OMA Discussion of Macroalgae Production and Density
Supplementary Information for "Negative Carbon via Ocean Afforestation"

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Two key factors for the success of Ocean Macroalgal Afforestation (OMA or Ocean Afforestation) are:

1. Macroalgae annual productivity: Many species of macroalgae grow rapidly. Marine biologists report annual productivity in dry tons/ha/yr. Each species of macroalgae has a different annual productivity in different locations and different years, depending on a number of variables listed below. Their ash free dry weight (AFDW) also varies considerably during the various seasons of the year and the stages in their growth cycles. Researchers in energy (particularly anaerobic digestion) report input feedstock as volatile suspended solids (VSS), which is essentially the same as AFDW.

The key issue is what amount can be practically and sustainably harvested for a given location and species. We have looked at the AFDW/ha/yr for likely feasible fast-growing macro-algae species, as reported in algal yields tab of the supplemental spreadsheet, "OMA Calculations." The available data seem to indicate that feasible sustainable annual harvest amounts vary from 6 – 90 ash-free tons/ha/yr, with an average value of 23 tons/ha/yr. We have used a conservative harvestable projection of about 18 ash-free tons per hectare per year, providing sufficient nutrients are available. (This is equivalent to 5 $g/m^2/day$.)

2. Macroalgae harvest fraction: We note that for some species in temperate climates, it appears that one harvest per year is optimal. For other species, such as kelp, it appears that four or more harvests per year of only the top meter, which quickly grows back in a few months, produce the optimal annual yield. In tropical climates, several harvests are also likely to be optimal. Some researchers using cultivated ponds report harvesting every two weeks is optimal. Our calculations assume two harvests per year as a conservative compromise for harvest frequency. The more times we harvest the more energy it takes to do the harvest, but maximizing the total annual tons harvested per forest is more important. We also want to sustain the productivity of the algal forest for fish and crustaceans.

Note that the amount available to be harvested will be reduced by the amounts eaten by fish and other predators, and occasional storms washing away the algae, so the harvest percentage is estimated at 75% as most likely, with 40% for the minimum, and 90% for the maximum harvest percentage.

Detailed Discussion

Over 200 references have been reviewed to provide the basis for the "Algal yields" tab of the OMA Calculations Supplement spreadsheet. Some authors have recommended average values worldwide, which include the most likely candidates for macroalgae species expected to be used in Ocean Afforestation around the world. The Algal yields tab reports the conclusions of the most recent review articles we have located, plus the older work by Chynoweth, which is still referred to by many authors. We have used an average ash-free percentage as 68% based on a survey of many articles (Chynoweth, et al., 1987; Esteves, et al., 2005; Freile-Pelegrín and Robledo, 2007; Lamare and Wing, 2001; Leese, 1976; Paine and Vadas, 1969; Taylor and Steinberg, 2005; Lenstra, et al., 2011).

The main variables contributing to annual sustainable productivity are:

1. Availability of key nutrients: especially nitrogen.
2. Speed of water movement through the algae growing area: fast enough to bring in the nutrients, but slow enough so the crop is not swept away (the speed limit varies with the species, e.g. benthic species are attached to the bottom, others are not).
3. Turbidity and depth can limit the sunlight reaching benthic species: but some prefer more light, others prefer less.
4. Water temperature limits rate of growth: some prefer higher, some lower temperatures.
5. Type and intensity of cultivation.

The Algal yields tab of the supplementary spreadsheet shows reported yield and density data for some likely species candidates based on the above criteria. We report only the yield and density data from ocean locations, since intensive, nutrient optimized ponds and tanks are not relevant to the ocean-based approach in this LCA. The ocean locations have many variables, such as:

1. Naturally occurring nutrients from natural ocean upwellings.
2. Nutrients from land runoff, including both human sewage and agricultural runoff.
3. Nutrients from adjacent fish farms.
4. Naturally growing stocks.
5. Human cultivated stocks.

The criteria for species selection to be considered in any practical energy generation should include the following criteria (in no particular order):

1. Reported as abundant
2. Already being harvested
3. Fast growing (high photosynthesis rates)
4. Relatively low ash content
5. Judged relatively easy to harvest
6. Sufficiently high density for economical harvesting
7. Likely to have ecosystem and human benefits, such as aiding biodiversity plus increased edible fish, mollusks, and crustacean populations
8. Sometimes found in excess, such as an "algal bloom."

The spreadsheet lists examples of the species currently identified as meeting some of the above criteria, for which we were able to find published data. There are many other potential species, but we did not include them because we did not find published data on annual yields.

The spreadsheet lists the date of publication, species, type of environment (such as in ponds or in natural wild surroundings), location, references, maximum and minimum densities reported in kg per square meter, and other reported data.

There are many ways macroalgae yield data is reported. Some data is reported as fresh or wet weight, other is reported as dry weight, which means the samples have been heated to about 60ºC to drive off the water, leaving only the "dry weight." Since only the organic compounds (the "ash-free" quantity) can be used by the bacteria to produce methane, all of the data has been converted in column N to "ash-free metric tonnes per hectare per year," (which is also indicated g AFDW/m2-d in column O).

An important factor in the growth rate is the presence or absence of nutrients, primarily nitrogen, which has generally been reported as the limiting factor for macroalgae. Ocean Afforestation will initially be done where there are sufficient natural nutrients to sustain initial harvestable densities of macroalgae. The approach is to recycle the ash remaining after anaerobic digestion. The recycling approach should provide more than sufficient nutrients to not only sustain the macroalgae growth, but to expand it to provide even greater yields.

We also note that the presence of various species of macroalgae is not a problem for OA, since all biomass of size larger than the net openings will be included in the harvest and will contribute to the methane production.

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