Macroalgae Farming: A Strategy for Economic Growth and Nutrient Mitigation

By

Alyson Myers

Dr. James Heffernan, Advisor
Dr. Jesko von Windheim, Adviser

Masters project submitted in partial fulfillment of the Requirements for the Master of Environmental Management degree in The Nicholas School of the Environment of Duke University
Macroalgae Farming: A Strategy for Economic Growth and Nutrient Mitigation

Executive Summary
Alyson Myers
April 2015
Email: alysonmyers1@gmail.com

The estuarine system of the Chesapeake Bay has experienced a “tragedy of the commons” through nutrient loading, degraded oxygen levels for marine life and a decrease in system function for the Bay watersheds’ inhabitants. The US government has called for the restoration of the Chesapeake Bay. This paper proposes an aquaculture practice that may assist that goal, macroalgae (seaweed) farming, which can convert excess nutrients to biomass for harvest and conversion to economic goods. While this practice cannot fix our nutrient problem—nutrients should be stopped at their sources, like farm fields, hardscape, power plants and automobile tailpipes—it can quantitatively reduce nutrients in the waterway.

This paper examines macroalgae farming for the practice’s production capability per square meter (tissue contains 3-5% Nitrogen, .01% Phosphorus, and 30% Carbon) in the waterway and as a method to meet regulatory goals of the Environmental Protection Agency (EPA). EPA calls for the “development of non-traditional Best Management Practices like algal scrubbers.” Similarly, NOAA refers to Ecosystem-based Management as a national priority and the “potential for aquaculture of shellfish and seaweed (algae) to mitigate impacts of climate change (e.g., sequestering carbon, bioextraction).” The farming process extracts nutrients through harvest and is sustainable by growing a biomass in waterways rather than relying, like agriculture, on fresh water (irrigation currently uses 60% of global fresh water which is not sustainable). Further, the practice does not use arable land, which is increasingly under pressure from growing populations and energy crops.

Macroalgae farming is an established 6 billion dollar industry worldwide. The biggest use is human consumption followed by markets such as cosmetics, aquaculture feed, agar and carrageenan, iodine, fertilizers and more. The global production of farmed seaweed doubled between 2000 and 2012. This paper recommends several niche markets that can make the enterprise profitable in the US. Nutrient trading also provides a revenue stream with current prices for nitrogen removal at $8/lb to $20/lb. It compares this price to other methods of nitrogen removal including Wastewater Treatment upgrades and agricultural practices (cover crops, etc). Production costs of macroalgae biomass, according to the literature and this author in the field, vary between $6.60/lb and $42/lb for nitrogen removal. Nutrient trading can probably not cover the cost of the practice, and therefore we must look to the private sector to monetize the biomass. The government could decide to engage in a Public-Private Partnership
to fund the strategy initially until the private sector undertakes the business enterprise with no further funding necessary.

The paper explores one scenario under which a Bay state, Virginia, may mitigate its atmospheric nutrient load (1%, or 578,001 pounds of Nitrogen), for which there are no Best Management Practices, by dedicating 3.8 square miles to the enterprise. The practice would result in 107,037,222 lbs of wet biomass available for use by markets.

The government spends approximately $.5 billion/yr to restore the Chesapeake Bay with only modest success. A dedication of 5%, or $25,000,000, would initiate the enterprise and, within two to three years could possibly be self-sustaining, with an increase in jobs and sustainable biomass for the economy. Such a project would provide a model for Restoration of the Commons, or restorative commerce, and could be implemented in eutrophic waterways around the globe.

Conclusions:

1. Macroalgae farming provides a way to harvest nutrients in eutrophic waterways
2. Atmospheric deposition has no Best Management Practice for mitigation
3. Macroalgae farming can mitigate, as an example, 1% of Virginia’s TMDL (atmospheric) through dedication of 3.8 sq mi of Chesapeake Bay
4. The harvested biomass can provide material for markets, like cosmetics, consumer fertilizer, and specialty papers.
5. Macroalgae farming cannot “fix” the nutrient problem of eutrophic waterways (too much marine space would be required), but it can positively impact the problem
6. Macroalgae outcompete microalgae, the cause of dead zones, and farming operations should be located close to nutrient hotspots, but beyond Submerged Aquatic Vegetation (which provides oxygen)
7. Biomass harvest must be timed to take advantage of oxygen production and avoid decomposition
8. A macroalgae farm can potentially lead to a profitable business venture and a productive public-private partnership.
# Table of Contents

Introduction .................................................................................................................................................. 5

Background on Eutrophication .................................................................................................................... 6

The Cause of Eutrophication ........................................................................................................................ 6
  Dead Zones .............................................................................................................................................. 8

Regulatory Background: TMDL’s and Best Management Practices in Chesapeake Bay ......................... 10

A Potential Solution to Eutrophication ........................................................................................................ 12

Carbon and Ocean Acidification (OA) ......................................................................................................... 20

Physiology .................................................................................................................................................. 21

Competition: Macro vs Micro ...................................................................................................................... 23

Mass Cultivation ......................................................................................................................................... 27

Markets and Uses ......................................................................................................................................... 29
  Organic Fertilizer Market (consumer market) ......................................................................................... 33
  Feed ....................................................................................................................................................... 35
  Cosmetics ............................................................................................................................................... 37
  Food ....................................................................................................................................................... 37
  Biorefinery .............................................................................................................................................. 37

Conclusion .................................................................................................................................................. 39

Appendix ..................................................................................................................................................... 45

Appendix A: Macroalgae in Waterways ........................................................................................................ 45

Appendix B: Green Macroalgae Under Microscope ..................................................................................... 48

Appendix C: Macroalgae Analysis for Paper Use ......................................................................................... 49

Appendix D: Aquaculture Systems .............................................................................................................. 51

Appendix E: Seeding and Harvesting (FAO) ................................................................................................ 52

Appendix F: Biomass Removal Analysis ..................................................................................................... 53
Introduction

The estuarine system of the Chesapeake Bay has experienced a “tragedy of the commons” through nutrient loading, degraded oxygen levels for marine life and a decrease in system function for the Bay watersheds’ inhabitants. As a society, we have called for the restoration of the Chesapeake Bay. This paper proposes an aquaculture practice that may assist that goal, macroalgae (seaweed) farming, which can convert excess nutrients to biomass for harvest and conversion to economic goods. While this practice cannot fix our broader nutrient problem--nutrients should be stopped at their sources like farm fields, wastewater treatment plants and hardscape--it can quantitatively reduce nutrients in the waterway. Regulatory efforts highlight the need to decrease the human impact of nutrients on our waterways. Instead of accepting the tragedy of the commons, it may be beneficial to think about the Restoration of the Commons. Macroalgae farming may assist the eutrophic, aquatic ecosystem by mitigating excess Nitrogen, Phosphorus and Carbon. NOAA refers to Ecosystem-based Management as a national priority and “potential for aquaculture of shellfish and seaweed (algae) to mitigate impacts of climate change (e.g., sequestering carbon, bioextraction).”¹ While this practice is just one method to complement land-based policy, it is hoped that society will continue to propose new practices until the aquatic system is oxygenated, resilient and once more biodiverse.

Macroalgae farming, through production of a renewable biomass for the economy, offsets the cost of the environmental service. The process is sustainable and does not use arable land, already under pressure from energy crops, or fresh water which is under pressure from land-based agriculture which uses 60% of fresh water for irrigation,² a practice that is not sustainable. Macroalgae farming is an established 6 billion dollar industry worldwide. While it is rarely practiced in the US, it may offer both economic and environmental benefits.

¹ NOAA email: NOAA Fisheries Draft Climate Science, April 2015.
Background on Eutrophication

Waterways provide critical economic and social benefits to society. Coastal ecosystems, however, are threatened by nutrient pollution, overfishing, loss of biodiversity and increasing CO2. Fifty-five percent (55%) of US waterways are in poor biological condition, according to the US Environmental Protection Agency (EPA), which is charged with protecting our waterways under the Clean Water Act (1972). The problem is not limited to the US, however; 762 coastal areas worldwide are impacted by eutrophication (excess nutrients) and/or hypoxia (low oxygen). The complex problem of excess nutrients’ link to hypoxia and degradation of aquatic habitats encourages a search for additional solutions beyond current regulation. EPA, in fact, recommends that the Chesapeake Bay states develop guidance and methodologies for the use of “non-traditional Best Management Practices (BMPs) such as algal scrubbers, oyster aquaculture, etc.” This project examines one of these novel techniques for nutrient reductions in the eutrophic waterway of the Chesapeake Bay. While existing policy encourages oyster replenishment and oyster aquaculture for their filtration services, other potential biological solutions exist. Aquatic plants, known as macroalgae, or seaweed, absorb nutrients at the approximate rate of Nitrogen 3.5%, Phosphorus 0.1% and Carbon 30%.

Macroalgae farming exists today with an established market. The practice may be examined as a means of harvesting nutrients from the Bay as a complement to land-based measures. The harvest of macroalgae can possibly reduce hypoxia, depending on the scale of the farming operation, and, if so, positively impact abundance and biodiversity of marine organisms. Society can use the renewable biomass to offset the cost of the environmental service.

The Cause of Eutrophication

Nutrient runoff and discharge, particularly nitrogen and phosphorus, from farms, pavement and atmospheric sources has placed the Chesapeake Bay on the EPA’s List of Impaired Waters. These sources represent about 60% of the pollution

---

3 40% of the nation’s rivers and streams have excessive levels of phosphorus, 27% have high levels of nitrogen; from 2004 to 2007, 7% fewer stream miles are in good biological condition. EPA. Draft National Rivers and Streams Assessment 2008-2009: A Collaborative Survey, delivered by webcast. Critics claim that EPA does not sufficiently connect biological condition to a nutrient cause.
and are difficult to monitor and regulate. Excess nutrients, like nitrogen, phosphorus and carbon, fuel algal blooms which eventually die and cause low oxygen zones harmful to marine life, commonly called “dead zones.”

According to Boesch et al, “it is becoming increasingly clear that nutrients emanating from nonpoint sources, be they from agriculture, atmospheric deposition, or urban runoff, cannot be adequately controlled at their sources. Nutrient reduction must also be addressed by increasing the capacity and effectiveness of nutrient sinks...”

“In tidal tributaries dominated by nonpoint sources,” according to Boesch et al, “nutrient concentrations have generally not declined and in some areas, nutrient concentrations actually increased over a 12-year period.” Further, “phosphorus levels increased in several areas, particularly in the Potomac and James Rivers and on Maryland’s Eastern Shore. The drop in the phosphorus score emphasizes that farmers need tools to reduce manure-related phosphorus pollution running off fields and degrading local waterways.”

As global context, the volume of agricultural fertilizer use has increased dramatically, from global production of less than 10 million metric tons of N in 1950 to approximately 80 million metric tons in 1990, and it will likely exceed 135 metric tons by 2030. As nutrients flow off farms and other surfaces, the supply rate of N and P significantly impacts the growth of algae and vascular plants in aquatic ecosystems.

Another important source of nitrogen is atmospheric deposition from the burning of fossil fuels for electricity generation and automobiles. This source is difficult to quantify by EPA and hard to control as nitrogen can travel long distances and is delivered directly to the surface waters of the Bay. EPA estimates that this source provides 10%-40% of the Bay’s nitrogen. Boesch et al uses the figure of “about one fourth” or 25%.

When these plants die eventually, bacterial decomposition creates low oxygen areas harmful to marine life, termed hypoxia, and commonly called “dead zones.”

---

7 Boesch et al. Chesapeake Bay Eutrophication.
8 Boesch et al. Chesapeake Bay Eutrophication
9 Ibid.
10 Vitousek et al., 1997b.
States, according to CBF, must implement required pollution reduction strategies, or EPA must impose sanctions.\textsuperscript{13} Billions have been spent on this goal (an estimated $15.5 billion to date with just under .5 billion/year federally,\textsuperscript{14} and this does not include non-profit or private money).

**Dead Zones**

Nutrients affect the system’s critical function—oxygen levels—which degrade the system causing a loss of biodiversity and decreased resiliency. According to Norm Christensen, “the web of interactions among microbes, plants and animals provides a complex conduit for the flows of nutrients and energy, it makes sense that the greater the diversity of species, the more complex the web and the more stable the ecosystem. The loss of species results in fewer alternative pathways for those flows and greater vulnerability to disturbance.”\textsuperscript{15} The vulnerable system has less ability to accommodate pressure. Eutrophication is one pressure on the system. CO2 absorption is another which causes a decrease in pH and negative impact on shelled organisms essential to the food web. The system has less and less ability to defend itself.

Most dead zones are caused by microalgal blooms. The 2013 Chesapeake Bay “dead zone” was 22.1 percent of the volume of the Bay. Oxygen levels less than 2 milligrams of oxygen per liter of water (mg/L) cannot support fish, crabs or oysters. The oxygen level goal is 5 milligram/liter. Fish and other organisms become stressed and begin to avoid a location at 4 milligrams/liter. Dead zones eliminate habitat during a time when most organisms’ metabolisms run faster (spawning and fast growth).

The Chesapeake Bay, like the Gulf, is expected to warm 2.7 degrees Celsius by 2100, which will exacerbate the problem, according to a study by the Smithsonian Institution and lead author, Andrew Altieri, and co-author Dr. Keryn Gedan. “Warmer water holds less oxygen, at a time when marine life’s metabolism increases.” There will also be longer summers, contributing to an increase in algae.\textsuperscript{16} Professor Don Boesch concurs that global warming will make the

\textsuperscript{13} Ibid.
\textsuperscript{14} Personal communication from Tom Wenz, The Chesapeake Bay Program Office, indicates 2014 federal funding is $461,000,000. For previous years, see: http://executiveorder.chesapeakebay.net/file.axd?file=2014%2f7%2fChes_Bay_FY14AP_FY13PR_2014-07-25.pdf
\textsuperscript{15} Personal communication, February 19, 2015.
problem of dead zones worse. This study and Dr. Boesch’s comment support the argument that we must act more quickly to reduce nutrient loads and dead zones.

The current strategy represents a continuation to “decrease loading through upgrades to wastewater treatment plants, additional stormwater management controls, implementation of agriculture practices like cover crops, and reductions in atmospheric deposition from cars and trucks that should result in an overall decline in the size of the Chesapeake Bay’s “Dead Zone” to minimal levels.”

Decreased biodiversity and decreased populations in the aquatic system mean there are fewer organisms to consume microalgae, which is the current cause of dead zones in the Chesapeake Bay. Algae also cause shading of underwater grasses that provide oxygen to the system. Feedback loops continue to degrade the system. The goal of trying to restore a system’s function provides positive impact throughout the food web building strength and resiliency.

Figure 1. Dissolved Oxygen (June – September, 2009-2011)

---

Regulatory Background: TMDL’s and Best Management Practices in Chesapeake Bay

The largest estuarine system in the US is the Chesapeake Bay\(^{18}\) with 12 distinct hypoxic or eutrophic zones, according to the World Resource Institute (WRI).\(^{19}\) President Obama issued an Executive Order (EO) in May 2009 calling on the Federal government, under the leadership of the Environmental Protection Agency (EPA), and including other departments such as Agriculture, to restore the Bay. The EO called for “the next generation of tools and actions to restore water quality”\(^{20}\) under the “swimmable, fishable” provisions of the Clean Water Act. EPA regulates point sources of these nutrients, such as wastewater treatment plants, but nonpoint sources, like farm fertilizers and manure, contribute about


\(^{20}\) Executive Order, Chesapeake Bay Protection and Restoration, Sec. 202.
60 percent of the nitrogen that reaches the Bay. The largest single source is agricultural runoff, according to EPA.\(^{21}\)

The six Bay states and DC issued a plan to meet EPA’s TMDL limits by 2025. The limits plus the states’ plans comprise the Clean Water Blueprint for the Chesapeake and its rivers and streams.\(^{22}\) Progress must be reported every two (2) years, so there is pressure to reduce loads, independent of population increase.

Regulators have focused on point sources, like wastewater treatment plants, but the Blueprint also outlines five primary conservation practices or Best Management Practices (BMP’s) on land:

* Streamside Buffers (35’ wide, filter excess fertilizer before it reaches streams)
* Streamside Fencing
* Nutrient Management Plans (NMPs)
* Continuous No-Till
* Cover Crops

The volume of the “dead zone” in the summer of 2013 was 22.1% of the Bay volume. The dead zone in the summer of 2014 was the eighth worst since recording began in the 1980’s, according to Maryland’s DNR.\(^{23}\) The U.S. Geological Survey estimated that 44,000 metric tons of nitrogen entered the bay from the Susquehanna and Potomac rivers between January and May of 2014, which is higher than the 36,600 metric tons delivered to the Bay during the same period in 2013.\(^{24}\) This is a substantial addition rather than reduction.

Billions have been spent to improve the state of the bay (approximately $15.5 billion to date with just under .5 billion/year federally.\(^{25}\) To date, the Chesapeake Bay has a consistent grade of D+ across many factors (including forested buffers,


\(^{23}\) Warrick, J. Washington Post. Large “Dead Zone” signals more problems for Chesapeake Bay. August 31, 2014.

\(^{24}\) Joint News Release NOAA and USGS. June 24, 2014.

dissolved oxygen, water clarity, etc)\textsuperscript{26} indicating a failure to meet the goals of the Federal government.\textsuperscript{27}

**A Potential Solution to Eutrophication**

Macroalgae Farming can be considered a BMP in the waterway. Macroalgae farming for eutrophic waterways combines a current commercial practice (see “Markets and Uses” below) with a known characteristic of bio-extraction\textsuperscript{28} of nutrients. Upon harvest of biomass, nutrients are removed from surrounding waters, and a renewable biomass is available for monetization to offset the cost of the environmental practice.

The larger forms of algae, called macroalgae are capable of growing, like oysters, within aquaculture systems designed for growth and harvest (see Appendix A). Oysters provide an ecosystem service through filtration of phytoplankton and detritus.\textsuperscript{29} Macroalgae similarly take up nutrients (Nitrogen, Phosphorus and Carbon) directly within the aquatic system and can, through harvest, provide a means of removal. In addition to taking up nutrients (in the ratio of approximately N: 3.5%, P: 0.1% and C: 30%), the harvested material can be used for a variety of purposes, including feed, food, fuel, soil amendments, and more.\textsuperscript{30}

To assess the viability of a nutrient extraction aquaculture system, we first look at nutrient uptake and to what extent biomass removal can assist the waterway and EPA’s goals of “fishable, swimmable” under the Clean Water Act. We then examine the value of that biomass to society to pay for the process.

Clearly, a new practice is not meant to replace government regulation but rather to address nutrients that are already resident in the aquatic system or that continue to enter the aquatic system despite regulation. Even regulated sources, like wastewater treatment, experience increasing costs as effluent reaches N and P of zero making absolute reductions impractical\textsuperscript{31} so even regulated sources add


\textsuperscript{28} Integrated Multi-Trophic Aquaculture (IMTA) refers to growing macroalgae to “extract” nutrients from aquaculture activity so as not to negatively impact waterways.

\textsuperscript{29} Bricker et al. 2014. From Headwaters to Coast: Influence of Human Activities on Water Quality of the Potomac River.

\textsuperscript{30} UN Food and Agriculture Organization. 2003. \url{ftp://ftp.fao.org/docrep/fao/006/y4765e/y4765e00.pdf}

\textsuperscript{31} Bricker, S
to overall system loading. Additionally, sources, like atmospheric deposition from electric power plants and automobiles, will only diminish with political determination and significant investment, and we need to address the nutrient problem (and hypoxia) as soon as possible to maintain biodiversity in the Bay. While government encourages Best Management Practices (BMP’s) for non-point sources (such as riparian buffers, nutrient management plans for farmers, etc), these are at best partially successful (up to 60%) for a number of reasons.\textsuperscript{32} An instream or in-the-water strategy can provide a nutrient safety net.

The potential environmental benefits of a macroalgae aquaculture system are to:

1. Mitigate a portion of excess nutrients in eutrophic waterways,
2. Assist oxygen levels for marine life, and
3. Increase biodiversity

These in turn may predictably increase resiliency of the aquatic system (through biodiversity and multiple pathways) and assist economic productivity. According to a 2009 study using a eutrophication model, “seaweed farms and aquaculture of shellfish present opportunities to potentially manage nutrients and alleviate hypoxia in eutrophicated waters...\textsuperscript{33}” Also, Virginia’s Marine Resource Commission, Chief of Habitat Management Division, Tony Watkinson discussed harvested macroalgae as a superior nutrient removal method to harvested clams.\textsuperscript{34}

Challenges of the plan include use of marine space that may interrupt navigation or interrupt homeowners’ views. Also, nutrient absorption rates of the biomass may require more space to significantly impact Bay nutrient levels than society/the government find desirable. An examination of the potential space available, according to VA’s Chief of Habitat Management Tony Watkinson shows that marine space is currently set aside for shellfish aquaculture in Virginia as follows: 100,000 acres for private aquaculture leases, 300,000 acres for public use and approximately 1,000,000 additional acres, or 1562 square miles, are available for lease.\textsuperscript{35} Evidence suggests that macroalgae farming can be deployed in some

\textsuperscript{32} Farmers are reluctant to use productive land for environmental purposes. Big storm events render these less effective in filtering nutrients.


\textsuperscript{34} Personal communication, with Tony Watkinson, VMRC Chief Habitat Management Division April 21, 2015.

\textsuperscript{35} Ibid.
of this available acreage to reduce nutrient loads and complement land-based strategies. A benefit of the technique is that its impact can be measured fairly accurately so that the government can assess nutrient reduction efficiency and benefit relative to costs. Tissue content of N, P and C can be measured through a given quantity of biomass.

Deployment of macroalgae farming as a nutrient reduction method requires initial funding until markets for biomass can be developed. At current funding levels for Chesapeake Bay restoration (approximately $.5 billion/yr), initial funding of 10% ($50,000,000) or 5% (25,000,000) could spur innovative techniques, like macroalgae farming, that would in the words of the White House Executive Order “develop focused and coordinated habitat and research activities that protect and restore living resources and water quality of the Chesapeake Bay...”36 A demonstration project of macroalgae farming could be one project tested under research provisions of the President’s Executive Order to establish new and effective Best Management Practices.

The six Bay states and DC issued a plan to meet EPA’s TMDL limits by 2025. The limits plus the states’ plans comprise the Clean Water Blueprint for the Chesapeake and its rivers and streams.37 Progress must be reported every two (2) years, so there is constant pressure to reduce loads, independent of population increase.

Regulators have focused on point sources, like wastewater treatment plants, but the Blueprint also outlines five primary conservation practices or Best Management Practices (BMP’s) on land:

* Streamside Buffers (35’ wide, filter excess fertilizer before it reaches streams)

* Streamside Fencing

* Nutrient Management Plans (NMPs)

* Continuous No-Till

* Cover Crops

Proponents claim that these practices reduce the most amounts of nitrogen and phosphorus per dollar spent. Some claim that these five practices can reduce nutrient pollution to the Bay as much as 60%, but when one examines the efficiency rates, the measurements show that, for example, riparian forest buffers on agricultural lands have efficiency of nitrogen reduction, depending on location, of 44-60%, for phosphorus reduction efficiency of 45-60% and sediment efficiency of 45-60%. The balance, then, is passing through buffers to streams and the Bay. Big storm events undermine these efficiencies through increased speed and volume of water moving fast through the buffer. As climate changes, the increase in these events indicate an increase in nutrients delivered to the Bay with worsening hypoxia.

Figure 2. BMP Efficiencies

<table>
<thead>
<tr>
<th>BMP</th>
<th>Description</th>
<th>Nitrogen Efficiency</th>
<th>Phosphorus Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riparian Forest Buffer</td>
<td>Linear woods near stream</td>
<td>44-70%</td>
<td>45-70%</td>
</tr>
<tr>
<td>Stream Fencing</td>
<td>Fence to exclude cows</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Poultry Waste Man’t Sys</td>
<td>Manage Poultry Waste</td>
<td>14%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Source: http://files.dep.state.pa.us/Water/BPNPSM/NutrientTrading/BMPDescriptions.pdf

Riparian buffers are not perfect remedies for nutrient flows. They are “effective sinks only as long as the plants are actively accumulating biomass (biomass production more than litter-fall).”

Proposals to “map headwater streams, establish concentrated flow paths and ecosystem and vegetative species may improve efficiencies,” but these are not yet implemented, nor are they a guarantee of success. Further, they do not capture atmospheric deposition. A determination of the quantity and location of

---

nutrient and sediment sources can, however, maximize the impact\(^\text{41}\) of both land-based BMP’s and the proposed in-the-water technique of macroalgae farming.

Moreover, some BMP’s limit agricultural productivity, creating opposition from farmers, the Farm Bureau, and attorneys general from 21 states who fear the federal government will make similar demands in their jurisdictions like the Gulf.\(^\text{42}\)

Additionally, their efficiencies vary. Plants in streamside buffers can absorb nutrients, pesticides and heavy metals, according to a study by the Chesapeake Bay Program, but extreme weather events and rising sea levels will impose greater volume and speed of water over land which will potentially decrease absorption.

Cost Estimates (according to the Chesapeake Bay Program): “The cost of planting and maintaining riparian buffers is highly variable due to the different buffer types, sizes, and planting stock. The Maryland maintenance and design manual for riparian forest buffers has the following cost comparison for tree establishment. For 435 bare root seedlings per acre, the cost range is listed as $1529 - $2060. For 300 containerized trees per acre, the cost range is listed as $3000 - $7500. Cost estimates include maintenance.”\(^\text{43}\) The cost per acre of macroalgae aquaculture installation is $6,900\(^\text{44}\) (within the range of tree buffer).

**Figure 3: Cost of Installation: BMP vs Macroalgae Farming**

<table>
<thead>
<tr>
<th>Cost of Installation: BMP vs Macroalgae Farming</th>
<th>Riparian Forest Buffer</th>
<th>Macroalgae Farming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td></td>
<td>Cost</td>
</tr>
<tr>
<td>$3000-7500/ac</td>
<td>300</td>
<td>$6900</td>
</tr>
<tr>
<td># of Trees</td>
<td></td>
<td>Algae Units/m²</td>
</tr>
</tbody>
</table>


\(^\text{42}\) http://www.cbf.org/how-we-save-the-bay/chesapeake-clean-water-blueprint/21-states-oppose-clean-water


\(^\text{44}\) 40 X 100m grid. 18m installed by 100m length at cost of $3/m + $1500 labor=Total Cost of $3.8333/meter
A goal for planting riparian buffers was 10,000 miles by 2010. As a buffer strip is 35’ wide, the goal is 10,000 miles x 35’. Consider the same goal for macroalgae farming as an in-water method to duplicate the land-based buffer to capture the lost efficiencies of BMP’s. There is benefit to co-locating macroalgae aquaculture just beyond SAV restoration for wave break (on SAV seedlings but also for protection from erosion on stream banks which impacts water clarity), nutrient uptake (competition to reduce microalgae growth/shading) and sediment capture (sediment accumulates on the macroalgae so may reduce on SAV).

See below for the Cost of Nitrogen Pollution Reduction by Sector and Practice (per pound). By calculating the cost per pound for macroalgae farming, it is possible to evaluate the technique relative to other methods. By taking our installed costs (materials and labor) and adding our net profit/loss from farming measured against nitrogen reduction, we should be able to establish how a new potential practice compares to existing practices of N removal.

**Figure 4. Average Cost of Selected Nitrogen Reduction Measures**

---

45 In addition to riparian buffers, goals exist for Submerged Aquatic Vegetation, which assists in nutrient uptake during the growing season. Historically, 200,000 acres of SAV grew along the banks of Chesapeake Bay and tributaries. Today the total acreage is much less, but a recent goal was 185,000 acres by 2010. SAV is negatively impacted by poor water clarity with storms and shading.
These are land based systems. The current goal of containing nutrients at their sources is correct (before diffusion in the waterway), but the difficulty of installing and monitoring BMP’s, loss in efficiency as well as legacy nutrients require the development of nutrient sinks. This proposal recommends a “use all tools” mentality. Further, the installation and testing of a system allows practitioners to learn and adapt at small scale to improve a system and maximize investment.

Let’s examine the goals of the Chesapeake Bay for nitrogen removal to see what area of marine space would need to be dedicated to the technique.

EPA issued a report on Nutrient Trading/Offsets Programs (http://stat.chesapeakebay.net/?q=node/130&quicktabs_10=3) which provides a guide to the status of various kinds of trades, Point Source to Point Source, Nonpoint Source to Point Source, etc in various stages of implementation Under Programs Recommendations Common to All Jurisdictions

“Several jurisdictions are considering developing or expanding their current programs. The jurisdictions should continue to develop guidance and methodologies to address meeting baseline for point and nonpoint source sectors

46 No water-based systems are included (ex: oysters, SAV).
including consideration of the use of non-traditional Best Management Practices (BMPs) such as algal scrubbers, oyster aquaculture, etc.” In this same section, EPA commits to updating enforcement policies and procedures...including inspectors’ access to off-site areas where credits or offsets are generated and...develop tracking and accounting systems for new and increased loads and offsets for those loads. These systems should be transparent and accessible to the public.

Algal scrubbers are specifically mentioned. The use of algal farming systems (scrubbers) provide the advantage of easy accountability (tissue content per unit of biomass harvested) and easy access for inspection/verification, as they’re in public waters. Moreover, they have a potential payment offset through sale of the biomass.

**TMDL: Surface Area Required for Nutrient Removal to Impact TMDL Goals**

The Chesapeake Bay and tributaries have a surface area of 4,480 sq miles.

Macroalgal Productivity via aquaculture is calculated in the table below.

**Figure 5. Macroalgal Productivity**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of (wet) biomass in 1 bag</td>
<td>1.2 lbs</td>
</tr>
<tr>
<td># of bags of biomass needed to harvest one sq meter surface</td>
<td>3</td>
</tr>
<tr>
<td>Amount of wet biomass harvested per sq meter</td>
<td>3.6 lbs</td>
</tr>
<tr>
<td>dry biomass as % of wet biomass</td>
<td>15%</td>
</tr>
<tr>
<td>Amount of dry biomass harvested per sq meter</td>
<td>0.54 lbs</td>
</tr>
<tr>
<td># of harvests per calendar year</td>
<td>3</td>
</tr>
<tr>
<td>Amount of dry biomass harvested per year per sq meter</td>
<td>1.62 lbs</td>
</tr>
<tr>
<td>% of Nitrogen in dry biomass</td>
<td>3.6%</td>
</tr>
<tr>
<td>Amount of Nitrogen harvested in dry biomass</td>
<td>0.05832 lbs per sq meter</td>
</tr>
</tbody>
</table>

One percent (1%) of Virginia’s nitrogen pollution, or 578,001 lbs is Non-Tidal Water Deposition (from the atmosphere) for which there is no available Best Management Practice for control. Given the absorption rate above of algal biomass for nitrogen, how much surface area is required to provide a removal technique for 578,001 lbs N? Similarly, if we harvest the necessary biomass, how much P and C are we also removing? See Excel Spreadsheet attached.

---


48 [http://stat.chesapeakebay.net/?q=node/130&quicktabs_10=3](http://stat.chesapeakebay.net/?q=node/130&quicktabs_10=3)
In order to remove 578,001 lbs of N, we need to dedicate 3.826 square miles to the project. We will also in that surface area remove 16,056 lbs of phosphorus and 4,816,675 lbs of carbon. The amount of wet biomass we need to harvest is 107,037,222.22 lbs.

For this nutrient removal project, labor is estimated at $24,777,134 and equipment at $25,000 for a total of $24,802,124 for a cost of N removed/lb of $42.91.

Figure [ ]. Comparison of Nitrogen Reduction Costs

<table>
<thead>
<tr>
<th>Name of Treatment</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormwater Management New Development</td>
<td>$92.40/lb</td>
</tr>
<tr>
<td>Wastewater Treatment Plant Upgrade (high)</td>
<td>$47.40/lb</td>
</tr>
<tr>
<td>Macroalgae Farming – Hand Harvest</td>
<td>$42.91/lb</td>
</tr>
<tr>
<td>Enhanced Nutrient Management</td>
<td>$21.90/lb</td>
</tr>
<tr>
<td>Wastewater Treatment Plant Upgrades (avg)</td>
<td>$15.80/lb</td>
</tr>
<tr>
<td>Macroalgae Farming - Mechanized Harvest</td>
<td>$6.60/lb</td>
</tr>
</tbody>
</table>

Summary: Macroalgae farming, at $42.91/lb is less expensive than Stormwater Management and Wastewater Treatment Plant Upgrades (high) but more expensive than Enhanced Nutrient Management and Wastewater Treatment Plant Upgrades (average). It is within the range of these techniques and adds benefits of Carbon removal and competition with microalgae, the primary cause of hypoxia/anoxia.

**Carbon and Ocean Acidification (OA)**

Carbon removal from the Bay was included in our estimates above. An increasing concern for coastal waters—and the shellfish industry—is Ocean Acidification. Oceans absorb approximately 26% of CO2. Increasing CO2 emissions, and resulting absorption by oceans, is decreasing the pH and acidifying our waterways. A recent report states that “marine ecosystems along the East and Gulf Coasts will experience acidification earlier than global projects indicate, owing to the presence of local amplifiers such as coastal eutrophication and discharge of low Ω river water.”

Macroalgae absorb Nitrogen and Phosphorus

---

49 Ekstrom et al. 2015. Vulnerability
on average 3.6% N and 0.5% P. They also use carbon to build biomass. Macroalgae typically contain 30% carbon, and harvest of these plants, may be considered part of a strategy of carbon sequestration for greenhouse gasses, depending on the use. If the macroalgae could be used to produce products that are currently based on fossil fuels, we could potentially reduce atmospheric carbon or at least recycle carbon so that no new carbon is added. A common green alga, Enteromorpha, and a red alga, Porphyra, “have the highest photosynthetic rates, which are 1-2 orders of magnitude higher than those of brown algae. Macroalgae have higher productivity rates than terrestrial biomass such as corn and switchgrass (Chung et al., 2011) and do not require freshwater irrigation or agricultural land.

Nellemann et al (2009) state that marine primary producers provide at least 50% of the world’s carbon fixation.

Chung et al (2011) estimate that macroalgae cultivation along coastlines could absorb 1 billion tons of carbon annually. Muraoka (2004) estimates that Japan can absorb 32000 tons of carbon annually through mass cultivation of seaweeds such as Laminaria, Undaria, Hizikia, Gelidium, and Porphyra spp.

How much carbon could mass cultivation of macroalgae absorb in the Chesapeake Bay and tributaries as well as the US?

Productivity in near bottom systems is 2000 g Dry Weight per square meter, and long-lines produce 300 g DW per square meter. This author has confirmed initial biomass harvest of 1.2 lbs wet weight per bag (34” x 18” mesh surface.) For math summary, see below. Production assumptions: 1.2lbs wet weight x 3 bags per meter x 3 harvests/yr. Figures assume 1 line of bags around the Chesapeake Bay and tributaries with breaks for nautical traffic, but the configurations could be different with 20 bags in a row in some areas and none in others.

Phyiology

The ideal macroalga for this process grows at the fastest rate, takes up the most nutrients and can outcompete other algae. Concern for aquaculture’s impact on surrounding waters recommend native strains. These should be inventoried and

---

50 Ibid.
utilized. While macroalgae fall into one of three categories (red, green, and brown), observation indicates that green macroalgae are a prevalent form in the Chesapeake Bay eutrophic waters. Valiela et al. (1997) write that opportunistic Ulvaean species often dominate in eutrophic conditions in temperate estuaries.

As nitrogen is the primary nutrient that limits seaweed growth, the supply of nitrogen will dictate growth rates. The uptake capacity depends on the surface-area: volume (SA:V) ratio\(^{51}\) (Hein et al. 1995). Typically, fast growing, opportunistic species take up the most nutrients, while slower growing macroalgae store nutrients. Here, the ulva or green species are favored for fast uptake rate.

Median ratio C:N:P for seaweeds is about 550:30:1 (i.e., C:N =18:1).\(^{52}\)

Macroalgae are classified as Green (Phylum Chlorophyta), Red (Rhodophyceae), and Brown (Phaeophyceae).

Macroalgae vary in pigment, growth and chemical composition according to their habitat, such as light, temperature, salinity, nutrients, pollution and water motion, and their taxonomical classes (Lobban et al, 1985). Regarding species, thin macroalgae (green species in the case of the Chesapeake Bay) take up nutrients faster per unit of biomass than thick thalli (for example, the brown species, \textit{fucus}) (Rosenberg et al., 1984, Wallentinus 1984, Fujita 1985, Hein et al. 1995). Observation indicates that green macroalgae are a prevalent form of macroalgae in the Chesapeake Bay eutrophic waters. This proposal recommends growing native species of macroalgae. Valiela et al. (1997) write that opportunistic Ulvaean species often dominate in eutrophic conditions in temperate estuaries.

The median ratio C:N:P for seaweeds is about 550:30:1 (i.e. C:N=18:1 and N:P=30:1). The average carbohydrate and protein contents of seaweeds have been estimated at 80 and 15% of the ash-free dry weight (Atkinson and Smith 1983). In contrast, carbohydrate and protein contents of phytoplankton are 35 and 50% respectively (Pars et al. 1977).\(^{53}\)

\(^{52}\) Hurd, C. L. Seaweed Ecology and Physiology. P. 280.
\(^{53}\) Ibid. P. 281.
Biomass production in the sea depends primarily on “irradiance, temperature, nutrients, grazing and stand density.”\(^{54}\) "According to Henley et al. (1991) when thali of Ulva torundata were transferred from low (100 umol photo m\(^{-2}\cdot\)x\(^{-1}\)) to high (1700 umol photo m\(^{-2}\cdot\)x -1) light conditions, daily surface area growth rates in N-sufficient plants increased six fold and light-saturated net photosynthetic capacity increased by 50%."\(^{55}\) If this finding holds true, given the goal of nutrient absorption, it may be beneficial to pursue lifting the macroalgae to the surface on an aquaculture system to increase productivity (biomass) for absorption of more nutrients. Provided the biomass is harvested, one could increase nutrient reductions from the waterway—the Chesapeake Bay Blueprint’s goal. According to Gao et al., “the N uptake has also been found to be enhanced by enrichment with CO\(_2\), in two Gracilaria species (Gao et al., 1993),” a common species growing on the US East Coast, including the Chesapeake Bay.

We have several pieces of the puzzle. We have a way to maximize primary productivity in the form of nutrient absorption, including carbon. We have a way to maximize nutrient absorption by establishing a species’ ideal placement in the water column (irradiance). We know macroalgae like current flow. (Gao et al., 1993). At the same time, harvest needs to be timed for ideal stand density, otherwise, nutrients, light and yield can be adversely affected. (Gao et al, 1993)

N uptake rate for green algae ranges from 3-400 umol g(dry wt)-1; that of brown algae from 7-31 umolgdry wt-1; and that of red algae from 3-29 umol g(dry wt)-1. Maximum rates for uptake of nutrients vary on external environmental conditions as well as internal factors (state of development and age.)\(^{56}\)

**Competition: Macro vs Micro**

According to CBF, the immediate cause of dead zones is microalgae, rather than macroalgae. Very few studies exist on the competition between macroalgae and microalgae, but some suggest that macroalgae can outcompete microalgae until the point when microalgae shade the macroalgae. (citation) Farming would provide an advantage to macroalgae by boosting the plants toward the sun for

---

\(^{54}\) Gao, Kunshan & McKinley, Kelton R., Use of macroalgae for marine biomass production and CO\(_2\) remediation

\(^{55}\) Ibid.

\(^{56}\) Ibid.
greater rates of photosynthesis and expansion of their growing area (normally in shallow water). This would allow them to potentially take up nutrients that would otherwise be available for microalgae production. This form of farming could be a tool to combat microalgae blooms that cause hypoxia and reduced habitat for marine life.

In an experiment conducted by D.W. Smith and A.J. Horne in mesocosms\textsuperscript{57}, the green macroalga, Ulva, was tested in the presence of microalgae and outcompeted the planktonic microalgae. Similar work was performed by Fong et al., again showing that macroalgae outcompeted microalgae. The literature review points to Ulva outcompeting microalgae in shallow estuaries where light is relatively equal.

If a system were designed to create maximum macroalgal biomass (for maximum nutrient harvest and to minimize microalgal growth, as dead zones are caused by microalgal blooms) how frequently could the macroalgae be harvested and still outcompete microalgae? Enteromorpha sp., and Ulvean species, has a photosynthetic rate of 1786 g wet\textsuperscript{-1} (Jung, K.A. et al, 2013) one of the highest listed among all the known algae and second only to the red alga Porphyra sp. The higher the rate of photosynthesis, the more nutrients used to create biomass and the greater the opportunity to harvest nutrients with the biomass. This author proposes that accelerating growth of Ulvean species (by lifting to the surface) and expanding their available surface area allows the species to:

<table>
<thead>
<tr>
<th>Goals of Macroalgae Farming</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
</tr>
<tr>
<td>II.</td>
</tr>
<tr>
<td>III</td>
</tr>
<tr>
<td>IV.</td>
</tr>
</tbody>
</table>

\textsuperscript{57} Smith, D.W. and A.J. Horne. 1988. Experimental measurement of resource competition between planktonic microalgae and macroalgae (seaweeds) in mesocosms simulating the San Francisco Bay-Estuary, California
If green macroalgae were put on a harvest schedule, literature indicates two-three (2-3) harvests per season are feasible. And what surface area of the water is necessary for biomass production to both avoid harm to SAV and to contribute to meaningful nutrient reductions according to Blueprint guidelines?

Green macroalgae grow typically close to shore in shallow, eutrophic water where they are close to light. While green macroalgae should receive the expanded area, because of their uptake rates, perhaps other macroalgae could occupy the lower depths of the water column. Classes of macroalgae are distributed vertically from the upper zone near the sea surface to the lower sublittoral zone (Lobban et al., 1985), as their specific pigments selectively absorb different wavelengths (Guiry, 2012). Other species of macroalgae could potentially contribute to nutrient absorption in the lower depths.

These decisions may also be impacted by tissue content for uses. Macroalgae have a high percentage of water (70-90% fresh wt.) and minerals. (Ross et al., 2008). They have low percentages of protein (7-15% dry wt.) and lipids (1-5% dry wt.) (Jensen 1993) (Becker 1994).

A comprehensive list of macroalgae from the Chesapeake Bay was compiled in 1980 by Patricia Orris, but an updated list would be useful to determine distribution, abundance, and reproduction compared to other objectives of nutrient absorption and market use.

A study looks at the question of microalgae vs macroalgae competition. The paper, Competition with macroalgae and benthic cyanobacterial mats limits phytoplankton abundance in experimental microcosms (Fong et al. 1993), used experimental microcosms (drums) to study the effects of nutrients on microalgae in the presence of macroalgae. The authors found that macroalgae outcompeted microalgae (phytoplankton). The authors write: “At high nutrient loading (nitrate-N = 77 FM d-l), the growth of phytoplankton was reduced by a factor of 10 in the presence of the algal mats. Without the algal mats the phytoplankton was very abundant (> 5 X 106 cells rill-l) and dominated by small flagellates, while in the presence of the algal mats the phytoplankton assemblage was sparse and diatoms, flagellates, and unicellular blue-greens were common. The competition

---

hierarchy was cyanobacterial mats >> attached green macroalgae > floating green macroalgae > phytoplankton.”

The study can be interpreted that macroalgae outcompete microalgae for nutrients in a confined space. One cannot extrapolate that in open systems, where both are present, macroalgae would outcompete microalgae, but one can look at the question and design a test in open systems. Examined from an aquaculture perspective, if macroalgae, which typically thrive in shallow lagoons, were placed on an aquaculture system (proximate to sunlight) and intended for harvest, they might absorb nutrients that might otherwise spur growth of microalgae, consistent with EPA’s goal.

Phytoplankton need for nutrients suggests that macroalgae growth devices should be located close to the worst nutrient sources on land in order to absorb those nutrients and reduce their availability for phytoplankton in the main open waters. As noted elsewhere, phytoplankton is the source of hypoxia or low oxygen in Chesapeake Bay. If we can reduce the phytoplankton population by diverting dissolved inorganic nutrients to macroalgae for harvest, we can theoretically decrease low oxygen zones. Success depends on surface area dedicated to the strategy.

To determine the feasibility of the plan, we want to answer the question: how productive (in terms of nutrient absorption) can a system be? For this we want to know how much biomass we can produce in a square meter and how many harvests we can accomplish in a year over the available marine space in a water body. Then, we want to look at the costs of such a proposal. We already have the costs for nitrogen. As important, can this biomass serve a social good and offset the cost of the system? Can growth of biomass absorb carbon in waterways as a way to mitigate ocean acidification (a lowering of pH as water absorbs carbon)? Conversely, how will increased carbon affect growth rates of micro or macroalgae? Some of these questions are beyond the scope of this project but could benefit from additional research.

59 Ibid.

The months of greatest concentrations (according to Bukaveckas (2013)) are May-October, with favorable factors of light, residence time, and nutrients. As a result, algal systems may only need to be in the water for 5-6 months of the year.

Mass Cultivation

China, Korea, Japan, Indonesia, and the Philippines produced 95% of the world’s macroalgae supply in 2010 (FAO, 2012a). These East Asian countries have refined farming techniques for local species, conditions and labor/materials costs. These techniques may inform potential farming methods for the US for nutrient extraction via green macroalgae. The dominant methods are rope culture and raft culture.

The shoreline of the Chesapeake Bay and its tidal tributaries is 11,684 miles, according to the Chesapeake Bay Program web site. Half of the water comes from the Atlantic Ocean, and half comes from the watershed. About 51 billion gallons a day flows from the tributaries, with 80% coming from the Susquehanna, Potomac and James rivers. Approximately 80,000 acres of bay grasses grow in the shallow regions of the Bay. If we were to design a system, we may concentrate our macroalgae system in the Susquehanna (provides 50% of the fresh water at 19 million gallons per minute), Potomac and James rivers. Alternatively, we can use existing software to establish hot spots of nutrient loading and co-locate when possible. There would be some rationale for a cost-share from the polluters.

Looking at the most recent Dissolved Oxygen map (June-September, 2009-2011), we see that the main stem of the Chesapeake Bay over the three year period has shown little improvement (the majority is in red).

The TMDL allocations are 207.57 million pounds of nitrogen (a 75.09 million pound reduction from 2009) and 14.46 million pounds of phosphorus per year (note, the nitrogen allocation included a 15.7 allocation for atmospheric phosphorus).

---


63 Additional information: Much of the Bay is quite shallow, less than 6’ deep, though the average depth is 21 feet. The surface area of the Bay and tributaries is approximately 4,480 square miles. The Bay is about 200 miles long. http://www.chesapeakebay.net/discover/bay101/facts, accessed February 19, 2015

deposition of nitrogen to tidal waters. These allocations are divided by the Bay states of Delaware, District of Columbia, Maryland, New York, Pennsylvania, Virginia and West Virginia, which are refining their Watershed Implementation Plans (WIP’s). Virginia’s TMDL requires reductions of Nitrogen 52,460,000 pounds, Phosphorus 6,460,000 pounds and Sediment 3,251,000,000 pounds (over 1985 levels).

The website indicates that the bulk of the load comes from agricultural runoff in Virginia and Pennsylvania (Potomac, James and Susquehanna Rivers). A plan to focus macroalgae farming efforts could examine the runoff sites on these rivers, compare to the flood plain maps (low areas), and run a macroalgae system parallel to these low areas. The location would be beyond sea grasses, which produce oxygen and provide habitat, but be as close as possible to runoff sites, at the beginning of the euphotic zone. The goal is to be a kind of scrubber as nutrients enter the Bay and tributaries but before dissolution. See below.

**Macrolalgae Farm**

*(In green beyond Submerged Aquatic Vegetation (SAV))*

---

66 Chesapeake Bay Program web site on TMDL calculations. Reduce computer-simulated nitrogen loads to the Bay by 75.09 million pounds, from 282.66 million in 2009, to 207.57 million by 2025*. [http://www.chesapeakebay.net/indicators/indicator/reducing phosphorus pollution](http://www.chesapeakebay.net/indicators/indicator/reducing phosphorus pollution), accessed February 20, 2015

67 Ibid.

68 Chesapeake Bay Program.
Markets and Uses

There are two monetization strategies for macroalgae: 1. the nutrient trading market and 2. the commercial market. The government could also decide to engage in a Public-Private Partnership to fund the strategy initially until the private sector undertakes the business enterprise.

**Nutrient Trading Market:** The nutrient trading market allows those that can reduce nutrients at low cost to sell credits to those facing higher-cost nutrient reduction options, according to WRI. Nutrient trading allows “sources of pollution ...to meet their pollution targets in a cost-effective manner and creates new revenue opportunities for farmers, entrepreneurs, and others who implement low-cost pollution reduction practices.”

A macroalgae producer can take advantage of both markets, as the trading of credits for nutrient reductions does not require disposal of the biomass; it can be sold at market provided it does not end up in the receiving body of water.

---

69 Jones, Cy et al. 2010. WRI. How Nutrient Trading Could Help Restore the Chesapeake Bay.
The Chesapeake Bay Watershed Model (Phase 5.2, using 2008 data) estimates reductions in Nitrogen as follows:

- Reduction in Nitrogen needed to stabilize the Bay: 75 million pounds/yr
- Potential nitrogen reductions from identified practices: 70 million pounds/yr
- Potential additional nitrogen reductions from new, innovative practices? 5 million pounds/yr?

- Scenarios of trading values of a pound of nitrogen range from $8/lb to $20/lb to $50/lb (the last number exceeds what Wastewater Treatment plants are willing to pay, with their internal costs of nitrogen reduction between $16/lb and $47/lb. However, this price would be below the cost to new Stormwater treatment of $92/lb representing a cost savings). This is presumed the market price of a trade without transaction costs. Costs of producing the reduction are not considered in these prices.
- Could macroalgae harvest contribute to reductions, along with other practices, of 5 million pounds/yr?

The value of the nutrient trading market is minor in terms of revenue for an aquaculture enterprise, but as a secondary revenue stream and as an environmentally beneficial practice that may assist marketing efforts to bring a premium price for a product, it may be useful.

Increasingly, we recognize the value of sustainable practices. The FAO’s Blue Growth initiative “promotes the sustainable use and conservation of aquatic renewable resources in an economically, socially and environmentally responsible manner. “ The practice is consistent with Blue Growth. Approximately 97% of earth’s water is oceanic saltwater. Available fresh water is approximately 1%. Freshwater supplies are of concern to policy makers, and 42% of freshwater is used for agriculture. As global population increases to 9.6 billion people by 2050 (a 38% increase from...), our practices will to be no only productive for today but sustainable for the long term. As a way to decrease pressure on fresh water, production of biomass in waterways, rather than on agricultural fields, can reduce freshwater usage as well as land usage.

---

71 http://www.wri.org/sites/default/files/factsheet_nutrient_trading_chesapeake_bay.pdf, Figure 7

Sustainability refers also to carbon. While not included in the TMDL for the Chesapeake Bay, carbon is a major concern globally, and our oceans, as the largest carbon sink in the world, are becoming increasingly acidic. Some 93 percent of carbon dioxide is stored in algae, vegetation, and coral under the sea. However, the increase in carbon and acidity has repercussions for shell-forming organisms and thus, the food web that depends on them. The role of oceans and especially coastal marine ecosystems could become important in mitigating climate change. Muraoka (2004) estimates that Japan can absorb 32000 tons of carbon annually through mass cultivation of seaweeds such as Laminaria, Undaria, Hizikia, Gelidium, and Porphyra spp. How much carbon could mass cultivation of macroalgae absorb in the Chesapeake Bay and tributaries? What end use is approved for sequestration (ex: soil amendments)? Last, could macroalgae farming participate one day in a carbon market depending on the use of the biomass?

**Commercial Market.** The second market is the commercial market. In 2012, it is estimated that 33 countries and territories harvested 23.8 million tonnes (wet weight) of 37 kinds of farmed aquatic algae, or seaweed, by aquaculture, while capture production was 1.1 million tonnes. China and Indonesia farmed 81.4 percent of the total, and production of farmed seaweeds more than doubled between 2000 and 2012. Approximately 9 million tonnes are for human consumption. The remainder serves other markets such as cosmetics (lotions, soaps, etc), aquaculture feed, agar and carrageenan, iodine, fertilizers and more. The growth in seaweed production coincides with the growth of global aquaculture as one of the fastest growing food production sectors.

With limited marine space in the Chesapeake Bay, and higher labor rates than Asia, it is anticipated that the biomass will be used for high value, niche markets (unless a low-labor technique can be devised) like cosmetics, until the demand is met. Afterwards, the enterprise will fill the next highest priced market and so on. For instance, a green seaweed crème is sold (60 grams) for $45.90 out of Chile.

---


74 Ibid.

75 FAO. 2014. The State of World Fisheries and Aquaculture.

76 FAO. 2014. The State of World Fisheries and Aquaculture.

77 BO Laboratories sells Crème Hidratante Algas Verdes with Vitamin E and Omega 3, 60 grams for $45.90
Other niche products include home fertilizers and handmade papers. For example, the commodity fertilizer market shows a farm price for Nitrogen fertilizer for 2013 as $410-592/(short)ton.\textsuperscript{78} However, the consumer market buys seaweed fertilizers in small quantities for: 1 oz (Sea Magic by Burpee) for $6.75-$8.99 and 32 oz (Organic Liquid Kelp) for $14.95.

Both are made from Ascophyllum nodosum, a brown macroalga, but according to the FAO seaweed report, this plant material was used because it is available in large quantities.\textsuperscript{79}

Another niche market is specialty papers which retail for $4-5/sheet at urban art stores and greeting card stores. A 140 urban store chain which specializes in handmade cards and artisan papers expressed willingness to view samples of algal paper and would consider purchasing for $2/sheet. A fairly low cost process could produce algal paper for $1/sheet and sell for $2/sheet. Eventually, the process would need to gain greater efficiencies for broader markets (sustainable packaging, for instance). Samples of green macroalgae were successfully fabricated at a papermaking studio (See Appendix C). Additionally, samples from the Potomac and Shenandoah Rivers were sent for strength analysis with results within range of the lab’s control of wood pulp.

Approximate Production Costs Per Sheet

<table>
<thead>
<tr>
<th>Step</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest</td>
<td>$ .25</td>
</tr>
<tr>
<td>Rinse/Dry</td>
<td>.25</td>
</tr>
<tr>
<td>Delivery to Manufacturer</td>
<td>.10</td>
</tr>
<tr>
<td>Paper Production</td>
<td>.75</td>
</tr>
<tr>
<td>Marketing and Delivery</td>
<td>.25</td>
</tr>
<tr>
<td>Finished Cost</td>
<td>$1.60</td>
</tr>
<tr>
<td>Profit/sheet ($2-1.60)</td>
<td>.40</td>
</tr>
</tbody>
</table>

Assumes minimum run of 3000 sheets for a profit of $1200.

\textsuperscript{78} Source: Agricultural Prices, National Agricultural Statistics Service, USDA.

\textsuperscript{79} http://www.fao.org/docrep/006/y4765e/y4765e0c.htm ; “Seaweed meal is dried, milled, and again it is usually based on the brown seaweeds because they are the most readily available.”
Organic Fertilizer Market (consumer market)

Macroalgae have been used for centuries by coastal people as a fertilizer on land. Dr. Scot Nixon (pers comm), at U of Rhode Island, displayed 19\textsuperscript{th} C land advertisements showing elevated land value that had seaweed resources available by oxen cart from a nearby beach.\textsuperscript{80} In Argentina, green seaweed collects on shore and is composted for use with tomato plants. Compost assists soils with water retention as well as plant health, so the technique solved a pollution problem and produced an organic fertilizer.\textsuperscript{81} Macroalgae fertilizer may be desirable for vegetarians who prefer to use a plant-based fertilizer rather than animal manure or synthetic fertilizers.

Macroalgae may possess trace nutrients that are good for plants but are not available in synthetic fertilizers. Very little treatment would be necessary to process the algae into fertilizer. Rinse, dry, grind and bag.

Sea Magic, a seaweed fertilizer, sells for $6.75-7.95 for 1 oz.

\textsuperscript{80} Personal communication during visit in 2000.
32 oz retails for $14.95 (Ascophyllum nodosum)

8 oz seaweed fertilizer sells for $14.95.

Company information: Brown Kelp's slow growth cycle packs it with maximum levels of amino acids, enzymes, micronutrients, plant hormones (auxins, cytokins, gibberillins) and soil biology that encourages vigorous and healthy plant growth. The growth hormones in Seaplex are essential for cell division, root development, and bud initiation, making it a natural growth enhancer.

**ANALYSIS OF HEBRIDES**

**LIQUID SEAWEED (Need photo)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6 to 9mg/kg</td>
<td>Iron</td>
<td>63</td>
</tr>
<tr>
<td>Calcium</td>
<td>410</td>
<td>Manganese</td>
<td>0.1</td>
</tr>
<tr>
<td>Magnesium</td>
<td>98</td>
<td>Copper</td>
<td>0.4</td>
</tr>
<tr>
<td>Sodium</td>
<td>2,689</td>
<td>Zinc</td>
<td>1.4</td>
</tr>
<tr>
<td>Potassium</td>
<td>15,862</td>
<td>Boron</td>
<td>11.2</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>38</td>
<td>Iodine</td>
<td>250</td>
</tr>
</tbody>
</table>
Aquaculture feed is the single highest cost for aquaculture, according to aquaculture specialist, Dr. Michael Schwartz of Virginia Tech. The US imports more than 90% of its seafood for an $11 billion trade deficit. Half of this is from aquaculture. The US can produce more of its seafood through aquaculture to provide jobs. In fact, aquaculture is the fastest growing sector of agriculture in the US.  

“Seaweed, as a feed ingredient, according to Mike Rust of NOAA (pers comm), can range from 5-35% protein, with red and green seaweeds typically higher than brown algae and harvest season being an important determinant of composition. The lipid portion is typically 2-6% of dry matter. The protein can be thought of as similar to soy protein, but the oil can contain long chain omega-3 fatty acids which makes a comparison to fish oil possible.”

A species of Gracilaria is also available in the Chesapeake Bay. It was used as bioremediation for a fish farm in north China. A study, published in 2005 by Zhou et al, found that “1-ha cultivation of the seaweed in coastal a fish farming waterway would provide an annual harvest of more than 70 t of fresh Gracilaria, or 9 t dry materials; 2.5 t C would be used, and 0.22 t N and 0.03 t P would be sequestered from the seawater by the seaweed.” Gracilaria grew best at 1-2 m depth.

---

83 By email
84 Zhou et al. (2005). Bioremediation potential of the macroalga Gracilaria lemaneiformis (Rhodophyta) integrated into fed fish culture in coastal waters of north China.
Gracilaria in Charleston, SC\textsuperscript{85}

Gracilaria species provide high nutrient absorption efficiency as well as commercial value for products. (Chopin et al., 2001; Neori et al., 2004)

Aquaculture feed has increased in price due to diminishing supplies of forage fish, fish meal and fish oil.\textsuperscript{86} According to NOAA, “farmed seaweed has significant growth potential as a source of food and fiber for both aquaculture feed and human consumption.”\textsuperscript{87}

Animals such as sheep, cattle and horses living near coastal areas have eaten seaweed over the decades. Sheep and cattle appear to be the most benefitted from eating seaweed. “An experiment for 7 years with dairy cows (seven pairs of identical twins) showed an average increase in milk production of 6.8 percent that lead to 13 percent more income. A trial involving two groups each of 900 ewes showed that those fed seaweed meal over a two-year period maintained their weight much better during winter feeding and also gave greater wool production,” according to FAO.\textsuperscript{88}

\textit{Ulva Lactuca} was fed to abalone with their growth improved by a high protein content, attained with high levels of ammonia present.\textsuperscript{89}

\textit{Ulva Lactuca}\textsuperscript{90}

\textsuperscript{85} http://zenscience.org/meet-zen-student-exchange-fellow-nico/\textsuperscript{,} accessed April 23, 2015
\textsuperscript{88} FAO. A guide to the seaweed industry.
\textsuperscript{89} Ibid. 9.3.Fish Feed.
Cosmetics
Extracts of seaweed, a typical ingredient of face, hand and body creams, refers to alginate or carrageenan in the product. Typically, these are from gracilaria. Cost information and ingredients lists are proprietary by the companies. One green seaweed cream was found in Chile (See above).

Food
Both Ulva (Green) and Gracilaria (Red) can be used as food. As Ulva / Enteromorpha is common, this is a good species to examine.

Enteromorpha prolifera and Enteromorpha intestinalis are both cultivated and found in the US. Enteromorpha can thrive in salt and brackish waters and grows typically at the top of the sublittoral zone. With about 20 percent protein, little fat, low sodium and high iron and calcium, the vitamin B-group content is generally higher than most vegetables, and while its vitamin A is high, it is only half of that found in spinach. It can be lightly toasted and used on soups and foods.

"Sea lettuce" or Ulva, grows in the mid to lower eulittoral zone. It is collected from the wild and sometimes used in aonori. It has a higher protein content than the Enteromorpha, but lower vitamin content, except for niacin.91

Biorefinery
According to Art Ragauskas et al (2006), biomass represents an abundant carbon-neutral resource for the production of bioenergy and biomaterials... Advances in...biotechnology, process chemistry, and engineering are leading to a new manufacturing concept for converting renewable biomass to valuable fuels and products, known as biorefinery.92 Biorefinery is defined as sustainable processing that can convert biomass into various marketable products and energy (IEA, 2009). Addressing macroalgae specifically, Jung et al (2012) indicates that “macroalgae contain various carbohydrates which are distinctly different from those of terrestrial biomasses... 93 A difference in carbohydrates may indicate that macroalgae has unique uses differentiated from terrestrial biomasses, but they also may require further analysis. Currently, the red and brown macroalgae have

---
90 Photo is Ulva Lactuca growing in Virginia on oyster aquaculture bags. Photo by author.
received more economic attention and thus mass cultivation. Green macroalgae are plentiful in eutrophic waters, however, and should be put to economic use in order to gain their ecological use of nutrient extraction. Enteromorpha sp. Has a photosynthetic rate of 1786 g wet\(^{-1}\) (Jung, K.A. et al, 2013) one of the highest listed among all the algae and second only to the red alga Porphyra sp.

Overview: Approximately 10 million tons of seaweed (wet weight) are produced globally for an estimated value of over $6 billion. Brown algae make up 7 million tons, of which Chinese production of kelp (Saccarina japonica) as food is 6.5 million tons, making it the largest single-species crop of aquaculture. Around 300,000 tons of the material is used in China to make 7,000 tons of alginates, viscous polysaccharides used in industry, especially food. Nori, from a red alga, . Seaweed gums and alginates come from brown algae. Agars and carrageenans come from red algae.

Recent needs for alternative sources of fuel have caused a land use change for bio-energy crops. Fargione et al (2008) and Dominguez-Faus et al (2009) reported that direct and indirect land use change for energy crop cultivation induces a significantly high carbon debt and high water consumption.\(^94\) Terrestrial-biomass based biorefinery seems not to be sustainable due to environmental as well as economic impacts. \(^95\) Macroalgae do not need land and freshwater for their cultivation (Lobban et al., 1985). Macroalgae can convert solar energy into chemical energy with higher photosynthetic efficiency (6-8%) than terrestrial biomass (1.8-2.2%) (FAO, 1997).

Given macroalgae’s productivity, and the environmental benefits of harvest, we turn to the business model and what products can be made from the biomass.

Fertilizer Macroalgae as a soil fertilizer provides important soil nutrients: 0.3% Nitrogen, 0.1% Phosphorus, 1.0% Potassium, and a range of trace elements and amino acids. Macroalgae is an alternative to synthetic fertilizer and also can replace animal manure. It can be dug into the soil.\(^96\)

According to the literature, “assessments of macroalgae-based refinery are essential to determine whether applying terrestrial-based technologies to

\(^{95}\) Ibid.
macroalgae or developing completely new technologies is feasible (Jung et al.(2012))⁹⁷

Conclusion
Nutrients continue to flow to the Chesapeake Bay and other eutrophic waterways. Policies to control nutrients on land have helped, but population increase and uneven success in control has prompted policy-makers to look for new solutions. Dead zones are expected to grow worse with warmer temperatures, as warmer water holds less oxygen, algae have a longer growing season, and there’s less mixing of lower and upper water in warmer months to oxygenate the lower water column. Dead zones in the Bay were recently about 22% of the volume of the Bay in summer months. At a time when most species are reproducing and their metabolisms require more oxygen than other times of year, oxygen supply is critical. For a variety of reasons related to efficiencies of controls and atmospheric deposition, evidence suggests that new measures to reduce nutrients in aquatic systems may need to be considered. Macroalgae farming could prove useful if located near nutrient sources.⁹⁸ The technique grows biomass at a faster rate (increasing nutrient extraction), but it may also compete for nutrients with microalgae lessening microalgae’s biomass productions and theoretically impact on hypoxia. Atmospheric deposition of nitrogen, cannot be addressed by BMP’s and therefore may require an in-water solution, such as macroalgae farming. The farming technique can potentially participate in nutrient trading markets as well as commercial markets, although revenue from nutrient trading will probably not influence whether the practice is adopted at current prices. The impetus for adoption would come from a government determination to deploy all useful techniques or the private sector’s development of biomass markets for profit.

Evidence suggests that government may not achieve nutrient reduction goals without new techniques or greater efficiency of existing techniques. Heavy storms render some BMP’s like Riparian Buffer Strips, less effective due to the speed and volume of water flowing across land. If climate change experts are correct, that storms could become more extreme in the future, or that population growth in coastal areas may result in more nutrients released to the Chesapeake Bay, then

⁹⁸ Myers, A. unpublished data. Woods Hole, MA. Summer of 2012. Identical macroalgae growth devices were tested at various distances from an effluent pipe and growth rates measured. Growth rates were highest closest to the pipe.
society will need to expand the range of solutions to adapt to these conditions. While any one solution may not solve the Bay’s problems, multiple, quantifiable techniques, such as macroalgae farming, can participate in reducing nutrients together with regulation and enforcement to foster goals for a healthy Chesapeake Bay. Engineering and design of more efficient algal production systems can potentially increase nutrient absorption per meter. Given current expenditures on Bay restoration of $.5 billion/yr, a dedication of 5-10% of that level of spending could test new methods and initiate new and enduring methods to reduce N, P and C (and sediment), including macroalgae farming. Similarly, the investment will foster economic productivity, in jobs and sustainable raw materials, and future resiliency for a system that will come under more pressure through population growth, extreme climate, warming and acidification. It is government’s responsibility to preserve our ecosystems for future generations. Every year we have the opportunity to invest in new solutions to increase oxygen levels, biodiversity and economic productivity of the Chesapeake Bay. This aquaculture practice is worthy of that investment given the environmental and economic returns.

Algae are more plentiful than ever in our coastal areas like Chesapeake Bay. Man’s addition of nutrients to the aquatic environment may have changed the balance of the system to favor the lower trophic level, but these nutrients, as well as overharvesting of fish and shellfish, are causing a loss of biodiversity. More than ever, we need resilient systems as we confront changes in our climate, temperature and waterway pH with attendant pressure on our marine life.

Aquaculture of macroalgae can assist waterways’ nutrient balance and provide a biomass for the economy without use of valuable land and fresh water. Marine space is available, at least in Virginia (1,000,000 acres) for aquaculture. The material is sustainable, economically viable and points the way to new, sustainable methods of production of food, feed, and fodder in the future when Earth and its systems may need to provide for population growth to 9.6 billion in 2050. As fresh water supplies become increasingly threatened with changing climate, humankind may have to turn to the sea for production of food, feed and fiber to compensate for the loss of irrigation water. Our systems will need to be resilient and our methods sustainable.

The idea of removing nutrients and biomass from our waterways will put people to work and positively impact those ecosystems. The opportunity exists to combine the work of scientists, environmentalists and the private sector to take advantage of new ways of producing raw materials that will benefit both the aquatic system and the economy.

In terms of the Chesapeake Bay, the proposed nutrient reduction technique of macroalgae farming and harvest may take advantage of a nutrient trading revenue stream while monetizing the biomass through a manufacturing enterprise. This analysis is a partial exploration of market opportunities but nowhere near complete. The environmental goal of reducing nutrients, reducing plant biomass and potentially reducing hypoxia are worth exploring the dedication of marine space for several months a year: March 1-August 31st

Preliminary evidence suggests that the combination of a nutrient trading revenue stream for N, P, and C coupled with use of the biomass as a raw material for industry could make a self-sustaining environmental enterprise. The project, if effective in the Chesapeake Bay, could be implemented in eutrophic waterways elsewhere and provide an example for citizens to work profitably and restoratively with our ecosystems. Collaboration between countries could hasten the development of processes to harvest algae biomass, and thus the nutrients, from coastal waters avoiding oxygen depletion for marine life, preserving biodiversity and assisting human economies.

Alyson Myers
Bibliography


Bilodeau, Michael. 2015. Pers Comm. “I don’t see many obstacles incorporating this material in commercial papermaking processes”

Boesch, Donald F, Russel B. Brinsfield, and Robert E. Magnien. 2001. Chesapeake Bay Eutrophication: Scientific Understanding, Ecosystem Restoration, and Challenges for Agriculture


Bricker, S.B., Rice, K.C., Bricker, O.P III. From Headwaters to Coast: Influence of Human Activities on Water Quality of the Potomac River Estuary. Aquatic Geochemistry.


Lapointe,


Appendix

Appendix A: Macroalgae in Waterways

Green macroalgae in the Potomac River, Washington, DC. 2014

Photo: Judy G. Rolfe
Green macroalgae growing on oyster bags in Tomales Bay, CA

Photo: NOAA

(http://www.noaanews.noaa.gov/stories2011/20110609_aquaculture.html)
Appendix B: Green Macroalgae Under Microscope

Green filamentous macroalgae under a microscope.
Appendix C: Macroalgae Analysis for Paper Use

Test Results of macroalgae compared to wood pulp by University of Maine:

The algae from each of the samples you sent to our lab were roughly refined using a lab blender. They were incorporated in a 10% (dry weight) level to a control pulp slurry and standard handsheets were produced. Samples of the produced handsheets are included with this report.

The algae containing handsheets were tested for tensile and tear strength in comparison with control handsheets. The data are shown in the table below:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tensile Index Nm/g</th>
<th>Stretch %</th>
<th>Tear Index mN/m²/g</th>
<th>Δ tensile</th>
<th>Δ Stretch</th>
<th>Δ Tear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>41.0</td>
<td>2.89</td>
<td>7.58</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Potomac</td>
<td>38.1</td>
<td>2.30</td>
<td>7.33</td>
<td>-7%</td>
<td>-20%</td>
<td>-3%</td>
</tr>
<tr>
<td>Shenandoah</td>
<td>39.1</td>
<td>2.54</td>
<td>6.83</td>
<td>-5%</td>
<td>-12%</td>
<td>-12%</td>
</tr>
<tr>
<td>Browns, Misc., Grac/Fucus</td>
<td>24.1</td>
<td>1.02</td>
<td>5.86</td>
<td>-41%</td>
<td>-65%</td>
<td>-22%</td>
</tr>
</tbody>
</table>

With a 10% substitution of algae for conventional wood pulp, the table shows varying reduction in strength. The tensile and tear strength are compared graphically below.
Kristina King (R) and Alyson Myers (L) make handmade paper February 2015 with green macroalgae from the Potomac River.

Photo: Judy G. Rolfe
Appendix D: Aquaculture Systems
Appendix E: Seeding and Harvesting (FAO)

FAO Report on Seeding and Harvesting of Enteromorpha (green macroalgae)

Seeding: “For cultivation, rope nets are seeded with spores by submerging them in areas where Enteromorpha is growing naturally, usually attached to rocks; the better areas have calm waters and sandy bottoms. In the Republic of Korea, seed collection is from June to August and the strings or ropes are taken to culture sites in September; in Japan, seeding is done in September, and by early November young plants are visible. The nets are placed in calm bays or estuaries using either fixed poles in shallow waters or floating rafts in deeper waters.”

Harvesting: “Can be done 2-3 times during the growing period, either by hand picking from the nets or by machine. As with Porphyra and Monostroma, the nets are dragged out of the water and over a cylinder equipped with cutters, mounted in a boat, and then fed back into the water. This is well illustrated in Figure 17A in Ohno and Largo (1998). Hand picking yields the best product, but is slow in comparison with machine harvesting.” Pre-treatment: “The harvested seaweed is washed in freshwater and dried in large trays.”

---

### Appendix F: Biomass Removal Analysis

#### Biomass Productivity

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of (wet) biomass per bag (18&quot;x36&quot;)</td>
<td>1.2 lbs</td>
</tr>
<tr>
<td># of bags of biomass needed to harvest one sq meter surface</td>
<td>3</td>
</tr>
<tr>
<td>Amount of wet biomass harvested per sq meter</td>
<td>3.6 lbs</td>
</tr>
<tr>
<td>dry biomass as % of wet biomass</td>
<td>15%</td>
</tr>
<tr>
<td>Amount of dry biomass harvested per sq meter</td>
<td>0.54 lbs</td>
</tr>
<tr>
<td># of harvests per calendar year</td>
<td>3</td>
</tr>
<tr>
<td>Amount of dry biomass harvested per year per sq meter</td>
<td>1.62 lbs</td>
</tr>
<tr>
<td>% of Nitrogen in dry biomass</td>
<td>3.6%</td>
</tr>
<tr>
<td>% of Phosphorous in dry biomass</td>
<td>0.1%</td>
</tr>
<tr>
<td>% of Carbon in dry biomass</td>
<td>30.0%</td>
</tr>
<tr>
<td>Amount of Nitrogen harvested in dry biomass</td>
<td>0.05832 lbs per sq meter</td>
</tr>
<tr>
<td>Amount of Phosphorus harvested in dry biomass</td>
<td>0.00162 lbs per sq meter</td>
</tr>
<tr>
<td>Amount of Carbon harvested in dry biomass</td>
<td>0.48600 lbs per sq meter</td>
</tr>
<tr>
<td>Amount of Nitrogen to be removed</td>
<td>578,001 lbs</td>
</tr>
<tr>
<td>Amount of Phosphorus that can be removed from 9910853.9 sq meters</td>
<td>16,056 lbs</td>
</tr>
<tr>
<td>Amount of Carbon that can be removed from 9910853.9 sq meters</td>
<td>4,816,675 lbs</td>
</tr>
<tr>
<td>Surface area needed for removal of 578001 lbs of Nitrogen</td>
<td>9,910,853.91 sq meters</td>
</tr>
<tr>
<td>Sq meters per sq mile</td>
<td>2,589,988.11</td>
</tr>
<tr>
<td>Surface area needed for removal of 578001 lbs amount of Nitrogen</td>
<td>3.8 sq miles</td>
</tr>
<tr>
<td>Surface area available to remove Nitrogen</td>
<td>1,562.5 sq miles</td>
</tr>
<tr>
<td>Amount of Nitrogen removed per 1562.5 sq miles</td>
<td>236,012,667 lbs</td>
</tr>
<tr>
<td>Amt of wet biomass needed per year to remove 578001 lbs of Nitrogen</td>
<td>107,037,222.22 lbs</td>
</tr>
</tbody>
</table>

#### Labor and Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Mechanized Harvest</th>
<th>Hand Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amt of time to harvest 1 sq meter</td>
<td>0.8 min</td>
<td>5.0 min</td>
</tr>
<tr>
<td>Amount of biomass harvested per sq meter</td>
<td>3.6 lbs</td>
<td>3.6 lbs</td>
</tr>
<tr>
<td># of harvests per calendar year</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Amount of biomass harvested per sq meter per year</td>
<td>10.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Annual labor per sq meter per year</td>
<td>2.3 min</td>
<td>15.0 min</td>
</tr>
<tr>
<td>Labor minutes per year</td>
<td>22,894,073</td>
<td>148,662,809</td>
</tr>
<tr>
<td>min in hrs</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Labor hrs per year</td>
<td>381,568</td>
<td>2,477,713</td>
</tr>
<tr>
<td>Minimum wage=$7.25 plus OH</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Cost of Labor per year</td>
<td>$3,815,679</td>
<td>$24,777,135</td>
</tr>
<tr>
<td>Cost of Boat and Warehouse per year $25,000</td>
<td>25,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Cost per pound of N removal</td>
<td>$6.64</td>
<td>$42.91</td>
</tr>
</tbody>
</table>