a cash flow analysis, a positive NPV reflects a favorable investment. A positive NPV reflects the project’s ability to recover initial capital investments as well as the annual costs incurred over time.

The formula for determining NPV is:

$$NPV\ (i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

N= total number of payment periods

R_t= net cash flow (inflow-outflow) at time t

t= time of the cash flow (year)

i= interest rate

Major outlays, such as capital costs, occur in time 0 are not discounted. The NPV function in Microsoft Excel was used for this analysis.

The notation for NPV is given as:

(P/A, i%, t)

The variables (i & t) are the same as defined in the NPV formula. P/A is defined as the present value of the annuity. In order to determine the yearly capital costs (“capital charge”), the present value of the capital cost was converted to an annuity. The notation is given as:

(A/P, i%, t)

Annuity factors given in an table found in Stermole & Stermole (2000) were used to convert the present value of the capital cost into a yearly payment.

2.3.5 Sensitivity Analysis

A sensitivity analysis was performed on the different variables used to calculate the break-even point and NPV. The purpose of this analysis is to determine which variables are most sensitive to change and which have little effect on the overall analysis. For break-even, these variables included varying the growth rate, annual cost, and the components of annual cost (electricity cost, capital charge, etc.). For NPV, the variables that were changed included algal growth rate, loan payback period, nutrient credit generation, capital cost, operations and maintenance cost, discount rate, and butanol price were all individually adjusted, holding all other variables equal. The percentages in which the variables are varied were arbitrarily chosen to show the robustness of the analysis. For the break-even sensitivity analysis, variables were adjusted ±25% where as the NPV sensitivity analysis variables were adjusted by ±10%. One reason a break-even analysis is preformed is to account for some uncertainty, such as the unknown market price for nutrient trading credits. Therefore, an increased percent adjustment of 25% was used to account the uncertainty and determine the robustness of the resulting price. The results of these analyses are depicted in a tornado plot. The longer the bars on a tornado plot, the more sensitive the variable.

Chapter 3 : Scenario Analysis

In order to determine the conditions in which the ATS makes the most sense, different scenarios were explored, many of which are based on real experimental systems. The motivation behind this approach is to systematically cut dominant costs, determined from the cost calculated in Chapter 2 analysis assumptions, as well as improve system efficiencies, through a number of different scenarios. An overview of the scenarios is depicted in Table 3.1. An X denotes the base case option, shown in parenthesis.

Table 3.1 Scenario comparison with different costs and location characteristics.

Scenario Description	Ag	Conowingo Dam	Year-round	Mechanized Harvest	Conventional Disposal	Best-case
Electrical Input (Grid)	X	-	X	X	X	-
Growing Season (270 days)	X	X	365	X	X	365
Harvest (Manual)	X	X	X	Mech	X	Mech
Biomass Treatment (Revenue)	X	X	X	X	Disposal	X

3.1 Agricultural Scenario

3.1.1 Scenario Description

The basis for this scenario is based on the ATS system in Bridgetown, MD, depicted previously in Figure 1.4. In terms of TMDLs, both point sources (wastewater treatment plants) and non-point sources (farmers) are expected to reduce their pollutant loads to Bay waterways. Therefore, if a farmer could reduce nutrients beyond their baseline by installing an ATS and sell the surplus on the credit market, the ATS would be a favorable BMP. The assumptions for this analysis are shown in Table 3.2.

Table 3.2 Assumptions for agricultural scenario.

Assumptions	
Interest rate	3%
Payback period (year)	10
Electrical source	Grid
Harvest method	Manual labor
Growing season (day/year)	270

3.1.2 Costs

The capital and operations and maintenance costs for this scenario are the same as depicted in Table 2.1 and Table 2.2. The opportunity cost of taking one acre of corn out of production was determined in order to assess the economic impact of putting a system like this into place. Corn was chosen because of its data availability for Maryland as well as biofuel implications. The cost of one acre of corn production was estimated using data from USDA NASS as well as USDA Economic Research Service (ERS). The cost of land was subtracted from the production cost in order to compare to ATS production cost per acre. Data from the USDA NASS on the price received in dollars per bushel for the state of Maryland was multiplied by the corn yield in bushels per acre for the upper eastern shore from 2002-2011 for the most current data (NASS, 2013). The costs per acre of production were determined from the USDA ERS historical data on corn production cost for the South Seaboard region, which includes Maryland (ERS, 2011). The data that was most specific to the eastern shore of Maryland was used when possible. The revenue from the corn yields were then subtracted from the costs and an average profit from corn per acre from the decadal data was found to be about $98.00/acre. A table of these calculations may be found in Appendix C.

3.1.3 Break-even

Using the costs depicted in Table 2.1 and Table 2.2, the nutrient credit price for both N and P needed to break-even was determined. The motivation behind the break-even analysis is to address the uncertainty associated with the Maryland nutrient market determine the market price needed for the system to break-even. For the focus of this analysis, the break-even price will not include revenue from butanol or fertilizer. These sources of revenue will be included in the cash-flow analysis. The break-even nutrient credit price for the agricultural scenario is shown in Table 3.3.

Table 3.3 Nutrient credit price without additional revenue needed to break-even by varying growth rate per acre per year.

Growth rate (g/m^2/day)	**Total nutrient quantity (lb)**	**Break-even price per credit ($/lb)**
10	807	$40
20	1614	$20
30	2421	$13

3.1.4 Cash flow

A cash flow analysis was performed using different levels of both trading and algal production rates. A 3% interest rate was assumed according the rates given to farmers that apply for the low interest loan for agricultural conservation (LILAC) at 3% interest rate for 10 years (MDA, 2012). The purpose of LILAC loans is to help farmers to install BMPs on their farms that help improve the water quality of the Chesapeake Bay and Bay waterways.

In order to determine a difference between the butanol revenue stream and fertilizer, two cash flows were prepared and are shown in Table 3.4 and Table 3.5. According to common accounting practices, negative values are in parenthesis. The different levels of trading are based on the sensitivity analysis shown in Table 2.5. Low nutrient trading corresponds to $1.22 and $1.45 per pound of N & P, respectively; medium nutrient trading corresponds to $5.00 per pound for both N & P; high nutrient trading corresponds to $15.00 and $10.00 per pound of N & P, respectively. The net income is calculated by subtracting the previously calculated annual capital cost and annual operating cost from the annual income.

Table 3.4 Cash flow analysis at different growth rates with revenue from nutrient trading and biofuel on per acre per year basis. Annual capital cost set at $5,424 and annual operating cost found to be $26,800.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	$1,636	$(30,587)	0.05
10	Med	$4,667	$(27,556)	0.14
10	High	$12,315	$(19,908)	0.38
20	Low	$3,272	$(28,951)	0.10
20	Med	$9,334	$(22,889)	0.29
20	High	$24,631	$(7,593)	0.76
30	Low	$4,909	$(27,315)	0.15
30	Med	$14,002	$(18,222)	0.43
30	**High**	**$36,946**	**$4,723**	**1.15**

Table 3.5 Cash flow analysis at different growth rates with nutrient trading and fertilizer production as revenue on per acre per year basis. Annual capital cost set at $5,424 and annual operating cost found to be $26,800.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	$1,514	$(30,709)	0.05
10	Med	$4,545	$(27,678)	0.14
10	High	$12,194	$(20,030)	0.38
20	Low	$3,029	$(29,195)	0.09
20	Med	$9,091	$(23,133)	0.28
20	High	$24,387	$(7,836)	0.76
30	Low	$4,543	$(27,681)	0.14
30	Med	$13,636	$(18,588)	0.42
30	**High**	**$36,581**	**$4,357**	**1.14**

The cash flows for both butanol and fertilizer revenue streams are very similar in terms of net income and benefit/cost ratios at varying levels of nutrient trading. Due to the similarity in revenue levels, the following scenarios will include cash flows from nutrient trading and butanol revenue streams.

The cash flow analysis shows that at a high market price of nutrient credits and a high growth rate, it would be worthwhile to install the ATS. According to Table 3.4 the ATS would yield a net annual income of about $5,000/acre at optimum nutrient trading ($15/lb N, $10/lb P) and growth rate (30 $g/m^2/day$), which is higher than the opportunity cost of $98.00/acre of growing corn for Maryland farmer (calculations in Appendix C). However, there is still risk involved with achieving these optimal conditions, such as dependence on an unknown market in Maryland that is yet to make a trade. Under proper operating conditions (fully functioning equipment) growth rates in the range of 20 $g/m^2/day$ are attainable, as shown in Table 1.1. However, in an agricultural setting, growth rates of 30 $g/m^2/day$ are necessary to break-even with high levels of nutrient trading, according to the Pennsylvania data. Therefore, risk adverse farmers would still prefer to continue to grow corn.

3.1.5 Net Present Value

The net present value of the system was determined the same assumptions as in Table 3.2. The following NPVs were determined for 3 cases: low growth and low nutrient trading, medium growth and medium level nutrient trading (base case), and then high growth and high nutrient trading. The different levels of trading are from the Pennsylvania data found in Table 2.5. The assumptions for each of these cases are described in Table 3.6. These cases also included the added revenue from butanol production, shown in Table 2.6.

Table 3.6 NPV scenario description.

Case	**Growth rate (g/m^2/day)**	**Level of nutrient trading**	**Cost per pound N**	**Cost per pound P**
Least favorable	10	low	$1.22	$1.45
Base case	20	med	$5.00	$5.00
Most favorable	30	high	$15.00	$10.00

Table 3.7 shows the NPV of the least favorable ATS scenario.

Table 3.7 NPV of least favorable case for ATS, (P/A 3%, 10). Revenue from butanol production, growth rate of 10 g/m^2/day, and low levels of nutrient trading.

Year	Cost	Revenue	Net	NPV
0	$(46,300)	$-	$(46,300)	$-
1	$(26,800)	$1,636	$(25,164)	$(70,731)
2	$(26,800)	$1,636	$(25,164)	$(94,450)
3	$(26,800)	$1,636	$(25,164)	$(117,478)
4	$(26,800)	$1,636	$(25,164)	$(139,836)
5	$(26,800)	$1,636	$(25,164)	$(161,543)
6	$(26,800)	$1,636	$(25,164)	$(182,617)
7	$(26,800)	$1,636	$(25,164)	$(203,077)
8	$(26,800)	$1,636	$(25,164)	$(222,942)
9	$(26,800)	$1,636	$(25,164)	$(242,228)
10	$(26,800)	$1,636	$(25,164)	$(260,952)

According to Table 3.7, at a growth rate of 10 g/m^2/day and low nutrient trading prices, the system is not able to recover its capital costs and turn a profit. Table 3.8 shows the base case scenario with medium levels of nutrient trading and a growth rate of 20 g/m^2/day.

Table 3.8 Base case for ATS (P/A 3%, 10). Revenue from butanol production, growth rate of 20 g/m^2/day, and medium levels of nutrient trading.

Year	Cost	Revenue	Net	NPV
0	$(46,300)	$-	$(46,300)	$-
1	$(26,800)	$9,334	$(17,466)	$(63,257)
2	$(26,800)	$9,334	$(17,466)	$(79,720)
3	$(26,800)	$9,334	$(17,466)	$(95,703)
4	$(26,800)	$9,334	$(17,466)	$(111,221)
5	$(26,800)	$9,334	$(17,466)	$(126,287)
6	$(26,800)	$9,334	$(17,466)	$(140,914)
7	$(26,800)	$9,334	$(17,466)	$(155,115)
8	$(26,800)	$9,334	$(17,466)	$(168,903)
9	$(26,800)	$9,334	$(17,466)	$(182,289)
10	$(26,800)	$9,334	$(17,466)	$(195,284)

Table 3.8 shows at that level of algal production and nutrient trading, the system is unable to recover capital costs. Table 3.9 shows the most favorable ATS case for NPV, high growth rates and high levels of nutrient trading.

Table 3.9 Most favorable case for ATS (P/A 3%, 10). Revenue from butanol production, growth rate of 30 g/m^2/day, and high levels of nutrient trading.

Year	Cost	Revenue	Net	NPV
0	$(46,300.00)	$-	$(46,300.00)	$-
1	$(26,800)	$36,946	$10,146	$(36,449)
2	$(26,800)	$36,946	$10,146	$(26,885.09)
3	$(26,800)	$36,946	$10,146	$(17,600)
4	$(26,800)	$36,946	$10,146	$(8,585)
5	**$(26,800)**	**$36,946**	**$10,146**	**$168**
6	**$(26,800)**	**$36,946**	**$10,146**	**$8,665**
7	**$(26,800)**	**$36,946**	**$10,146**	**$16,915**
8	**$(26,800)**	**$36,946**	**$10,146**	**$24,925**
9	**$(26,800)**	**$36,946**	**$10,146**	**$32,701**
10	**$(26,800)**	**$36,946**	**$10,146**	**$40,251**

Table 3.9 shows that at optimum growth rates and trading conditions, the system is able to recover capital costs by year 5 and have a NPV of over $40,000 by the end of year 10. A positive NPV was expected for this case because for a growth rate of 30 g/m^2/day a break-even price of $13/lb is needed, shown in Table 3.3. In the following scenarios only the base case NPV will be shown.

3.1.6 Sensitivity Analysis

A sensitivity analysis was performed on different variables that could affect the break-even price per credit of the ATS, shown in Figure 3.1.

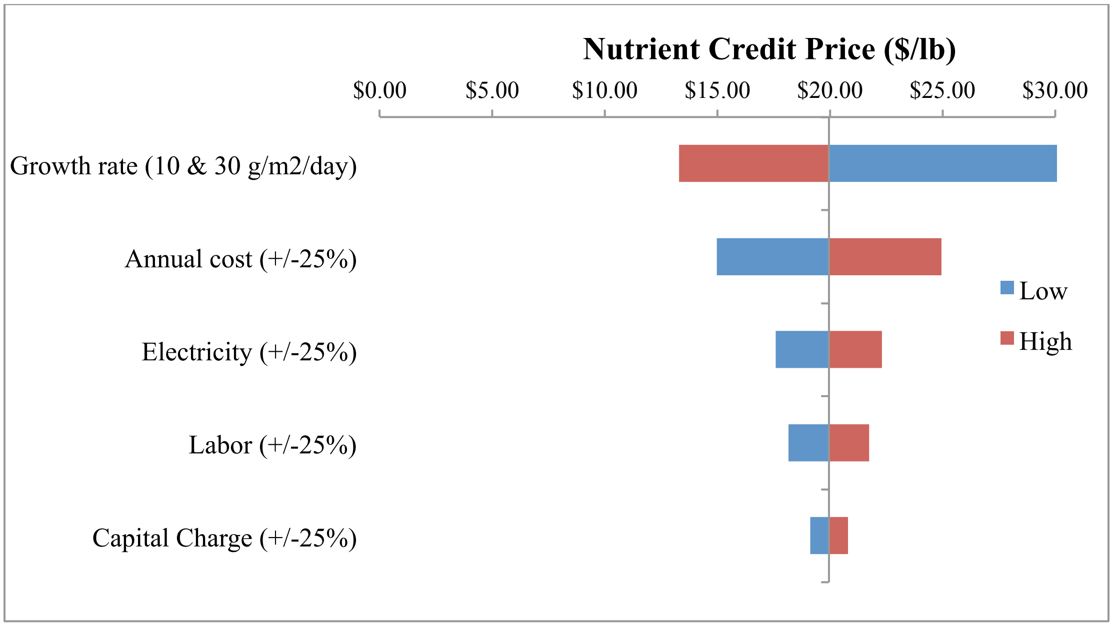

Figure 3.1 Sensitivity analysis for nutrient credit break-even price, adjusting each variable and holding all other variables equal. The base case was set as the breakeven price at a growth rate of 20 g/m^2/day at $20/lb reduced.

Figure 3.1 shows that the growth rate is the most sensitive argument and has a range in break-even prices from $13-$30/lb. A tornado plot is interpreted as the longest bars showing the most sensitivity. Excluding growth rate, each cost was manipulated by adjusting the cost plus or minus 25%. These resulting sensitivities are in line with the cost percentages displayed in Figure 2.1.

A sensitivity analysis was also performed on the base case NPV in order to determine which variables had the greatest influence on NPV. The base case scenario, the same as depicted in Table 3.8, had a NPV of $(195,284) after 10 years at an interested rate of 3%. The previously mentioned variables were adjusted to both lower and higher values, calculating NPVs higher or lower than $(195,284). The results of this sensitivity analysis are shown in Figure 3.2.

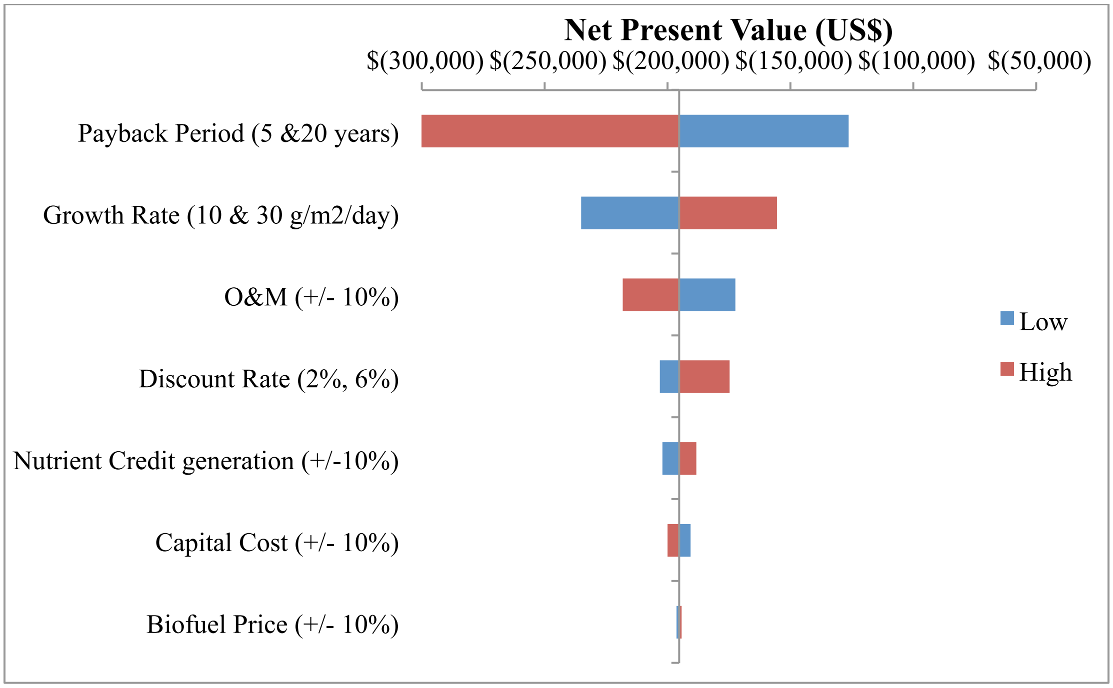

Figure 3.2 Sensitivity analysis for agricultural revenue stream, adjusting each variable individually and holding all other variables equal to the base case of NPV of $(195,284).

According to Figure 3.2, the payback period was the most sensitive in the analysis. This is due to the fact that costs very heavily outweighed revenue, which had compounding negative effects with a longer payback period. Growth rate is the second most sensitive variable in the analysis. This was an expected result because the revenue streams, nutrient trading and biofuel generation, are directly dependent on algal growth. Biofuel price was the least sensitive variable in the analysis because it has such a small effect on the revenue stream. Therefore, optimizing growth rate conditions is a very important variable in the success of an ATS system. Also, adjusting the nutrient credits generated had a significant effect on the profitability of the system. Due to the spread of prices received for trading credits, a 25% adjustment was chosen to account for the range of prices.

3.2 Conowingo Dam Scenario

3.2.1 Scenario Description

The Conowingo Dam, shown below in Figure 3.3, is located on the Susquehanna River in Northern Maryland and operated by Exelon Generation Company, LLC (Hirsch, 2012). The dam has a maximum height of 94 feet and a total length of 4,648 feet (Exelon, 2013). In total, the plant consists of 11 turbines and has a capacity of 572 MW. According to decadal data from 2001-2010 (2011 was not included due to outliers from Tropical Storm Lee) the average discharge over the decade was 18,900,000 gallon/minute (USGS, 2013). Table in depicting this data may be found in Appendix C.

Figure 3.3 Photo of the Conowingo Dam in located Maryland. Photo taken from USGS.gov.

The Conowingo Dam is situated at the downstream end of the Susquehanna River Basin, which then flows directly into the Chesapeake Bay. Therefore, locating an ATS at the mouth of the Susquehanna River could prevent nutrients from entering the Chesapeake Bay. In addition, it is possible to siphon the headwater of the dam into the system, no longer requiring the electrical input.

According to the agricultural model, a 1-acre system requires 15 gallons/minute/foot of raceway. A raceway with a width of 131 feet would then require approximately 2000 gallons/min. Compared to the historical data from the last decade, the percent of flow that would be diverted to the ATS is approximately 0.0104%, which is negligible compared to total dam discharge. Therefore, the addition of an ATS would not significantly effect the electrical generation of the dam. Table 3.9 shows the assumptions for this scenario.

Table 3.10 Assumptions for Conowingo Dam scenario.

Assumptions	
Interest rate	4%
Payback period (year)	10
Electrical source	none
Harvest method	Manual labor
Growing season (day/year)	270

3.2.2 Costs

Due to the unique characteristics of this site, the pump cost is no longer included in the capital costs of this scenario. The new capital costs are denoted in Table 3.11.

Table 3.11 Capital costs for Conowingo Dam ATS.

Item	Cost 2012 US$
Site preparation: grading compaction	$5,000
Site preparation: labor	$7,200
Liner and Installation	$16,351
Surge boxes and plumbing	$4,247
ATS screen	$3,398
Subtotal	$36,195
Engineering and contingencies (15% subtotal)	$5,429
Total capital investment	$41,625
Rounded ($100) total capital investment	**$41,600**

A 4% interest rate is assumed, according to the interest rate for a commercial business loan for a large business in 2013 borrowing between $10,000 and $99,000 (Federal Reserve, 2013). The operations and maintenance costs for a system not using grid power also decreases. Table 3.12 shows the new annual costs.

Table 3.12 Operations and maintenance costs for Conowingo Dam system.

Item	Notes	Cost ($)
Capital charge	1	$5,132
Labor and overhead	2	$11,571
Total annual costs		$16,704
Total Annual Cost rounded ($100)		**$16,700**
No capital charge		$11,568
Rounded ($100)		**$11,600**

Notes:

1) Capital charge of 0.1233 for A/P 4%, 10 (Stermole & Stermole, 2000).
2) Estimated cost of 1 laborer per week, 20 hrs/week at $15/hr for 52 weeks.

The elimination of electricity costs decreases the yearly annual costs (not including capital charge) by 57%, as compared to the agricultural scenario.

The opportunity cost of diverting 600 gallons/minute of water from the Conowingo Dam was established by determining the potential profit lost to the electric company. The potential energy of the diverted water was determined using the formula:

$$Potential\ Energy = mass \times gravity \times height$$

As previously mentioned, the dam has a height of 94 feet (28.7 meters), and assuming a conversion efficiency of 90% for hydroelectric dams, the potential energy lost to the ATS is calculated to be 9.6 kW or about 83,900 kWh/year (USBR, 2005). Assuming a cost of production of \$0.04/kWh and a price of \$0.1268/kWh, the company could expect a profit of approximately \$24,000 from the diverted water (C2ES, 2009). This is an approximate estimation and is not specific to the Conowingo Dam but to the hydroelectric industry as a whole. The purpose of this calculation is to prove that the addition of an ATS would be negligible to the profit potential of a utility company. These calculations are available in Appendix B.

3.2.3 Break-even

New break-even prices for the system were determined according to the adjusted annual system cost in Table 3.13

Table 3.13 Nutrient credit prices needed to break-even varying growth rate for ATS at Conowingo Dam.

Growth rate ($g/m^2/day$)	**Total nutrient quantity (lb/acre)**	**Breakeven price per credit (\$/lb)**
10	807	\$21
20	1614	\$10
30	2421	\$7

Compared to the agricultural scenario, the break-even prices for the Conowingo Dam ATS are lower. However, because the same quantity of nutrients is reduced in each scenario, the difference in price at each different growth rate decreases as the growth rate increases.

3.2.4 Cash flow and benefit/cost ratio

Reduced capital and operations and maintenance costs also affected the cash flow of this scenario. At lower outflows but the same inflows of cash, the net income is generally higher for this situation, as is the benefit to cost ratio, according to Table 3.14.

Table 3.14 Cash flow analysis of different growth rates with nutrient trading and biofuel production as revenue on per acre per year basis without electrical input. Annual capital cost set at $5,132 and annual operating cost found to be $11,600.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	$1,636	$(15,096)	0.10
10	Med	$4,667	$(12,065)	0.28
10	High	$12,315	$(4,417)	0.74
20	Low	$3,272	$(13,460)	0.20
20	Med	$9,334	$(7,398)	0.56
20	**High**	**$24,631**	**$7,899**	**1.47**
30	Low	$4,909	$(11,824)	0.29
30	Med	$14,002	$(2,731)	0.84
30	**High**	**$36,946**	**$20,214**	**2.21**

The cash flows depicted in Table 3.14 are higher than the agricultural scenario. Additionally, the cash flows for 20 and 30 $g/m^2/day$ at high levels of nutrient trading are both positive, compared to only the 30 $g/m^2/day$ at high trading levels as positive in the agricultural scenario. This is due to the fact that the electrical input is such a large component of the total annual costs, therefore the elimination of the input all together gives a much more favorable cash flow at more than one growth rate.

3.2.5 Net Present Value

A NPV analysis was performed to determine if a decrease in operations and maintenance costs had an effect on the rate of capital recovery of the system. At a discount rate of 4% and a loan period of 10 years, a NPV analysis over 10 years is shown in Table 3.15.

Table 3.15 NPV of no electricity scenario for ATS, (P/A 4%, 10), growth rate of 20 $g/m^2/day$, medium nutrient trading, and revenue from butanol.

Year	Cost	Revenue	Net	NPV
0	$(41,600)	$-	$(41,600)	$-
1	$(11,600)	$9,334	$(2,266)	$(43,778)
2	$(11,600)	$9,334	$(2,266)	$(45,873)
3	$(11,600)	$9,334	$(2,266)	$(47,887)
4	$(11,600)	$9,334	$(2,266)	$(49,824)
5	$(11,600)	$9,334	$(2,266)	$(51,686)
6	$(11,600)	$9,334	$(2,266)	$(53,476)
7	$(11,600)	$9,334	$(2,266)	$(55,198)
8	$(11,600)	$9,334	$(2,266)	$(56,853)
9	$(11,600)	$9,334	$(2,266)	$(58,445)
10	$(11,600)	$9,334	$(2,266)	$(59,975)

Similarly to the base case agricultural NPV analysis found in Table 3.8, a positive NPV is not reached in year 10. However, the NPV at year 10 for the Conowingo Dam scenario is much lower, due to the lack of electricity cost, which is the largest contributor to the annual cost in the agricultural scenario. Thus, lowering annual costs also effectively lowers the capital recovery period for the system.

3.2.6 Sensitivity Analysis

A sensitivity analysis was performed to determine the most sensitive variables in the analysis. A sensitivity analysis for both break-even and the NPV analysis were prepared.

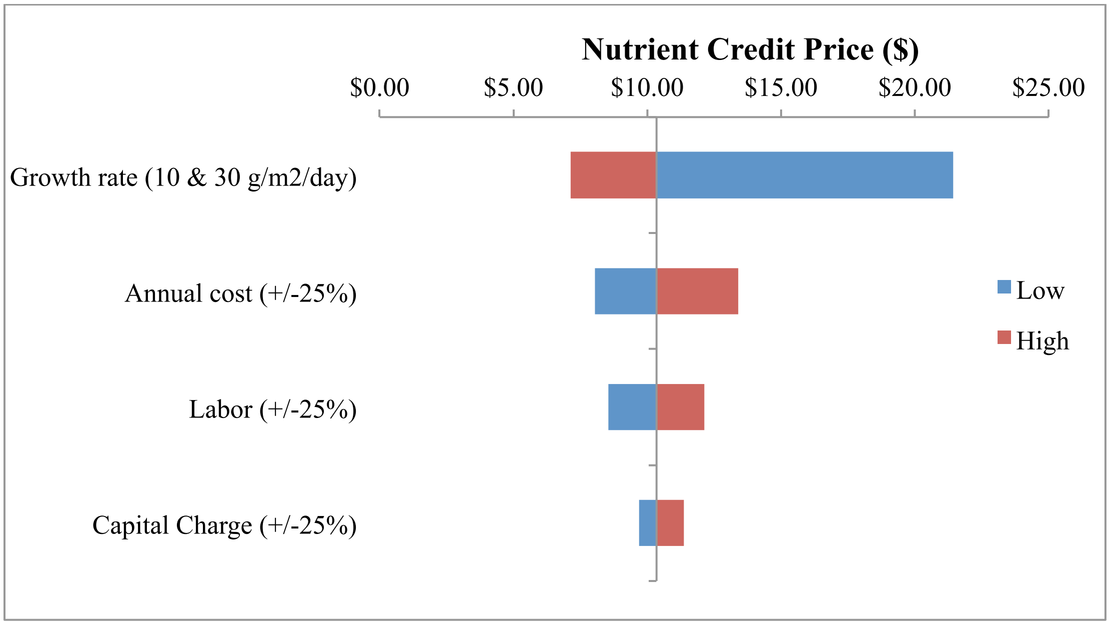

Figure 3.4 Sensitivity analysis for nutrient credit break-even price, adjusting each variable and holding all other variables equal. The base case was set as the breakeven price at a growth rate of 20 g/m^2/day at \$10/lb reduced.

Similar to the sensitivity analysis performed for the NPV of the agricultural system a sensitivity analysis for the break-even price was also done for the Conowingo Dam ATS, as shown in Figure 3.4. Figure 3.4 shows that the growth rate continues to be the most sensitive argument. Due to different lending rates between farmers and commercial businesses, the NPV analysis uses an interest rate of 4%. In Figure 3.5, the base case is \$(59,975) which is the NPV reached at year 10 at a growth rate of 20 g/m^2/day, high nutrient trading, and biofuel production.

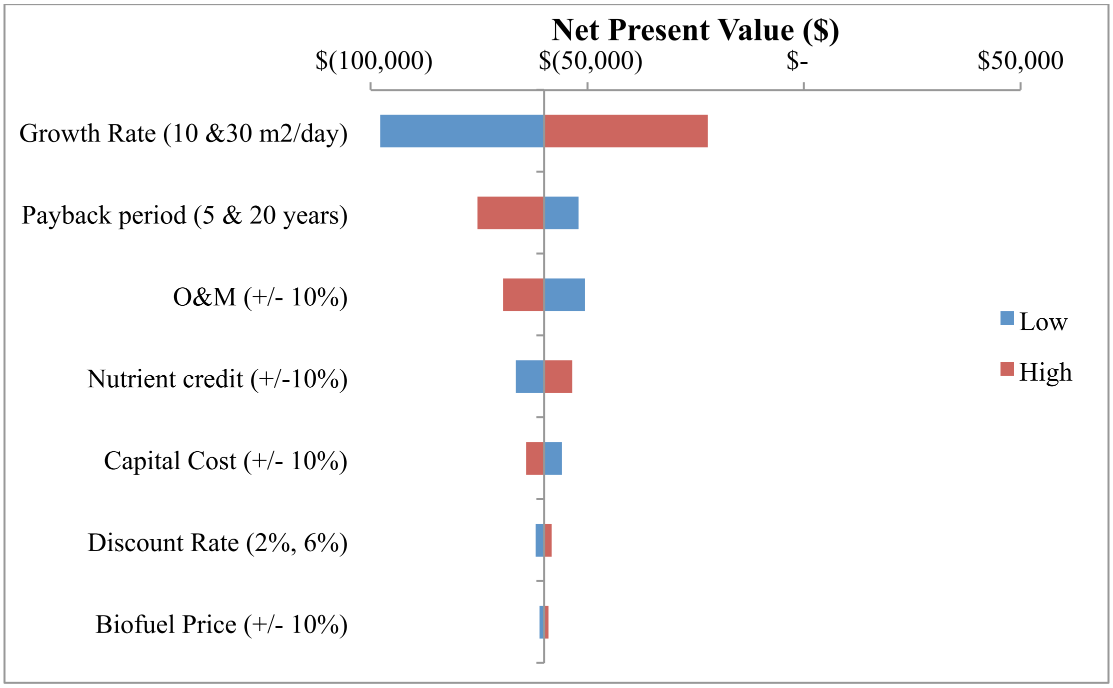

Figure 3.5 Sensitivity analysis for Conowingo Dam ATS, adjusting each variable individually and holding all other variables equal to the base case of NPV of $(59,975).

According to the sensitivity analysis depicted in Figure 3.5, growth rate is the most sensitive variable, followed by the payback period of the loan. Due to the relatively small percentage of the revenue stream of the biofuel price contribution, it was the least sensitive variable in the analysis.

3.3 Year-round ATS Scenario

3.3.1 Scenario Description

The ability to reduce nutrients and produce biomass year-round would improve the economics of the system. In a recent study that positioned an ATS in the Baltimore inner harbor, algae was successfully grown for an entire year, without stopping in the winter months due to decreased light and temperature (May et al., 2013). While operations during the winter months may lead to lower productivity rates, it may still be profitable to extend the growth season of the ATS even at these low rates.

In order to compensate for the loss in productivity in the winter months, it would be beneficial to position a system near relatively warm source water. We currently have a system at the Peach Bottom Nuclear Power Facility, operated by Exelon. The system is located adjacent to the Susquehanna River in southeastern Pennsylvania (Kangas, 2011). Therefore, it would be beneficial to determine the production costs and quantities for a system that runs for an entire year. When compared our Muddy Run system with unheated discharge waters across the Susquehanna River, the Peach Bottom system had a higher productivity rate at corresponding dates. This suggests that the higher temperature at the Peach Bottom site increased algal metabolism and resulted in increased productivity. Therefore, this scenario looks at the economic feasibility of a system with a year-round growth season.

Table 3.16 Year-round ATS assumptions.

Assumptions	
Interest rate	4%
Payback period (year)	10
Electrical source	Grid
Harvest method	Manual labor
Growing season (day/year)	365.25

3.3.2 Costs

The same capital costs were assumed as the agricultural scenario. However, due to the fact that we are extending the growing season, the operations and maintenance costs will increase accordingly. Table 3.17 shows the adjusted annual costs for the system. A 4% interest rate is assumed (Federal Reserve, 2013).

Table 3.17 Adjusted operations and maintenance cost for a year-round algal production system.

Item	Notes	Cost 2012 US$
Capital charge	1	$5,704
Labor and overhead	2	$15,654
Electrical power for pumps	3	$20,563
Total annual costs		$41,921
Total Annual Cost rounded ($100)		**$41,900**
No capital charge		$36,217
Rounded ($100)		**$36,200**

Notes:

3) Capital charge of 0.1233 for A/P 4%, 10 (Stermole & Stermole, 2000).
4) Estimated cost of 1 laborer per week, 20 hrs/week at $15/hr for 52 weeks.
5) Electricity based on 365.25 days, running 24 hours/day, 18.5 kw pump at rate of $0.1268/kwh average residential rate for Maryland December 2012 (EIA, 2013).

3.3.3 Break-even

In order to determine new break-even prices, new production quantitates must be determined with a system that runs all year. Table 3.18 shows the production quantities that can be expected with a 1-acre ATS that runs year-round. The same assumptions are made as with the agricultural system, only changing the growth season from 270 days to 365.25.

Table 3.18 Production quantities for a 1-acre ATS at a continuous growth season.

Growth Rate	**Algal growth**	**Butanol**	**Nitrogen**	**Phosphorus**	**Dissolved Oxygen**
g/m^2/day	ton/acre/yr	gallon/acre/yr	lb/acre/yr	lb/acre/yr	ton/acre/yr
10	16	244	978	114	6
20	33	489	1955	228	12
30	49	733	2933	342	17

Using the same assumptions as with the agricultural revenue stream, the production quantities in Table 3.18 were then multiplied by their respective monetary values per unit to give system revenues, shown in Table 3.19.

Table 3.19 Production revenues for a 1-acre ATS at year-round growing season.

Growth Rate	**Butanol**	**Nitrogen**	**Phosphorus**	**Dissolved Oxygen**
g/m^2/day	$/acre/yr	$/acre/yr	$/acre/yr	$/acre/yr
10	$855	$606	$84	$1,397
20	$1,711	$1,212	$169	$2,793
30	$2,566	$1,818	$253	$4,190

Table 3.18 and Table 3.19 show a 35% increase in production quantity and revenue on a year-round growing season. Therefore, strategic system placement that optimizes the algal growing season is an important siting consideration.

Using the new annual costs for the extended growing season scenario and adjusting for the new production quantities for a year-round ATS growing season, the break-even cost for the price per pound reduced is about the same as the agricultural, according to Table 3.20.

Table 3.20 Break-even price per credit at year-round growing season.

Growth rate (g/m^2/day)	**Total nutrient quantity (lb)**	**Break-even price per credit ($/lb)**
10	1092	$38
20	2183	$19
30	3275	$13

Increasing the pounds reduced per year by extending the growing season also increases the annual operations and maintenance costs, neutralizing the additional algal growth with additional costs. Therefore, in order to lower the break-even price per credit for the system, we must both decrease system costs and increase production efficiencies.

3.3.4 Cash flow and benefit/cost ratio

Similar to the agricultural revenue stream, a cash flow analysis was prepared, shown in Table 3.21 at different prices received per credit in addition to revenue from butanol production. In this analysis we were interested to see the effect of an extended growth season had on the cash flow analysis of this scenario.

Table 3.21 Cash flow analysis of different growth rates with nutrient trading and biofuel production as revenue for year-round system. Annual capital cost set at \$5,704 and annual operating cost found to be \$36,200.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	\$2,213	\$(39,691)	0.05
10	Med	\$6,314	\$(35,591)	0.15
10	High	\$16,660	\$(25,244)	0.40
20	Low	\$4,427	\$(37,477)	0.11
20	Med	\$12,627	\$(29,277)	0.30
20	High	\$33,320	\$(8,584)	0.80
30	Low	\$6,640	\$(35,264)	0.16
30	Med	\$18,941	\$(22,963)	0.45
30	**High**	**\$49,980**	**\$8,076**	**1.19**

When comparing this cash flow to the agricultural scenario, the benefit/cost ratio is overall higher due to the added income due to a prolonged growth season. This analysis shows that the additional income does in fact provide a benefit that outweighs the additional electrical and labor costs associated with extending the growth season by 3 months.

3.3.5 Net Present Value

A NPV analysis was performed to determine if an extended growing season and increased costs and revenues had an effect on the rate of capital recovery of the system. At a discount rate of 4% and a loan period of 10 years, a NPV analysis over 10 years is shown in Table 3.22.

Table 3.22 NPV of year-round ATS, (P/A 4%, 10), growth rate of 20 g/m^2/day, high nutrient trading, and revenue from butanol.

Year	Cost	Revenue	Net	NPV
0	$(46,300)	$-	$(46,300)	$-
1	$(36,200)	$12,627	$(23,573)	$(68,966)
2	$(36,200)	$12,627	$(23,573)	$(90,760)
3	$(36,200)	$12,627	$(23,573)	$(111,716)
4	$(36,200)	$12,627	$(23,573)	$(131,866)
5	$(36,200)	$12,627	$(23,573)	$(151,241)
6	$(36,200)	$12,627	$(23,573)	$(169,870)
7	$(36,200)	$12,627	$(23,573)	$(187,784)
8	$(36,200)	$12,627	$(23,573)	$(205,008)
9	$(36,200)	$12,627	$(23,573)	$(221,570)
10	$(36,200)	$12,627	$(23,573)	$(237,494)

Table 3.22 shows that compared to the agricultural system, the year-round ATS has a slightly lower NPV at year 10 but it is still negative. The year-round scenario has a more negative NPV at year 10 compared to the Conowingo Dam scenario NPV of $(59,975) at year 10. Therefore, while extended the growth season does improve the NPV of the system, cutting costs has a larger effect in terms of recovering capital costs.

3.3.6 Sensitivity Analysis

A sensitivity analysis was performed to determine how an extended growth period would affect individual variables in this analysis. As before, tornado plots displaying the sensitivities of for both the break-even analysis and the NPV analysis. Figure 3.6 shows the sensitivity analysis for the break-even analysis.

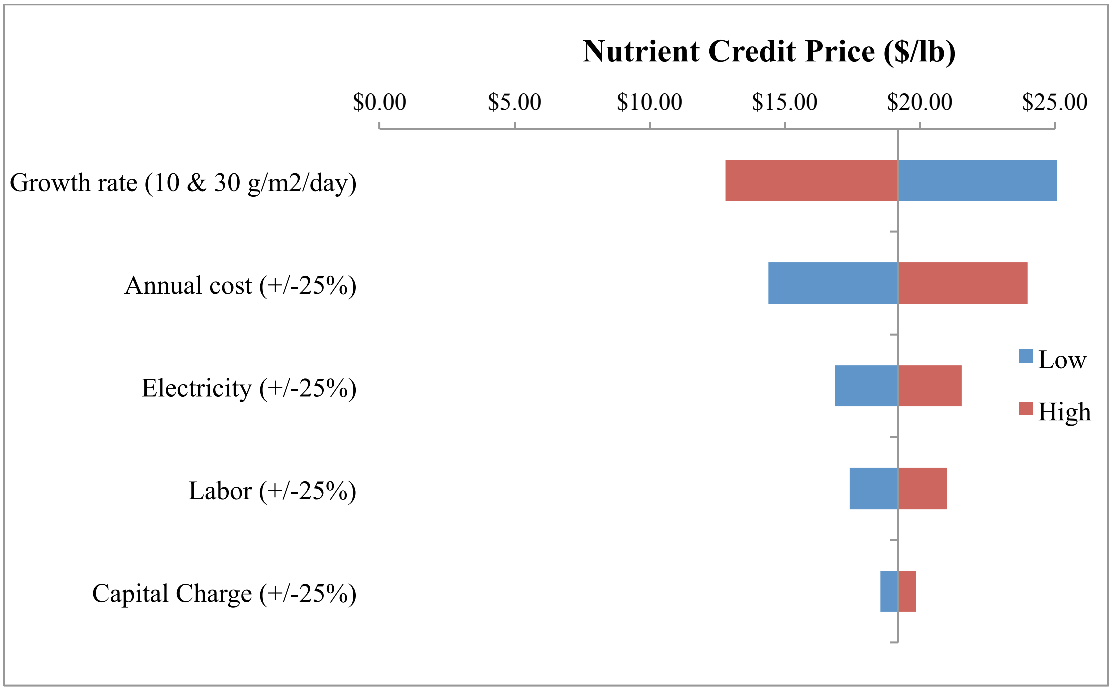

Figure 3.6 Sensitivity analysis for extended growth season ATS, adjusting each variable individually and holding all other variables equal. The base case was set as the breakeven price at a growth rate of 20 g/m^2/day at $19/lb reduced.

In addition to the break-even analysis, a sensitivity analysis was also performed on the NPV analysis in order to determine how extending the growing season affects the time value of money. The results are shown in Figure 3.7.

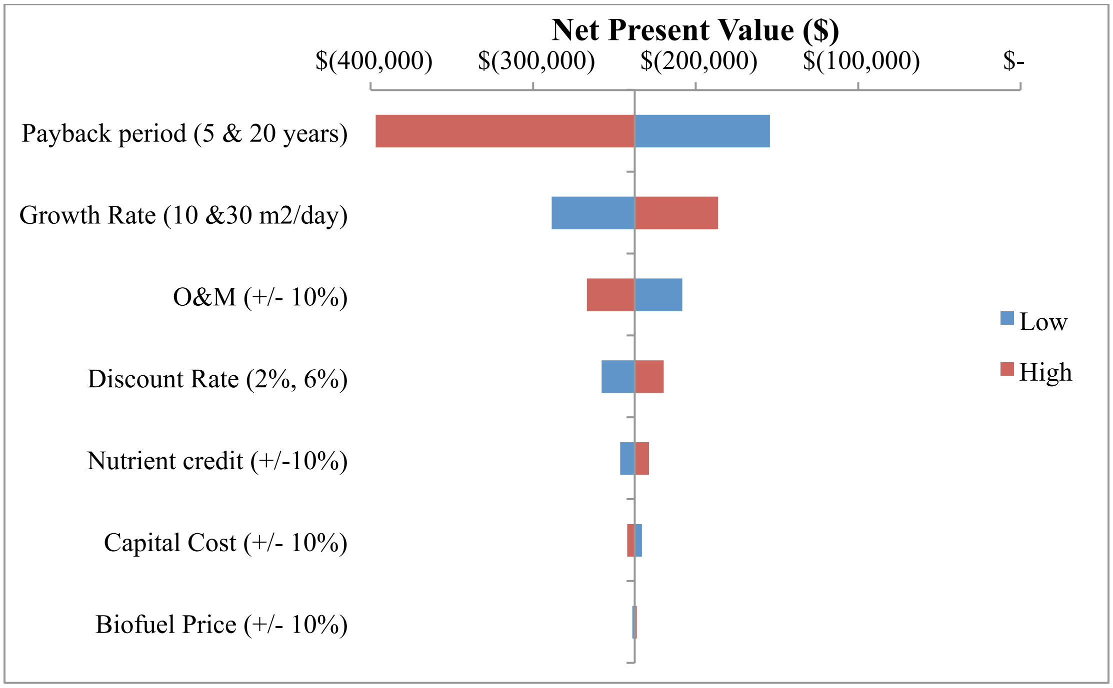

Figure 3.7 Sensitivity analysis for extended growth season ATS, adjusting each variable individually and holding all other variables equal to the base case of NPV of $(237,494).

In the extended growth scenario, operations and maintenance costs are extended as well as the growing season. While this is favorable in terms of recovering capital costs, as seen in Figure 3.7 the break-even price for the system is relatively the same as the agricultural scenario. However, eliminating some costs altogether, such as the elimination of electricity in the Conowingo Dam scenario, does have an effect on the overall nutrient credit break-even price of the system. Therefore, in order to reduce the cost of the system it would be favorable to eliminate costs as well as optimize the growing season.

3.4 Mechanized Harvesting Scenario

3.4.1 Scenario Description

According to Figure 2.1, the largest component of the operations and maintenance cost is the labor. While the Conowingo Dam scenario eliminates the need for electricity, there is still the potential to further reduce annual costs by mechanized harvesting. A good proxy for mechanized harvesting for a system such as the ATS is a model similar to lawn mowing services. We envision a mechanized harvest in the form of a worker handling machinery, such as attaching a rake to a riding lawnmower in order to harvest the technology as opposed to manually pushing the algae from the raceway as in the agricultural scenario. HydroMentia, Inc. uses a similar mechanized harvesting system by means of an automatic self-cleaning rake (HydroMentia Inc., 2013). The assumptions for this scenario are depicted in Table 3.23.

Table 3.23 Assumptions for mechanized harvesting.

Assumptions	
Interest rate	3%
Payback period (year)	10
Electrical source	Grid
Harvest method	Mechanized
Growing season (day/year)	270

Three lawn-mowing companies around Maryland were called and quotes were given for a flat, 1-acre lot harvest. The companies called are given in Appendix C. The median price for this service was found to be \$60 per acre and the time needed for mowing was 1-hour across for all three companies. In this scenario we assume the harvesting will be outsourced and the ATS owner will not purchase any additional equipment.

3.4.2 Costs

The same capital costs were assumed as the agricultural scenario, according to Table 2.1. However, the labor cost was adjusted in the operations and maintenance costs and is shown accordingly in. The assumptions for this scenario are the same as the agricultural scenario, as in Table 3.2, only differing the labor input.

Table 3.24 Operations and maintenance cost for an algal production system with mechanized harvesting.

Item	Notes	Cost 2012 US$
Capital charge	1	$5,424
Labor and overhead	2	$2,314
Electrical power for pumps	3	$15,201
Total annual costs		$22,939
Total Annual Cost rounded ($100)		**$22,900**
No capital charge		$17,515
Rounded ($100)		**$17,500**

Notes:

1) Capital charge of 0.11723 for A/P 3%, 10 (Stermole & Stermole, 2000).
2) Estimated cost of 1 harvest per week, $60 harvest for 39 weeks.
3) Electricity based on 270 days, running 24 hours/day, 18.5 kw pump at rate of $0.1268/kwh average residential rate for Maryland December 2012 (EIA, 2013).

3.4.3 Break-even

The production costs, revenues, and quantities are the same as those assumed for the agricultural scenario in Table 2.3-Table 2.7. The new total annual cost, displayed in Table 3.24 as $22,900 was used to determine new break-even prices for this scenario. Table 3.25 shows these new prices, varied by different growth rates.

Table 3.25 Break-even price for nutrient trading with mechanized harvesting.

Growth rate (g/m^2/day)	**Total nutrient quantity (lb)**	**Break-even price per credit ($/lb)**
10	807	$28
20	1614	$14
30	2421	$9

According to Table 3.25, decreases the labor input also decreases the price needed per pound of nutrient reduced to break-even. Due to the fact that labor is a larger component than electricity, this resulted in a higher price reduction in price per pound than the Conowingo Dam scenario. Compared to the agricultural scenario, mechanized harvesting resulted in a 29% decrease in break-even price.

3.4.4 Cash flow and benefit/cost ratio

As with the previous scenarios, a cash flow and benefit/cost ratio analysis was performed in order to determine if reducing the cost of harvesting has an impact the system's economic feasibility. Table 3.26 shows the results of that analysis.

As with the previous scenarios, a positive cash flow is dependent on both price received per credit as well as the growth rate of the system. As with the other scenarios, decreased cost improves the cash flows at varying growth rates and nutrient trading levels but does not improve to the point where additional levels of growth and nutrient trade turn a positive cash flow.

Table 3.26 Cash flow analysis at varying algal growth rate and nutrient market prices for a mechanized harvest system. Annual capital cost set at \$5,424 and annual operating cost found to be \$17,500.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	\$1,636	\$(21,287)	0.07
10	Med	\$4,667	\$(18,256)	0.20
10	High	\$12,315	\$(10,608)	0.54
20	Low	\$3,272	\$(19,651)	0.14
20	Med	\$9,334	\$(13,589)	0.41
20	**High**	**\$24,631**	**\$1,707**	**1.07**
30	Low	\$4,909	\$(18,015)	0.21
30	Med	\$14,002	\$(8,922)	0.61
30	**High**	**\$36,946**	**\$14,023**	**1.61**

3.4.5 Net Present Value

As with the previous analyses, a NPV was performed at a growth rate of 20 $g/m^2/day$ and high nutrient trading levels and butanol production with mechanized harvesting. These results are depicted in Table 3.27.

Table 3.27 NPV (P/A 3%, 10), growth rate of 20 $g/m^2/day$, medium nutrient trading, and revenue from butanol.

Year	**Cost**	**Revenue**	**Net**	**NPV**
0	\$(46,300)	\$-	\$(46,300)	\$-
1	\$(17,500)	\$9,334	\$(8,166)	\$(54,228)
2	\$(17,500)	\$9,334	\$(8,166)	\$(61,924)
3	\$(17,500)	\$9,334	\$(8,166)	\$(69,397)
4	\$(17,500)	\$9,334	\$(8,166)	\$(76,652)
5	\$(17,500)	\$9,334	\$(8,166)	\$(83,696)
6	\$(17,500)	\$9,334	\$(8,166)	\$(90,534)
7	\$(17,500)	\$9,334	\$(8,166)	\$(97,174)
8	\$(17,500)	\$9,334	\$(8,166)	\$(103,619)
9	\$(17,500)	\$9,334	\$(8,166)	\$(109,878)
10	\$(17,500)	\$9,334	\$(8,166)	\$(115,954)

Table 3.27 shows that the decreased operations and maintenance has a higher NPV than the year-round ATS at year 10 but still yields a negative NPV. The mechanized harvest is the second largest decrease in total annual cost of the

aforementioned scenarios. Thus, both higher revenue inflows in addition to lower cost outflows are necessary for the system to reach a positive NPV.

3.4.6 Sensitivity Analysis

Sensitivity analyses were performed for both the break-even analysis and the NPV analysis for the mechanized harvest system. The results are shown in Figure 3.8 and Figure 3.9.

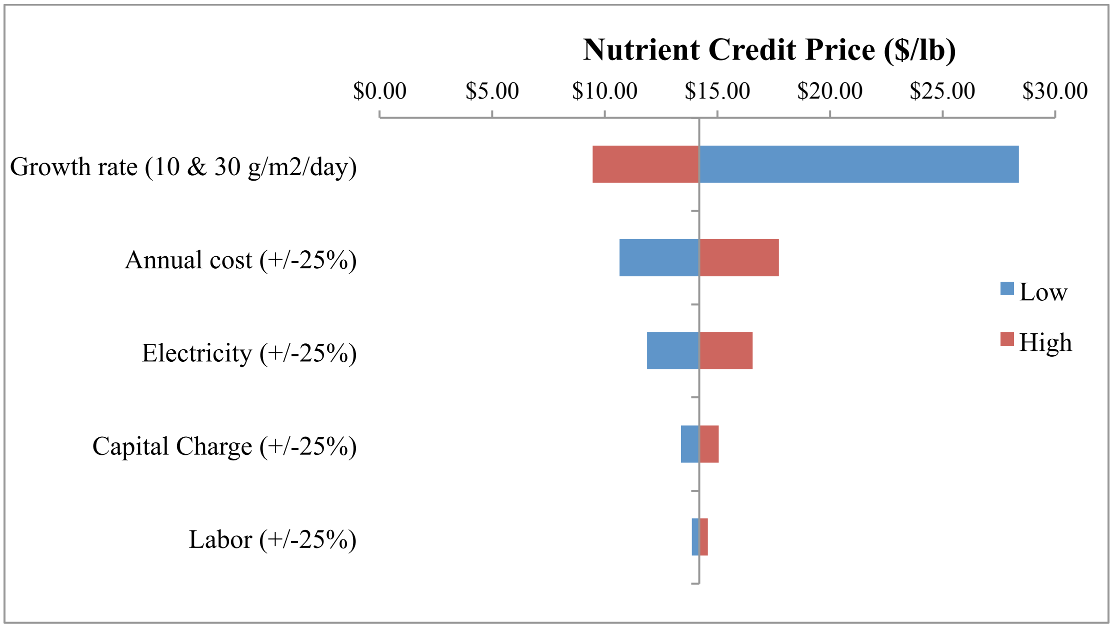

Figure 3.8 Sensitivity analysis for nutrient credit break-even price for mechanized harvest, adjusting each variable individually while holding all other variables constant. The base case was set as the breakeven price at a growth rate of 20 g/m^2/day at $14/lb reduced.

In the mechanized harvest scenario, the labor input was significantly reduced, holding all other costs and revenues equal to the agricultural scenario. Thus, when the annual cost inputs are disaggregated, electricity is the next cost that most affects the nutrient credit price.

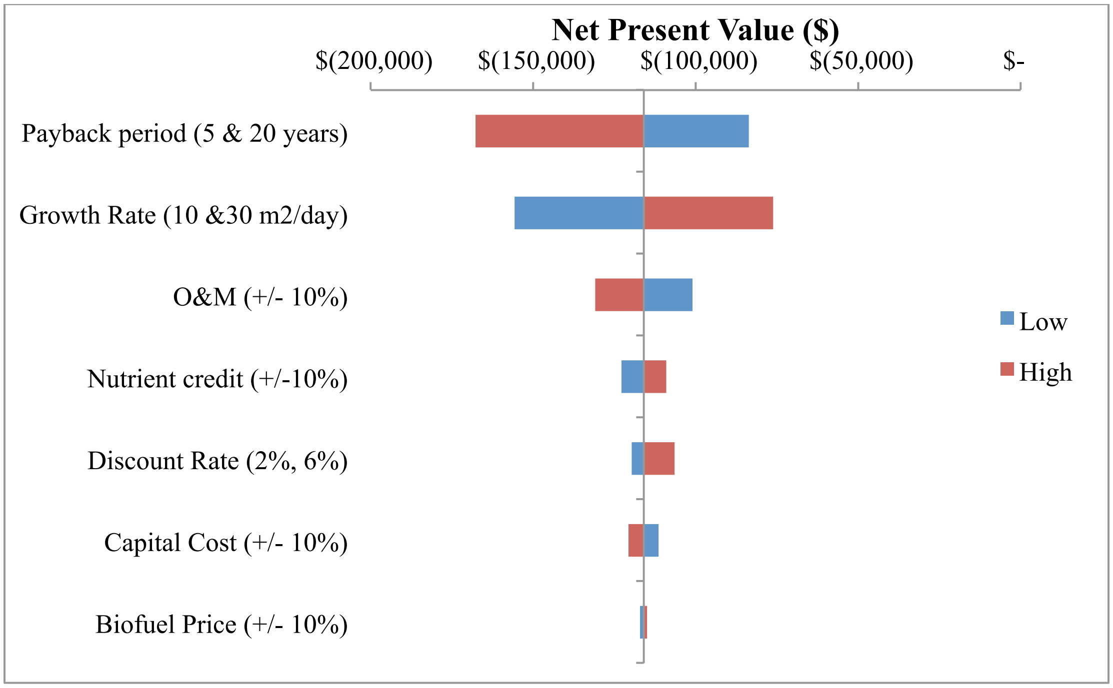

Figure 3.9 Sensitivity analysis for a mechanized harvest system, adjusting each variable individually and holding all other variables equal to the base case of NPV of $(115,954).

Due to the reduction in annual costs by using a mechanized harvest system, the operations and maintenance cost is relatively insensitive to change. As with the other analyses, the payback period and growth rate is extremely important in generating revenues to pay back capital costs. Under the current medium level revenue stream and production rate of 20 g/m^2/day, the system is unable to recover the capital costs. A combination of cutting costs and generating higher revenue at a higher production rate is needed for the system to turn a positive NPV. This is evident in the positive cash flows seen in 20 and 30 g/m^2/day at high levels of nutrient trading in Table 3.26.

3.5 Conventional Disposal of Biomass Scenario

3.5.1 Scenario Description

In order to consider the value of utilizing the algal biomass, a scenario in which the biomass disposal must be paid for is now considered. The tipping cost will be added to the agricultural scenario. Nutrient trading credits will still be evaluated but no other revenue streams that come from utilizing the biomass will be considered. Table 3.28 gives the assumptions for this scenario.

Table 3.28 Conventional disposal of biomass scenario assumptions.

Assumptions	
Interest rate	3%
Payback period (year)	10
Electrical source	Grid
Harvest method	Manual labor
Growing season (day/year)	270
Additional costs	Tipping fee

3.5.2 Costs

The same capital costs are assumed as the agricultural scenario in

Table 2.2. The addition of algal biomass disposal does increase operations and maintenance costs as an additional line item. Table 2.31 shows the additional costs incurred due to disposal at a growth rate of 20 g/m^2/day. The cost for the tipping fee were found to be $58 per ton, according to the Midshore regional solid waste facility fee schedule (MES, 2011).

Using the Bridgetown ATS system as a starting point, the distance to the solid waste facility was found to be about 22 miles, round trip. Assuming the owner would use a vehicle already owned to transport the algal biomass, assumed 15 mile per gallon gas efficiency for a truck and gas price of $3.50 per gallon (DOE, 2013). Abbreviated annual costs at growth rates of 10, 20, and 30 g/m^2/day are shown in Table 3.30. Figure 2.31 shows the composition of these costs and their percentage of total cost in a pie chart.

Table 3.29 Operations and maintenance cost of an agricultural system using conventional waste disposal.

Item	Notes	Cost 2012 US$
Capital charge	1	$5,424
Labor and overhead	2	$11,571
Electrical power for pumps	3	$15,201
Tipping fee and transport	4	$1,595
Total annual costs		$33,791
Total Annual Cost rounded ($100)		**$33,800**
No capital charge		$28,367
Rounded ($100)		**$28,400**

Notes:

1) Capital charge of 0.11723 for A/P 3%, 10 (Stermole & Stermole, 2000).
2) Estimated cost of 1 laborer per week, 20 hrs/week at $15/hr for 39 weeks.
3) Electricity based on 270 days, running 24 hours/day, 18.5 kw pump at rate of $0.1268/kwh average residential rate for Maryland December 2012 (EIA, 2013).
4) Estimated cost of disposal with tipping fee rate at $58 per ton at 20 g/m^2/day growth rate, disposed of weekly including transportation cost. Transportation

cost estimated by using location of Bridgetown system to closest regional solid waste facility, 22 miles round trip (MES, 2011). Assumed \$3.50/gallon for gas and efficiency of 15 mile per gallon (DOE, 2013). Estimated cost per trip to be \$5.13.

Table 3.30 Expenses incurred due to disposal of algae with \$58/ton tipping fee at different growth rates.

Growth rate	**Production quantity**	**Cost with tipping fee**	**Cost with tipping fee and transportation**	**Annual expense**	**Total annual expense**
g/m^2/day	ton/acre/wk	\$/acre/wk	\$/acre/wk	\$/acre/yr	\$/acre/yr
10	0.31	\$18	\$23	\$897	\$33,092
20	0.62	\$36	\$41	\$1,595	\$33,791
30	0.94	\$54	\$59	\$2,294	\$34,490

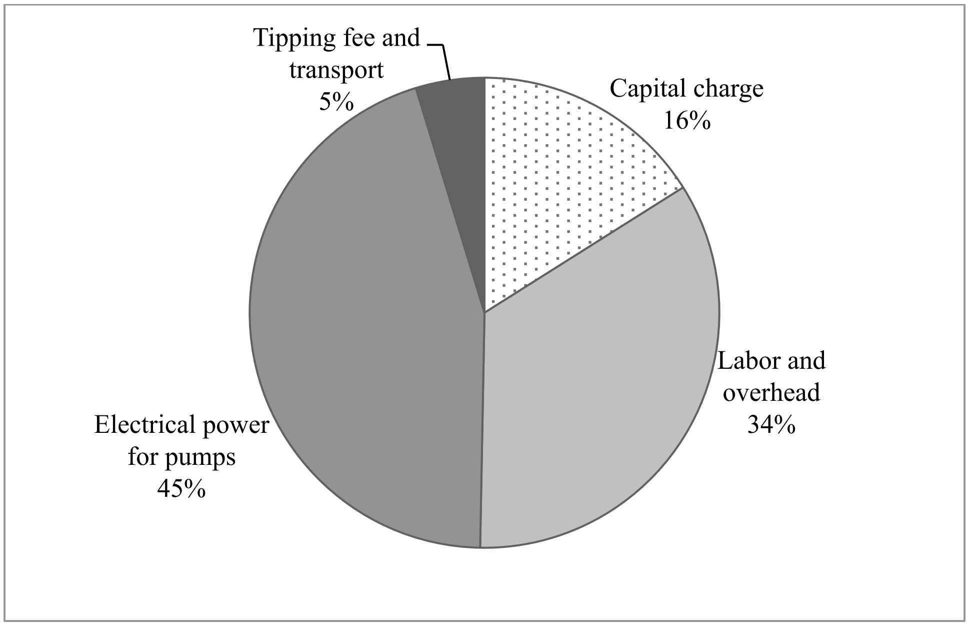

Figure 3.10 Breakdown of annual cost including tipping fees for biomass production rate of 20 g/m^2/day.

3.5.3 Break-even

In order to determine the effect conventional disposal will have on the economics of the system, a break-even analysis was performed. The analysis assumes the same capital cost, production quantities, and 270 day growing season as the agricultural system. The annual costs in Table 3.29 are used to determine the break-even price. The results of this analysis are shown in Table 3.31.

Table 3.31 Break-even analysis of ATS with conventional biomass disposal.

Growth rate ($g/m^2/day$)	**Total nutrient quantity (lb)**	**Break-even price per credit**
10	807	$41
20	1614	$21
30	2421	$14

Compared to the break-even price for the agricultural revenue stream, these prices are only slightly higher. This is due to the fact that the added cost of disposal is relatively small, 5% of the total annual costs for a 20 $g/m^2/day$ growth rate.

3.5.4 Cash flow and benefit/cost ratio

A cash flow and benefit/cost ratio was calculated in order to determine the affect of the added cost of biomass disposal to the economic feasibility, shown in Table 3.32.

Table 3.32 Cash flow analysis at varying algal growth rates and nutrient trading levels including tipping fees. Annual capital cost set at $5,424.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Operating Cost**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	$(27,669)	$1,004	$(32,088)	0.03
10	Med	$(27,669)	$4,035	$(29,057)	0.12
10	High	$(27,669)	$11,683	$(21,409)	0.35
20	Low	$(28,367)	$2,008	$(31,783)	0.06
20	Med	$(28,367)	$8,070	$(25,721)	0.24
20	High	$(28,367)	$23,366	$(10,425)	0.69
30	Low	$(29,066)	$3,012	$(31,478)	0.09
30	Med	$(29,066)	$12,105	$(22,385)	0.35
30	**High**	$(29,066)	$35,049	**$560**	**1.02**

The additional incurred cost of a tipping fee and the lack of revenue from the biomass had an overall negative effect on the cash flow of the system. In the Conowingo Dam and mechanized harvest scenarios, a positive cash flow was reached at high levels of nutrient trading at both 20 and 30 $g/m^2/day$. However, additional costs compounded with smaller cash inflows caused a negative cash flow for the med growth rate at high levels of nutrient trading. Importantly, this shows that the system is particularly sensitive to additional costs when calculating the cash flow.

3.3.5 Net Present Value

An NPV analysis was performed to determine if the added cost of disposing the algae instead of using the biomass for revenue affected the system's ability to recover capital.

Table 3.33 NPV (P/A 3%, 10), growth rate of 20 $g/m^2/day$, medium nutrient trading, and conventional waste disposal of algal biomass.

Year	Cost	Revenue	Net	NPV
0	$(46,300)	$-	$(46,300)	$-
1	$(28,400)	$8,070	$(20,330)	$(66,038)
2	$(28,400)	$8,070	$(20,330)	$(85,201)
3	$(28,400)	$8,070	$(20,330)	$(103,806)
4	$(28,400)	$8,070	$(20,330)	$(121,869)
5	$(28,400)	$8,070	$(20,330)	$(139,406)
6	$(28,400)	$8,070	$(20,330)	$(156,433)
7	$(28,400)	$8,070	$(20,330)	$(172,963)
8	$(28,400)	$8,070	$(20,330)	$(189,012)
9	$(28,400)	$8,070	$(20,330)	$(204,593)
10	$(28,400)	$8,070	$(20,330)	$(219,721)

With the additional annual cost of conventional waste disposal and the lack of the biofuel revenue stream, the system is unable to reach a positive NPV and recover the capital investment. This also shows that the system is sensitive to increases in cost and decreases in revenue.

3.3.6 Sensitivity Analysis

Sensitivity analyses on the break-even price and NPV were performed in order to determine which variables are most sensitive when adding the cost of disposal to the system. The results are shown in Figure 3.11 and Figure 3.12.

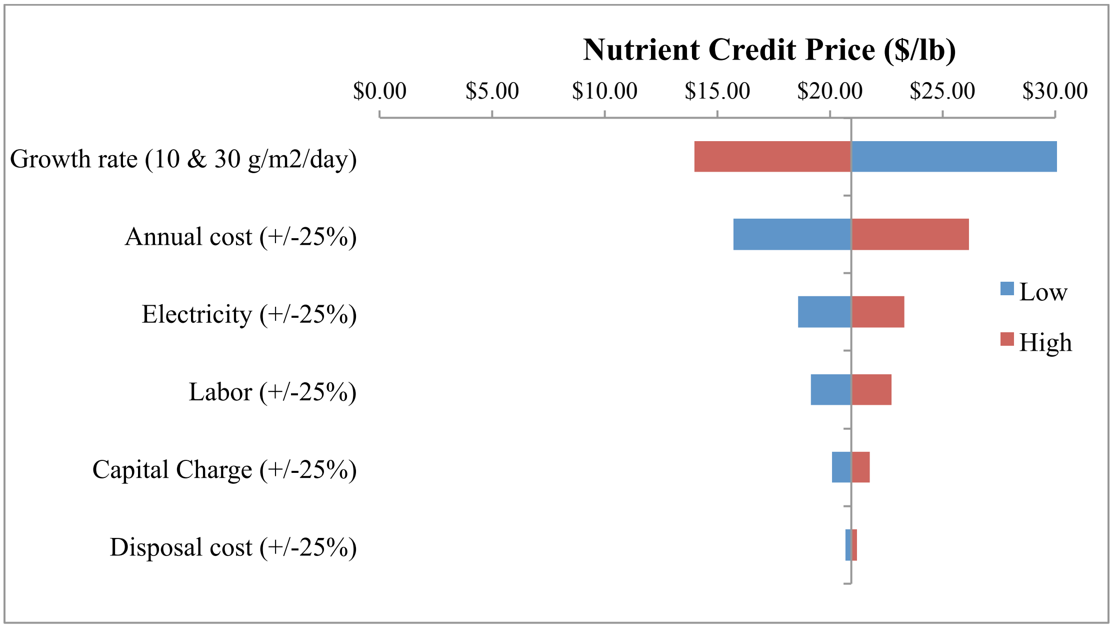

Figure 3.11 Sensitivity analysis for nutrient credit break-even price including disposal fees, adjusting each variable individually while holding all other variables constant. The base case was set as the breakeven price at a growth rate of 20 $g/m^2/day$ at $21/lb reduced.

According to Figure 3.11, growth rate is the most sensitive variable in the analysis, holding all other variables equal, ranging in nutrient credit price from $10-$30. Compared to the agricultural situations, these break-even prices are within $1 of those prices, showing the addition of a disposal cost or removal of income from biofuel at current prices do not have a large effect on the overall nutrient credit price needed to break-even.

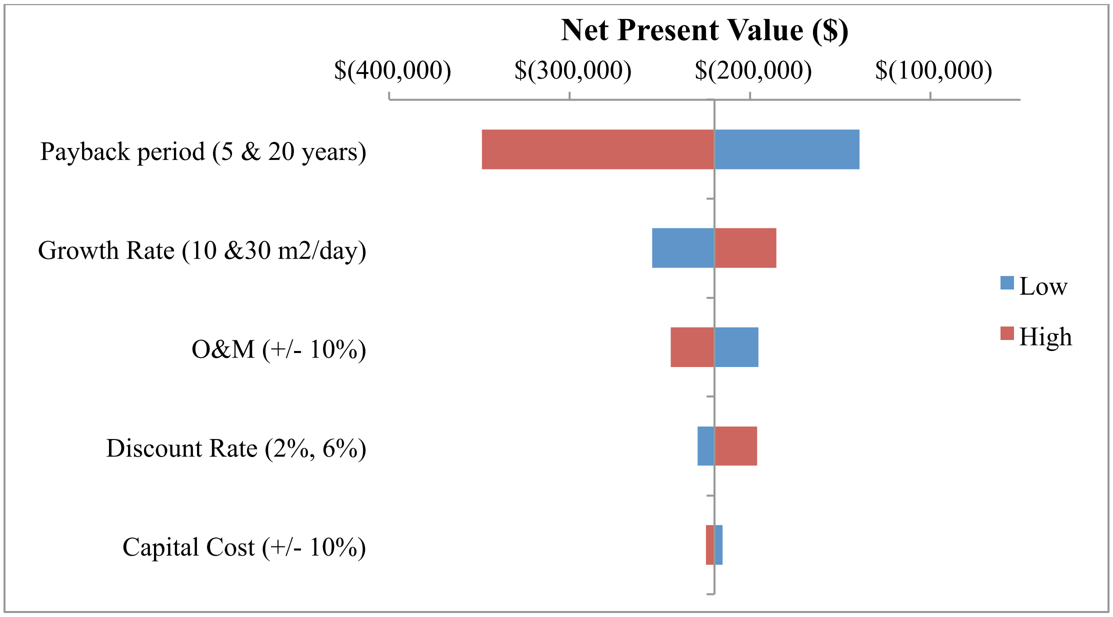

Figure 3.12 Sensitivity analysis for conventional disposal scenario, adjusting each variable individually and holding all other variables equal to the base case of NPV of $(219,721).

Shown in Figure 3.12 revenue from nutrient credits, operations and maintenance, and the payback period all were close in the same base cost and when adjusted shared relatively the same sensitivity, holding all other variables equal. Growth rate dominates the analysis as the most sensitive variable.

3.6 Best-case Scenario

3.6.1 Scenario Description

A best-case scenario encompassing all possible cost and production efficiencies was created to determine if the effects of all these efficiencies had an impact on the overall economics of the system. While a system that actually encompasses all of these qualities may not be realistic, the purpose of this exercise is to determine the costs and revenues of a system like this and compare it to the others. The following is a list of characteristics this best-case scenario would encompass:

- Absence of electrical input by siphoning water from high potential energy source
- Year-round growing season
- Mechanized harvesting

Due to the fact that most of these qualities are characteristic of a utility company, a 4% interest rate will be used when evaluating the time value of money. An assumption table for this scenario is shown in Table 3.34.

Table 3.34 Assumptions for best-case scenario.

Assumptions	
Interest rate	4%
Payback period (year)	10
Electrical source	None
Harvest method	Mechanized
Growing season (day/year)	365.25

3.6.2 Costs

The same capital costs are assumed as for the Conowingo Dam scenario given in Table 3.11 at $41,600. The operations and maintenance costs are shown in

Table 3.35 Operations and maintenance cost of best-case scenario.

Item	**Notes**	**Cost 2012 US$**
Capital charge	1	$5,132
Labor and overhead	2	$3,120
Total annual costs		$8,252
Total Annual Cost rounded ($100)		**$8,200**
No capital charge		$3,120
Rounded ($100)		**$3,100**

Notes:

1) Capital charge of 0.1233 for A/P 4%, 10 (Stermole & Stermole, 2000).
2) Estimated cost of 1 harvest per week, $60 harvest for 52 weeks.

According to Table 3.35, total annual costs are reduced by 67% when compared to the agricultural scenario. All other major operations and maintenance costs are reduced, including capital charge since pumps are no longer necessary. Also, this scenario shows that extending the growth season does not have such an adverse effect on operations and maintenance cost because there are no electricity inputs. However, the labor cost for mechanized harvesting was increased to reflect the extended growing season.

3.6.3 Break-even

The nutrient price needed to break-even is shown in Table 3.36 with the decreased system cost.

Table 3.36 Break-even analysis of best-case algae production system.

Growth rate ($g/m^2/day$)	**Total nutrient quantity (lb)**	**Break-even price per credit ($/lb)**
10	1092	$8
20	2183	$4
30	3275	$3

Compared to the agricultural system, the break-even price shown in Table 3.36 is considerably lower, ranging from 75%, 88%, and 91% percent change from low to high growth rate, respectively. The 30 $g/m^2/day$ shows the highest percent change due to the extended growth rate taken into account for the best case scenario, therefore there are increased quantities of pounds of nutrients reduced compared to the agricultural scenario.

3.6.4 Cash flow and benefit/cost ratio

A cash flow analysis incorporating the new cost reduction and system efficiencies are shown in Table 3.37. The analysis is varied by growth rate in addition to nutrient trading levels. Revenue from biofuel is also included.

Table 3.37 Cash flow analysis at varying algal growth rate and nutrient market prices for best-case scenario, including revenue from biofuel. Annual capital cost set at $5,132 and annual operating cost found to be $3,100.

Algal growth rate ($g/m^2/day$)	**Level of nutrient trading**	**Annual Income**	**Net Income**	**Benefit/ Cost**
10	Low	$2,213	$(6,019)	0.27
10	Med	$6,314	$(1,919)	0.77
10	**High**	**$16,660**	**$8,428**	**2.02**
20	Low	$4,427	$(3,805)	0.54
20	**Med**	**$12,627**	**$4,395**	**1.53**
20	**High**	**$33,320**	**$25,088**	**4.05**
30	Low	$6,640	$(1,592)	0.81
30	**Med**	**$18,941**	**$10,709**	**2.30**
30	**High**	**$49,980**	**$41,748**	**6.07**

Table 3.37 reveals that reducing costs and extending the growth rate of the system greatly increases net income and increases the instances of a positive cash flow. Compared to the agricultural system that only saw a positive cash flow at high levels of nutrient trading and 30 $g/m^2/day$ growth rates, the best-case scenario has a total of 5 instances of positive net income. At all high levels of nutrient trading a positive cash flow is calculated. This shows that while this system does hinge on growth rate, low growth rates can be overcome at high levels of nutrient trading and low operations and maintenance cost. In addition, this is the only scenario in which a benefit/cost ration greater than one is observed for medium levels of trading at 20 and 30 $g/m^2/day$ growth rates. Thus, cutting costs across the board and extending the

growing season increases the instances of a positive cash flow at varied growth rates and nutrient trading levels.

3.6.5 Net Present Value

In order to assess how cost reduction and an extended growth period affects the recovery of capital, a NPV analysis was performed on the best-case scenario at 20 g/m^2/day including revenue from high trading levels and biofuel production.

Table 3.38 NPV of best-case scenario (P/A 4%, 10), growth rate of 20 g/m^2/day, high nutrient trading, and revenue from butanol.

Year	Cost	Revenue	Net	NPV
0	$(41,600)	$-	$(41,600)	$-
1	$(3,100)	$33,320	$30,220	$(12,542)
2	**$(3,100)**	**$33,320**	**$30,220**	**$15,398**
3	**$(3,100)**	**$33,320**	**$30,220**	**$42,264**
4	**$(3,100)**	**$33,320**	**$30,220**	**$68,096**
5	**$(3,100)**	**$33,320**	**$30,220**	**$92,935**
6	**$(3,100)**	**$33,320**	**$30,220**	**$116,819**
7	**$(3,100)**	**$33,320**	**$30,220**	**$139,783**
8	**$(3,100)**	**$33,320**	**$30,220**	**$161,865**
9	**$(3,100)**	**$33,320**	**$30,220**	**$183,097**
10	**$(3,100)**	**$33,320**	**$30,220**	**$203,513**

Reducing overall annuals costs allows for a quick recovery of capital costs. By year 2, the system turns a positive NPV. In addition, the NPV at year 10 is the highest of all scenarios, nearly $200,000 more than the agricultural scenario at year 10 and $180,000 more than the mechanized harvest scenario. Thus, reducing capital and operational costs and increasing the revenue potential by extending the growing season increases the capital recovery of the system.

3.6.6 Sensitivity Analysis

As with the other scenarios, a sensitivity analysis was performed to show which variables are the most sensitive to change, for the break-even and NPV analysis. The results of this sensitivity analysis are shown in Figure 3.13 and Figure 3.14.

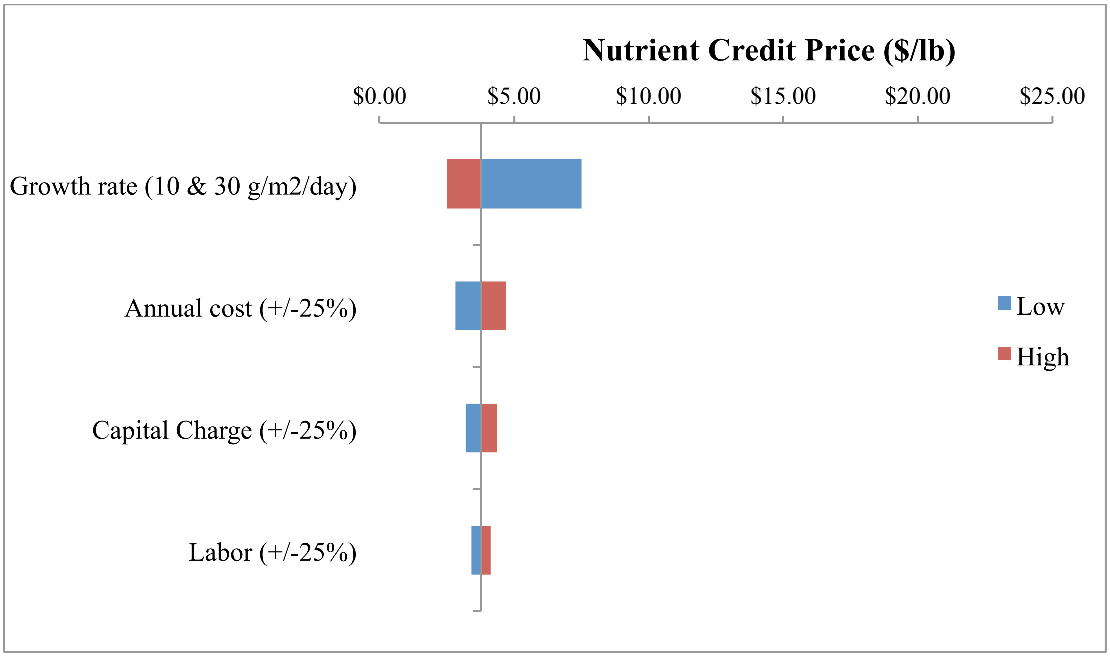

Figure 3.13 Sensitivity analysis for nutrient credit break-even price for best-case scenario including high nutrient trading levels, and revenue from biofuel adjusting each variable individually while holding all other variables constant. The base case was set as the breakeven price at a growth rate of 20 g/m^2/day at $4/lb reduced.

The sensitivity analysis in Figure 3.13 shows that the variables are relatively insensitive to change due to the cost reductions imposed in the base case scenario. As expected, the growth rate is the most sensitive to changes in break-even price because the growth rate dictates the quantities available to spread out the price.

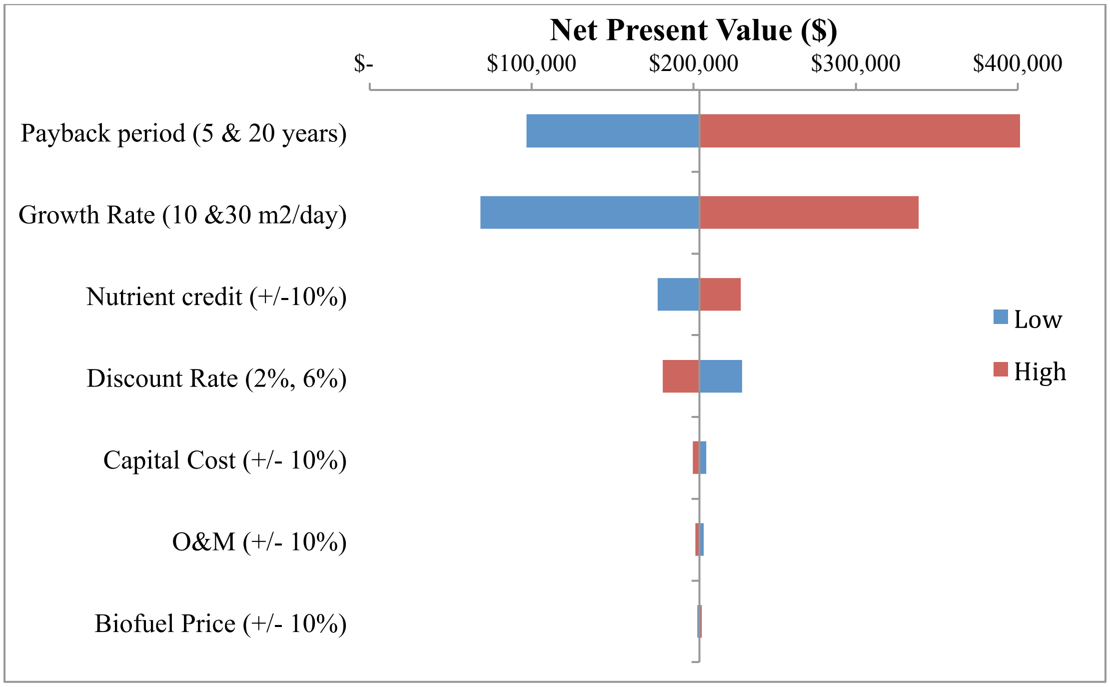

Figure 3.14 Sensitivity analysis for the best-case scenario, adjusting each variable individually and holding all other variables equal to the base case NPV of $203,513.

Figure 3.14 reveals that the reduction of cost and the improvement of the growing season causes the payback period to be the most sensitive variable in this analysis, holding all other variables constant. The growth rate is a close second, with a NPV range of $69,000 at 10 g/m^2/day and $339,000 at 30 g/m^2/day.

Chapter 4 : Summary and Discussion

4.1 Summary

4.1.1 Summary Results

Figure 4.1 shows the break-even price for each scenario at various growth rates. Table 4.1 provides a key for the scenarios.

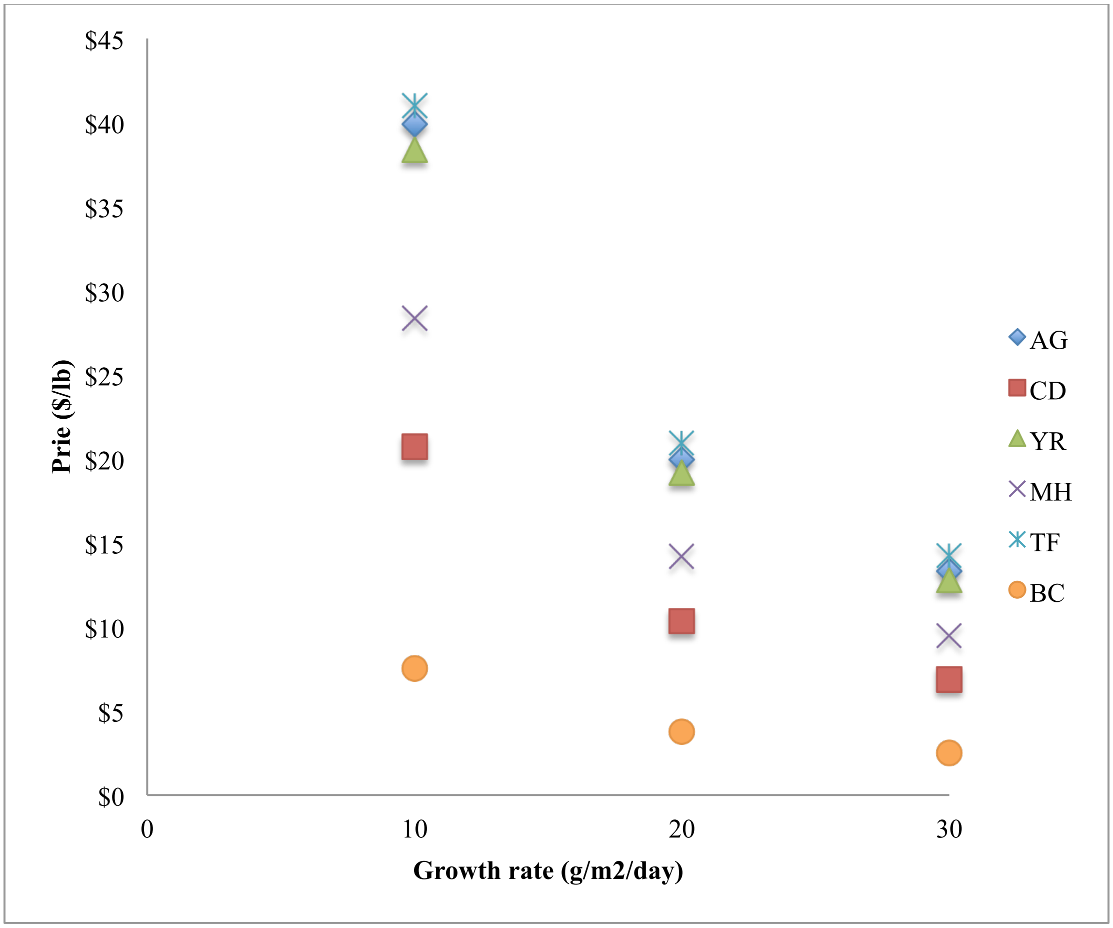

Figure 4.1 Break-even price for nutrient credit generation at different scenarios and growth rates.

Table 4.1 Abbreviations and corresponding scenarios.

Abbreviation	**Scenario**
AG	Agricultural
CD	Conowingo Dam
YR	Year-round
MH	Mechanized harvesting
TF	Conventional disposal of biomass
BC	Best-case scenario

As expected, according to Figure 4.1, the best-case scenario also has the lowest break-even price per credit. Figure 4.1 also shows two general trends: 1) as costs are decreased the price per pound decreases across growth rates; 2) the difference between scenarios within a particular growth rate decreases as growth rate increases. These two trends show that the ATS becomes more affordable at higher growth rates but the system is limited by the quantity of pounds reduced and therefore the difference between scenarios in the price per pound decreases over higher growth rates. This issue is addressed in the extended growth rate scenario but without increases algal nutrient uptake efficiency, there seems to be a limit to the price per pound reduced.

It is important to note the system's dependency on nutrient trading in order to be economically feasible. Using the same cash flows for each scenario in Chapter 3 but subtracting the revenue from nutrient trading, a benefit/cost ratio for each scenario at 20 $g/m^2/day$ at medium trading rates of \$5/lb for nitrogen and phosphorus can be seen in Figure 4.2.

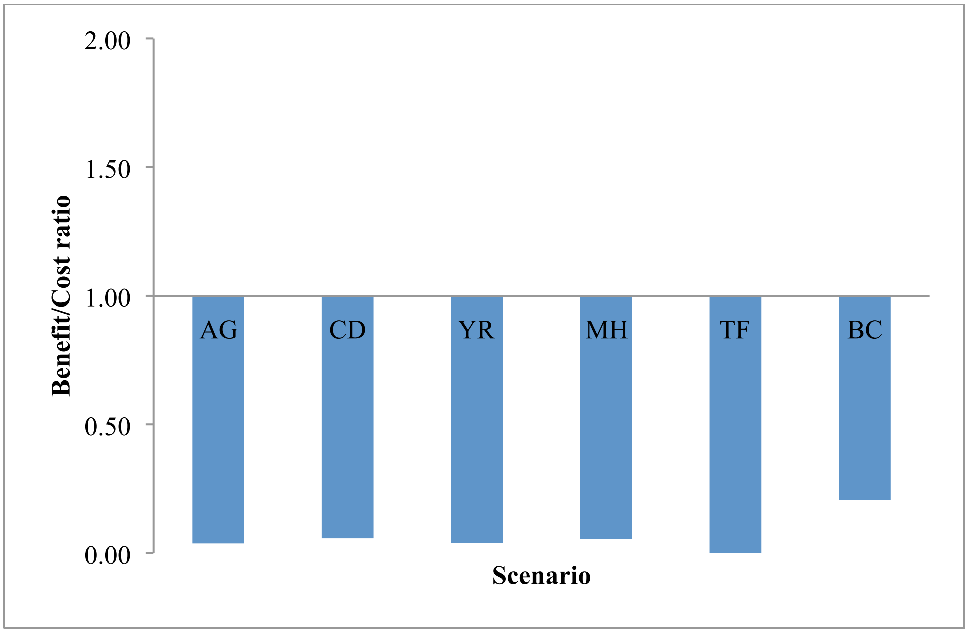

Figure 4.2 Benefit cost ratio at 20 g/m^2/day growth rate with no nutrient trading but revenue from butanol.

In order to show the importance of the contribution from nutrient trading, Figure 4.3 shows the benefit/cost ratio for the different scenarios at 20 g/m^2/day at trading rates of $5/lb for both nitrogen and phosphorus and butanol production.

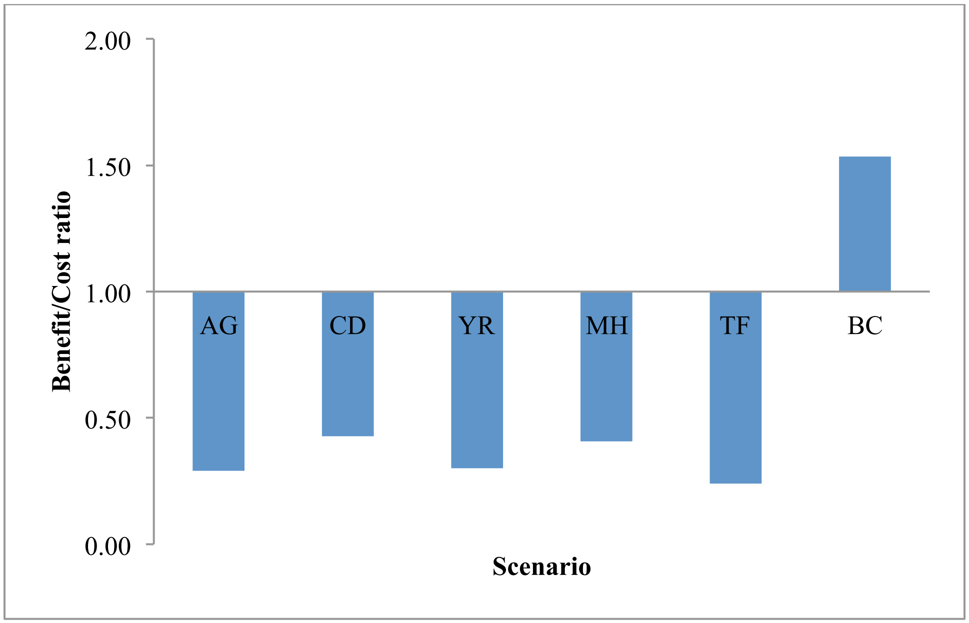

Figure 4.3 Benefit cost ratio at 20 g/m^2/day growth rate and medium level nutrient trading ($5/lb nutrient) and butanol.

Figure 4.3 has a higher overall benefit/cost ratio for each scenario with the additional revenue from nutrient trading, compared to Figure 4.2. According to Figure 4.3, the only scenario that has a benefit/cost ratio greater than 1 at a growth rate of 20 g/m^2/day is the best-case scenario. This shows promise for the ATS, if correctly sited, that at medium growth rates and medium nutrient trading levels the system is economically feasible.

4.2 Discussion

4.2.1 Siting

The greatest areas for nutrient reduction potential have already been identified by Maryland Department of Natural Resources (MDNR) through Maryland's Chesapeake and Costal Bays Trust Fund Priority Areas (MDNR, 2012). These areas were identified using the expertise of scientists in the region, a regression based model created by United States Geographical Survey that can discriminate watershed that likely contribute to the highest loads, and biologically impaired waterways that have a high possibility for removal from Maryland's list of impaired waters. Urbanized and agricultural waterways were considered separately when evaluating priority areas. Figure 4.4 shows the map created by MDNR with the identified Trust Fund Priority Areas.

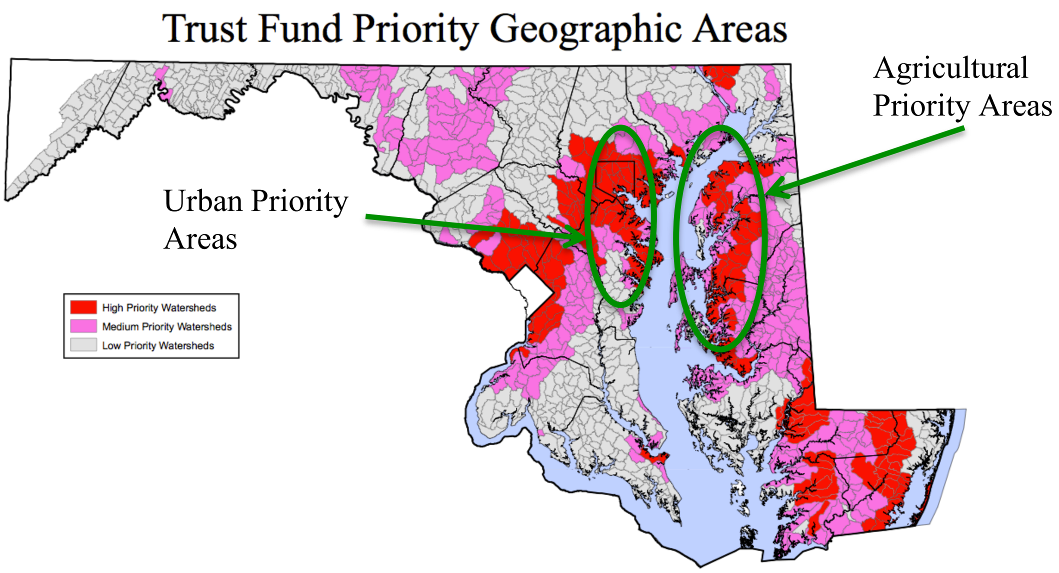

Figure 4.4 Priority areas for the Chesapeake and Atlantic Coastal Bay Trust Fund. High priority areas colored in red denote priority watersheds with the top 10% delivered yields for nutrients while medium priority areas in pink show the top 25% delivered yields for nutrients. Low priority watersheds in gray denote the lowest 75% delivered nutrient yields.

It is important to strategically site ATS systems in areas that both cut costs and have high nutrient loadings, such as those identified by MDNR. Areas with high nutrient loadings or "hot spots" have the highest potential for ecological remediation as well as economic feasibility.

4.2.2 Comparison to Cover Crops

A common agricultural nutrient reduction practice with published cost estimations is the annual planting of cover crops. Also, cover crops provide a good comparison because of the opportunity cost associated with the implementation of an ATS. Once an ATS is put in place, the land use is converted from cropland to algae production and therefore cover crops are not longer an option. Therefore, it would be useful to review the costs of cover crops in order to compare the economics of each nutrient reduction practice.

A report by Wieland et al. (2009) compares the cost efficiencies of different agricultural BMPs, including cover crops. Due to the difference in nutrient loads between the coastal plains and non-coastal plain regions of Maryland, the Wieland et al. study reports the cost efficiencies for different cover crops by region. The pounds reduced per acre as well as the price per pound for rye, barley and wheat are calculated for normal planting which is defined as before October 15th. These unit load reductions and efficiencies are then compared to the ATS. Table 4.2 compares the different cover crop types and geographical locations with the central nitrogen and cost values for the ATS that are used in this study. The yearly cost of $32,200 to run an agricultural was divided by the total annual pounds of nitrogen captured by the system to achieve the cost of reduction.

Table 4.2 Comparison of ATS and grain cover crop practices reduction and cost efficiencies adapted from Wieland et al. (2009) not including cost sharing programs.

	Growth Rate	**Unit Load Reduction**	**Reduction cost per pound**
ATS	g/m^2/day	lbs N/acre	$/lb N
	10	723	44.56
	20	1445	22.28
	30	2168	14.85
Coastal Plain	**Cover Crop Type**		
	Rye	9.1	4.39
	Barley	6.11	6.55
	Wheat	6.15	6.56
Non-Coastal Plain	Rye	16.47	2.43
	Barley	11.48	3.48
	Wheat	12.18	3.28

While the cost of reduction for the ATS is higher than both the coastal plain and non-coastal plain cover crop types, the ATS has a much higher overall unit load reduction. Table 4.2 also shows that the ATS may be used for a more intensive nutrient reduction approach, while cover crops cover a larger area and should be used for extensive nutrient reduction. This is due in part to the fact that the ATS has a much longer growing season as well as higher harvest frequency that cover crops. In terms of annual \$/acre, the ATS costs \$32,200 per where as cover crops run about \$40 per acre.

According to the Maryland Budget Highlights from FY 2012, approximately \$16.2 million were allocated for the cover crop program (Department of Budget & Management, 2011). In the next year, the Maryland Budget Highlights from FY 2013 reported that farmers enrolled 567,000 acres of land into the cover crop program, leading to the reduction of 5,062,331 pounds of nitrogen (Department of Budget & Management, 2012). This comes out to an approximate cost of \$3.20 per pound of nitrogen reduced. If the same amount of money were dedicated to the implementation of algal turf scrubbers, based on the agricultural scenario costs, approximately 660 acres would be dedicated to ATS installation. This would reduce between 700,000 and 2,100,000 pounds of nitrogen, for growth rates of 10 and 30 $g/m^2/day$, respectively. This was calculated taking the \$16.2 million allocated to cover crops and dividing by the price per pound of nitrogen reduced according to Table 4.2. These results are shown in Figure 4.5.

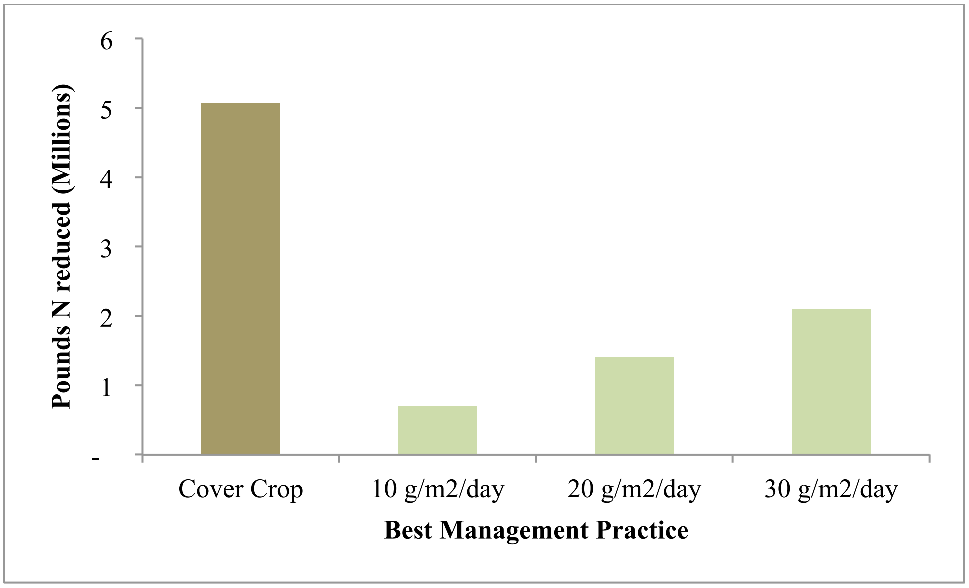

Figure 4.5 Pounds of nitrogen reduced for cover crops and ATS at different growth rates with $16.2 million investment.

However, if the same amount of acres, 567,000 were dedicated to ATS installation rather than cover crops, the potential reduction of nitrogen is far greater. This is due to the fact that while the ATS is a more expensive technology in terms of price per pound, it is a more efficient technology in terms of pounds per acre. Using a similar back-of-the-envelope estimation technique as before, multiplying the 567,000 acres by the pound per acre reduction of the ATS according to Table 4.2, the ATS is capable of reducing between 400,000,000 and 1,000,000,000 pounds of nitrogen per year, at 10 and 30 g/m^2/day growth rates, as shown in Figure 4.6. It should be noted that putting this amount of land out of production is not the point or intention of this calculation. Rather, the aim is to show the potential for significant nutrient reduction with large-scale ATS systems.

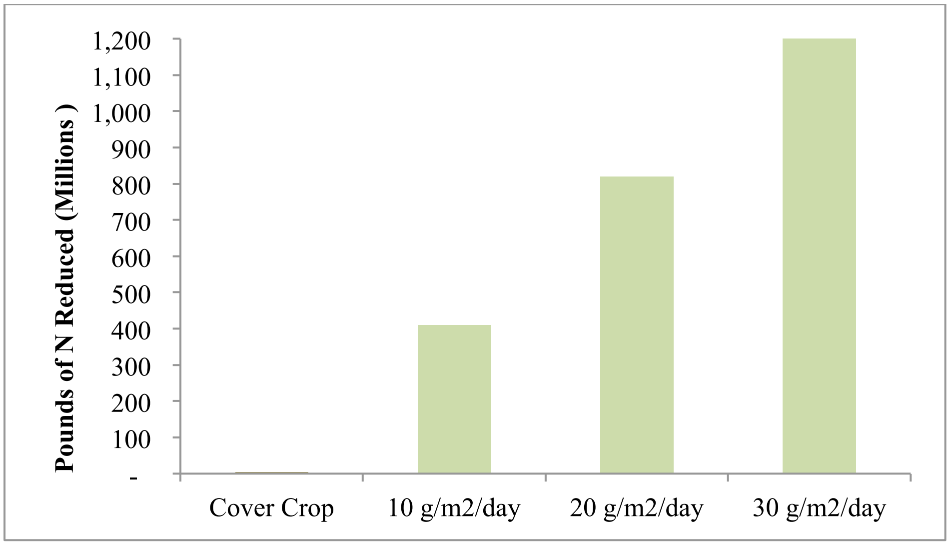

Figure 4.6 Pounds of nitrogen reduced for cover crops and ATS at different growth rates with 567,000 acre installation.

Therefore, while the cost of reduction is higher for the ATS in comparison to the cover crops, there is a much higher credit generation potential for the ATS compared to the cover crops. Also, the table reveals that the cost of reduction is lower in the coastal plains, which could be an important component when determining the most favorable locations for an ATS system. On the one hand, cover crops are a more extensive nutrient reducer, on the other hand the ATS is an intensive nutrient reducer The different nutrient reduction attributes of the ATS compared to cover crops shows the possibility of a complementary nutrient reduction plan rather than a rivalry.

4.2.3 Water Quality Multiplier Effects

In a study by Lipton (2004) improved water quality of the Chesapeake Bay was valued through revealed preference surveys given to boaters. The study revealed that boaters are willing to for improvements in water quality, ranging from \$30.25 to \$93.26, depending on the type of boat owned. While this study is specific to the willingness to pay of boaters to improve the water quality of the Chesapeake Bay, it is an important component in determining the total societal benefits from improved water quality.

Improving water quality via the ATS technology could lead to multiplier effects due to the remediation of hypoxic zones from DO injection as well as the uptake of nutrients to prevent dead zones from occurring in the first place. Improving water quality could also help improve the productivity of the Bay, thus boosting the economy from a fisheries perspective.

4.2.4 Creation of Green Jobs

While the economic analysis indicated that labor was the most prominent cost for the system, if the only concern was pounds reduced per acre, the labor input could be viewed as an additional benefit of the ATS at a large scale. Thus, the ATS could provide a socioeconomic benefit of improving unemployment in addition to improving water quality. The actual mechanism for an employment system like this would be based on the successful lawn care industry, it is unknown if the ATS would have the same type of success

4.2.5 Economies of Scale

The purpose of this feasibility study was to determine if a small, modular, 1-acre ATS system was viable. However, in order to make significant nutrient reduction and water quality improvements, we envision a system that is tens to hundreds of acres. Scaling up from a 1-acre system would benefit from economies of scale, such as materials at a discount in addition to the manual labor aspect. Large areas of ATS systems would not be recommended on agricultural land, taking a significant amount of productive land out of production and would not be viable for nutrient trading. However, there are other areas in the Bay watershed that are critically impaired in which the state or local government may have a vetted interest in remediation via ATS treatment.

Chapter 5 : Conclusion

5.1 Conclusion

The ATS is an innovative wastewater treatment technology with applications beyond its primary use of water remediation and nutrient management. The success of the technology is apparent by the breadth of publications regarding the technology as well as the numerous patents regarding the ATS. While this is a scientifically proven technology, the uncertainty involved with the markets that the ATS could have a real stake in elicits a "wait and see" response to larger scale and real impact applications. The following are the conclusions of this analysis:

- The ATS is an intensive, effective nutrient removal technology in terms of pounds reduced per acre and may be complementary to other BMPs;
- The ATS can be potentially applied in a number scenarios including: agricultural, Conowingo Dam, year-round, mechanized harvest, conventional waste disposal, and the best-case scenario that incorporates characteristics from each scenarios.
- Without support from the nutrient trading market the ATS cannot self-finance on byproducts alone at current prices for biofuel and fertilizer;
- The ATS can be profitable at nutrient credit price at $20/lb (N & P) at 20 g/m^2/day for most scenarios;
- Ecosystem services provided by the ATS do not currently have market prices but may provide economic uplift in terms of improving fisheries and creating green jobs.

5.2 Future Study

The sensitivity analysis in this report revealed that the growth rate has a large effect in terms of reducing pounds in order to generate credits. This analysis focused on determining which costs contributed the most to production and explored different ways to reduce those costs. Therefore, it would be beneficial to determine the qualities and conditions of the algae with high growth rate and nutrient content. One way this could be done is through a multi-variable regression analysis that determined the most important variables that contribute to the algal growth rate and how they can be optimized, in conjunction with the cost efficiencies already discovered in this analysis.

Appendix A : Production Summaries

Article Title: Coral reef algal turfs: master producers in nutrient poor seas
Journal: *Phycologia*
Author: Walter H. Adey and Timothy Goertemiller
Publication Year: 1987
Location of study: Trade wind belt of southeastern Bahamas; ocean vs. lagoon
Study timeframe: January to June 1983
Size of system: 3 types, each attached to rafts and suspended at depths of 15, 30, and 45 cm

1. 1.6 x 4.8 mm mesh 1 m^2
    a. Laminated to upper surfaces to mimic substrate of a reef
    b. Placed horizontally in water at depth of 30 cm
2. 1.6 x 4.8 mm, 1 m^2
    a. Double layered screen
    b. Bottom of screen black polypropylene
    c. Upper layer 1 mm^2 polyester
3. 1.6 x 4.8 mm, 1 m^2
    a. Single screen
    b. Polypropylene

Flow rates: current of ocean
Harvest intervals: 7 days
Harvest techniques: Scraped with plexiglass
Productivity rates: production peak at 30 cm, average production of double lagoon screens at 30 cm depth was 13.8 dry g/m^2/day; ocean double screens at 30 cm was 5.0 dry g/m^2/day
Units: Dry g/m^2/day
Source water conditions: Maximum concentration of dissolved nitrogen 0.130 µm
Nutrient uptake: N/A
Dominant species: Green algae: *Enteromorpha chaeotomorphoides*, *Cladophora laetevirens*, *Bryopsis pennata*, *Pesudobryopsis* sp.; Brown algae: *Gifforida* sp., *Sphacelaria* sp., *Spacelaria tribuloides*; Red algae: *Geildium* sp, *Gelidium pusillum, Amphiroa* sp., *Amphiroa fragilissima*, *Jania* sp., *Grallatoria reptans, Antithamnion* sp., *Wragelia penicillata, Callithamnion* sp., *Griffithsia barbata, Griffithsia globuliefera, Ceramium* sp., *Ceramium flaccidum, Centroceras clavulatum, Dasya* sp., *Polysiphonia binneyi, Polysiphonia ferulacea, Polysiphonia sphaerocarpa, Polysiphonia simplex, Herposiphina pectea-veneris, Herposiphonia secunda, Lophosiphonia cirstata, Laurencia* sp.; Blue-green algae: *Calthrix, Nostoc, Anabaena, Oscillatoria, Schizthrix*; Several genera and species of diatoms were also observed
Unique findings: Wide range of production rates resulted from light rather than nutrient differences

Article Title: Purification of industrially contaminated groundwaters using controlled systems
Journal: *Ecological Engineering*
Author: Walter H. Adey, Christopher Luckett, Matthew Smith
Publication Year: 1996
Location of study: New Jersey industrial site
Study timeframe: Phase 1: 70 days on four units; Phase 2: 62 days on two units; Phase 3 28 days on 2 units
Size of system: Four 480 liter, 1 meter squared, glass-walled aquatic microcosms that were controlled by a 0.76-1.25 m^2 ATS experimental systems contained in a greenhouse
Flow rates: 20 l/min
Harvest intervals: N/A
Harvest techniques: N/A
Productivity rates: Mean of 13.94 dry g/m^2/day for phase 1 and 2; Mean of 7.50 dry g/m^2/day for phase 3
Units: dry g/m^2/day
Source water conditions: COD of 1300 mg/l, TSS of 2000 mg/l, inorganic elements including magnesium, iron and manganese, heavy metals, organic compounds including trichloroethylene, vinyl chloride, acetone, and others for a concentration averaging 1071 mg/l.
Nutrient uptake: algal uptake rates: 330 mg/day iron, 55 mg/day manganese, 2360 mg/day calcium, 3.6 mg/day zinc, 8.5 mg/day barium, 4360 mg/day TOC
Dominant species: Green algae: *Enteromorpha clathrata and Cladophora gracilis;* Blue-green filamentous: *Oscillatoria* and *Anabaena*; Several diatom species
Unique findings: Low levels of UV-B applied to the ATS allowed for full drinking water standards to be achieved

Article Title: A controlled stream mesocosm for tertiary treatment of sewage
Journal: Ecological Engineering
Author: Rupert J. Craggs, Walter H. Adey, Benjamin K. Jessup, William J. Oswald
Publication Year: 1996
Location of study: Central Valley of California, USA
Study timeframe: August 30th, 1993- October 24th, 1994
Size of system: 152.4 m x 6.7 m; total surface area 1021 m^2
Flow rates: Varied between 436 and 889 m^3
Harvest intervals: 1 or 2 intervals, dependent on season
Harvest techniques: mechanical
Productivity rates: Mean yearly rate of 35 g dry solids/m^2/day
Units: dry grams/m^2/day
Source water conditions: Effluent from wastewater treatment facility
Nutrient uptake: Mean nitrogen= 1.11± 0.48 g N/ m^2/day; Mean phosphorus= 0.78 ± 0.28 g P/ m^2/day
Dominant species: Cyanobacteria (*Oscillatoria* and unidentified fine filamentous species); diatoms (*Navicula* sp., *Nitzchia* sp., and *Cyclotella* sp.); filamentous species (*Ulothrix* sp., *Cladophora* sp., *Stigeoclonium* sp., *Spyrogyra* sp., *Tribonema* sp., and *Rizoclonium* sp.)
Unique findings: Potential to use a controlled stream mesocosm for nutrient removal from secondary treated wastewater.

Article Title: Nitrogen and phosphorus removal rates using small algal turfs grown with dairy manure
Journal: *Applied Phycology*
Author: C. Pizarro, E. Kebede-Westhead and W. Mulbry
Publication Year: 2002
Location of study: USDA in Beltsville, MD
Study timeframe: N/A
Size of system: Replicate subsections of 0.032 m^2 of turf screens
Flow rates: Placed on a rocking shaker to similar water motion
Harvest intervals: weekly
Harvest techniques: N/A
Productivity rates: 15-20 dry g/m^2
Units: dry g/m^2
Source water conditions: Anaerobically digested dairy manure containing 5 to 80 mg/L NH_4-N and 1 to 20 mg/L PO_4-P over 2 hour incubation period
Nutrient uptake: Nitrogen removal of 0.72 g/m^2/day and phosphorus removal of 0.33 g/m^2/day
Dominant species: *Ulothrix, Oedogonium,* and *Rhizoclonium*
Unique findings: Rates of removal were 5 to 8-fold lower than rate measured on laboratory-scale ATS units using undisturbed turfs

Article Title: Production and nutrient removal by periphyton grown under different loading rates of anaerobically digested flushed dairy manure
Journal: *Journal of Phycology*
Author: Elizabeth Kebede-Westhead, Carolina Pizzarro, Walter W. Mulbry
Publication Year: 2003
Location of study: Anaerobically digested flushed dairy manure from the Dairy Research Unit of the University of Florida in Gainesville was shipped to Maryland to be treated by an ATS
Study timeframe: N/A
Size of system: Three 1-m^2 units
Flow rates: 110 L/min
Harvest intervals: 3-7 days
Harvest techniques: Harvested by removing the screens of the ATS unit and scraping the biomass with a rigid plastic ruler
Productivity rates: Increased mean algal production with loading rates from 7.6±2.71 to 19.1±2.73 dry g/m^2/day
Units: dry g/m^2/day
Source water conditions: Anaerobically digested flushed dairy manure water with loading rates ranging from 0.8-3.7 g total N and 0.12-0.58 g total P/m^2/day
Nutrient uptake: Maximum removal rates of N and P per unit algal biomass were 70 and 13 mg/g dry weight/m^2/day, respectively
Dominant species: filamentous green algae: *Microspora willeana*, *Ulothrix ozonata*, *Rhizoclonium hieroglyphicum*, and *Oedognium* sp.; at higher loading rates the mentioned filamentous green algae species were partially replaced by filamentous cyanobacteria: *Oscillatoria* spp.; and diatoms: *Navicula, Nitzshia,* and *Cyclotella* sp.
Unique findings: Increased algal production was due to increased irradiance level from 60 μmol photons/m^2/second in previous studies to about 270 μmol photons/m^2/second in the present study. The N and P contents were lower at the higher irradiance levels, which may be explained by low irradiance levels promoting slower growth rates and the accumulation of nutrients.

Article Title: Treatment of dairy manure effluent using freshwater algae: Algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers
Journal: Bioresource Technology
Author: Walter Mulbry, Shannon Kondrad, Carolina Pizarro, Elizabeth Kebede-Westhead
Publication Year: 2008
Location of study: Central Maryland
Study timeframe: April 1- December 31 (270 days) from 2003-2006
Size of system: Four 30 m^2 outdoor ATS raceways
Flow rates: 93 l/min
Harvest intervals: 4-12 days
Harvest techniques: Wet/dry vacuums
Productivity rates: At lowest influent loading rate mean productivity value of 2.5 g dry m^2/day; at highest influent loading rate mean productivity value of 25 g dry m^2/day
Units: g dry m^2/day
Source water conditions: Recirculating effluent consisted of freshwater and daily additions or raw or anaerobically digested manure effluent; mean raw manure effluent nutrient vales were 1600 mg/L total nitrogen and 230 mg/L total phosphorous; spring of 2004 effects of CO_2 supplementation on productivity maintaining pH between 7.0-7.5; nutrient loading rates of 0.3-2.5 g total nitrogen and 0.05-0.40 g total phosphorous /m^2/day
Nutrient uptake: Nutrient recovery mean values ranged fro 70%-110% for N and P
Dominant species: Filamentous green algae: *Rhizoclonium hieroglyphicum*, *microspore willeana*, *Ulothrix ozonata, Rhizoclonium hieroglyphicum*, and *Oedogonium* sp.
Unique findings: No significant difference in algal productivity, algal N and P content, or N and P recovery values from raceways with carbon dioxide supplementation compared to values from raceways without supplementation

Article Title: Algal turf scrubber (ATS) floways on the Great Wicomico River, Chesapeake Bay: Productivity, algal community structure, substrate and chemistry
Journal: *Journal of Phycology*
Author: Walter H. Adey, Dail Laughinghouse IV, John B. Miller, Lee-Ann C. Hayek, Jesse G. Thompson, Steven Bertman, Kristin Hampel, and Shanmugam Puvanendran
Publication Year: 2013
Location of study: Great Wicomico River
Study timeframe: 22 months
Size of system: 2 types

1. 0.61 m x 15.2 m (#1)
    a. 1% slope
    b. 2-D screen
2. 0.61 m x 24.4 m (#2)
    a. 2% slope
    b. 3-D screen

Flow rates: 38 l/min
Harvest intervals: Every 7 days in summer and every 14 days in the winter
Harvest techniques: Shop vac
Productivity rates:

1. Floway #1
    a. 15.4 g/m^2/day yearly mean
2. Floway #2
    a. 39.6 g/m^2/day yearly mean
    b. 47.7 g/m^2/day by avoiding high summer harvest temperatures

Units: Dry g/m^2/day
Source water conditions: Moderate nutrient levels and not likely limiting for the production levels
Nutrient uptake: Nutrient composition

1. Floway #1
    a. P: 0.147 ± 0.051 wt%/g x g^{-1} algae
    b. N: 2.125 ± 0.070 wt%/g x g^{-1} algae
2. Floway #2
    a. P: 0.177 ± 0.052 wt%/g x g^{-1} algae
    b. N: 2.438 ± 0.590 wt%/g x g^{-1} algae

Dominant species:

1. Floway #1: 86 algal taxa, seven different phyla, dominated by Ochrophyta (54%), Chlorophyta (24%), Cyanobacteria (22%) and less than 1% of Rhodophyta and Dinophyta
2. Floway #2: 98 algal taxa, seven different phyla dominated by Ochrophyga (68%), Chlorophyta (7%), Cyanobacteria (24%) and less than 1% of Rhodophyta and Dinophyta

Unique findings: A 3-D substrate significantly enhances diatom retention and biomass productivity

Appendix B : Calculations

Calculations based on growth rate of 10 g/m^2/day

B.1 Growth rate calculations:

$$\frac{10g\ dry\ wt.}{m^2 \times day} \times \frac{4046.86\ m^2}{acre} \times \frac{270\ days}{year} = \frac{10926511\ g}{acre \times year}$$

Assuming growing season based on 270 days

B.2 Butanol Production Potential:

$$\frac{15\ gallons\ bu\tan ol}{2000\ lb\ a\lg ae} \times \frac{1\ lb}{453.95\ g} \times \frac{10926511\ g}{acre \times year} = \frac{180.67\ gallons\ bu\tan ol}{acre \times year}$$

Butanol Price calculation
Based on 1 million gallon/year system
Capital Cost: \$5,000,000
Operational Cost: \$3,000,000/year
10 year capital straight-line depreciation period used factory (Anderson, 2009)

Annual Capital Cost Estimation (\$/gallon)

$$D = \frac{C}{10 \times V}$$

C=Capitol Cost
10 year depreciation
V= production volume

$$D = \frac{\$5{,}000{,}000}{10 \times 1{,}000{,}000\ gallon/year} = \$0.50/gallon$$

Annual Operating Cost Estimation

$(\$3{,}000{,}000/yr)/\ (1{,}000{,}000\ gallon/yr) = \$3.00$/gallon

Total Cost= Capital + Operating
\$0.50/gallon + \$3.00/gallon= \$3.50/gallon

Retail price: \$7.00/gallon (ICIS, 2006)
Profit (revenue-cost)= \$7.00/gallon - \$3.50/gallon= \$3.50

$$\frac{180.67\ gallons\ butanol}{acre\ x\ year} \times \frac{\$3.50}{gallon} = \frac{\$632.34}{acre \times year}$$

B.3 Fertilizer Potential:

Nitrogen Removal rates:
Nitrogen content of 3%.

$$\frac{10\ g}{m^2 \times day} \times 0.03\ N = \frac{0.3\ g\ N}{m^2 \times day}$$

$$\frac{0.3\ g\ N}{m^2 \times day} \times \frac{4046.86\ m^2}{acre} \times \frac{270\ days}{year} \times \frac{1\ lb}{453.95\ g} = \frac{722.67\ lb\ N}{acre \times year}$$

Source: (USDA ERS, 2012)
March 2012
Nitrogen:
Urea: \$554/ton
45 % Nitrogen
Calculations based on example from Colorado State Extension Factsheet (Barbarick & Westfall, 2013)

$$2000\ lb\ urea \times 0.45\ (\%\ N) = 900\ lb\ N$$

$$\frac{\$554}{900\ lb\ N} = \$0.62 / lb\ N$$

$$\frac{722.67\ lb\ N}{acre \times year} \times \frac{\$0.62}{lb\ N} = \frac{\$448.06}{acre \times year}$$

Phosphorus
Phosphorus Removal rates:
Phosphorus content of .35%
See above calculations for Nitrogen removal potential for Phosphorus.

$$\frac{84.31\ lb\ P}{acre \times year}$$

Super Phosphate: \$665/ton
45 % Phosphorus
See above Nitrogen calculations for Phosphorus
Price: \$0.74/lb P

$$\frac{84.31\ lb\ P}{acre \times year} \times \frac{\$0.74}{lb\ P} = \frac{\$62.39}{acre \times year}$$

B.4 Dissolved Oxygen Valuation

Aeration price based on MARS Aeration kit from Triple Point Water (Clearwater Habitats, 2013).

Cost per kit: \$3600
Aeration Area: 1 Square Acre, 1 foot deep
Pump Specs: 115V, 4 Amps
Aeration rate: 37 lb O_2/day; 9,990 O_2/year (based on 270 day growing season)
Kits needed: 1 Kit, 2 pumps
Capital cost: \$3600
Operational cost/year (based on 9 month operation, running 24 hrs/day)
10 year capital depreciation period

Annual Capital Cost Estimation (\$/lb O_2)

$$D = \frac{C}{10 \times V}$$

C=Capitol Cost
10 year depreciation
V= production volume

$$D = \frac{\$3600}{10 \times 9990\ lb\ O_2/year} = \$0.0360/lb\ O_2$$

Annual Operational Costs
Electricity Cost per pump
$4\ Amps \times 115\ Volts = 460\ Watts\ or\ .460\ kW$
$.460\ kW \times 6480\ hrs \times \$0.1268/kWh\ = \$377.97/pump$
Electricity- \$755.93/yr
Maintenance- 15% Annual Capital= \$54.00
Total Operations and Maintenance per year=\$809.93
$(\$809.93/yr)/(\ 9990\ lb\ O_2/yr) = \$0.081/lb\ O_2$
Total Annual Cost= Capital + Operating
Total Annual Cost= \$0.036/lb O_2 + $\$0.081/lb\ O_2$=$\$0.117/lb\ O_2$

*Calculations for 20 g/m^2/day and 30 g/m^2/day based on above calculations

Aeration price based on 4400AF Aeration kit from Kasco Marine, Inc. (Kasco Marine, 2013).

Cost per kit: \$1,310
Aeration Area: 1 Square Acre, 1 foot deep
Pump Specs: 120V, 11.3 Amps, 1 HP
Aeration rate: 3 lb O_2/HP/hr; 9,720 O_2/year (based on 270 day growing season)
Kits needed: 1 Kit, 1 pump
Capital cost: \$1,310
Operational cost/year (based on 9 month operation, running 24 hrs/day)
10 year capital depreciation period

Annual Capital Cost Estimation (\$/lb O_2)

$$D = \frac{C}{10 \times V}$$

C=Capitol Cost
10 year depreciation
V= production volume

$$D = \frac{\$1310}{10 \times 9720\ lb\ O_2/year} = \$0.0135/lb\ O_2$$

Annual Operational Costs
Electricity Cost per pump
$11.3\ Amps \times 120\ Volts \times .95\ efficiency = 1288\ Watts\ or\ 1.288 kW$
$1.288\ kW \times 6480\ hrs \times \$0.1268/kWh\ = \$1{,}058.47/pump$
Electricity- $1,058.47/yr
Maintenance- 15% Annual Capital= $19.65
Total Operations and Maintenance per year=$1,078.12
$(\$1{,}078.12/yr)/(\ 9720\ lb\ O_2/yr) = \$0.111/lb\ O_2$
Total Annual Cost= Capital + Operating
Total Annual Cost= \$0.0135/lb O_2 + $\$0.111/lb\ O_2$=$\$0.124/lb\ O_2$

Seasonal average of 5.0 g O_2/m^2/day for average growth rate of 14 dry g/m^2/day algae (Kangas et al., 2009).
Assumed linear relationship between growth rate and O_2 production

$$\frac{14\ g\ a\lg ae / m^2 / day}{5\ g\ O_2 / m^2 / day} = \frac{10\ g\ a\lg ae / m^2 / day}{x\ g\ O_2 / m^2 / day}$$

For a 10 dry g/m^2/day, expect an oxygen production rate of 3.57 g O_2/m^2/day
Average cost of O_2/lb$(\$0.117/lb\ O_2\ + \$0.124/lb\ O_2)/2 = \$0.12/lb\ O_2$

$$\frac{3.57\ g\ O_2}{m^2 \times day} \times \frac{4046.86\ m^2}{acre} \times \frac{270\ days}{year} \times \frac{1\ lb}{453.95\ g} \times \frac{\$0.12}{lb\ O_2} = \frac{\$1{,}032}{acre\ x\ year}$$

B.5 Hydroelectric Dam Opportunity Cost

Conowingo dam is 94 ft tall or 28.7 m, constant for gravity is 9.8 m/s^2, diverting 1968.5 gpm (Exelon, 2013).

$$Potential\ Energy = mass \times gravity \times height$$

$$m = \frac{1968.5\ gallon}{minute} \times \frac{3.785\ liters}{1\ gallon} \times \frac{1\ minute}{60\ seconds} = \frac{124.2\ liters}{second}$$

$$\frac{124.2\ liters}{second} \times \frac{1\ kg\ water}{1\ liter} = \frac{124.2\ kg}{second}$$

$$PE = \frac{124.2\ kg}{second} \times \frac{9.8m}{s^2} \times 28.7m = 34871\ Watts$$

Assuming 90% conversion efficiency (USBR, 2005).

$$34871\ Watts \times 90\% \times \frac{1\ kW}{1000\ Watts} = 31.38\ kW$$

$$31.38\ kW \times \frac{24\ hours}{day} \times \frac{365.25\ days}{year} = 275{,}113\ kWh/year$$

Assuming \$0.04/kWh production cost (C2ES, 2009).

$$\frac{\$0.04}{kWh} \times \frac{83854\ kWh}{year} = \$11{,}005\ production\ cost$$

Assuming sell price of \$0.1268

$$\frac{\$0.1268}{kWh} \times \frac{83854\ kWh}{year} = \$34{,}884\ annual\ revenue$$

$$Profit = \$34{,}884 - \$11{,}005 = \$23{,}880$$

Appendix C : Data

C.1 Pennsylvania Nutrient Trading Data

Data adapted from Pennsylvania Infrastructure Investment Authority (Pennvest, 2013).

Table C.1 Pennsylvania nutrient credit trades to date

Year	Trades	N($/lb)	N (lb)	P ($/lb)	P (lb)
2013	1	2.98	10,000		
2013	1	3.12	5,000		
2012	1	1.22	5123		
2012	1			1.45	181
2012	1	3.18	2000		
2012	1	3.18	4000		
2012	1	3.18	6000		
2012	1			2.25	400
2012	1	3.17	16650		
2012	1	3.23	3000		
2012	1	3.23	2000		
2012	1	3.23	3000		
2012	1			2.6	200
2012	1	3.75	20000		
2012	1	3.54	3000		
2012	1	4	55224		
2012	1	2.98	30000		
2012	1	2.98	30000		
2012	1	2.98	30000		
2011	1	3.1	20859		
2011	1			4.73	700
2010	1	2.75	41000		
2010	1	3.04	21000		
2009	1	10	635	5	48
2009	1	15	8	10	11
2008	1	5	20000		
2008	1			4.5	21.5
2008	1	15	546	10	53
2007	1	3.81	11718		
2007	1	9	1592	4	73
2006	1	9	223	4	3
total	31	125.65	342578	48.53	1691
average		4.83	13176	4.85	169
median		3.21	5562	4.25	63
min		1.22	8	1.45	3
max		15	55224	10	700

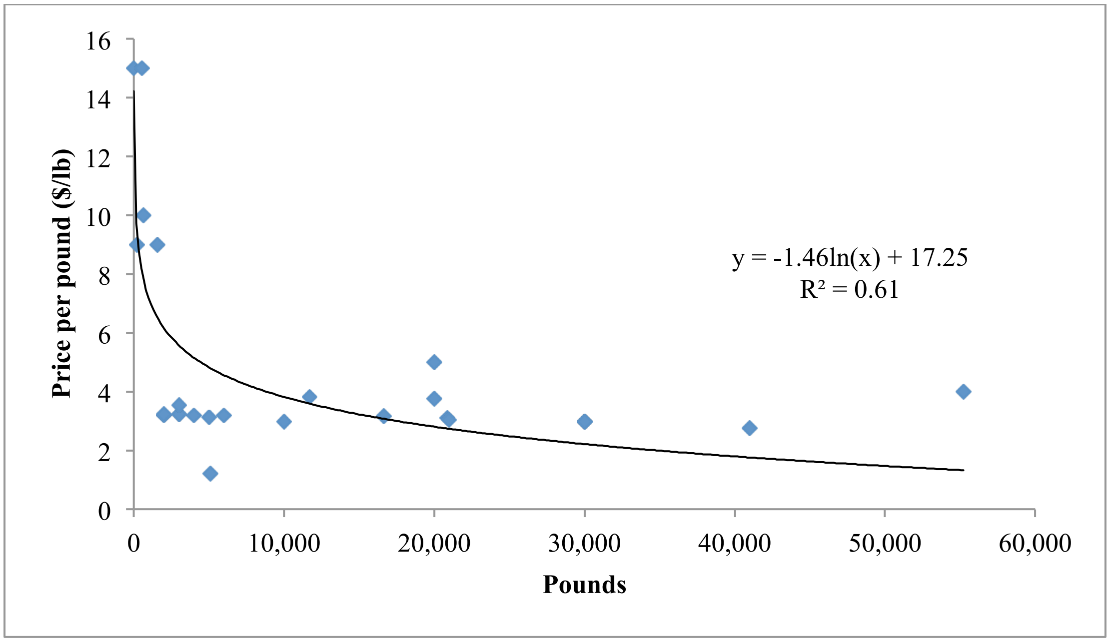

Figure C.1 Demand function of nitrogen credits

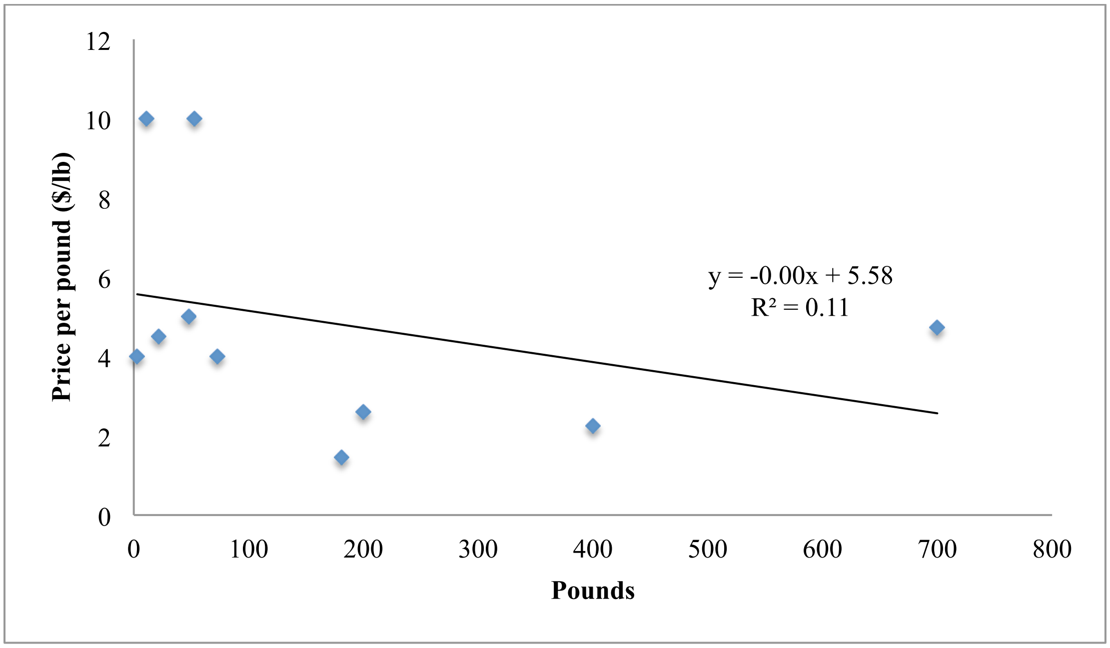

Figure C.2 Demand function of phosphorus credits

Demand functions were created for the Pennsylvania trading markets shown in Figure C.1 and Figure C.2. These demand curves were not utilized due to the low R-squared value based owed to the small number of trades that have been made thus far.

C.2 Agricultural Data

Table C.2 Data used to find the cost and revenue from corn grain

Year	Value (corn, grain- price received for Maryland \$/BU)[1]	Yield (corn, grain BU/acre) Upper Eastern Shore[2]	Revenue (\$/acre)[3]	Cost (southern seaboard)[4]	Cost – land[5]	Profit (\$/acre)[6]	Profit (\$/acre) - land cost[7]
2011	6.70	106.30	712.21	605.09	532.98	107.12	179.23
2010	6.05	119.30	721.77	538.74	471.86	183.03	249.91
2009	3.71	148.00	549.08	511.80	437.55	37.28	111.53
2008	4.42	119.00	525.98	495.86	431.36	30.12	94.62
2007	4.64	105.90	491.38	412.50	354.88	78.88	136.50
2006	3.41	152.10	518.66	380.91	327.11	137.75	191.55
2005	2.19	141.80	310.54	357.90	303.21	-47.36	7.33
2004	2.17	155.90	338.30	363.46	310.08	-25.16	28.22
2003	2.83	123.40	349.22	343.76	292.44	5.46	56.78
2002	2.85	71.10	202.64	328.42	277.94	-125.79	-75.31
Average	4.23	123.20	506.22	449.10	401.24	57.11	98.04

Notes:

1. USDA NASS data for the price received for corn grain in Maryland (NASS, 2013).
2. USDA NASS data for the yield of corn in the Upper Eastern Shore (NASS, 2013).
3. Revenue was calculated as the price received multiplied by the yield.
4. Cost per acre of production for the South Seaboard Region (ERS, 2011).
5. The cost per acre minus the land cost. Land cost was available in the previous cost data.
6. Profit per acre was calculated as the cost minus revenue.
7. Profit per acre not including land cost was calculated cost as not including land minus revenue.

C.3 Conowingo Dam Data

Data taken from USGS historical data from the National Water Information System monitoring site at Conowingo Dam (USGS, 2013)

Table C.3 Average decadal discharge from Conowingo Dam

Year	Mean discharge cubic feet/second	Mean discharge cubic feet/minute)	Mean discharge gallon/min
2001	23560	1413600	10574506
2002	33390	2003400	14986535
2003	60680	3640800	27235189
2004	65540	3932400	29416517
2005	45810	2748600	20561041
2006	47080	2824800	21131059
2007	35620	2137200	15987433
2008	39740	2384400	17836625
2009	34090	2045400	15300718
2010	35530	2131800	15947038
Average	42,104	2,526,240	18,897,666

C.4 List of Lawn Care Companies

Well Kept Lawns, LLC
301-442-7089
Cost to cut 1 acre of lawn: $65
Time: 1 hour

R & M Landscaping
301-678-8132
Cost to cut 1 acre of lawn: $50
Time: 1 hour

Millennium Landscaping
301-593-2087
Cost to cute 1 acre of lawn: $60
Time: 1 hour

Glossary

Algal turf scrubber (ATS)- Ecologically engineered wastewater treatment technology composed of algae attached to a raceway.

Capital charge- The annual payment or annuity owed on an investment each year, taking into account the interest rate and payment period.

Capital cost- Fixed, one-time incurred cost needed to construct the project.

Benefit/cost ratio- Cash inflows (revenue) divided by cash outflows (expenses).

Break-even- Price at which revenue (price x quantity) and total costs are equal.

Economic analysis- Analysis that precludes taxes and subsidies and accounts for opportunity costs.

Financial analysis- Analysis that includes taxes and subsidies and opportunity costs are calculated by using local farm-gate prices

Net present value- Sum of discounting future cash flows to present value by means of a discount rate.

Operations and maintenance cost- Annual reoccurring costs needed in order to operate the system.

Opportunity cost- Value of the next best option, which is forgone to pursue a certain option.

Replacement cost- Amount an entity would pay in order to replace the good or service currently rendered; not always a market value.

Total annual cost- Cost that includes yearly capital cost annuity (capital charge) in addition to yearly operations and maintenance cost

Total maximum daily load (TMDL)- Pollution diet established in response to clean water act that regulates how much nitrogen, phosphorous, and sediment may be released in a waterway.

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