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A Study of Algal Biomass Potential in Selected Canadian Regions

Geoffrey T. Klise, Jesse D. Roach, and Howard D. Passell

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Abstract

A dynamic assessment model has been developed for evaluating the potential algal biomass and extracted biocrude productivity and costs, using nutrient and water resources available from waste streams in four regions of Canada (western British Columbia, Alberta oil fields, southern Ontario, and Nova Scotia). The purpose of this model is to help identify optimal locations in Canada for algae cultivation and biofuel production. The model uses spatially referenced data across the four regions for nitrogen and phosphorous loads in municipal wastewaters, and CO_2 in exhaust streams from a variety of large industrial sources. Other data inputs include land cover, and solar insolation. Model users can develop estimates of resource potential by manipulating model assumptions in a graphic user interface, and updated results are viewed in real time. Resource potential by location can be viewed in terms of biomass production potential, potential CO_2 fixed, biocrude production potential, and area required. The cost of producing algal biomass can be estimated using an approximation of the distance to move CO_2 and water to the desired land parcel and an estimation of capital and operating costs for a theoretical open pond facility. Preliminary results suggest that in most cases, the CO_2 resource is plentiful compared to other necessary nutrients (especially nitrogen), and that siting and prospects for successful large-scale algae cultivation efforts in Canada will be driven by availability of those other nutrients and the efficiency with which they can be used and re-used. Cost curves based on optimal possible siting of an open pond system are shown. The cost of energy for maintaining optimal growth temperatures is not considered in this effort, and additional research in this area, which has not been well studied at these latitudes, will be important in refining the costs of algal biomass production. The model will be used by NRC–IMB Canada to identify promising locations for both demonstration and pilot-scale algal cultivation projects, including the production potential of using wastewater, and potential land use considerations.

Acknowledgments

This work was done under funding support to Sandia National Laboratories from the Office of Biomass Program (OBP) within the US Department of Energy's Office of Energy Efficiency and Renewable Energy. The author's wish to thank Joanne Morello and Joyce Yang from OBP. We also thank Stephen J.B. O'Leary, Patrck McGinn and Shabanna Bhatti from NRC-IMB, Phil Pienkos from NREL, Jake Whalen from SmartWhale Consulting and Barbara Moreland and Ron Pate from Sandia National Laboratories for their support and insight.

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Acronyms and Abbreviations

C	carbon
CAD	Canadian dollar
CCOG	Canadian Council on Geomatics
CO_2	carbon dioxide
DOE	Department of Energy
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographic information system
ha	hectare
IMB	Institute for Marine Biosciences
N	nitrogen
NPRI	National Pollutant Release Inventory
NRC	National Research Council
NREL	National Renewable Energy Laboratory
P	phosphorus
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratories
TAG	triacylglyceride
U.S.	United States
WWTP	wastewater treatment plant

1. Introduction

One of the advantages of high lipid bearing microalgae as a feedstock for power generation or transportation fuels is that microalgae can be cultivated using water and nutrient resources from industrial and municipal waste streams. Algae can be grown using wastewater from municipal sewage treatment plants and CO_2 from fossil-fuel-fired electricity generation plants and other stationary industrial sources that would otherwise be directly released to the atmosphere (Ho et al., 2011; Zeng et al., 2011). In addition, algae can be grown on otherwise non-arable lands, and cultivation will only compete with food production if recycled nutrients are not utilized (Borowitzka and Moheimani, 2011). This is an issue that has also been explored with other biofuel feedstocks (Singh et al., 2011, Dismukes et al., 2008; Smith et al., 2010).

However, these waste streams and land resources are not always co-located or otherwise configured in such a way as to make their use in algae cultivation economical or sensible. In some cases wastewater with nutrients from sewage treatment or CO_2 from industrial processes will need to be moved some distance to the available land where large-scale algae cultivation and processing can occur. Also in some cases water, nutrients, CO_2, land, or some combination of these, may be inadequate for algae production at the required scales. Tools and processes are required to help identify optimal locations where sufficient resources exist within sufficient proximity of each other, and with appropriate climatic conditions. Scientists from Sandia National Laboratories (SNL) in the United States, the Institute for Marine Biosciences (IMB) from the National Research Council (NRC) Canada, the National Renewable Energy Laboratory (NREL) in the United States, and the U.S. Department of Energy (U.S. DOE) collaborated on the development of such a set of tools and processes.

The NRC–IMB is researching ways to commercialize the production of algae biomass primarily in regions of southern Canada. This poses a unique challenge due to the less-than-optimal growing conditions in terms of solar resource availability and ambient air temperatures needed for large-scale production (McGinn et al., 2011). Mitigating for these and other potential issues may prove to be expensive in terms of developing a biofuel product at scale with reduced GHG footprint that is also cost-competitive with a fossil-based fuel, especially in a country that has tremendous fossil fuel resources. However, the establishment in July 2011 of a national 2%

renewable biodiesel mandate in Canada, as well as other future measures to reduce greenhouse gas (GHG) emissions, may help lay the groundwork necessary for creating demand as well as a regulatory environment to allow for large-scale algae biofuel commercialization. Through the collaboration described above, the NRC–IMB aims to identify and characterize native algae strains that may have large-scale cultivation potential, and to determine areas suitable for locating its first pilot-scale cultivation facility in a way that takes advantage of the co-location of resources, land availability, and solar insolation.

Geographic assessments of areas suitable for algae production in North America initially focused on the U.S. southwest, due primarily in part to the high levels of solar radiation available for photosynthetic algae growth as well as the presence of inland brackish groundwater sources and large tracts of undeveloped public and private land (Vigon et al., 1982; Maxwell et al., 1985; Neenan et al., 1986). More recent research has focused on national level assessments in the United States. In the National Algal Biofuels Technology Roadmap, the U.S. DOE suggests southern U.S. latitudes are generally preferred, though northern latitudes may have potential if resources are co-located (USDOE, 2010, p.76). Pacific Northwest National Laboratory (PNNL) created a geobrowser tool to evaluate microalgae production and assessment at the 'unit farm' level over the entire continental United States (Wigmosta et al., 2009), and subsequent research by PNNL suggests that in terms of lessening impacts to water resources, locations near the Gulf Coast, the Eastern Seaboard, and near the Great Lakes would be ideal due to greater freshwater availability (Wigmosta et al., 2011). Pate et al. (2011) looked at resource (land, water, CO_2, N, and P) demand implications for algae biofuels scale-up in the United States for four production scenarios within four geographic regions, primarily focused in the southern half of the United States. These recent studies present a current 'snapshot' of resource availability using different scales, geographic perspectives, and assumptions of CO_2, water, nutrients, and land availability. Due to the abundant solar resource and more suitable temperature regimes in the southern United States, the conclusions of these studies generally point to the most favorable regions as being the southern latitude states.

There is a great deal of research being conducted worldwide looking at what is considered a more *sustainable* approach of using non-fresh water sources such as wastewater or seawater, and waste nutrient and CO_2 streams, all of which would otherwise be discharged into the waterways or the atmosphere. Using these water sources, algae can be grown at wastewater treatment plants (WWTPs) for biogas production through anaerobic digestion of algal biomass or direct production of algal biofuels (Lundquist et al., 2010; Christenson and Sims, 2011; Jiang et al., 2011; Park et al., 2011; Pittman et al., 2011; Rawat et al., 2011). Even more useful for our analysis, research into these processing techniques is being conducted with algae and nutrient streams from wastewater facilities at northern latitudes where light intensity is lower (Baliga and Powers, 2010; Wang et al., 2010; McGinn et al., 2011; Min et al., 2011; Zhou et al., 2011; Li Y et al., 2011). Lower levels of solar insolation at these higher latitudes will require a greater production 'footprint' for growing autotrophic algae in an open pond or photobioreactor when compared to the same production rates in more southern latitudes (assuming that artificial lighting is not used).

Due to the sunlight and temperature challenges in southern Canada, the co-location of nutrients, CO_2 and suitable land will be important to successful large-scale production efforts. The dynamic assessment tool developed by SNL and NRC-IMB can show tradeoffs for moving wastewater and/or CO_2 to areas of suitable land in terms of overall production and resource availability, as well as providing a preliminary look at costs of operation and for moving nutrients to the desired land area. This tool differs from traditional GIS analysis because it gives the model user the ability to immediately view dynamic spatial output based on user modifiable input assumptions. By identifying optimal areas for both demonstration and pilot-scale facilities, NRC–IMB can focus their resources into the more promising locations for potential scale-up.

It is important to note that our analysis is limited to nutrients derived exclusively from wastewater treatment and does not consider other sources, such as dairy or poultry waste, or any commercial fertilizer-type nutrients.

2. Methodology

2.1 Data Gathering

Four areas were delineated for this analysis by NRC–IMB to capture both the coastal and inland areas in locations of high and low population density, different land uses, and different quantities of, and access to, nutrients and CO_2 sources (Figure 1). These areas include metropolitan Vancouver and Victoria (southeastern Vancouver Island) in British Columbia, northeastern Alberta, southern Ontario (Great Lakes region) and the entire province of Nova Scotia. These areas were selected to take advantage of the presence of existing infrastructure, feedstocks, and/or markets which may support potential algae biomass and biofuel production.

Figure 1. Study areas in Canada for determining a location of a pilot-scale facility.

The model is designed to screen different WWTPs for dry algae biomass production at what NRC-IMB has defined for the purposes of this study as demonstration (500 kg day^{-1}) and pilot scale (1000 kg day^{-1}) within the context of available CO_2 and land resources and different algae production assumptions. Due to the theoretical nature of this study (there are no existing demonstration, pilot, or large-scale commercial algae production facilities in Canada), an easy to use graphic user interface was developed to give the user the ability to easily change the input parameters as more information becomes available. The model is a framework allows expert users to model certain production scenarios now and in the future with either theoretical or observation based data. The current version of the model requires multiple assumptions, which are explained in more detail in the subsections that follow.

The data used in the model were compiled from various sources available from the Canadian government and elsewhere. A report of potentially available data was compiled by Whalen (2010a) to determine which datasets would be most appropriate for the modeling efforts. A lack of data on wastewater treatment facilities led to an effort to contact many of the largest wastewater treatment facilities through an online survey to gain more insight into their operations (Whalen, 2010b). Data gathered for input in the model is presented in Table 1 along with the resolution and the source of the data. These data required some processing prior to use in the model.

Table 1. Summary of geospatial data used in the model for developing algae production scenarios.

Data Type	Resolution	Source
Carbon dioxide – stationary sources	Stationary point sources reportable to Environment Canada's National Pollutant Release Inventory (NPRI) for facilities that emit greater than 50,000 tonnes of CO_2 equivalent or more in a year.	Environment Canada (2011). Individual facility data is available at: http://www.ec.gc.ca/inrp-npri/default.asp?lang=en
Wastewater Treatment Facilities (NPRI)	Stationary point sources of 67 wastewater facilities reportable to Environment Canada's NPRI for facilities that have reportable releases equal to or greater than 10 tonnes per year of nitrogen (total ammonia) and phosphorus into waterways.	Environment Canada (2010). Current substance list reporting requirements can be found at: http://www.ec.gc.ca/inrp-npri/default.asp?lang=En&n=E2BFC2DB-1
Wastewater Treatment Facilities (Survey)	Surveys were sent to 87 facilities with 58 responses of varying degrees of completeness. These also include the list of NPRI sites. Of the 58 total responses, 36 provided more detailed data in spreadsheet format.	Data compiled by Whalen (2011) from an online survey targeted at specific wastewater treatment facilities.
Solar Radiation	Solar radiation for each study area reported as the annual mean daily global solar radiation in MJ m^{-2}. Map scale is 1:12,500,000.	Energy, Mines and Resources Canada (1984).

Elevation	1 km gridded data published in 2008.	ArcGIS 9 media kit – Elevation and Image Data – World.
Land Cover	The land cover data was derived from 1:250,000 scale grids that were merged and converted into polygon features for analysis.	Canadian Council on Geomatics (CCOG) 2000. Geobase: http://www.geobase.ca/geobase/en/index.html

2.1.1 Carbon Dioxide

The information on stationary CO_2 sources contained in the analysis includes National Pollutant Resource Inventory NPRI identification, latitude, longitude, province, facility name, company name, and the total annual discharge of CO_2. Because of threshold reporting requirements, the NPRI data only include values for sources larger than 50,000 tonnes yr^{-1}. We assume that either as a fraction of flue gas, or in pure form, the algal CO_2 requirement (up to source size) is made available for algal uptake. Our analysis focused on 75 large, quantified sources for which emissions data were available. Many smaller sources exist for which no quantitative information was available. These large sources are distributed in the regions as follows: Alberta –14; Nova Scotia–8; southern Ontario–44; and Vancouver/Victoria–9.

2.1.2 Wastewater

Wastewater treatment facility effluent composition was obtained from Canada's NPRI data. Nitrogen is a key feedstock for algae and is abundant in wastewater, and is reported as total ammonia (NH_3 and NH_4^+). Phosphorus is also important for algae growth, and is reported by NPRI as total phosphorus as phosphorus equivalents (PO_4). The pollutant volumes represent different levels of treatment, as these requirements may differ in each province. Some facilities had only one value reported, typically ammonia, and not phosphorus. This data source only includes facilities regulated at the 10 tonne yr^{-1} threshold and excludes smaller facilities which may discharge detectable concentrations of both nitrogen and phosphorus below this threshold.

An additional source of wastewater data was compiled from an online survey (Whalen 2010b). Questions included the population served, sludge de-watering techniques, use of anaerobic digestion, methane production, CO_2 emissions, levels of treatment for nitrogen, phosphorus and dissolved organic carbon in the waste stream, effluent discharge volumes and temperatures, and adjacent CO_2 emitters, if known. This information will be useful to NRC–IMB for gaining insight into specific facility configurations, water discharge volumes and treatment types and levels.

For the purposes of this analysis, it is assumed that annual average wastewater discharge volumes are sufficient for algae cultivation, as volumetric discharge data were not available for all wastewater facilities. For cost calculations however, the nitrogen (as ammonia) and phosphorous loads were assumed to be 20 and 10 mg l^{-1} respectively. The number of wastewater facilities used in the analysis is as follows: Alberta–1; Nova Scotia–8; southern Ontario–46; and Vancouver/Victoria–12.

2.1.3 Solar Radiation and Temperature

Annual solar radiation data available from the Canadian government (Energy, Mines and Resources Canada, 1984) were used as input for the algae growth portion of the model, with the assumption that only autotrophic algae species will be analyzed in an open pond system. These default regional values (4393 MJ m^{-2} yr^{-1} for Alberta and Nova Scotia, 4937 MJ m^{-2} yr^{-1} for southern Ontario, and 4184 MJ m^{-2} yr^{-1} for Vancouver/Victoria) can be adjusted by the model user if more site-specific information is available.

The climate of each study area is a very important aspect in the overall feasibility, as portions of fall, winter, and spring months are cold enough to warrant a heating source to keep the ponds operational. For this effort, ambient temperature data is assumed to be adequate and we also assume that the wastewater is generally warm due to heat generated in the active biological process during treatment. However, that heat will dissipate quickly when transferred to large uncovered algae cultivation systems; therefore, supplemental heat would be necessary. If a CO_2 source were co-located, the use of waste heat is an option, but this is not explored in this paper. For this analysis, it is assumed that desired temperatures can be maintained, and that when a type of facility is determined by NRC–IMB for pilot and demonstration scale (open pond, photobioreactor, or hybrid system), a more detailed analysis of the energy required and associated cost for a certain size production facility could be modeled. At this time, the model does not conduct this type of analysis; nor does the model calculate the energy (and costs) required to maintain water and air temperatures appropriate for algae cultivation, although these requirements could raise the energy demands considerably.

2.1.4 Land Availability

Land cover analysis was used to identify potential locations for algae production. The data used represent year 2000 land cover in the four study areas (Canadian Council on Geomatics, 2000). Land use category attributes were merged to allow for easier analysis with the remaining dataset consisting of grassland, shrubland, and forest/trees. At this scale, agricultural land is included in the grassland category. Further processing reduced the available land to contiguous areas greater than 10 ha (a simplifying assumption) with a slope between 0–1% based on Benemann et al. (1982) for use in the final datasets and analyses. Land ownership information was not available, and thus not included in this analysis.

2.1.5 Costs for Production Facility and Transporting Wastewater/CO_2

To get an idea of the costs associated with modeled production scenarios, an economics module was created within the model to look at the capital and operating costs for an open pond system based primarily on work performed by Benemann and Oswald (1996), supported where necessary by Benemann et al. (1982) and Weissman and Goebel (1987). This functionality represents a baseline estimate, as the model includes both the 30 and 60 g m^{-2} day^{-1} productivity cost estimates from Benemann and Oswald (1996) and takes 1996 U.S. dollars, which can then be adjusted for inflation (on a U.S. basis) for years 1997 to 2010. These values are then converted to Canadian dollars (CAD) with a user defined exchange rate. The user has the option to override the default values to include more detailed information that would be relevant to a specific facility, if those data are available. The costs are then calculated for producing algal biomass in units of USD and CAD $tonne^{-1}$.

For more detailed techno-economic work, Davis et al. (2011) present a framework for analyzing the costs for both open-pond and tubular photobioreactor systems, looking at the cost sensitivities of different stages in algal biofuel production. Recent work by Sun et al. (2011) provides a comparison of many different cultivation techniques and resulting cost of triacylglyceride (TAG) adjusted to 2008 U.S. dollars per gallon. Considering these recent efforts, we decided to start with the Benemann and Oswald (1996) study in order to utilize the capital and operating expense categories. This framework in our model allows work from studies such as Sun et al. (2011) and Davis et al. (2011) to be incorporated if desired by NRC-IMB. It is worth noting that one of the reasons costs are much higher for the other studies discussed in Sun et al. (2011) is due to the more expensive extraction techniques for converting algal biomass to algal oil. The cost analysis presented in this work only includes the cost of producing algal biomass, as requested by NRC-IMB, and different design assumptions can be made beyond what is presented as the model default setting. For example, if NRC–IMB would like to calculate the energy costs for heating and maintaining water at temperatures appropriate for cultivation, the inputs allow for adding the capital and operating expenses associated with that cost. This also applies for cases where they may want to look at using the biomass for conversion to a liquid fuel or for generating electricity. Section 3 shows some preliminary results using the costs of operating a theoretical facility.

2.1.6 Costs for Wastewater and CO_2 Transport

The costs for moving wastewater and CO_2 to a desired land parcel as presented in the economics module within the model were based on some of the same assumptions by Benemann and Oswald (1996), and supported where necessary by Benemann et al. (1982) and Weissman and Goebel (1987). More detailed equations for transporting CO_2 and wastewater in terms of pipe diameter, friction factors, pressure loss, and the energy costs for operations were done from work initially geared towards natural gas pipelines, and can be modified for moving both CO_2 and water. References to this work can be found in Munson at al. (1994), Parker (2004), McCoy and Rubin (2005), and McCollum and Ogden (2006).

There are three categories in the model for looking at capital and operating costs for moving CO_2 and wastewater from the source to desired production location. These include (1) costs of using straight flue gas blown from the power plant as the CO_2 source (CO_2 source and production facility must be less than 5 km); (2) costs of using pure CO_2 (compressed) that is moved to the production facility via truck or pipeline from the power plant; and (3) costs of wastewater transportation through a pipeline. Pipeline elevation changes are ignored. All base dollar figures for this are from 1996, but can be adjusted for different years within the model using a U.S. GDP historic price index. The model then calculates the amount in CAD using a user-defined exchange rate for the year being analyzed.

2.2 Model Development and Capabilities

This model was built to allow multiple custom inputs specific to algal growth that will assist NRC–IMB efforts to determine the best location for a pilot-scale facility. The data described above are stored in a spreadsheet and called by the model when necessary for estimating different scenarios. The model is relatively simple to use but powerful enough to deal with the complexities of conducting real-time geographic assessments for analyzing scenarios and tradeoffs. Powersim Studio 8, an object-oriented modeling platform, is used for this analysis in large part due to a user interface capability that allows users to change inputs via slider bars, switches, and dials, and view results dynamically in charts, graphs, and maps.

2.2.1 Determining Biomass and Algal Oil Production

The model is based on nutrient stoichiometry in waste streams, and algae cultivation. The default algae nutrient requirements are modeled after the Redfield ratio of carbon to nitrogen to phosphorous (Redfield, 1958), which is based primarily on saline algae species, and a ratio of hydrogen and oxygen to carbon from Bayless et al. (2003) (Figure 2). The user has the option to override those default inputs and use other elemental ratios. Nutrient uptake efficiencies for nitrogen, phosphorus, and carbon default to 100% based on NRC batch experiments (Patrick McGinn, personal communication, August, 2011) but are presented as slider bars for the user to adjust because in many cases the algae may not utilize all nutrients in the waste stream (Perez-Garcia et al., 2010; Sobczuk et al., 2000; Laws and Berning, 1991). The model calculates available nitrogen and phosphorus from the NPRI reported loads. In the case where either nitrogen or phosphorus data are missing from a WWTP, the user has the option to either assume that nutrient is unlimited, or ignore those facilities with missing data altogether. The model also allows a nutrient to be recycled. Options are available for looking at the distribution of all wastewater treatment facilities as a function of either the potential biomass produced, CO_2 fixed, algal oil (biocrude) produced, or land area required. Figure 2 gives an example of the distribution of potential biomass production for all four study areas.

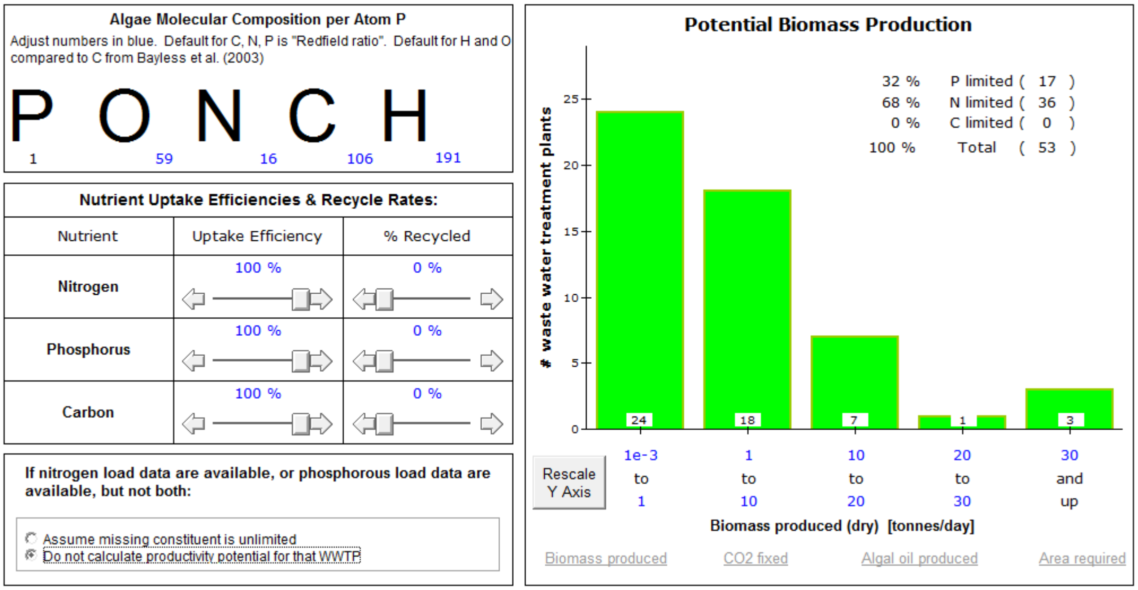

Figure 2. Example of model output for the number of WWTPs binned into average daily biomass production for all WWTPs in the four study areas. Nutrient concentration data is from NPRI reported results.

Spatial output options are available to view the potential biomass produced, CO_2 fixed, algal oil (biocrude) produced, and land area required to utilize the nutrients at each WWTP (Figure 3). The data presented in Figure 3 show the nutrient-limited potential biomass productivity as a function of the nitrogen and phosphorus loads at each WWTP, assuming sufficient CO_2 availability. This is the geographic disaggregation of the southern Ontario portion of the histogram of potential biomass production shown in Figure 2. Because this is a dynamic model, returning to the interface in Figure 2 and changing molecular composition, uptake efficiencies, or assumptions about missing nitrogen or phosphorus would change the productivities shown in Figure 3.

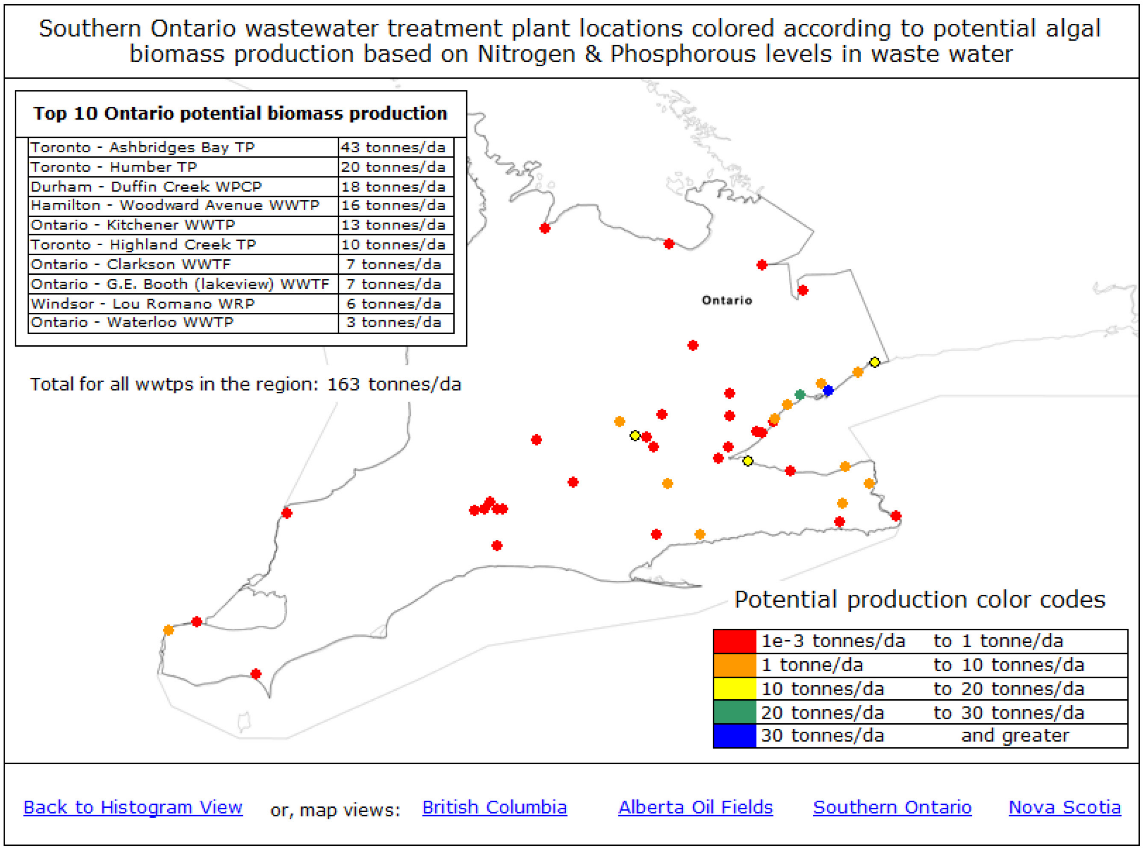

Figure 3. Southern Ontario WWTPs showing the nutrient-limited potential productivities for all NPRI reporting facilities. The output shown in this figure is a function of the efficiency assumptions and molecular composition presented in Figure 2.

Information about available solar insolation as well as specific parameters related to algae production are necessary for the model to return estimates of overall algal biocrude production (Figure 4) and overall land area requirements (Figure 5). Model defaults for determining algal oil productivities and area requirements for production are based on the *best case* assumptions presented in Weyer et al. (2010), and can be adjusted downwards for more realistic analysis. This includes a photon transmission percentage by region as well as the parameters inherent to specific algae species. Future work on the characteristics of native algal strains will provide more specific data that can be input to the model. Currently, by presenting these results as slider bars and input tables, the user can easily adjust these assumptions to analyze production results for other scenarios. The histogram presented in Figure 4 shows the overall distribution of the number of WWTPs and the potential algal biocrude that could be produced in all four regions as a result of the model inputs.

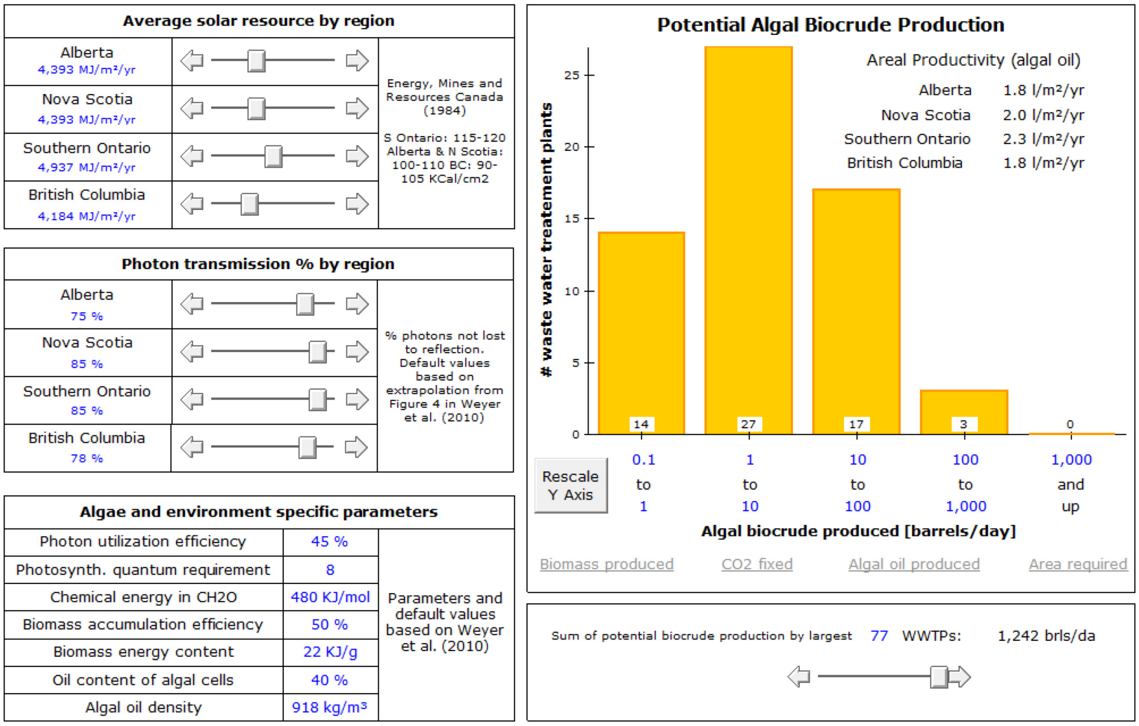

Figure 4. Potential algal biocrude production for all four study areas. The production scenarios are also a function of the efficiency assumptions and molecular composition presented in Figure 2.

2.2.2 Determining Land Area Requirements

The land area requirements are a function of the nutrient and solar energy requirements of the algae, the nutrient availability in the waste streams, and the solar energy availability per unit area of land. The histogram presented in Figure 5 shows the overall distribution of the number of WWTPs and the area that would be required to fully utilize the nitrogen and phosphorous nutrient loads of the WWTPs for all four study areas.

While the potential biomass produced, CO_2 fixed, algal oil (biocrude) produced, and areal requirements are all shown in the model interface as a function of nutrient sources and solar insolation, the land selection and economic module are different in that they are linked together to try and minimize costs associated with moving nutrients. In these two modules, for each WWTP the model looks for a land parcel of sufficient size whose location minimizes the cost of biomass production. The minimum cost land parcel is found by exhaustive search of all combinations of WWTPs, CO_2 sources, and sufficiently large land parcels. A land parcel in this case refers to a contiguous piece of land with the same land use and a slope of less than 1%, but with no land ownership information. Thus, the parcels considered by the model vary in size from 10 hectares (minimum size considered) to thousands of hectares.

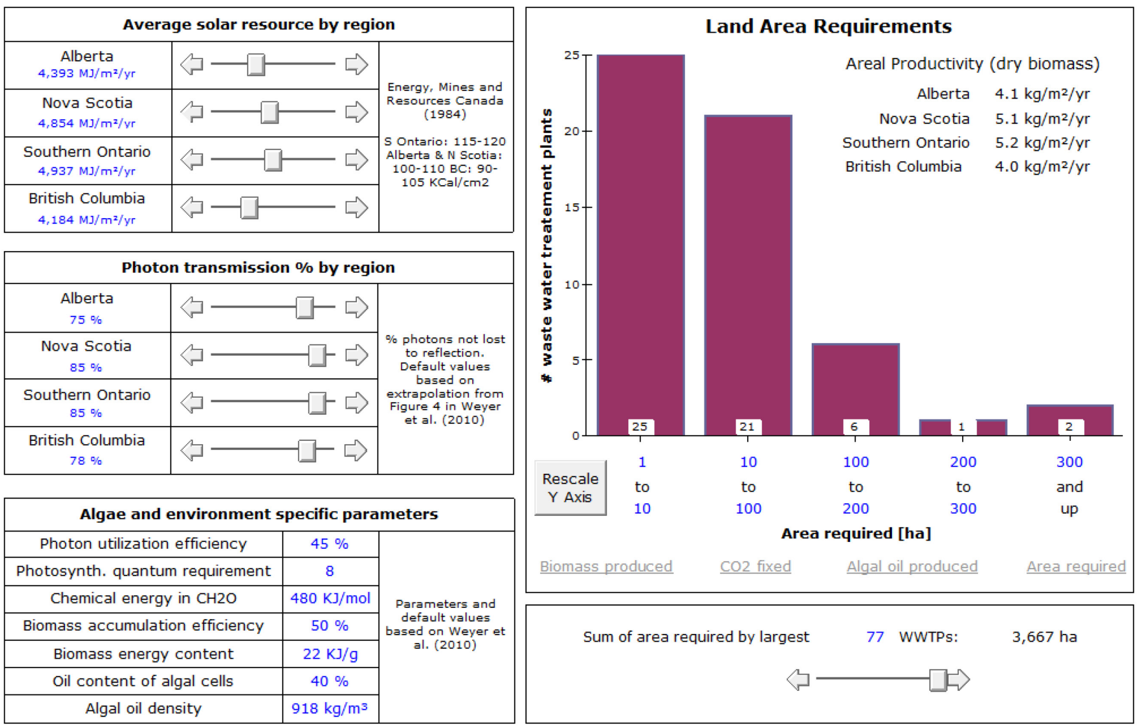

Figure 5. Land area requirements for areal productivity in all four study areas. Production scenarios are a function of the efficiency assumptions and algae biomass composition presented in Figure 2 along with the average solar resource, photon transmission percentage, and algae specific parameters.

Figure 5 shows an aggregation of all four study areas as a function of the distribution of nutrient limitations associated with wastewater facilities for dry algal biomass produced, CO_2 fixed, algal oil produced, and area required. An option for looking at individual wastewater facilities was created to gain a more detailed look into the land availability and potential distances to move both CO_2 and wastewater to the closest land parcel of sufficient size. Figure 6 gives an example for the Vancouver/Victoria area. After setting up the desired scenario as shown in Figures 2 and 5, the user can then choose an individual WWTP and have the model determine the straight line distance from the cost minimizing land parcel of sufficient size (grassland, shrubland, or forest/trees) to fully utilize the (limiting) nutrients from the WWTP and closest CO_2 source.

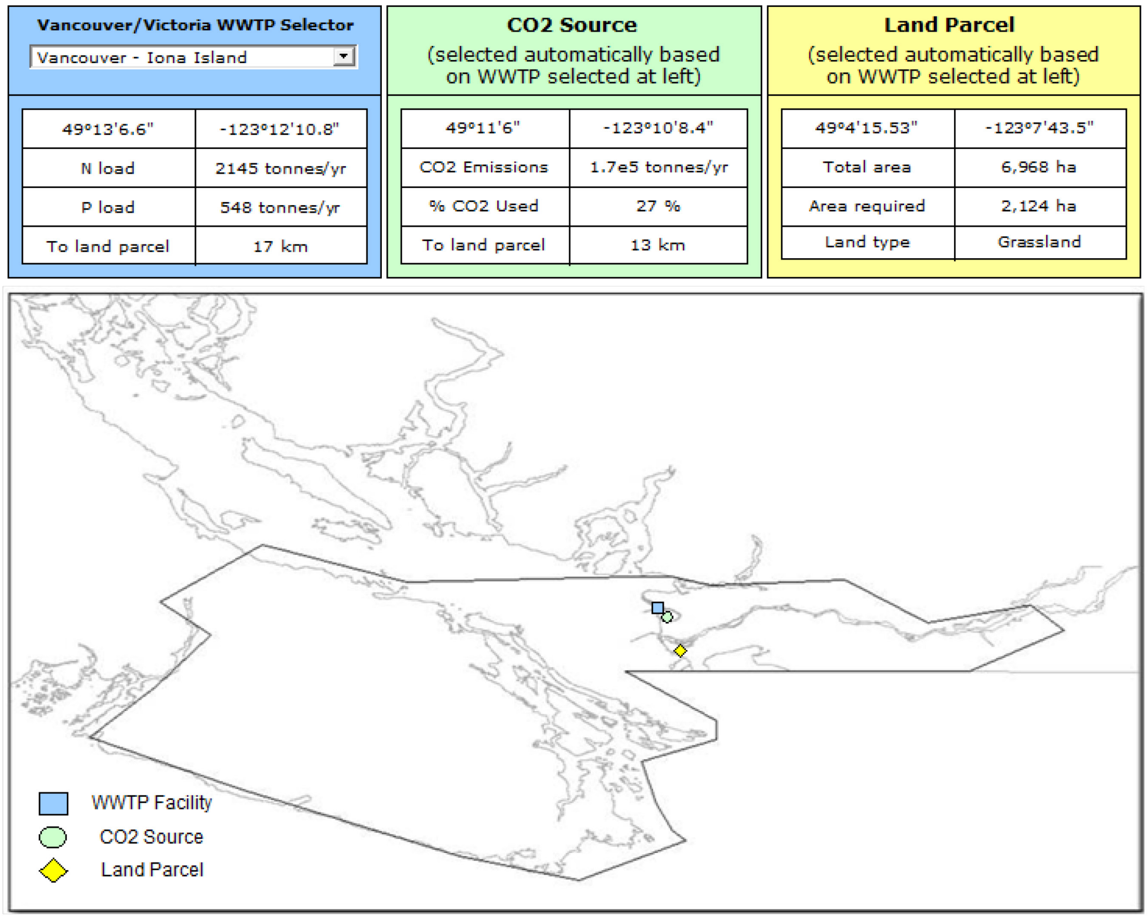

Figure 6. Example of the WWTP selector showing the shortest distances to move CO_2 and wastewater to a desired land parcel.

As the land requirements for algae biomass production are high and many WWTPs are in urban areas and bounded by a coastal or inland water source on one side (making it potentially difficult to co-locate onsite), the model was set up to look at moving water and CO_2 to a contiguous undeveloped land parcel that meets the needed area requirement. The model only looks at moving nutrients from one wastewater facility and one CO_2 facility at a time to the cheapest land parcel that is large enough to support the nutrient-limited production potentials. It is not possible at this point to choose individual land parcels, land types, or CO_2 sources, as the model determines this internally with a function that minimizes the cost to move wastewater and CO_2. The model user is given the option to determine what combination of land type categories will be used in the minimizing function. For example, the user can constrain the analysis to forested land and grassland (and exclude shrubland) or choose to look only at grassland and exclude both forest and shrubland. The cost of production is also analyzed in the selection of a land parcel, and is described in more detail below.

2.2.3 Cost Framework for Biomass Produced in an Open Pond System

To use economic considerations for selection of a land parcel, the model must have the costs to move wastewater, as well as the costs to move either pure CO_2 or flue gas. Because of toxicity and corrosive effects when compressed, heterogeneous flue gas cannot be efficiently moved any significant distance. The CO_2 can be moved any distance as pure CO_2, either by pipeline or truck. Based on CO_2 and water volumes to be moved, the model calculates the diameter of pipeline that would be required for transmission. Average natural gas pipeline costs as a function of diameter reported in Parker (2004) are used to estimate CO_2 and water pipeline capital costs. Pipeline operating costs are added as a fraction of capital costs. For water, electricity costs necessary to overcome head losses are also added. The model assumes that CO_2 is available at all power plant sources either at no cost as flue gas (where there could be a financial or regulatory incentive for a power plant to sequester or re-use the CO_2), or for \$40 tonne^{-1} (1996 dollars) in pure compressed form (which includes the costs of compressing and purifying the CO_2) (Benemann and Oswald, 1996), which would then need to be moved by pipeline or truck to point of use. Following Benemann et al. (1982), pure CO_2 can be transported (presumably by truck) for \$10 ton^{-1} per 50 miles (assumed to be 1981 dollars). Costs for moving the flue gas 5 km are given in Benemann and Oswald (1996), and are assumed to be the same for any distance up to 5 km. For pure CO_2, in default cases the trucking costs were less than pipeline costs for all CO_2 sources. The energy costs for transport are included in the cost estimates.

Figure 7 shows the options for looking at the biomass cost as a function of the type of CO_2 utilized, where the model is forced to look at pure CO_2 or flue gas only, or determine the lowest cost option between the two for moving CO_2. It is worth mentioning that when flue gas is chosen as the CO_2 source, distances to move it to a land parcel are constrained to 5 km, which will then force the wastewater to potentially be moved further to get to the desired land parcel.

Figure 7. Histograms showing the output for three options for determining which cost the model will use for moving CO_2. All WWTPs analyzed in the model are included.

Once all location and CO_2 type-specific costs have been calculated and a minimum cost location and CO_2 type selected for each WWTP, all remaining costs are added following Benemann and Oswald (1996). These include costs that are dependent on areal productivity. For these situations, the areal productivity calculated for each WWTP is used to calculate the specific cost.

3. Scenario Analysis and Results

The analysis presented below shows the results of three production scenarios for nutrient-limited algae production within the four areas in Canada, and discusses the sensitivities of certain parameters including desired land cover classification, nutrient uptake efficiencies, and algae specific parameters. An analysis of moving wastewater and CO_2 to the cheapest available land parcel is made in order to determine if there are any regional considerations or overall trends in the type of available land and to what degree the parcels are co-located with the wastewater and CO_2 sources. Additionally, a preliminary analysis of cost is presented as a series of cost curves for producing algal biomass for all parcels of land within each study area, based on the Benemann and Oswald (1996) framework for an open pond system.

To set up the model for analysis, the following inputs in Table 2 are based on the *theoretical maximum* and *best case* from Weyer et al. (2010), and the modified best case specific to the authors' *Chlorella vulgaris* spp. scenario, but also using additional parameters derived from research by Perez-Garcia et al. (2010), Sobczuk et al. (2000), and Laws and Berning (1991) that look at nutrient uptake efficiencies. For all analysis results, the region specific solar resource was used with assumed autotrophic growth in open ponds.

Table 2. Inputs for simulation model for each of the study areas. Our analysis uses values and methods derived from published literature. Values underlined and in bold represent a change from the preceding scenario.

	Nitrogen uptake efficiency (%)	Phosphorus uptake efficiency (%)	CO_2 uptake efficiency (%)	Solar Resource ($MJ.m^{-2}.yr^{-1}$)	Photon transmission (%)	Photon utilization efficiency (%)	Photosynthetic quantum requirement	Chemical energy in CH_2O ($kJ.mol^{-1}$)	Biomass accumulation efficiency (%)	Biomass energy content ($kJ.kg^{-1}$)	Algal oil content (%)	Algal oil density ($kg.m^{-3}$)
Theoretical Maximum 'Modified'[i]												
Alberta	100	100	100	4393	75	100	8	483	100	22	50	918
Nova Scotia				4393	85							
Southern Ontario				4937	85							
Vancouver/Victoria				4184	80							
Best Case[i]												
Alberta	100	100	100	4393	75	<u>**50**</u>	8	483	<u>**50**</u>	22	50	918
Nova Scotia				4393	85							
Southern Ontario				4937	85							
Vancouver/Victoria				4184	80							
***C. vulgaris* Best Case[ii]**												
Alberta	<u>**17**</u>	<u>**21**</u>	<u>**75**</u>	4393	75	50	8	483	50	22	<u>**35**</u>	918
Nova Scotia				4393	85							
Southern Ontario				4937	85							
Vancouver/Victoria				4184	80							

i – Uses parameters from Weyer et al. (2010), with the exception of solar resource data, which is specific to the four regional study areas. The model assumes autotrophic growth in an open pond.

ii – Utilizes assumptions described in 'i' as well as *C. vulgaris* specific parameters including: N and P uptake efficiencies from Perez-Garcia et al. (2010), CO_2 uptake efficiency derived from Sobczuk et al. (2000) and Laws and Berning (1991), and algal oil density derived from Liang et al. (2009).

3.1 National Level Results

High level results from all four study areas for the three different scenarios presented below in Table 3 show which nutrients are limiting, and the total distance to move CO_2 and wastewater to the land parcel. In these scenarios we optimize for the cheapest geographic configuration for moving wastewater and CO_2 to a land area that can fully utilize the resources. Costs are not analyzed for these scenarios. The goal of these scenarios is to look at the aggregate of all wastewater facilities in terms of the different production scenarios in a wastewater constrained system and be able to compare productivity results and tradeoffs across each study area.

For the 14 wastewater facilities that are missing nitrogen or phosphorus data, a model option was utilized to assume the missing nutrient is unlimited, allowing for an analysis of all wastewater facilities. There are no changes from the theoretical maximum to the best case scenario for which nutrient is limiting (Table 3). However, a change in nutrient uptake efficiencies (Table 2) increases the number of facilities that are nitrogen-limited and decreases the facilities that are phosphorus-limited. For all scenarios, there is sufficient carbon from CO_2 sources within 100 km reasonable distances, and that carbon is not found to be limiting. These results are directly attributable to the molecular composition and nutrient uptake efficiencies.

Table 3. Percentage and number of WWTPs in the model where nitrogen (N), phosphorus (P), or carbon (C) is the limiting nutrient.

	N-Limited (%, #WWTPs)		P-Limited (%, #WWTPs)		C-Limited (%, #WWTPs)	
Assume missing nutrient is unlimited						
Theoretical Maximum 'Modified'	73%	49	27%	18	0%	0
Best Case	73%	49	27%	18	0%	0
***C. vulgaris* Best Case**	79%	53	21%	14	0%	0
Facilities with both N and P						
Theoretical Maximum 'Modified'	68%	36	32%	17	0%	0
Best Case	68%	36	32%	17	0%	0
***C. vulgaris* Best Case**	75%	40	21%	13	0%	0

Because one of the objectives of algae biofuel production is to lower overall GHG emissions associated with fuel production and combustion, the removal of forested land for the installation of algae production facilities may not be viable. There may also be political and social issues that would make it difficult to utilize forested land. For all study areas, comparing the total distance to move CO_2 and wastewater first by having the model choose the closest parcel, then constraining the model to choose grassland, results in a 7–8% increase in total distance to move CO_2 and wastewater, with increased distances for all study areas ranging between 106 and 126 km (Table 4). Additional analysis would be required to evaluate whether the life cycle impacts of clearing grasslands that are farther away or forested land that is closer would result in a change in GHG emissions.

Table 4. Total distance to move wastewater and CO_2 to desired land parcel (all four study areas) comparing the model choosing the closest parcel and constraining model to choose grassland only.

Model Choice	To closest land parcel (km)	To closest grassland parcel (km)	Change in total distance (%)
Theoretical Maximum 'Modified'	1444	1570	8 ↑
Best Case	1503	1609	7 ↑
***C. vulgaris* Best Case**	1438	1549	7 ↑

The next analysis presented illustrates the overall potential for dry algal biomass production, algal biocrude production, fixed CO_2, and areal productivities for dry algal biomass and algal oil, assuming algal biomass would be generated from wastewater at each location in the study area. The results in Table 5 are based on the inputs presented previously in Table 2.

The change between model output from the theoretical maximum and the best case are in the areal productivities, where there is a 75% decrease in dry biomass and algal oil productivities. The number of barrels produced per day stays the same as the model essentially increases the area required to compensate for a decrease in the photon utilization efficiency and biomass accumulation efficiency. Comparing the best case to the *C. vulgaris* case for all four study areas shows about an 80% reduction in potential dry algal biomass production and CO_2 fixed for all four regions with algal areal oil productivity dropping by about 30% and biocrude production decreasing by almost 90%. Based on the results presented above, the Vancouver/Victoria area represents the greatest production potential primarily due to nutrient load from 12 WWTPs reporting to NPRI Canada. Southern Ontario is the next highest despite having 34 more WWTPs than the Vancouver/Victoria study area. As evidenced by the inputs presented in Table 2, these decreases in modeled output are attributable to decreases in nutrient uptake efficiency, photon utilization, biomass utilization efficiencies, and algal oil content. In terms of potential biocrude production from the *C. vulgaris* scenario comparing Vancouver/Victoria to the other study areas, this region has the potential to generate 34% more biocrude than southern Ontario, 93% more biocrude than Nova Scotia, and close to 100% more biocrude than Alberta. These results are based on assumptions discussed earlier in this paper.

Table 5. Results for algae production, areal productivities, and CO_2 fixed for the three scenarios applied to each study area. Summaries of each analysis category are presented at the end of each scenario.

	Dry algal biomass production (tonnes day^{-1})	Potential CO_2 fixed (tonnes day^{-1})	Dry algal biomass areal productivity (kg m^{-2} yr^{-1})	Algal oil areal productivity (L m^{-2} yr^{-1})	Algal biocrude production (brls day^{-1})
Theoretical Maximum 'Modified'					
Alberta	0.02	0.04	18.4	10.0	0.08
Nova Scotia	19	34	20.8	11.3	66
Southern Ontario	163	286	23.4	12.7	559
Vancouver/Victoria	271	474	18.7	10.2	928
Total	*453*	*794*	*81.3*	*44.2*	*1553*
Best Case					
Alberta	0.02	0.04	4.6	2.5	0.08
Nova Scotia	19	34	5.2	2.8	66
Southern Ontario	163	286	5.8	3.2	559
Vancouver/Victoria	271	474	4.7	2.5	928
Total	*453*	*794*	*20.3*	*11.0*	*1553*
***C. vulgaris* Best Case**					
Alberta	0.004	0.007	4.6	1.8	0.01
Nova Scotia	3	6	5.2	2.0	8
Southern Ontario	31	54	5.8	2.2	75
Vancouver/Victoria	47	82	4.7	1.8	113
Total	*81*	*142*	*20.3*	*7.8*	*196*

3.2 Production Feasibility for Scaled Analysis

As NRC–IMB is interested in the ability of the WWTPs to meet the threshold demand of 500 kg day^{-1} dry biomass production for a demonstration scale facility and 1000 kg day^{-1} for a pilot-scale facility, the model was configured to show the results of the different scenarios for each study area (Table 6). Costs are not included in this scenario analysis.

Table 6. Results showing the number of WWTPs that meet the demonstration and pilot-scale thresholds along with the total area required within the study area.

	Number of Facilities that meet Demonstration Scale (500 kg day^{-1}) Dry Biomass Production	Number of Facilities that meet Pilot Scale (1000 kg day^{-1}) Dry Biomass Production	Total Area Required for 500 kg day^{-1} Dry Biomass Production (ha)	Total Area Required for 1000 kg day^{-1} Dry Biomass Production (ha)
Theoretical Maximum 'Modified'				
Alberta	0	0	0	0
Nova Scotia	8	6	33	31
Southern Ontario	26	17	246	237
Vancouver/Victoria	12	12	521	521
Best Case				
Alberta	0	0	0	0
Nova Scotia	8	6	132	122
Southern Ontario	26	17	981	946
Vancouver/Victoria	12	12	2091	2091
***C. vulgaris* Best Case**				
Alberta	0	0	0	0
Nova Scotia	3	1	17	8
Southern Ontario	11	10	170	166
Vancouver/Victoria	9	8	354	348

As shown above, the total area required is the sum of the area needed from the contributing facilities that at a minimum meet the dry biomass production threshold. Between the theoretical maximum and best case scenarios, the number of facilities stays the same, but the total area required increases. Comparing the best case and the *C. vulgaris* scenario, the number of suitable facilities drops for all areas and the total area required also decreases. Between the theoretical maximum and best case for Vancouver/Victoria, all facilities meet both thresholds, with only one that does not meet the pilot-scale threshold for the *C. vulgaris* scenario. For each scenario, southern Ontario has the highest number of facilities that meet both thresholds, followed by Vancouver/ Victoria and Nova Scotia. The single WWTP analyzed in Alberta does not have a sufficient nutrient load to meet the required biomass production thresholds. The decrease in area required between the 500 and 1000 kg day^{-1} scenarios is due to the decrease in facilities that can meet that production threshold. Also, the number of facilities in Vancouver/Victoria is less than southern Ontario as shown in Table 6, though productivities are higher at the Vancouver/Victoria facilities when compared to southern Ontario (Table 5), primarily due to higher nutrient concentrations.

3.3 Available Land Results

The model also utilizes the same framework of inputs as described above to present the results of different land availability options and total area required as a function of the nutrient load at individual WWTPs. Like the scenarios in sections 3.1 and 3.2, costs are not included in this available land analysis. Figure 6 shows the model interface for Vancouver/Victoria. For the three input scenarios (Table 2) and results in this section, 66 wastewater facilities were analyzed with the model choosing the closest CO_2 source and the closest land parcel. The model was also run with all three scenarios constraining the land parcel types to grassland. Overall, the model chooses primarily between forest and grassland, as shrubland percentages are much lower, with the highest percentage of total available shrubland (10%) occurring in Nova Scotia.

For the theoretical maximum case, having the model choose the closest parcel results in 42% chosen as forest and 58% as grassland in Vancouver/Victoria, which is representative of the proportion of forest and grassland under 1% slope in that study area. The percentage of grassland increases to 82% when moving to the best case and to 63% overall when looking at the *C. vulgaris* case. The increase in grassland is due to the greater availability of grassland as larger parcels are required to grow the algae if the photon utilization and biomass accumulation decrease. The decrease from the best case to *C. vulgaris* is due to the drop in nutrient uptake efficiencies and algal oil content. For southern Ontario with a larger amount and proportion of grassland than forested land, results were reversed. There was a large decrease (78% to 58%) in the amount of grassland (and subsequent increase in forested land) when comparing the theoretical maximum to the best case. The grassland percentages in southern Ontario are about the same when comparing the theoretical maximum case to the *C. vulgaris* case. For both Nova Scotia and Alberta, forested land parcels are chosen exclusively over grassland and shrubland, with forested land representing 70% and 87% of the total available land, respectively.

Looking at every facility available, and not just the ones that meet the production thresholds as presented above in Table 6, the total land required in each study area (which is a function of the nutrient-limited production and areal productivities), along with the percentage of that land category from the total available land of that category, is presented in Table 7. Results for the model choosing the land or constraining the land to shrubland (not presented here) are essentially the same in terms of total area required, however the percentage of utilized land from the total available land of that category are different. Due to decreased photon utilization efficiencies, the land requirements increase 72–75% between the theoretical maximum and best case for all study areas, and then due to reduced nutrient uptake, total land requirements decrease 81–83% between the best case scenario and the *C. vulgaris* scenario.

Table 7. Results of land area required from each scenario along with the change in land area comparing theoretical maximum to best case, and best case to *C. vulgaris*.

Area Required	Theoretical Maximum 'Modified' (ha)	Best Case (ha)	*C. vulgaris* Best Case (ha)	% Change (Theoretical Max. to Best Case)	% Change (Best Case to *C. vulgaris* Best Case)
Alberta	0.05	0.18	0.03	72 ↑	83 ↓
Nova Scotia	33	132	23	75 ↑	82 ↓
Southern Ontario	251	1001	191	75 ↑	81 ↓
Vancouver/Victoria	521	2091	363	75 ↑	83 ↓

To put the results of land required in perspective, when the model chooses the closest available land using the best case results from all Vancouver/Victoria wastewater facilities, which also have the highest area requirements (Table 6), the required area is at most around 1.5% and 3.1% of available (1% slope or less) forested land and grassland, respectively. When the model is forced to choose grassland exclusively in Vancouver/Victoria, the required area rises up to 3.8% of available grassland. For the other three study areas, the required land areas represent less than 1% of the total available (1% slope or less) land whether the model chooses the closest land or is forced to look only at grassland.

Plotting algal biocrude production against the minimum distances needed to move wastewater and CO_2 illustrates optimal combinations (Figure 8). The best combinations represent locations that have the highest potential biocrude production as well as the shortest distance to move both wastewater and CO_2 (not including costs). For example, in the best case scenario with the model choosing from all available land categories, two potential land parcels in Vancouver/Victoria and two in southern Ontario represent production greater than 20,000 barrels yr^{-1}, and a distance to move wastewater and CO_2 below 10 km. The remaining land parcels represent greater distances for moving wastewater and CO_2, and have lower potential productivity based on the wastewater nutrients.

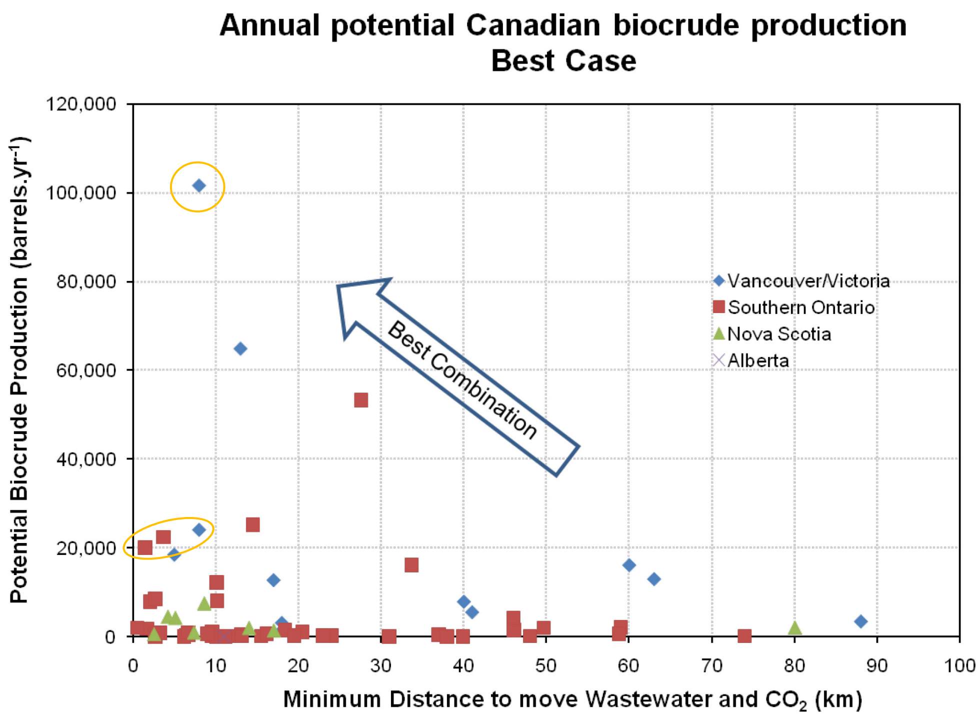

Figure 8. Scatterplot of potential annual biocrude production vs. the minimum distance to move both wastewater and CO_2. Circled locations represent the highest productivity/lowest transport for two locations in Vancouver/Victoria and Southern Ontario.

When looking at the potential annual biocrude production as a function of land area for all scenarios, there is a linear relationship between the slope of the trend line and the land required. This is a function of the average annual photosynthetic requirements for each region (Figure 9). As shown in Figure 4, southern Ontario has the highest solar resource, followed by Nova Scotia, Alberta, and Vancouver/Victoria. Translating this into biocrude production and land area shows the nutrient-limited production for the three different scenarios. A trend line for Alberta is not shown in this figure as there is only one location analyzed for this study. This relationship varies depending on the model input parameters, and can be used to determine potential biocrude production for a variety of land areas or vice versa.

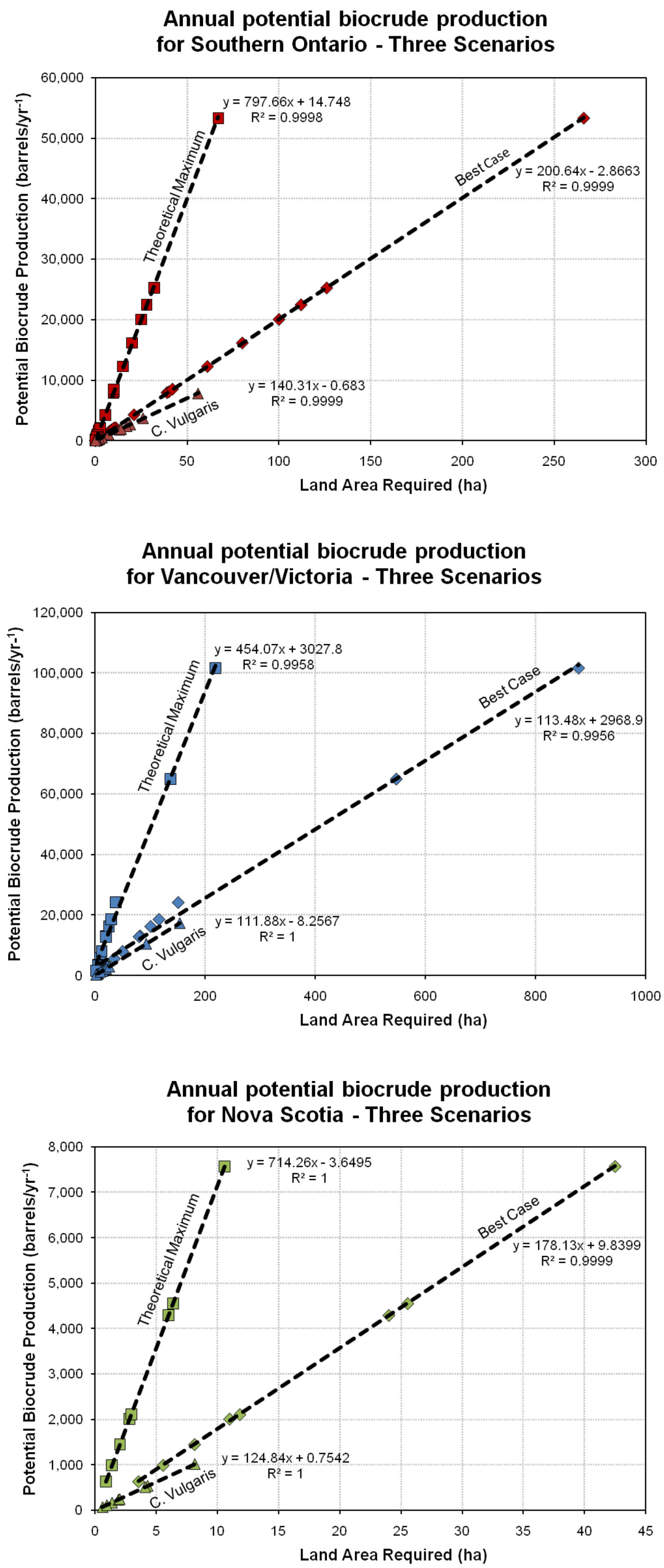

Figure 9. Scatterplot of potential annual biocrude production vs. the required minimum land area for that production scenario.

3.4 Open Pond Cost Framework Results

As discussed earlier, the open pond framework costs in the model are based on costs initially proposed by Benemann and Oswald (1996) for an open pond production facility, along with detailed transportation costs also from Benemann and Oswald (1996) and others for moving CO_2 and wastewater. These costs are translated into 2010 CAD for this report. Because a pilot or demonstration scale facility has not yet been constructed in Canada, the primary purpose of looking at costs is to determine where to site these facilities in the four study areas. Cost estimates here are preliminary and will change with greater data on specific algae characteristics and facility design parameters.

Figure 10 shows cost curves developed using four scenarios, including the three model scenarios and one more for comparative purposes: theoretical maximum, best case, *C. vulgaris* best case, and *C. vulgaris* best case where 50% of the wastewater nutrients are recycled. These curves show the relationship between the biomass production costs in CAD $tonne^{-1}$ and the cumulative biomass production potential in tonne yr^{-1}. The orange circles on the curves are locations where the model chose to use pure CO_2 and the black squares on the curves are locations where the model chose flue gas CO_2, with both sets of locations defined by nutrient availability at WWTP facilities. For each scenario, the order of WWTPs as shown by the points on the curve represents a different order of facilities, as there are factors that may make the cost effectiveness of, for example, a high productivity site change due to the different assumptions about algal growth. The first ten sites for each scenario as shown on the cost curve are shown in Table 8 where the order of facilities is different for each scenario. The Appendix shows the full tabular results of the four scenarios in Figure 10. The biggest change between the best case scenario and the two *C. vulgaris* scenarios are reductions in the nutrient update efficiency, which has a large impact on the overall cost to produce algal biomass. Adding in a 50% recycle rate for nitrogen, phosphorus, and CO_2 moves that curve down and toward the right, but nowhere close to the best case scenario where all nutrients were assumed to be utilized by the algae.

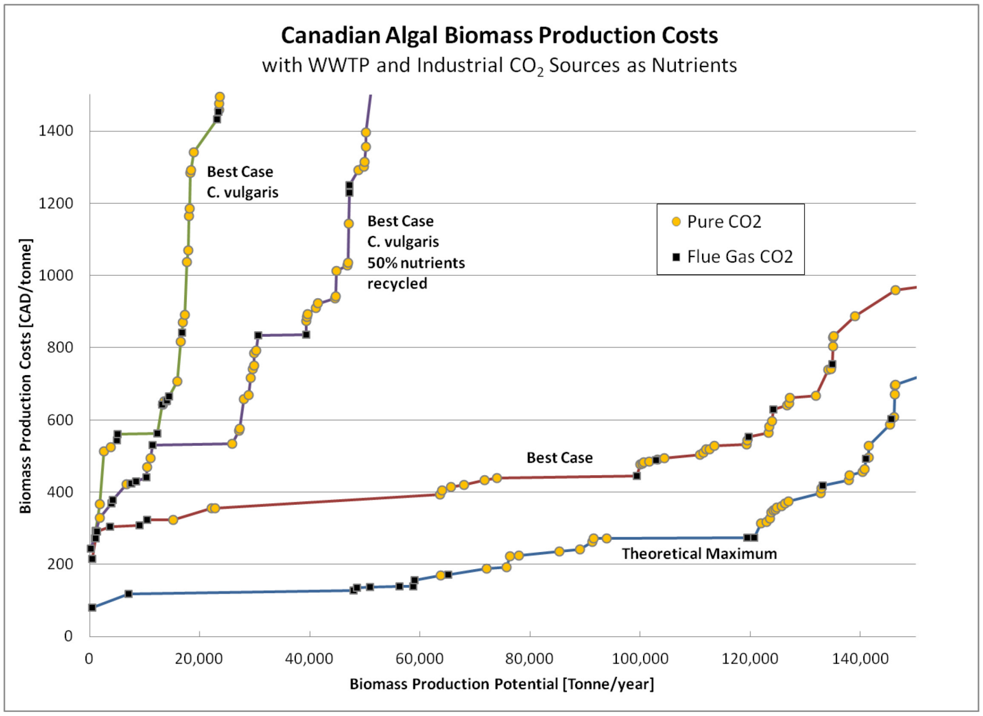

Figure 10. Cost curve of four different production scenarios with biomass production costs vs. the cumulative biomass production potential.

Southern Ontario has between 60–80% of the top ten locations with the lowest cost. These are primarily dominated by the potential to transfer flue gas due to the close proximity of both the power plant and WWTP to the desired land area. Vancouver/Victoria follows next with 20–30% of the top ten locations. Nova Scotia ends up with 10% (one location) in the theoretical maximum and best case scenarios, but is not within the top ten in the more 'realistic' scenarios in terms of algae utilization of nutrients.

Table 8. Top ten WWTP sources with the lowest production cost for each production scenario. Biomass cost in CAD $tonne^{-1}$ is the cumulative cost. Halifax locations are shown in green; Vancouver locations are shown in yellow. Remaining locations are in southern Ontario.

Theoretical Maximum				*Best Case*			
WWTP	Cumulative Biomass Produced (tonne yr^{-1})	Biomass Cost (CAD $tonne^{-1}$)	CO_2 type	WWTP	Cumulative Biomass Produced (tonne yr^{-1})	Biomass Cost (CAD $tonne^{-1}$)	CO_2 type
Niagara - Port Dalhousie WWTP	516.73	79.26	Flue gas	Niagara - Port Dalhousie WWTP	516.73	215.03	Flue gas
Durham - Duffin Creek WPCP	7070.82	117.88	Flue gas	Brantford WPCP	1109.30	271.35	Flue gas
Vancouver - Annacis Island WWTP	47996.90	126.74	Flue gas	Halton - South East Oakville WTP	1395.70	290.92	Flue gas
Brantford WPCP	48589.46	135.58	Flue gas	Windsor - Lou Romano WRP	3713.50	303.81	Flue gas
Windsor - Lou Romano WRP	50907.27	136.41	Flue gas	Vancouver - Lions Gate WWTP	9120.57	308.54	Flue gas
Vancouver - Lions Gate WWTP	56314.33	138.32	Flue gas	Halifax - Eastern Passage WPCP	10449.26	323.19	Flue gas
Ontario - Clarkson WWTF	58799.92	138.72	Flue gas	Ontario - Kitchener WWTP	15161.26	323.31	Pure
Halton - South East Oakville WTP	59086.32	155.15	Flue gas	Vancouver - Lulu Island WWTP	22201.52	354.90	Pure
Ontario - Kitchener WWTP	63798.31	168.34	Pure	Niagara - Welland WWTP	22796.39	356.09	Pure
Halifax - Eastern Passage WPCP	65127.01	170.61	Flue gas	Vancouver - Annacis Island WWTP	63722.47	393.60	Pure

C. vulgaris Best Case				*C. vulgaris Best Case - 50% recycled nutrients*			
WWTP	Cumulative Biomass Produced (tonne yr^{-1})	Biomass Cost (CAD $tonne^{-1}$)	CO_2 type	WWTP	Cumulative Biomass Produced (tonne yr^{-1})	Biomass Cost (CAD $tonne^{-1}$)	CO_2 type
Hamilton - Woodward Avenue WWTP	994.47	272.41	Flue gas	Niagara - Port Dalhousie WWTP	217.03	243.47	Flue gas
Niagara - Port Dalhousie WWTP	1102.98	292.50	Flue gas	Ontario - Kitchener WWTP	1819.11	327.82	Pure
Ontario - Kitchener WWTP	1904.02	367.40	Pure	Durham - Duffin Creek WPCP	4047.50	368.59	Flue gas
Toronto - Highland Creek TP	2655.14	512.53	Pure	Brantford WPCP	4296.37	377.55	Flue gas
Vancouver - Lulu Island WWTP	3851.98	523.43	Pure	Vancouver - Lulu Island WWTP	6690.06	421.64	Pure
Durham - Duffin Creek WPCP	4966.17	542.73	Flue gas	Windsor - Lou Romano WRP	7478.11	423.08	Flue gas
Brantford WPCP	5090.61	560.65	Flue gas	Halton - South East Oakville WTP	7598.40	424.16	Flue gas
Vancouver - Annacis Island WWTP	12273.24	562.77	Flue gas	Ontario - Clarkson WWTF	8443.50	429.89	Flue gas
Vancouver - Lions Gate WWTP	13192.44	641.36	Flue gas	Vancouver - Lions Gate WWTP	10281.90	440.87	Flue gas
Niagara - Welland WWTP	13293.57	641.40	Pure	Niagara - Welland WWTP	10484.16	469.53	Pure

For the *C. vulgaris* best case with 50% recycled nutrients, the costs are broken down into capital and operating expenses, wastewater transport, and CO_2 transport, as shown in Figure 11. Costs for each category for the top ten facilities in terms of the lowest biomass production costs are reported in CAD tonne^{-1} for 2010, and reflect the same values in Table 8 as well as the first 10 values shown in the cost curve. It is evident which three facilities have a higher cost due to the use of pure CO_2, as that cost represents over 50% of the total transport costs for both CO_2 and wastewater.

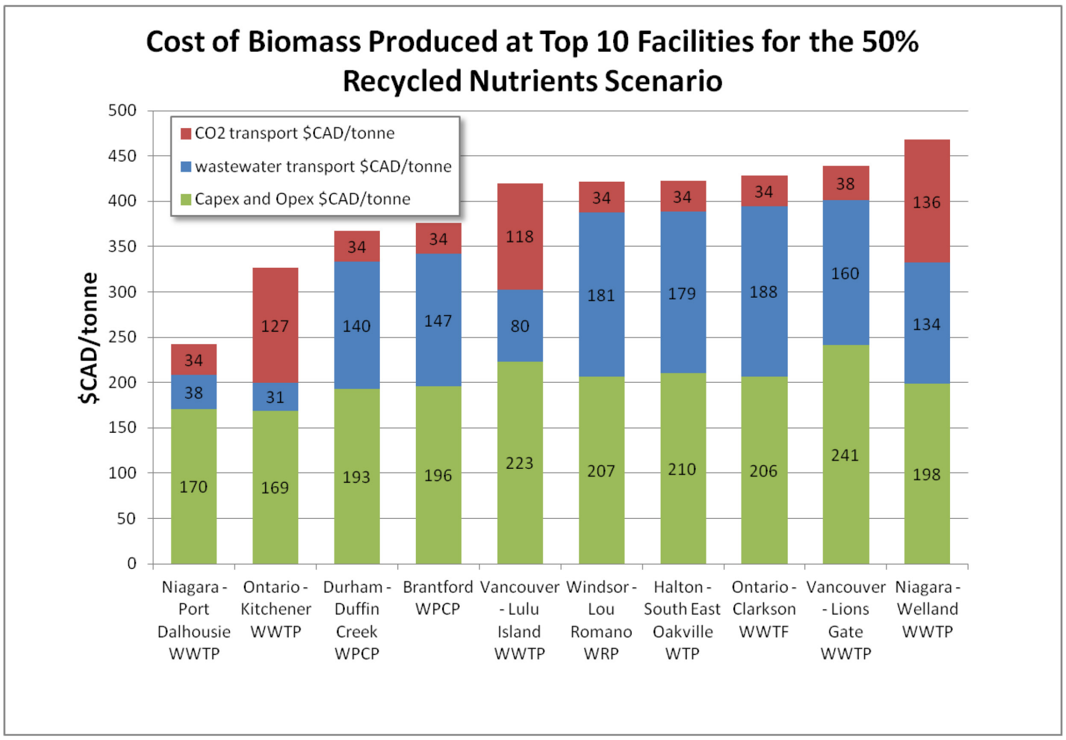

Figure 11. Costs broken down by capital and operating expense (for 2010), CO_2 transport, and wastewater transport for the *C. vulgaris* best case – 50% nutrient recycled scenario.

Overall, results from the model indicate that trucking costs for pure CO_2 would only enter the picture economically when the distances start exceeding the 5 km threshold. Generally, the cost to move large volumes of water overwhelms the cost to move much smaller volumes of CO_2, though flue gas is a much more cost effective option than using pure CO_2. Thus, these results indicate that the low cost alternatives will require the WWTP and CO_2 source to be located very close together and close to a land parcel of sufficient size and acceptable slope.

Results also suggest that flue gas is the most economical form of CO_2, and that nutrients from wastewater are thus only economically beneficial to an algae cultivation operation when they are available in close proximity to a CO_2 source. It is important to note again that the database of CO_2 sources used for this study was limited to large sources that reported actual CO_2 emissions. Smaller sources were not included, but may prove to have enough CO_2 and be close enough to the WWTPs.

These capital and operating costs for producing algal biomass are in the range of the Benemann and Oswald (1996) (p. 146) estimates of \$180 to \$320 per tonne of algal biomass (inflation adjusted, then converted to 2010 CAD) when comparing both *C. vulgaris* scenarios where nutrient uptake and recycling are introduced. The calculated costs are within this range for the first two out of 66 WWTPs (Figure 11 and Appendix—see first three facilities) with the remaining facilities showing costs above \$350 per tonne (2010 CAD).

To get an idea of the distances needed to move wastewater and CO_2 to a desired land parcel, the output from the two lowest cost options, as shown in Figure 11, are presented. These two sites, Niagara – Port Dalhousie WWTP, and Ontario – Kitchener WWTP, are both in southern Ontario. Based on the model output, the Niagara site moves flue gas 0.7 km as the CO_2 source (16% of total cost) and pipes water 0.1 km (18% of total cost), to a grassland land parcel where 3.7 ha is required to get an overall productivity of 217 tonne yr^{-1} at a cost of \$243 CAD per tonne (Figure 12).

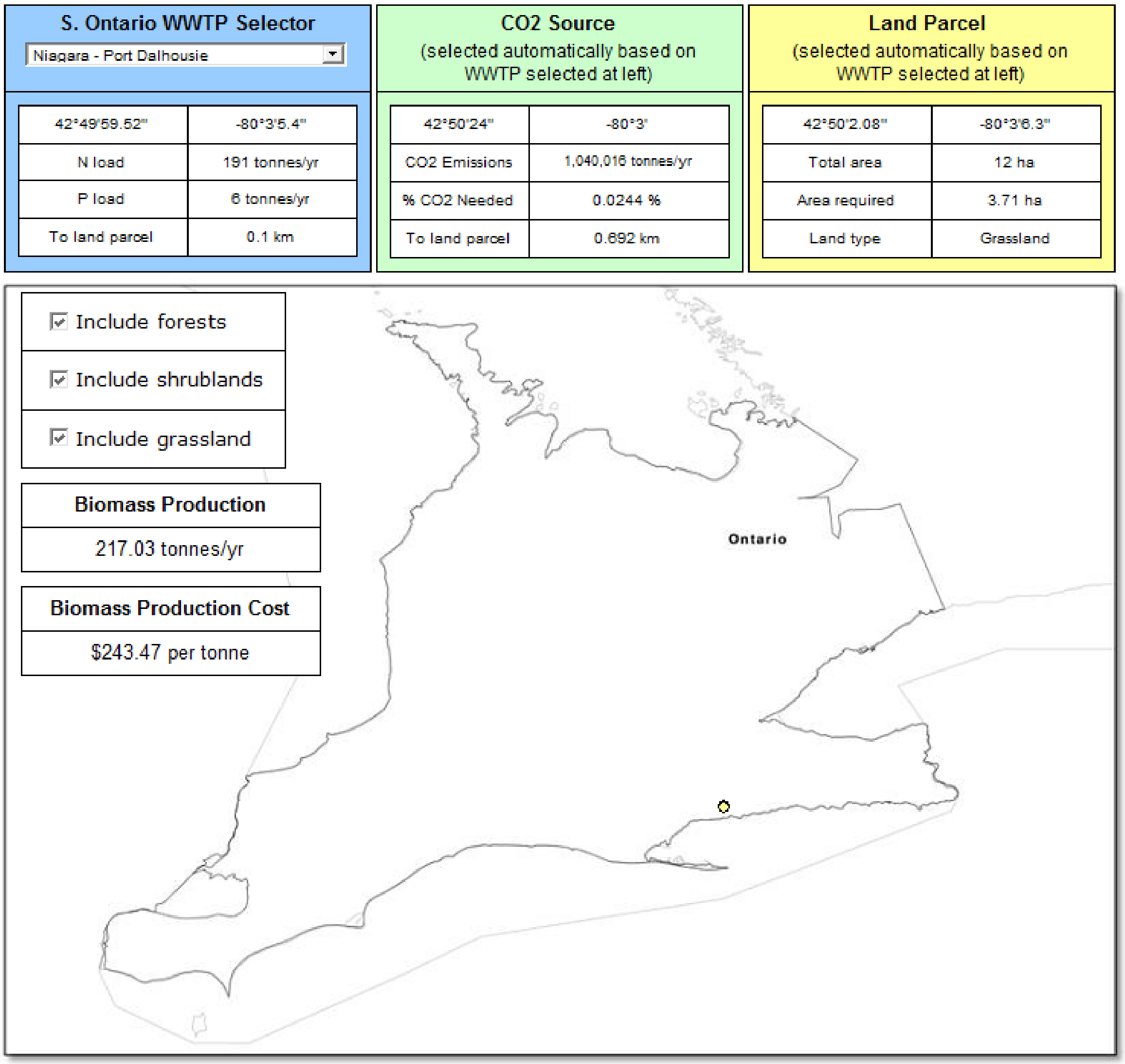

Figure 12. Location of WWTP, CO_2 source, and land parcel for the Niagara – Port Dalhouise location. Due to the close proximity of all points, all three points appear stacked in this location, which is located near Lake Erie.

The Ontario site uses pure CO_2 which is moved 33 km (64% of total cost) and water piped 0.4 km (10% of total cost), to a forested parcel where 27.37 ha are needed to get an overall productivity of 1602 tonne yr^{-1} at a cost of $327 CAD per tonne (Figure 13).

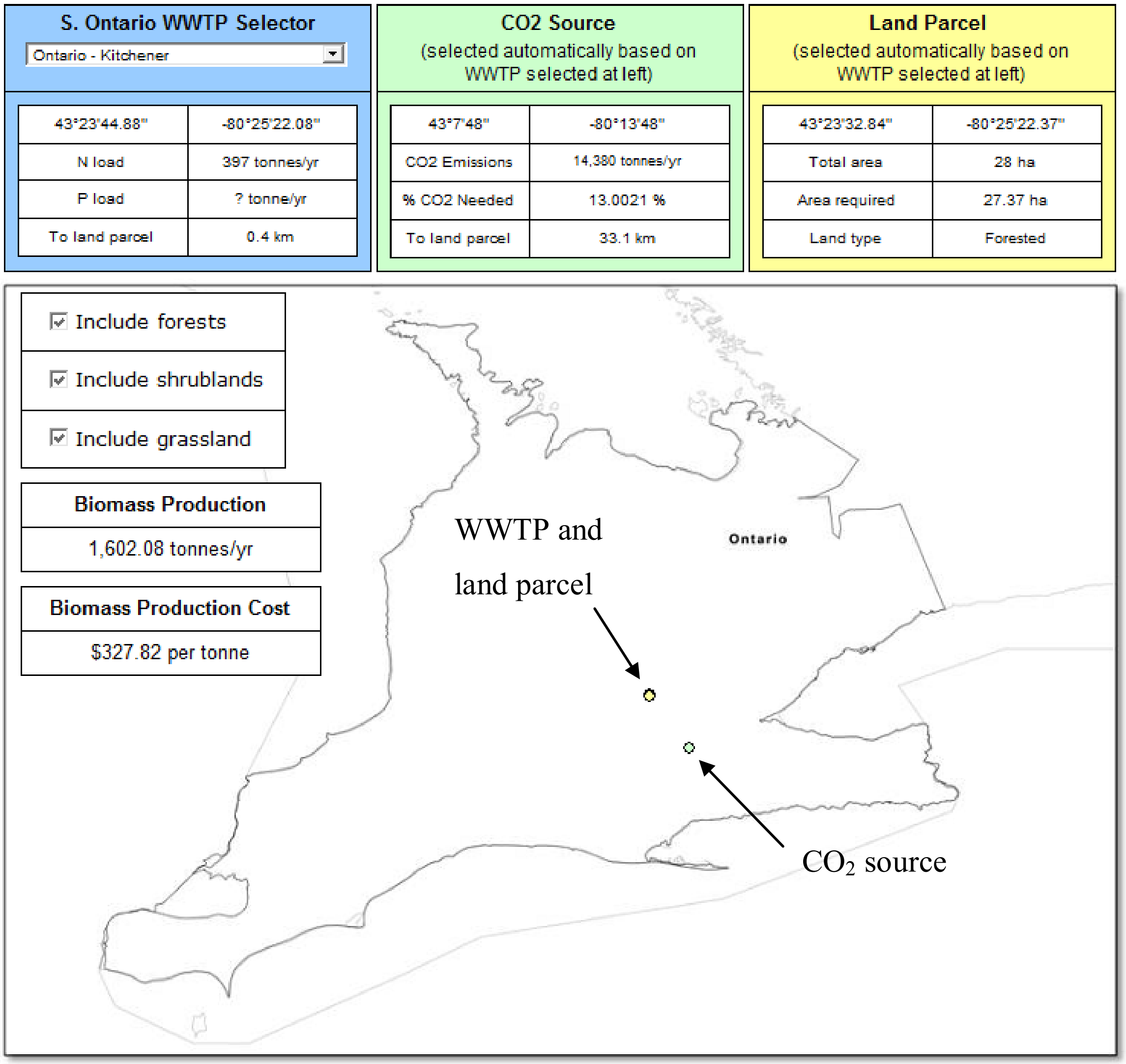

Figure 13. Location of WWTP, CO_2 source, and land parcel for the Ontario – Kitchener location. Both the WWTP and land parcel are close, only 0.4 km away. The CO_2 source is located 33 km southeast of the land parcel.

These two locations, based on the best case *C. vulgaris* from Table 2 (including 50% nutrient recycling), show that the Niagara site, which is the lowest cost due to the CO_2 source with, land parcel and WWTP being essentially co-located, and the Ontario site (next lowest cost), which is co-located for wastewater but not CO_2, meet the threshold of 500 kg day^{-1} for a demonstration scale facility. The Ontario site also exceeds the 1000 kg day^{-1} threshold for a pilot-scale facility. Other sites in the other three locations can also meet the production thresholds as envisioned by NRC–IMB, however costs for producing biomass at those locations will likely be higher.

4. Conclusions

One primary task was to construct a robust model that would identify the optimal configurations in the four modeled regions considering nutrient availability, algae cultivation and productivity, land area required, and CO_2 sequestered, in order to assist NRC–IMB in determining potential demonstration and pilot-scale facilities. Our results show there are many options, primarily within southern Ontario and Vancouver/Victoria. These options appear due to the higher density of co-located resources and available land. The number of facilities that meet production targets is slightly higher in southern Ontario.

CO_2 availability for all regions in the model generally dwarfed N and P availability from wastewater, causing most of the simulated systems to be N- or P-limited. The main reason for that CO_2 abundance is that the model only analyzed fossil fuel burning power production sources that emit more than 50,000 tonnes of CO_2 per year. This relative abundance is so large that only when CO_2 uptake efficiency is reduced below 1% does the model begin to see carbon limitations associated with certain WWTPs. This suggests that the use of smaller CO_2 sources may be a viable option in some cases where the emissions are sufficient and the location is more convenient than a larger source utilized in this analysis.

The nutrient limitation also illuminates the challenge of producing large amounts of algae biofuel using water and nutrients from WWTPs. One reason the nutrient levels are low is because the WWTP discharge data show water quality after final treatment, which is either primary, secondary, or tertiary, depending on the WWTP. The Vancouver/Victoria area has the greatest potential in terms of algal biomass production, despite the fact there are more facilities in southern Ontario that support a larger population and discharge greater volumes of wastewater. This is due in part to reduced treatment levels required for waste discharged to the Strait of Georgia and the Strait of Juan de Fuca near Vancouver/Victoria compared to southern Ontario, where discharges are made to water bodies that ultimately become sources of drinking water for both the United States and Canada. Once a more complete dataset is available, different scenarios can be run which may show greater production potential in all study areas due to higher concentration of nutrients at earlier treatment phases. The nutrient limitation also illuminates the importance of nutrient recycling in the algae biofuel production process and the potential importance of other nutrient sources, such as animal waste from feedlot operations.

The issue of how to keep a theoretical open pond system at a desired temperature was not included in this analysis, and consequently the costs of this energy requirement were not included. Studies on the energy requirements for these facilities at northern latitudes are only now starting to be published. It is worth noting that a recent study in upstate New York for a theoretical greenhouse-enclosed photobioreactor system looked at the energy requirements of natural gas heating for maintaining water and greenhouse temperatures (Baliga and Powers, 2010). Their results for a facility producing around 200 tonne yr^{-1} (essentially the same production rate as NRC–IMB desired pilot-scale facility of 500 kg day^{-1}) show that if waste heat is not used and natural gas is supplied for heating, 25–30% of the overall energy requirements goes to heating the greenhouse and 7–12% goes to water heating (starting with a groundwater source of 12°C and increasing it to 25°C). The use of artificial lighting was also analyzed, consuming between 20–25% of the total energy requirements, depending on location.

Results confirm that the lowest cost alternatives will require that WWTP and CO_2 sources be located very close to each other and to close to the properly sized land parcel. Results suggest that pipeline costs for CO_2 only become important if distances exceed a 5 km threshold. In general, the costs for moving large volumes of water overwhelm the cost to move much smaller volumes of CO_2.

Results also suggest that flue gas is the most economical form of CO_2, and that nutrients from wastewater are thus only economically beneficial to an algae cultivation operation when they are available in close proximity to a CO_2 source. It is important to note again that the database of CO_2 sources used for this study was limited to large sources that reported actual CO_2 emissions. Smaller sources were not included, but may prove to have enough CO_2 and be close enough to the WWTPs.

When looking at the best facilities for low-cost production, the province of Ontario dominates the top ten facilities in terms of the lowest biomass cost, primarily due to the high abundance of available land and lower costs to move both CO_2 and wastewater as compared to locations in Vancouver/Victoria, Nova Scotia, and Alberta study areas. Vancouver is right behind Ontario with between two or three locations in the top ten for each scenario, followed by Nova Scotia with one facility showing up in the top ten in two out of the four scenarios. Overall, comparing the cost results to those in Benemann and Oswald (1996) using the same inputs shows that for the more realistic scenarios where uptake efficiencies are below 100%, there are facilities that have potential for further analysis in terms of adding on an oil extraction process and associated cost, or looking at the potential savings of burning biogas for electricity generation. This is based on 1996 assumptions and the cost for a system does not include the energy cost for maintaining pond temperature. Once more data are available, the analysis can to be refined to reflect a design scenario of interest to NRC–IMB.

5. Recommendations

Future work should include the following ideas, reflecting suggestions by SNL and NRC–IMB:

- Incorporate smaller CO_2 sources (that do not report CO_2 emissions) that are within 5 km of any wastewater facility. This may help co-locate more CO_2 sources with land parcels and WWTPs and potentially drive down estimated costs.
- Include a pond temperature model for determining the energy requirement in winter months, which would better refine cost estimates for biomass production. Alternatively, the model might be modified to allow production to be shut down during winter months, or shift to production using a colder weather strain of algae during the winter months.
- Include a method for determining the volumetric production that could be attained in a photobioreactor based system. This would also include creating a cost section specific to photobioreactors and estimates of temperature requirements for optimal growth.
- Modify model to allow for mixotrophic growth due to potential light issues in winter months. This would allow for research into the cost of supplementing light for an autotrophic species versus the cost of additional organic carbon nutrients needed by a mixotroph.
- Bring in all discharge volumes from each WWTP, and incorporate more data from the WWTP survey conducted by Whalen (2010b).
- Include a more robust system using GIS for determining the distance between facilities and desired land using a least-cost path analysis.

- Include a more robust option for determining anaerobic digestion needs (including required range of C:N balance for good digester performance) and subsequent electricity offsets for biogas burning.
- Include biomass recycling from anaerobic digestion waste, and nutrients not utilized in wastewater stream.
- Enable the model to determine nutrient shortage for a targeted desired productivity. Also add potential costs for bringing in that nutrient from an external source if it is not recycled.
- Add to the model the ability to move multiple nutrient sources to a specific location rather than just one as it is currently configured.
- Conduct life cycle assessment analysis for water use, energy use, and GHG emissions once system type, design, and algae species is chosen by NRC–IMB.

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Appendix

Theoretical Max

WWTP	Cumulative Biomass Produced [tonnes/yr]	Biomass Cost [CAD/tonne]	CO_2 type
Niagara - Port Dalhousie WWTP	516.73	79.26	Flue gas
Durham - Duffin Creek WPCP	7070.82	117.88	Flue gas
Vancouver - Annacis Island WWTP	47996.90	126.74	Flue gas
Brantford WPCP	48589.46	135.58	Flue gas
Windsor - Lou Romano WRP	50907.27	136.41	Flue gas
Vancouver - Lions Gate WWTP	56314.33	138.32	Flue gas
Ontario - Clarkson WWTF	58799.92	138.72	Flue gas
Halton - South East Oakville WTP	59086.32	155.15	Flue gas
Ontario - Kitchener WWTP	63798.31	168.34	Pure
Halifax - Eastern Passage WPCP	65127.01	170.61	Flue gas
Vancouver - Lulu Island WWTP	72167.27	187.26	Pure
Toronto - Highland Creek TP	75744.00	192.37	Pure
Niagara - Welland WWTP	76338.87	222.73	Pure
Chilliwack - Wolfe Road WWTP	77972.06	223.82	Pure
Toronto - Humber TP	85340.47	235.05	Pure
Abbotsford - JAMES PCC	89077.44	240.98	Pure
Halifax - Mill Cove WPCC	91287.10	261.61	Pure
Niagara - Baker Road WWTP	91595.77	271.68	Pure
Ontario - G.E. Booth (lakeview) WWTF	93953.01	272.20	Pure
Vancouver - Iona Island WWTP	119447.40	272.90	Flue gas

Best Case

WWTP	Cumulative Biomass Produced [tonnes/yr]	Biomass Cost [CAD/tonne]	CO_2 type
Niagara - Port Dalhousie WWTP	516.73	215.03	Flue gas
Brantford WPCP	1109.30	271.35	Flue gas
Halton - South East Oakville WTP	1395.70	290.92	Flue gas
Windsor - Lou Romano WRP	3713.50	303.81	Flue gas
Vancouver - Lions Gate WWTP	9120.57	308.54	Flue gas
Halifax - Eastern Passage WPCP	10449.26	323.19	Flue gas
Ontario - Kitchener WWTP	15161.26	323.31	Pure
Vancouver - Lulu Island WWTP	22201.52	354.90	Pure
Niagara - Welland WWTP	22796.39	356.09	Pure
Vancouver - Annacis Island WWTP	63722.47	393.60	Pure
Niagara - Baker Road WWTP	64031.13	405.04	Pure
Chilliwack - Wolfe Road WWTP	65664.32	413.71	Pure
Ontario - G.E. Booth (lakeview) WWTF	68021.56	420.11	Pure
Abbotsford - JAMES PCC	71758.53	432.33	Pure
Halifax - Mill Cove WPCC	73968.19	439.08	Pure
Vancouver - Iona Island WWTP	99462.59	444.90	Flue gas
Kings County - Regional STP	100078.35	477.55	Pure
Halton - Mid-Halton WWTP	100375.50	477.84	Pure
London - Greenway PCC	100684.05	482.75	Pure
Port Alberni - Sewage Lagoon	101708.25	484.06	Pure

Theoretical Max			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Halifax - HRM Dartmouth Outfalls	120699.98	274.43	Flue gas
Ontario - Waterloo WWTP	121944.13	313.50	Pure
Port Alberni - Sewage Lagoon	122968.33	316.86	Pure
Kings County - Regional STP	123584.09	327.68	Pure
Halton - Mid-Halton WWTP	123881.25	344.48	Pure
London - Greenway PCC	124189.79	349.39	Pure
Vancouver - Northwest Langley WWTP	124632.69	351.02	Pure
London - Oxford PCP	124789.17	357.23	Pure
Duncan-N Cowichan JUB Lagoons	125721.11	361.24	Pure
County of Colchester - WWTF	126308.07	368.47	Pure
Niagara - Niagara Falls WWTP	126933.14	375.16	Pure
Hamilton - Woodward Avenue WWTP	132782.95	397.74	Pure
Simcoe STP	132963.51	410.68	Pure
Sarnia - WPCC	133189.19	417.70	Flue gas
Capital - Macaulay Point PS	137913.45	433.84	Pure
Collingwood - WWTP	138037.25	447.37	Pure
Nanaimo - Greater Nanaimo PCC	140358.69	455.73	Pure
Toronto - North Toronto TP	140803.20	463.50	Pure
Owen Sound WPCP	141058.05	492.95	Flue gas
Cape Breton - Battery Point TP	141481.57	496.73	Pure
Ontario - Galt WWTP	141568.03	527.97	Pure
Capital - Clover Point PS	145378.81	587.00	Pure
Halifax - Roaches Pond PS	145668.40	601.74	Flue gas

Best Case			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Halifax - HRM Dartmouth Outfalls	102960.83	488.56	Flue gas
London - Oxford PCP	103117.31	490.60	Pure
Ontario - Waterloo WWTP	104361.46	493.43	Pure
Durham - Duffin Creek WPCP	110915.54	504.25	Pure
Niagara - Niagara Falls WWTP	111540.61	508.52	Pure
Vancouver - Northwest Langley WWTP	111983.51	518.23	Pure
County of Colchester - WWTF	112570.47	518.35	Pure
Duncan-N Cowichan JUB Lagoons	113502.40	528.44	Pure
Hamilton - Woodward Avenue WWTP	119352.22	531.10	Pure
Simcoe STP	119532.77	544.04	Pure
Sarnia - WPCC	119758.45	553.47	Flue gas
Toronto - Highland Creek TP	123335.18	564.64	Pure
Collingwood - WWTP	123458.99	580.73	Pure
Toronto - North Toronto TP	123903.50	596.87	Pure
Owen Sound WPCP	124158.35	628.72	Flue gas
Ontario - Clarkson WWTF	126643.94	640.70	Pure
Cape Breton - Battery Point TP	127067.46	646.60	Pure
Ontario - Galt WWTP	127153.92	661.34	Pure
Capital - Macaulay Point PS	131878.18	666.17	Pure
Nanaimo - Greater Nanaimo PCC	134199.61	739.91	Pure
Niagara - Port Weller WWTP	134651.86	741.02	Pure
Halifax - Roaches Pond PS	134941.45	754.32	Flue gas
London - Pottersburg PCP	135033.61	803.38	Pure

Theoretical Max			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Niagara - Port Weller WWTP	146120.65	607.66	Pure
London - Pottersburg PCP	146212.81	670.02	Pure
Oxford - Woodstock WWTP	146253.45	695.22	Pure
Guelph - City of Guelph WWTP	146402.73	697.94	Pure
Toronto - Ashbridges Bay TP	161964.96	778.04	Pure
East River Pollution Abatement System - East River ECC	162150.05	851.45	Flue gas
London - Adelaide PCC	162199.45	859.31	Pure
St. Thomas - WPCP	162255.55	908.69	Pure
Orangeville WPCP	162290.63	995.60	Pure
Windsor - Little River PCP	162401.44	1048.42	Pure
Halton - Southwest Oakville WWTP	162600.84	1408.13	Flue gas
Barrie - Barrie WPCC	162811.57	1423.51	Pure
Niagara - Fort Erie WWTP	162865.37	1545.34	Pure
Niagara - Port Colborne WWTP	162914.18	1873.43	Pure
Ontario - Stratford WWTP	162986.39	2071.67	Pure
London - Vauxhall PCP	163006.51	2598.58	Pure
Leamington PCC	163082.22	2914.80	Pure
York - Keswick WPCP	163090.56	4044.61	Pure
Hamilton - Main Street WWTP - 2	163105.84	9104.39	Flue gas
Hamilton - King Street WWTP	163115.01	10564.04	Pure
Ontario - Preston WWTP	163121.01	10944.40	Pure
Halton - Milton WTP	163125.20	16910.60	Pure

Best Case			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Oxford - Woodstock WWTP	135074.26	828.58	Pure
Guelph - City of Guelph WWTP	135223.54	831.31	Pure
Capital - Clover Point PS	139034.32	888.08	Pure
Toronto - Humber TP	146402.73	960.34	Pure
Toronto - Ashbridges Bay TP	161964.96	991.41	Pure
London - Adelaide PCC	162014.36	992.67	Pure
East River Pollution Abatement System - East River ECC	162199.45	1004.03	Flue gas
St. Thomas - WPCP	162255.55	1042.05	Pure
Orangeville WPCP	162290.63	1128.97	Pure
Windsor - Little River PCP	162401.44	1181.78	Pure
Halton - Southwest Oakville WWTP	162600.84	1543.90	Flue gas
Barrie - Barrie WPCC	162811.57	1556.88	Pure
Niagara - Fort Erie WWTP	162865.37	1678.70	Pure
Niagara - Port Colborne WWTP	162914.18	2006.79	Pure
Ontario - Stratford WWTP	162986.39	2205.04	Pure
London - Vauxhall PCP	163006.51	2731.95	Pure
Leamington PCC	163082.22	3048.17	Pure
York - Keswick WPCP	163090.56	4177.97	Pure
Hamilton - Main Street WWTP - 2	163105.84	9240.16	Flue gas
Hamilton - King Street WWTP	163115.01	10697.40	Pure
Ontario - Preston WWTP	163121.01	11077.77	Pure
Halton - Milton WTP	163125.20	17043.96	Pure

Theoretical Max

WWTP	Cumulative Biomass Produced [tonnes/yr]	Biomass Cost [CAD/tonne]	CO_2 type
Halton - Georgetown WWTP	163126.97	39685.14	Pure
Wood Buffalo - Fort McMurray ST	163135.46	42662.22	Pure
Clean Harbors Inc. WWT	163135.46	999999.99	

Best Case

WWTP	Cumulative Biomass Produced [tonnes/yr]	Biomass Cost [CAD/tonne]	CO_2 type
Halton - Georgetown WWTP	163126.97	39818.50	Pure
Wood Buffalo - Fort McMurray ST	163135.46	42832.08	Pure
Clean Harbors Inc. WWT	163135.46	999999.99	

C. vulgaris Best Case

WWTP	Cumulative Biomass Produced [tonnes/yr]	Biomass Cost [CAD/tonne]	CO_2 type
Hamilton - Woodward Avenue WWTP	994.47	272.41	Flue gas
Niagara - Port Dalhousie WWTP	1102.98	292.50	Flue gas
Ontario - Kitchener WWTP	1904.02	367.40	Pure
Toronto - Highland Creek TP	2655.14	512.53	Pure
Vancouver - Lulu Island WWTP	3851.98	523.43	Pure
Durham - Duffin Creek WPCP	4966.17	542.73	Flue gas
Brantford WPCP	5090.61	560.65	Flue gas
Vancouver - Annacis Island WWTP	12273.24	562.77	Flue gas
Vancouver - Lions Gate WWTP	13192.44	641.36	Flue gas
Niagara - Welland WWTP	13293.57	641.40	Pure
Chilliwack - Wolfe Road WWTP	13571.21	651.21	Pure
Windsor - Lou Romano WRP	13965.24	651.71	Flue gas

C. vulgaris Best Case - 50% recycled nutrients

WWTP	Cumulative Biomass Produced [tonnes/yr]	Biomass Cost [CAD/tonne]	CO_2 type
Niagara - Port Dalhousie WWTP	217.03	243.47	Flue gas
Ontario - Kitchener WWTP	1819.11	327.82	Pure
Durham - Duffin Creek WPCP	4047.50	368.59	Flue gas
Brantford WPCP	4296.37	377.55	Flue gas
Vancouver - Lulu Island WWTP	6690.06	421.64	Pure
Windsor - Lou Romano WRP	7478.11	423.08	Flue gas
Halton - South East Oakville WTP	7598.40	424.16	Flue gas
Ontario - Clarkson WWTF	8443.50	429.89	Flue gas
Vancouver - Lions Gate WWTP	10281.90	440.87	Flue gas
Niagara - Welland WWTP	10484.16	469.53	Pure
Chilliwack - Wolfe Road WWTP	11039.44	494.47	Pure
Halifax - Eastern Passage WPCP	11491.20	529.61	Flue gas

C. vulgaris Best Case			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Halton - South East Oakville WTP	14025.38	653.87	Flue gas
Ontario - Clarkson WWTF	14447.93	665.33	Flue gas
Toronto - Humber TP	15995.30	706.76	Pure
Abbotsford - JAMES PCC	16630.58	816.60	Pure
Halifax - Eastern Passage WPCP	16856.46	842.37	Flue gas
Niagara - Baker Road WWTP	16921.28	869.59	Pure
Halifax - Mill Cove WPCC	17346.37	891.74	Pure
Ontario - G.E. Booth (lakeview) WWTF	17747.10	1036.96	Pure
Port Alberni - Sewage Lagoon	17921.22	1069.36	Pure
Kings County - Regional STP	18025.90	1165.36	Pure
Ontario - Waterloo WWTP	18237.40	1184.61	Pure
Niagara - Niagara Falls WWTP	18368.67	1283.87	Pure
London - Oxford PCP	18401.53	1292.60	Pure
Nanaimo - Greater Nanaimo PCC	18889.03	1340.30	Pure
Vancouver - Iona Island WWTP	23223.08	1433.00	Flue gas
Halifax - HRM Dartmouth Outfalls	23436.01	1453.06	Flue gas
Vancouver - Northwest Langley WWTP	23511.31	1458.79	Pure
Halton - Mid-Halton WWTP	23561.82	1475.84	Pure
London - Greenway PCC	23614.28	1494.29	Pure
Duncan-N Cowichan JUB Lagoons	23772.71	1519.20	Pure
County of Colchester - WWTF	23872.49	1584.96	Pure
Simcoe STP	23905.12	1746.13	Pure
Toronto - North Toronto TP	23998.46	1790.23	Pure

C. vulgaris Best Case - 50% recycled nutrients			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Vancouver - Annacis Island WWTP	25856.46	532.99	Pure
Abbotsford - JAMES PCC	27127.02	570.57	Pure
Niagara - Baker Road WWTP	27256.66	575.57	Pure
Ontario - G.E. Booth (lakeview) WWTF	28058.12	656.60	Pure
Halifax - Mill Cove WPCC	28908.31	668.16	Pure
Port Alberni - Sewage Lagoon	29256.54	716.77	Pure
Ontario - Waterloo WWTP	29679.55	740.18	Pure
Kings County - Regional STP	29888.91	751.02	Pure
London - Oxford PCP	29954.63	785.00	Pure
Niagara - Niagara Falls WWTP	30217.16	793.14	Pure
Halifax - HRM Dartmouth Outfalls	30643.03	834.96	Flue gas
Vancouver - Iona Island WWTP	39311.13	836.69	Flue gas
Halton - Mid-Halton WWTP	39412.16	874.64	Pure
London - Greenway PCC	39517.07	884.93	Pure
Vancouver - Northwest Langley WWTP	39667.65	892.19	Pure
Toronto - Highland Creek TP	41169.88	909.55	Pure
Duncan-N Cowichan JUB Lagoons	41486.74	922.36	Pure
Toronto - Humber TP	44581.47	936.57	Pure
County of Colchester - WWTF	44781.04	942.42	Pure
Simcoe STP	44846.29	1012.52	Pure
Hamilton - Woodward Avenue WWTP	46835.23	1028.60	Pure
Toronto - North Toronto TP	47021.92	1034.94	Pure
Collingwood - WWTP	47064.02	1143.24	Pure

C. vulgaris Best Case			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Capital - Macaulay Point PS	24801.59	1850.62	Pure
Collingwood - WWTP	24822.64	1995.52	Pure
Owen Sound WPCP	24876.15	2262.41	Flue gas
Sarnia - WPCC	24914.52	2306.37	Flue gas
Cape Breton - Battery Point TP	24986.52	2327.30	Pure
Niagara - Port Weller WWTP	25081.49	2418.05	Pure
Ontario - Galt WWTP	25096.19	2509.25	Pure
Capital - Clover Point PS	25744.02	2637.41	Pure
Toronto - Ashbridges Bay TP	29012.09	3247.09	Pure
Halifax - Roaches Pond PS	29061.32	3378.39	Flue gas
London - Pottersburg PCP	29076.98	3391.61	Pure
Guelph - City of Guelph WWTP	29102.36	3473.65	Pure
Oxford - Woodstock WWTP	29109.27	3529.39	Pure
London - Adelaide PCC	29117.67	4487.90	Pure
St. Thomas - WPCP	29127.21	4777.75	Pure
Orangeville WPCP	29133.75	4838.54	Pure
East River Pollution Abatement System - East River ECC	29165.21	4847.32	Flue gas
Windsor - Little River PCP	29184.05	5615.75	Pure
Barrie - Barrie WPCC	29228.31	6281.40	Pure
Halton - Southwest Oakville WWTP	29262.20	7844.16	Pure
Niagara - Fort Erie WWTP	29271.35	8360.42	Pure
Niagara - Port Colborne WWTP	29279.65	10356.76	Pure

C. vulgaris Best Case - 50% recycled nutrients			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Owen Sound WPCP	47171.05	1228.43	Flue gas
Sarnia - WPCC	47247.78	1250.41	Flue gas
Capital - Macaulay Point PS	48854.03	1291.77	Pure
Nanaimo - Greater Nanaimo PCC	49829.03	1301.01	Pure
Cape Breton - Battery Point TP	49973.03	1314.83	Pure
Niagara - Port Weller WWTP	50162.98	1356.64	Pure
Ontario - Galt WWTP	50192.37	1396.05	Pure
Capital - Clover Point PS	51488.04	1548.33	Pure
Halifax - Roaches Pond PS	51586.50	1797.62	Flue gas
London - Pottersburg PCP	51617.83	1832.43	Pure
Toronto - Ashbridges Bay TP	58153.97	1880.90	Pure
Guelph - City of Guelph WWTP	58204.72	1881.88	Pure
Oxford - Woodstock WWTP	58218.54	1902.40	Pure
London - Adelaide PCC	58235.34	2382.34	Pure
St. Thomas - WPCP	58254.41	2527.33	Pure
East River Pollution Abatement System - East River ECC	58317.34	2532.09	Flue gas
Orangeville WPCP	58330.43	2558.51	Pure
Windsor - Little River PCP	58368.11	2944.69	Pure
Barrie - Barrie WPCC	58456.61	3291.20	Pure
Halton - Southwest Oakville WWTP	58524.41	4058.80	Pure
Niagara - Fort Erie WWTP	58542.70	4335.29	Pure
Niagara - Port Colborne WWTP	58559.30	5326.66	Pure

C. vulgaris Best Case			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Ontario - Stratford WWTP	29291.92	11599.08	Pure
London - Vauxhall PCP	29295.34	14734.05	Pure
Leamington PCC	29308.21	16544.49	Pure
York - Keswick WPCP	29309.63	23149.62	Pure
Hamilton - Main Street WWTP - 2	29312.23	53404.54	Flue gas
Hamilton - King Street WWTP	29313.79	61581.89	Pure
Ontario - Preston WWTP	29314.81	63765.53	Pure
Halton - Milton WTP	29315.52	98910.35	Pure
Halton - Georgetown WWTP	29315.82	232878.14	Pure
Wood Buffalo - Fort McMurray ST	29317.27	250380.22	Pure
Clean Harbors Inc. WWT	29317.27	N/A	

C. vulgaris Best Case - 50% recycled nutrients			
WWTP	**Cumulative Biomass Produced [tonnes/yr]**	**Biomass Cost [CAD/tonne]**	**CO_2 type**
Ontario - Stratford WWTP	58583.85	5940.02	Pure
London - Vauxhall PCP	58590.69	7503.87	Pure
Leamington PCC	58616.43	8414.18	Pure
York - Keswick WPCP	58619.27	11720.92	Pure
Hamilton - Main Street WWTP - 2	58624.46	26799.49	Flue gas
Hamilton - King Street WWTP	58627.58	30928.58	Pure
Ontario - Preston WWTP	58629.62	32025.91	Pure
Halton - Milton WTP	58631.04	49593.25	Pure
Halton - Georgetown WWTP	58631.65	116577.15	Pure
Wood Buffalo - Fort McMurray ST	58634.53	125351.22	Pure
Clean Harbors Inc. WWT	58634.53	N/A	

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