INTEGRATING SPATIAL IMPLICATIONS INTO SOLVING LIFE-CYCLE CHALLENGES OF BIOFUELS AND INDUSTRIAL SYMBIOSIS

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Biofuels have demonstrated great promise for global energy production. In the United States, the Renewable Fuel Standard (RFS2) of the Energy Independence and Security Act of 2007 (EISA) calls for the production of 15.2 billion gallons of renewable fuels per year by 2013, 1.28 billion gallons of which need to be biomass-based diesel. Increased biofuel production can help meet rising energy demands, however most biofuel production processes are land- and nutrient-intensive, and must be managed throughout the life cycle to ensure sustainability.

The goal of this dissertation was to evaluate industrial symbiosis as a sustainable approach to U.S. biofuel and energy production by creating a framework using GIS that integrates the spatial implications of land and nutrient supply. Defined by the synergistic collaboration of industries enabled by geographic proximity, industrial symbiosis is a key element in resource conservation, as it uses traditionally defined waste outputs as resource inputs.

Four systems were examined in this dissertation: a coupled wastewater-power plant system, a sunflower biodiesel production system using urban marginal land, a national biodiesel production system using contaminated waste sites, and an algal biodiesel production system using wastewater and waste CO_2. Results from the wastewater-power plant system indicated that secondary-treated wastewater can provide cooling water to power plants, however traditional

metrics and tools used to evaluate sustainability are inadequate for such complexity. Spatial assessment is needed to efficiently design transportation and conveyance within the system.

Two land-identification frameworks were created using GIS to identify regional and national "waste" lands, or marginal lands, and to evaluate these lands for sunflower, soybean, and algal biodiesel production. A nutrient-availability framework was also created to identify synergistic opportunities for algal biodiesel production. While regional production of sunflower biodiesel generated trivial contributions to the RFS2, marginal sites at the national level could meet 7 to 19% of the RFS2, depending on the distribution of feedstocks. Algal biodiesel produced using waste CO_2 and wastewater could meet 0.3% to 17% of the RFS2, depending on the nutrient concentration of the wastewater. These ranges highlight spatial variability of results and emphasize the benefit of GIS in life-cycle sustainability studies.

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NOMENCLATURE

CBA   Cost-Benefit Analysis

DOE   Department of Energy

EIO   Economic Input-Output

EISA   Energy Independence and Security Act

GHG   Greenhouse Gas

GHI   Global Horizontal Irradiance

GIS   Geographic Information System

LCA   Life Cycle Assessment

LCC   Life Cycle Costing

LCI   Life Cycle Inventory

LCIA   Life Cycle Impact Assessment

MFA   Material Flow Analysis

NRCS   Natural Resources Conservation Service

NREL   National Renewable Energy Laboratory

PBR   Photobioreactor

PVC   Polyvinyl Chloride

RFS   Renewable Fuel Standard

STPP   Sodium Tripolyphosphate

SVR   Surface area-to-Volume Ratio

TDS   Total Dissolved Solids

TJ   Terajoule

TSS   Total Suspended Solids

US   United States

USDA   United States Department of Agriculture

UV   Ultraviolet

VOC   Volatile Organic Compound

WWTP   Wastewater Treatment Plant

CONVERSION FACTORS

1 hectare (ha) = 2.471 acres

1 liter (L) = 0.264 US gallon (gal)

PREFACE

I am deeply grateful to my dissertation advisor, Dr. Amy E. Landis, and to my IGERT co-advisor Dr. Melissa Bilec, for offering me the opportunity to pursue this research. Thank you for your guidance and for challenging me along the way. Thank you also to committee members Dr. Radisav Vidic and Dr. Bill Harbert for your collaboration, questions, and comments, all of which have improved the quality of this work.

Many thanks to my SGD peers, CEE colleagues, and Pittsburgh friends for the intellectual engagement and personal encouragement over the last four years. You have truly made this city into a home.

None of this would have been possible without the love, understanding, and support of my family: heartfelt appreciation to my mother, father, and co-doctoral sister, Alison. You are each an inspiration to me. Thank you for being you.

1.0 INTRODUCTION

1.1 MOTIVATION AND RATIONALE

Biofuels have demonstrated great promise for global energy production. In the United States, the Renewable Fuel Standard (RFS2) of the Energy Independence and Security Act of 2007 (EISA) calls for the production of 15.2 billion gallons of renewable fuels per year by 2013, 1.28 billion gallons of which need to be biomass-based diesel by 2013 (U.S. Environmental Protection Agency, 2012). Increased biofuel production can help meet rising energy demands, however most of these biofuel production processes are also land-intensive. Therefore, in addition to optimizing the biofuel production process, it is imperative to optimize the manner in which the land is used.

Industrial symbiosis offers a technique with which to approach the land-biofuel system. Defined by the synergistic collaboration of industries enabled by geographic proximity (Chertow, 2000), industrial symbiosis is a key element in resource conservation as it uses traditionally defined waste outputs as resource inputs. The most famous example of industrial symbiosis is an entire district, or 'industrial ecosystem' in Denmark, named Kalundborg, where all excess resources from the central power plant are used in other parts of the district (Ehrenfeld and Gertler, 1997). In the United States, the Department of Energy has expressed interest in industrial symbiosis using the wastewater treatment and CO_2-emitting industries for algae

production (U.S. DOE, 2010). The DOE's algae biomass roadmap calls for the use of life cycle assessments and spatially explicit tools to engineer sustainable algae biorefineries; likewise, these tools will aid in the design of efficient and sustainable industrial symbiotic systems that provide the needed nutrients and resources, such as land, to biofuel systems.

1.1.1 Intellectual Merit

Analysis and design of biofuel production systems has traditionally evaluated single metrics such as greenhouse gas emissions or net energy return when assessing the sustainability of biofuels, and overlooks scarce inputs such as phosphorus fertilizers and land. An industrial symbiosis approach assessed from a systems perspective enables one to utilize wastes as resources and examine multiple factors that are important to sustainable biofuel systems. Systems analysis, as currently practiced in life cycle assessment and industrial symbiosis, is often limited to individual case studies or to theoretical models, where the data are either site-specific or can be created and shaped mathematically. Systems analysis as currently applied to biofuel systems lacks a spatially explicit component. This dissertation presents an adaptable framework for evaluating industrial symbiosis using GIS to address spatially explicit challenges related to the interconnected life cycles of land, nutrients, and biofuels.

1.2   GOALS AND OBJECTIVES

1.2.1   Goals

This dissertation aims to evaluate industrial symbiosis as a sustainable solution to creating sustainable biofuels and energy in the U.S. by creating a framework that integrates spatial implications into a systems approach to providing nutrients and land to biofuel systems. The goals of this thesis are to:

1) Theoretically demonstrate the feasibility of using wastes as resources in industrial symbiotic systems (addressed in Chapters 2, 3, 4, and 5).

2) Establish the need for systems analysis and for spatially explicit tools to assess feasibility and sustainability of industrial symbiotic systems (addressed in Chapters 2, 3, 4, and 5).

3) Integrate spatial analysis tools, such as GIS, with life-cycle systems approaches for assessing the sustainability of biofuels and their potential to meet the RFS2 (addressed in Chapters 3, 4, and 5.)

1.2.2   Objectives

The specific objectives of the dissertation research are to:

a) Identify and evaluate appropriate metrics for assessing the sustainability of industrial symbiotic systems (addressed in Chapter 2);

b) Evaluate the need for spatially explicit tools in designing systems that employ industrial symbiosis (addressed in Chapter 2);

c) Create and demonstrate a framework for utilizing GIS to identify marginal lands for use in small-scale biofuel production (addressed in Chapter 3);

d) Create and demonstrate a framework for utilizing GIS to identify U.S. marginal lands and assess the lands' potential for facilitating renewable energy production (addressed in Chapter 4);

e) Create and demonstrate a framework for utilizing GIS to identify industrial symbiosis opportunities for cultivating algal biofuels from industries producing waste CO_2 and waste nutrients (addressed in Chapter 5); and

f) Assess the extent to which biofuels produced using an industrial symbiosis approach can contribute to the RFS2 (addressed in Chapters 3, 4, and 5).

1.3   BACKGROUND

1.3.1   Life Cycle Assessment

Life cycle assessment (LCA) quantifies the environmental impacts of a product or process over its life cycle, from raw materials extraction to end of life. Process LCA is defined by the ISO 14040 series as the "assessment of the environmental impact of a given product throughout its life span" (International Organization for Standardization (ISO), 2006). The ISO 14040 series specifies four steps in an LCA: 1) definition of goal and scope; 2) inventory of system inputs and outputs; 3) impact assessment; and 4) interpretation. The second step of the LCA, life cycle inventory (LCI), tracks specific materials and emissions over the life-cycle. LCIs are usually made up of thousands of materials and emissions making it difficult to evaluate the impacts of

the entire system. Therefore, most LCA practitioners follow the full ISO process and conduct a life cycle impact assessment (LCIA), which expresses the LCI data in meaningful terms. LCIA groups emissions into categories in which they have similar impacts, like global warming, and aggregate them based on equivalency. Common LCIA categories that represent major environmental impacts include global warming potential, ecotoxicity, acidification, eutrophication, human health impacts, and smog formation. This inventory-to-impact conversion serves as one of LCA's greatest assets, however currently available characterization factors and impact assessment methods tend to be either global in nature or rooted in national databases that rarely correspond to the location and scale of the study.

Land use is one LCIA category where spatial differentiation is crucial. Different types of land uses will impact different environmental systems in different ways. Only one impact assessment method—the Tool for the Reduction and Assessment of Chemical Impacts (TRACI)—offers characterization factors more specific than the national level. TRACI was developed by the USEPA (Bare, Norris et al., 2003), is the only tool with characterization factors specific to the US, and includes characterization factors for some LCIA categories primarily at the state level and some land use factors for selected areas at the county level. No LCIA method currently available offers characterization factors for the regional, biome, or ecosystem levels, though several methods are under development (Beck, Bos et al., 2010; Scientific Certification Systems, 2011; UNEP-SETAC Life Cycle Initiative, 2011). The work presented in this dissertation uses GIS as a tool to map the LCI, perform a wide variety of spatial analyses to assess system impacts and opportunities, and creates the potential for future experts to fully integrate an LCIA land use category on a geographic information system (GIS) platform.

1.3.2   Geographic Information Systems

A geographic information system (GIS) is a decision-support system in which computer software is used to model spatial processes to solve problems analytically. GIS is designed to visualize, manipulate, query, analyze, and display spatial data (Ormsby, Napoleon et al., 2010)

There are four components to a GIS: hardware, software, data, and personnel. The hardware consists of the computer and the server on which the software is run. The software includes the GIS program, in this case *ArcGIS 10*, as well as any additional software, such as spreadsheet software for storing and manipulating tabular data. Data are often the most important component of the GIS and can be the most difficult to obtain due to availability or cost. Fortunately, a wide variety of databases are accessible online, many of which are maintained by government agencies and are free to the user. Finally, the GIS requires a user or personnel to manage the hardware, software, and data to create a meaningful product.
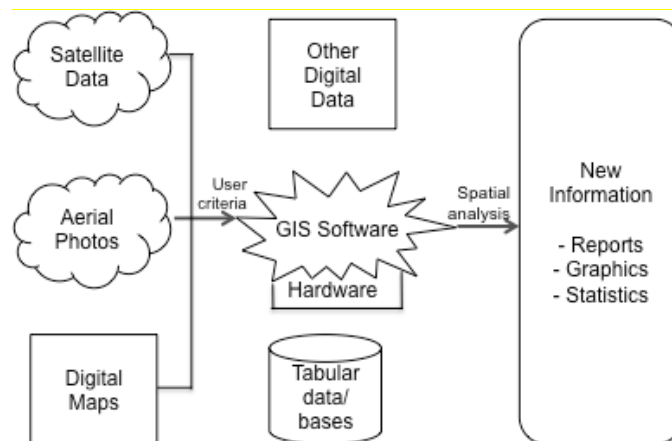
Figure 1-1. Data and information flows in GIS.

Adapted from (USGS, 2007).

One of the first documented uses of GIS was in 1854 when English physician John Snow determined the water source responsible for a London cholera outbreak by mapping homes of people affected by the disease. From this map emerged clusters of affected homes, which Snow then used to trace back to the contaminated well. Over a century later, Ian McHarg (1920-2001), commonly known as the father of modern GIS, popularized the idea of georeferenced transparent map overlays in his 1969 book, *Design with Nature* (McHarg, 1969).

Today GIS practitioners call these overlays "layers" or collections of geographic elements that are alike (Ormsby, Napoleon et al., 2010). Some common layers might include countries, cities, rivers, and soils. Each object of the layer is called a feature. Features can vary in shape and size, but they can all be classified into one of three types: polygon, line, or point. A polygon feature represents a shape with boundaries, such as countries or property parcels. Line features represent objects too narrow to be represented as polygons, given the scale of the layer. Line features might include road centerlines, pipelines, or rivers. Point features are displayed without dimensions and represent objects too small to be polygons. Examples of point features include trees, buildings, and wells.

GIS data can be divided into two categories: vector and raster. Raster data are divided into a grid of pixels. Each pixel is assigned a value corresponding to a particular display color. Changing the value of the cell changes the data represented and the color displayed. Vector data simulate traditional hand-drawn maps. The attributes of each point, line, and polygon feature are stored with the object and not in a grid of cells. Data in raster format can be converted into vector format and vice versa, though reduction in quality may occur. Vector data can be scaled; raster data cannot. Vector data are easier to manipulate given the direct mathematical representation, whereas the raster must call and retrieve each cell's value to manipulate the image.

GIS can be arduous, time-intensive, and is not necessary or even appropriate for every project. It does, however, have several advantages. First and foremost, GIS provides a way in which to organize and analyze spatial data that would otherwise be impossible. Clusters of data and new information emerge from combining layers that may not hold much value individually. The information gathered via GIS can be used to assess opportunities and feasibility of a project, highlight areas for further research, and create spatially based improvements.

1.3.3 Land Use in Life Cycle Assessment

Researchers have employed GIS at the regional (Volvontas, Assimacopoulos et al., 2001; Beccali, Columba et al., 2009; Fiorese and Guariso, 2010; Geyer, Storms et al., 2010), national (Lovett, Sünnenberg et al., 2009; Tang, Xie et al., 2010), and global (Field, Campbell et al., 2008; Cai, Zhang et al., 2011) scales to better understand the volumetric yields and land use implications of traditional biomass production. Only a portion of this work, however, has been conducted within a life cycle assessment framework due to the fact that LCA still lacks a standardized impact assessment category to evaluate land use.

Land use is one impact where spatial differentiation is crucial. Different types of land uses will impact different environmental systems in different ways. In the United States, only one impact assessment method—the Tool for the Reduction and Assessment of Chemical Impacts (TRACI)—offers characterization factors more specific than the national level (Bare, Norris et al., 2003). TRACI was developed by the USEPA and includes characterization factors for some LCIA categories primarily at the state level and some land use factors for selected areas at the county level. No LCIA method currently available offers characterization factors for the regional, biome, or ecosystem levels, though several methods are under development (Beck, Bos

et al., 2010; Scientific Certification Systems, 2011; UNEP-SETAC Life Cycle Initiative, 2011). The few LCA methods that do include some form of land use fail to define any standard metric: metrics ranging from land occupation and transformation (Milà i Canals, Bauer et al., 2007) to pH and soil organic matter (Mattsson, Cederberg et al., 2000) are all presented in the literature. Results from these methods cannot be directly compared as they lack a common unit for comparison.

1.3.4 Biofuels

Biofuels are categorized into three generations. First-generation, or conventional, biofuels are made from the sugars, starches, and oils of arable crops, such as sugarcane, corn, and various oilseeds. Second-generation biofuels, or cellulosic biofuels, are derived from plant cellulose of non-arable crops, such as switchgrass and miscanthus, or from agricultural residues, such as corn stover. Third generation biofuels can be derived from algae. Algal feedstock tends to exhibit higher rates of productivity than first- or second-generation feedstocks, but the technology for large-scale cultivation is not yet widely available.

Biofuels are considered a promising form of low-carbon energy that could mitigate climate change by removing carbon dioxide from the atmosphere through carbon sequestration by the biofuel crop, or feedstock (Fargione, Hill et al., 2008; Zimmermann, Dauber et al., 2012). Studies have shown, however, that to mitigate climate change, the feedstock must be grown in such a way that it leaves the soil's organic carbon stocks relatively in tact and retains the surrounding vegetation and ecosystems (Fargione, Hill et al., 2008). Otherwise the carbon payback period could last decades or centuries, depending on the type of biofuel system and land use change involved. In addition, biofuels often experience increased water quality- and land

use- related environmental impacts when compared to fossil fuels (Miller, Landis et al., 2007; Miller, 2010). One type of land use change that is of particular concern is the conversion of croplands to grow biofuel feedstocks instead of edible crops. This practice often exacerbates food scarcity by increasing global crop prices and leading farmers to clear more forest and grasslands to replace the edible crops (Searchinger, Heimlich et al., 2008).

1.3.5 Biofuels, GIS, and Land Use in LCA

All three main themes (industrial symbiosis, GIS-driven spatial analyses, and the life-cycle sustainability of biofuel production) intersect with one another. Increasingly extensive LCA studies have led to improvements in the sustainability of the biofuels system. Whereas the LCA focus was traditionally on the mechanics of the chemical production and transportation processes, land use has become a key issue in current biofuels and LCA studies. Spatial assessments via GIS are now also being used to monitor a wide variety of production systems and to search for synergistic opportunities. Interest in understanding the spatial implications of environmental impacts is also growing in LCA. Particularly as land use gains importance as a future life cycle impact assessment category, GIS-assisted LCA research concerning land use and biofuels will continue to expand. Therefore, it is crucial to understand each element individually—biofuels, GIS, and land availability—and examine their interactions in the field. Figure 1 illustrates the relationships between these concepts.
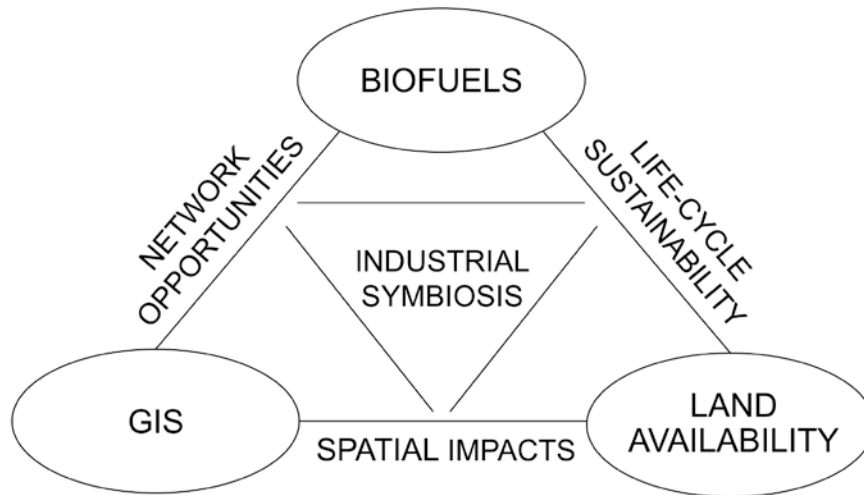
Figure 1-2. Relationships between biofuels, GIS, and land availability.

1.4   ORGANIZATION OF THESIS

The body of this thesis is presented as four individual papers in Chapters 2 through 5. Each chapter addresses multiple goals (described in the Goals section), and each chapter addresses one to two research objectives (described in the Objectives section). Chapter 2, "Evaluating Sustainability Tools and Metrics for Application to Reuse of Treated Municipal Wastewater in Power Plant Cooling Systems," presents a snapshot of an LCA of a coupled wastewater-to-power-plant system. It shows that wastewater can be used as a resource to provide cooling water to power plants and that spatial assessment is needed to efficiently design the means of conveyance. Chapter 3, "Using Geographic Information Systems to Assess Potential Biofuel Crop Production on Urban Marginal Lands," demonstrates industrial symbiosis in the context of land reclamation and small-scale sunflower biodiesel production. Chapter 4, "Assessing Renewable Energy Potential of United States Marginal Land," expands upon Chapter 3 by mapping land quality across the entire United States and considering specific contaminated sites,

such as brownfields, closed landfills, and abandoned mine lands, for renewable feedstocks such as soybean, sunflower, and algae. Chapter 5, "Using GIS to Highlight Industrial Symbiosis Potential for Microalgal Biodiesel Production in the United States" evaluates the industrial symbiosis of co-locating microalgal production systems with CO_2-emitting sources while using nitrogen (N) and phosphorus (P) as nutrients from nearby municipal wastewater treatment plants. Chapters 2 through 5 all consider the respective biodiesel contributions to the Renewable Fuel Standard (RFS2).

2.0   EVALUATING SUSTAINABILITY TOOLS AND METRICS FOR APPLICATION TO REUSE OF TREATED MUNICIPAL WASTEWATER IN POWER PLANT COOLING SYSTEMS

Parts of the following chapter appear as proceedings of the Life Cycle Assessment XII Conference with the citation:

Niblick, B., Theregowda, R., Dzombak, D., Vidic, R., A.E. Landis (2012). "Evaluating sustainability tools and metrics for application to reuse of treated municipal wastewater in power plant cooling systems." LCA XII in Tacoma, WA.

Chapter 2 presents a snapshot of an LCA of a coupled wastewater-to-power plant system, using traditional LCA methods and a survey of plant operators. The system diagrams (Figures 1 and 2), table of sustainability challenges (Table 1), and results Figures 4-9 are included in the proceedings. The results indicate that wastewater can be used as a resource to provide cooling water to power plants and that spatial assessment is needed to efficiently design the piping or other means of conveyance.

2.1   ABSTRACT

Treated municipal wastewater can be used for power plant cooling to avoid using freshwater resources. This paper presents a snapshot of current practices and explores metrics and tools for assessing the sustainability of recycling treated municipal wastewater for power plant cooling. In the studied system, wastewater effluent is piped from the wastewater treatment plant to the power plant for use in the power plant's cooling system. The environmental, economic, and social pillars of the system's sustainability are analyzed via life cycle assessment (LCA) and survey methods. Metrics studied include life-cycle environmental impacts, water cost and value, and public engagement.

Four challenges (A through D) facing the use of wastewater for power plant cooling were identified as follows: Challenge A – biofouling, scaling, and corrosion, Challenge B – wastewater delivery, Challenge C – public perception of wastewater reuse, and Challenge D – valuation of freshwater versus wastewater (Li, Chien et al., 2011). Comparative LCA results of three chemical treatment scenarios for Challenge A indicate that, while three chlorine-based disinfectant options (Cl, ClO_2, or NH_2Cl) exhibit minimal differences in terms of environmental impacts, trade-offs do exist: ClO_2 has approximately half the impact of Cl with regard to fossil fuel usage and climate change, while Cl exhibits a 28 percent greater relative impact in carcinogenic potential. Furthermore, when comparing impacts among treatment combinations consisting of one of the three chlorine-based disinfectants, the anti-scalant H_2SO_4, and the anti-corrosive sodium tripolyphosphate ($Na_5P_3O_{10}$ or STPP), it is found that STPP contributes most toward environmental impacts – over 60 percent in the categories of land use (land transformation for mineral extraction) and carcinogenic potential.

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With regard to Challenge B – wastewater delivery, comparative LCA results between ten miles of PVC and ten miles of concrete piping indicate that the majority of environmental impacts are associated with PVC. The remaining challenges were addressed through a survey of select wastewater treatment and power plant operators because, while the reuse of wastewater may seem intuitively sustainable, LCA is not currently tailored to adequately address the sustainability of water reuse. Survey results show that chemical treatment (Challenge A) is primarily conducted at the power plants rather than requiring wastewater treatment plants to prepare the effluent for recycling. Survey responses regarding piping distances between plants (Challenge B) indicate that collaborating plants are often located within five miles of one another. Survey responses also indicate that, while some power plants and wastewater treatment plants do offer informational tours for visitors, the majority of plants do not engage in any deliberate public outreach activities (Challenge C). This lack of engagement may contribute to a lack of public understanding and support. Finally, the majority of power plants report paying less than $0.66 per 1,000 gallons of treated wastewater (Challenge D), a price that does not accurately reflect the inherent value of water resources.

Given ever-increasing costs and challenges of the water-energy nexus, as well as the growing range of LCA applications under development, it is imperative that the value of recycled wastewater in LCA receive further attention. Other tools and metrics also need to be used in conjunction with LCA to fully evaluate the sustainability of a system.

2.2   INTRODUCTION

Industrial symbiosis, or the synergistic collaboration of industries enabled by geographic proximity (Chertow, 2000), has been shown to offer a wide array of environmental, economic, and social benefits (Ehrenfeld and Gertler, 1997; Adamides and Mouzakitis, 2009). This study uses principles of industrial symbiosis to describe the engagement of power plants that use treated municipal wastewater effluent for their cooling water systems. The boundaries of the system extend from the exit of the wastewater effluent from the wastewater treatment facility to the exit of the effluent from the power generation facility.

In addition to evaluations of feasibility and effectiveness, it is important to quantify the sustainability of the system from the perspective of the three sustainability pillars: environment, economy, and society. An evaluation of sustainability requires sustainability metrics. Therefore, this paper presents a snapshot of the system and discusses different tools and metrics for assessing sustainability for the coupled wastewater-power plant cooling system.

Four main challenges (A through D) associated with the sustainability of reusing wastewater for power plant cooling are identified: Challenge A – biofouling, scaling, and corrosion, Challenge B – wastewater delivery, Challenge C – public perception of wastewater reuse, and Challenge D – valuation of freshwater versus wastewater. Sustainability metrics including environmental impacts, water cost and value, and public perception were evaluated through life cycle assessment and survey administration, all of which are discussed in subsequent sections.

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Much research has already been conducted in the area of wastewater reclamation and reuse, but only a tiny portion of this has included sustainability analyses using life cycle assessment. Some authors, such as Feeley at al. (2007), have investigated the rate of freshwater withdrawal in the thermoelectric industry (Feeley, 2007). Others have examined wastewater reclamation from a life cycle perspective (Hospido, Moreira et al., 2004; Chen, Yeh et al., 2005; Ammary, 2006; Hospido, Moreira et al., 2008) and have considered cooling water reuse within power plants (Jin-Kuk Kim, 2004). Few researchers, however, have addressed the broader scenario of freshwater depletion and wastewater recycling from a life cycle assessment perspective (Bayart, Bulle et al., 2010). The sustainability challenges of reusing treated municipal wastewater for power plant cooling have largely been left unexamined, as have any previous collaborations between power plants and wastewater treatment plants for this purpose.

2.2.1 System description

In 2005, thermoelectric power plants were responsible for 49 percent of total freshwater withdrawals in the United States (Barber, 2009). This water is used in cooling towers to transfer extra heat generated from the plant to the atmosphere. Due to progressively stricter water withdraw and discharge regulations, such as Section 316(b) of the U.S. Clean Water Act, which limits power plants' freshwater withdrawals and requires closed-loop cooling systems, more and more power plants are beginning to use reclaimed water for their cooling processes.

One alternative source of cooling water is treated municipal wastewater. It avoids new freshwater withdrawals, but the levels of biodegradable organic matter, nitrogen, and phosphorus contained in the wastewater, even after it is treated, pose significant challenges for power plants

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with respect to biofouling, corrosion, and scaling in the cooling systems. In most cases, treated municipal wastewater requires additional chemical treatment to control these operational problems for use in power plant cooling. However, chemical treatment can be costly and contribute to increased levels of environmental impacts; both concerns need to be addressed.

A process flow diagram for the coupling of wastewater treatment facilities with power plants for cooling is shown in Figure 1. The wastewater treatment plant includes primary and secondary treatment and sometimes includes tertiary treatment. Upon receipt of the wastewater, the power plant usually further treats the water by adding of chemicals to control biofouling, corrosion, and scaling in the cooling processes.
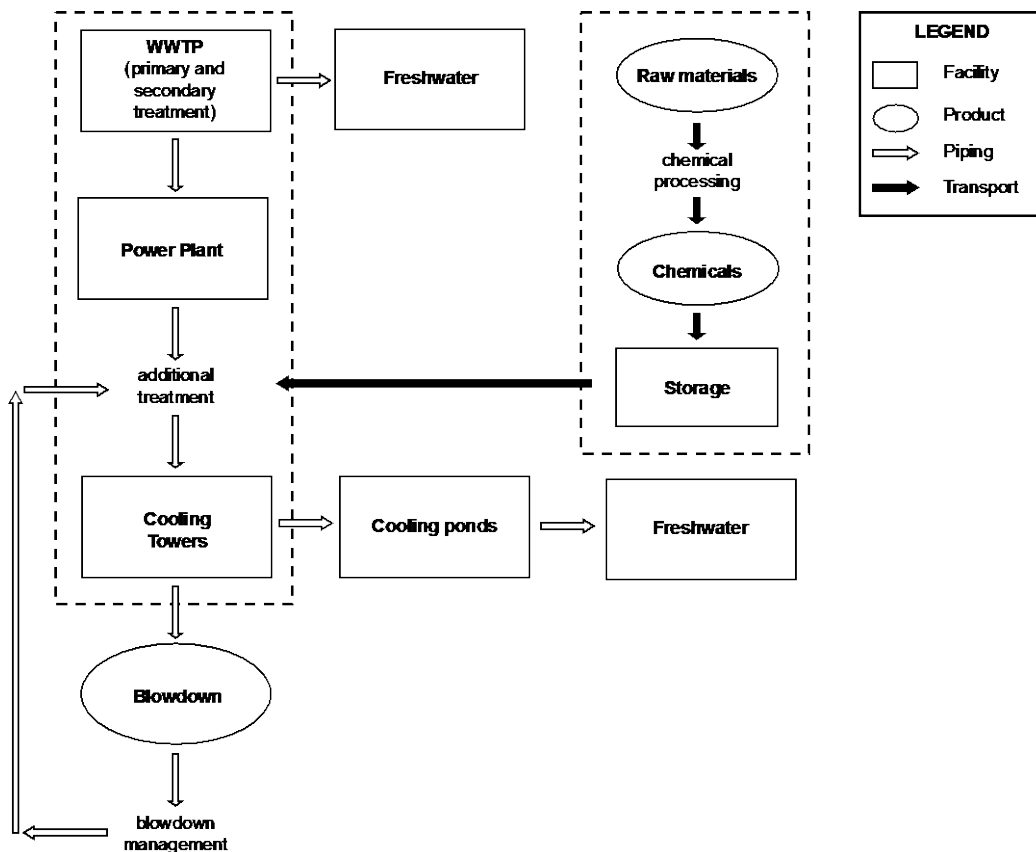
Figure 2-1. Process flow diagram for coupling wastewater treatment plants with power plants to provide cooling water.

System boundaries for the life cycle assessment are identified with dashed lines (- - -) and include the wastewater effluent site to the cooling water effluent site. WWTP = wastewater treatment plant.

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2.2.2   Challenges to sustainable reuse of wastewater for power plant cooling

This study identifies four main challenges of reusing wastewater in power plant cooling systems for which sustainability metrics and tools will be evaluated. Challenge A includes the technical aspects of addressing biofouling, scaling, and corrosion. Challenge B addresses technical and environmental issues related to methods for wastewater delivery. Challenge C evaluates public perception of wastewater reuse, while Challenge D addresses the valuation of freshwater versus wastewater.

2.2.2.1 Challenge A: Biofouling, Scaling, and Corrosion

Secondary treated wastewater typically exhibits high concentrations of total dissolved solids (TDS), total suspended solids (TSS), organic matter, bacteria, ammonia (NH_3), and phosphate (PO_4). These characteristics present certain challenges for reuse and must be addressed through chemical, biological, and physical treatment. As TDS levels increase, rates of corrosion and scaling also increase. Corrosion often occurs on the surface of the power plant's metal heat exchangers and transport pipes due to the metal's exposure to the environment (Li, Chien et al., 2011). Corrosion can ultimately result in equipment failure. Scaling refers to mineral deposition on pipes and occurs when the recirculating water evaporates, leaving supersaturated salts to precipitate and form scale (Li, Chien et al., 2011). Biofouling occurs when residual amounts of phosphorous, nitrogen, and organic matter still in the treated wastewater foster biological growth on the surfaces of equipment at the power plant (Li, Chien et al., 2011). This paper considers a life-cycle sustainability analysis of the chemicals used to treat biofouling, scaling, and corrosion. Other research is being conducted by two of the co-authors to better understand the mechanisms

of biofouling, scaling, and corrosion, and to devise more effective methods of chemical treatment for these impaired waters (U.S. Department of Energy, Office of Fossil Energy et al., 2009).

2.2.2.2 Challenge B: Wastewater Delivery

In addition to treatment, the delivery of the wastewater from the wastewater treatment facility to the power plant can be a challenge, depending on the level of cooperation between the two facilities. In most cases, piping needs to be installed between the plants for conveyance of the water and a contract needs to be signed, specifying the length of agreement and any fees charged for the water or other services.

The use of geographic information systems (GIS) and network modeling can be helpful in planning the logistics of wastewater delivery (Leitão, Matos et al., 2005; Kallali, Anane et al., 2007). GIS can be used in preliminary stages to map distance and terrain between the wastewater treatment plant and power plant and to determine hydraulic capacity of the network. During operational stages, GIS can be used to maintain the pipe networks, check for leakage or breakage, and identify pipes and other infrastructure in need of repair (Tabesh and Saber, 2012).

2.2.2.3 Challenge C: Public Perception

The public has traditionally been opposed to wastewater reuse, largely due to a lack of information (Friedler and Lahav, 2006; Jimenez and Asano, 2008). Compounding the problem, the information that is made available is often difficult to understand without some technical background knowledge. While the public tends to look favorably upon natural conservation projects, lack of public understanding can often lead to difficulties in obtaining permits and other legal issues (Hartley, 2006).

2.2.2.4 Challenge D: Valuation of Freshwater vs. Wastewater

It can be difficult to quantify the value of freshwater versus wastewater. Freshwater may appear to be more accessible as a good of the commons, but given factors related to water rights and environmental regulations, treated wastewater may be cheaper in the long term. In addition, the technology required to treat wastewater can appear to be more expensive in the short term than the cost of leaving wastewater untreated (Romero-Hernandez, 2004). By factoring in the benefits of treating and reusing wastewater, the disparities between water pricing and water value can be better understood and addressed.

2.2.3 Sustainability metrics and tools

Over the past decade, several different metrics have been suggested for use with sustainability tools such as LCA, material flow analysis (MFA), cost-benefit analysis (CBA), and carbon-footprinting (Barbier, Markandya et al., 1990; Brunner and Rechberger, 2004; International Organization for Standardization (ISO), 2006; Wackernagel, 2009). The scope, accuracy and applicability of these tools vary widely. Some of the tools are based on quantitative measurements while others are based on qualitative evaluations. While no sustainability measurement tool is perfect, some are more suited to certain applications than others. In the end, the results yielded from each tool are only as good as the tool itself. One of the goals of this study is to evaluate several different tools and metrics that can assess the sustainability of utilizing wastewater for power plant cooling.

Examples of common sustainability measurement tools include carbon and ecological footprints, water and energy balances, LCA, and material flow analysis. Definitions for carbon footprint vary, but in general the carbon footprint quantifies the total amount of carbon dioxide

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and other greenhouse gases emitted from a product or process over its life cycle; the methods are similar to LCA, but only greenhouse gases are quantified (Wackernagel, 2009). The ecological footprint, originally defined as "the total area of land required to sustain an urban region" (Rees, 1992), can also be understood as the "human appropriation of ecosystem products and services in terms of the amount of bioproductive land and sea area needed to supply these services" (Wackernagel, 2009). Likewise, water and energy balances describe a wide range of tools, all of which measure the amount of water or energy produced or consumed by a system. Finally, material flow analysis (MFA) can be defined as a "systematic assessment of the flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger, 2004). MFA does not describe environmental impacts, but rather is an accounting tool used to track the materials and energy entering and leaving a system within a given period of time.

Life cycle assessments quantify the environmental impacts of a product or process over its life cycle, from raw materials extraction to ultimate end of life. There are three main types of LCAs: process, input-output, and hybrid. Process LCA is defined by the ISO 14040 series as the "assessment of the environmental impact of a given product throughout its life span" (International Organization for Standardization (ISO), 2006). ISO 14040 specifies four major steps in an LCA: 1) definition of goal and scope; 2) inventory of system inputs and outputs; 3) impact assessment; and 4) interpretation of results at each step along the way (International Organization for Standardization (ISO), 2006). The second step of the LCA, life cycle inventory (LCI), can be useful to track and evaluate specific materials or emissions over the life-cycle, however LCIs are usually made up of thousands of materials and emissions making it difficult to evaluate the impacts of the entire system. Therefore, most LCA practitioners follow the full ISO process and conduct a life cycle impact assessment (LCIA), which utilizes existing tools to group

emissions into like categories and aggregate them based on equivalency factors, called characterization factors. Common LCIA categories that represent major environmental impacts include global warming potential (or climate change), ecotoxicity, acidification, eutrophication, human health impacts, and smog formation.

Process LCAs rely on data gathered along the supply chain to calculate the total associated environmental impact. However, it is often difficult to locate the specific data needed to create a comprehensive process-based LCA (Bilec, Ries et al., 2006; Hendrickson, Lave et al., 2006). Economic input-output LCA (EIO-LCA) compensates for this lack of data by mapping the economic flows between sectors of the economy and calculating the amounts of material, energy, and emissions associated with the flows (CMU, 2008). Hybrid LCA combines process LCA and EIO-LCA to create an integrated analysis (Suh, 2004).

Due to the complex nature of the coupled wastewater treatment facilities and power plant system, merely using one sustainability tool or metric will not provide an adequate assessment of the sustainability of the entire system and its challenges. Therefore, this study assesses several tools and metrics for quantifying and evaluating the sustainability associated with the aforementioned challenges facing utilizing wastewater for power plant cooling; these metrics and tools are summarized in Table 1.

Table 2-1. Metrics, tools, and data sources to evaluate sustainability challenges of reusing wastewater in power plants.

	Challenges	Potential Sustainability Metrics	Potential Tools
A	Biofouling, corrosion, scaling	Effectiveness of chemical treatment	Treatment records, lab tests, survey
		Environmental impacts[a]	LCA
		Cost	Life-cycle costing, survey
B	Wastewater delivery	Environmental impacts[a]	LCA, GIS
		Cost	Life-cycle costing, survey, GIS
C	Public perception	Complaints, lawsuits, etc.	Survey, public court records
		Public events, communications[a]	Survey
		Willingness to live nearby	Survey
D	Freshwater vs. wastewater valuation	Value	Survey
		Cost[a]	Life-cycle costing, survey
		Volume of water[a]	Water balance, MFA[b], LCA
		Water quality	LCA, risk assessment
		Regional ecosystem quality	LCA, risk assessment

[a] Denotes metrics evaluated in this research.

[b] Material flow analysis

The sustainability of potential additional treatment processes used to mitigate biofouling, scaling, and corrosion can be evaluated through an LCA of the chemicals and methods used to treat the water (Challenge A). The sustainability metrics available to evaluate Challenge A include feasibility and performance, cost, and environmental impacts.

The sustainability of wastewater delivery (Challenge B) can be addressed through an LCA of the conveyance, i.e. piping, of the water. The sustainability metrics relevant for Challenge B include environmental impacts and cost. Geographic Information Systems (GIS), not included in the scope of this study, can be used to assess the spatial location of the wastewater treatment and power plants, as well as the piping distance and terrain between the plants (Leitão, Matos et al., 2005; Kallali, Anane et al., 2007). These GIS-based assessments can further minimize environmental impacts and cost by adding a spatial dimension and increasing the precision of planning and maintenance of the coupled-plant system from a life-cycle perspective.

Public perception (Challenge C) can be assessed by administering a survey to wastewater treatment and power plant personnel. The survey questions can be designed to elicit responses regarding relationships with customers and other stakeholders by using metrics such as number of complaints and lawsuits filed, willingness of people to live near the plants, the number of public events hosted by the plants, and the number of communications issued by the plants.

Water valuation (Challenge D) considers cost, water volume, water quality, and regional ecosystem quality and can be assessed through metrics such as surveys and literature reviews. In this study, environmental impacts, cost, value, and public relations were evaluated as sustainability metrics, and life cycle assessment and survey administration were used as the corresponding sustainability assessment tools.

2.3   METHODS

This study uses two main tools to evaluate different metrics for sustainability: LCA and a survey instrument. Both tools are described in more detail below.

2.3.1   Life Cycle Assessment

A comparative process-based LCA was conducted on a snapshot of the system related to Challenges A and B, the system boundaries of which are depicted in Figure 1. The LCA framework of the ISO 14040 was utilized when compiling the LCI data to address the aforementioned challenges to utilizing wastewater for power plant cooling. The system

boundaries were drawn from the exit of the wastewater effluent from the wastewater treatment facility to the exit of the effluent from the power generation facility. Challenge A (biofouling, corrosion, and scaling) occurs at the power plant, while Challenge B (wastewater delivery) occurs between the wastewater treatment plant and the power plant.

The life cycle inventory (LCI) is the stage during which life-cycle data is gathered for each element of the system. For Challenge A, data was gathered on three chemical treatment scenarios. For Challenge B, data was gathered on the construction of pipes between the wastewater treatment plant and the power plant. Both of these LCI data-gathering processes are detailed below. The functional unit was defined as 1,000 gallons of treated wastewater effluent and therefore, each piece of data was documented proportional to 1,000 gallons.

The life cycle impact assessment (LCIA) describes environmental effects, i.e. impacts, in specific categories such as global warming potential (or climate change) and eutrophication potential. The LCIA tool used in this study is Eco-indicator 99 and its results are reported at the midpoint (Goedkoop and Spriensma, 1999). Different LCIA tools employ different calculation methods, each with different emphases (Dreyer, Niemann et al., 2003; Landis and Theis, 2008). The Eco-indicator categories used in this study include ecotoxicity, respiratory organics, acidification and eutrophication, radiation, land use, carcinogens, fossil fuels, and climate change.

For Challenge A—biofouling, corrosion, and scaling—the system boundaries encompass the chemical production process, extending from the raw material extraction to the storage of the finished product. Transportation to the power plant was not included, nor were use-phase operations at the power plant. (Emphasis, instead, was placed on the process of integrating LCA with other sustainability assessment tools.) Typical chemical proportions used in industry were

assumed for each treatment cycle, as described in Appendix A. Most of the basic chemical data were collected from the Ecoinvent version 2.0 database (Frischknecht, Jungbluth et al., 2007), except for chlorine (Cl), which was taken from BUWAL 250 data (Spriensma, 2004). Monochloramine (NH_2Cl) was built from a combination of compounds including sodium hypochlorite, ammonia, and sodium hydroxide. These data came from the Ecoinvent version 2.0, Industry data 2.0 (Plastics Europe), and US LCI databases (Pré Consultants, 2004), respectively.

The LCA for Challenge B—wastewater delivery—included the pipes between the wastewater treatment plant and the power plant. Figure 2 depicts the flow and system boundaries for the pipes used in this study. These boundaries include the extraction of raw materials, the production of PVC, the production of concrete, and pipe manufacture. Installation, operation, and maintenance of the pipes are not included in this LCA. Material calculations are based on 12-inch nominal size pipe and a 10-mile average distance between the wastewater treatment plant and power plant. LCI data came from the Industry data 2.0 database for PVC and from the Ecoinvent version 2.0 database for concrete.
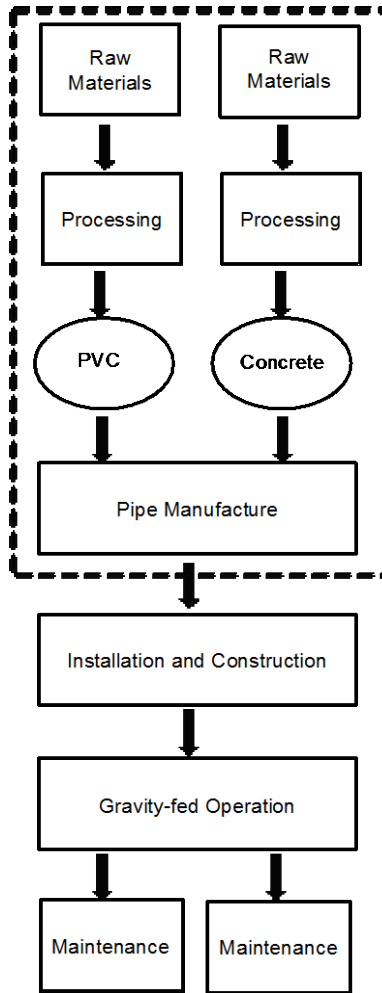
Figure 2-2. Flow chart of LCA of pipes used for transport of treated municipal wastewater to power plant cooling towers.

System boundaries marked with dashed line.

2.3.2 Survey

Two surveys were developed to obtain data related to Challenges A, B, and C. One survey was tailored to U.S. power plants and the other survey was tailored to U.S. wastewater treatment plants. Both surveys were administered via telephone and e-mail, depending on responder preference, to targeted plant personnel with chemical treatment experience and other experiences

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pertinent to the survey. The survey questions were modified only to match the type of plant (power or wastewater); otherwise, the questions were equivalent. All of the surveyed plants had been identified as those currently producing or using treated municipal wastewater for cooling system makeup water. Their responses helped to identify cooling water management practices and contributed to the data used in the life cycle inventory. Challenge A questions pertained to wastewater treatment conducted at both plants; Challenge B questions pertained to wastewater delivery distances and methods; Challenge C questions pertained to public awareness, public concerns voiced, and community outreach; and Challenge D questions pertained to the price paid for treated wastewater. Out of the 18 wastewater treatment plants and 32 power plants surveyed, staff at 4 wastewater treatment plants and 6 power plants completed the survey, representing a 22% and 19% response rate, respectively, which is consistent with typical survey response rates.

2.4   RESULTS AND DISCUSSION

Data from the survey and LCA were analyzed to assess their potential application to sustainability tools for evaluating wastewater reuse practices in power plant cooling systems. Results from the surveys were used to define specific parameters in the LCA. The results are presented based on the four challenges.

2.4.1 Challenge A: Biofouling, Scaling, and Corrosion Sustainability Analysis using LCA and Survey

Challenge A considers the chemical treatment required to control biofouling, corrosion, and scaling. All three treatment issues inevitably arise when working with reclaimed wastewater and can be effectively addressed through physical, biological, and chemical means.

Both the wastewater treatment plant and the power plant have distinct roles to play in terms of system quality. The wastewater treatment plant conducts secondary and sometimes tertiary treatment, while each power plant conducts additional treatment to address issues more specific to its unique operational equipment and cooling water chemistry. For the wastewater treatment plants, secondary treatment includes the removal of organic matter, removal of suspended solids, and sometimes disinfection. Tertiary treatment is used to remove residual suspended solids, nutrients, and also includes disinfection (Eddy, 2003). For the power plants, additional treatment can vary, but usually involves some amount of chlorine added for the control of pathogenic organisms in the incoming water. Figure 3 shows the range of treatment methods used, as reported by wastewater treatment plant and power plant personnel.
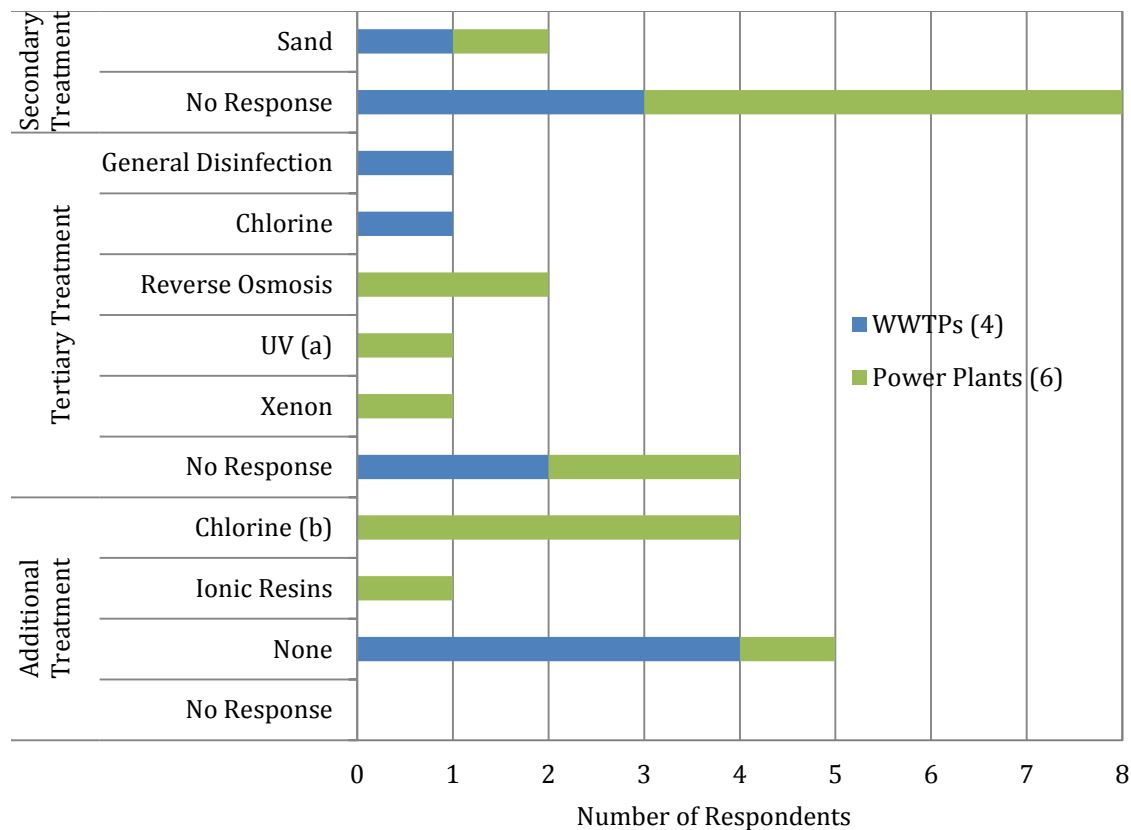
(a) UV light, followed by super-chlorination
(b) includes chlorine and hypochlorite responses

Figure 2-3. Treatment cited by wastewater treatment and power plant survey respondents to address Challenge A--biofouling, scaling, and corrosion--when using wastewater effluent as cooling makeup water.

Assuming that the power plant and wastewater treatment plant are not co-located, additional chemical treatment (labeled "additional treatment" in Figure 3) typically begins after the arrival of effluent at the power plant. None of the wastewater treatment plants surveyed treat the water beyond the tertiary level. In most cases, the power plants receive the same treated effluent that would otherwise be discharged back into the environment; thus the burden for additional treatment, in practice, falls to the power plant. The survey responses indicated that reverse osmosis was the most common method of tertiary treatment for the power plants, though other methods were used. Almost all of the power plants surveyed conducted additional treatment of the water using chlorine-based compounds, which serve as general disinfectants and biocides.

Figure 4 shows survey responses regarding the chemicals used by power plants to control biofouling, scaling, and corrosion. The data received for anti-scalants and anti-corrosives were less conclusive than the biocide data, as many plants did not supply information for the former two categories. Out of the responses received, two plants reported using organic polymer for anti-scalant purposes and one plant reported using a phosphorous-based compound for anti-corrosive purposes. Lack of positive responses regarding anti-corrosives and anti-scalants could be due to confidential operating practices or could indicate that these plants are not currently using anti-scalants and anti-corrosives in their systems. Respondents were given the option of entering "None" on the survey to indicate no use of anti-scalants or anti-corrosives. Given the prevalence of scaling and corrosion in power plant systems, it is likely that the lack of positive responses is a result of proprietary operations.
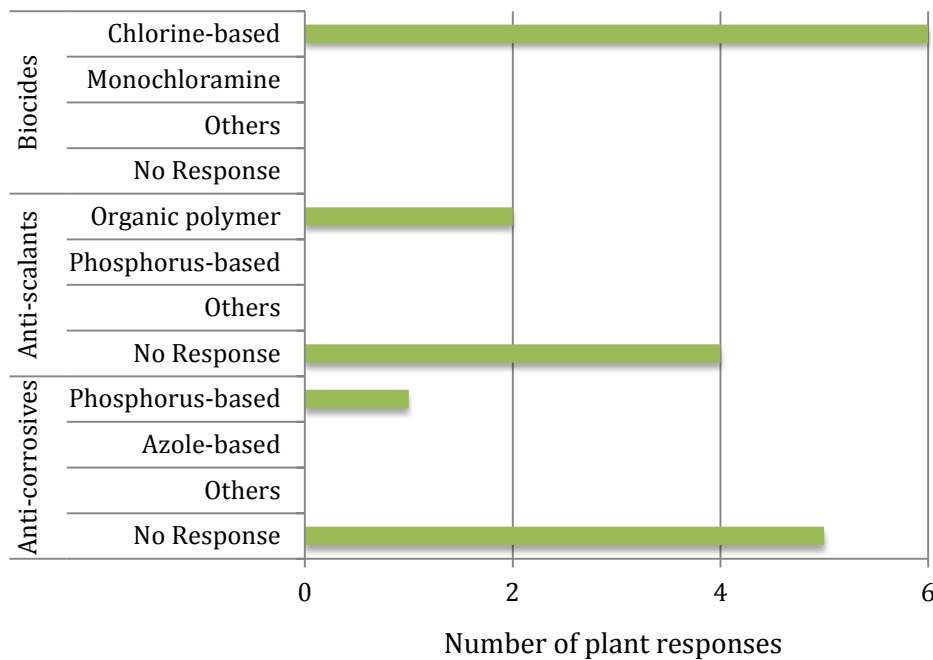
Figure 2-4. Chemicals used by power plant survey respondents to control biofouling, scaling, and corrosion when reusing treated municipal wastewater for cooling makeup water.

Based on the survey data collected from power plants shown in Figs. 3 and 4, LCA was used to quantify the environmental impacts of the chemicals used to treat biofouling, scaling, and corrosion. The system boundaries focus on the production of the chemicals and extend from the raw material extraction phase to the storage of the finished product. Figure 5 shows impact assessment results for three chemical treatment scenarios, where the chlorine compound treatment is varied within each scenario. The three scenarios are based on three compounds: sulfuric acid (H_2SO_4), sodium tripolyphosphate (STPP), and a chlorine-based compound (Cl, ClO_2, or NH_2Cl). H2SO4 is commonly used to address scaling issues, STPP for corrosion, and chlorine-based compounds for biofouling and general disinfection. The concentration of H_2SO_4 and STPP are held constant for the comparison while the concentration of the chlorine-based compounds is varied according to previous research (Dzombak, Vidic et al., 2010). The dosages for each chemical scenario are detailed in Supplementary Table 1.
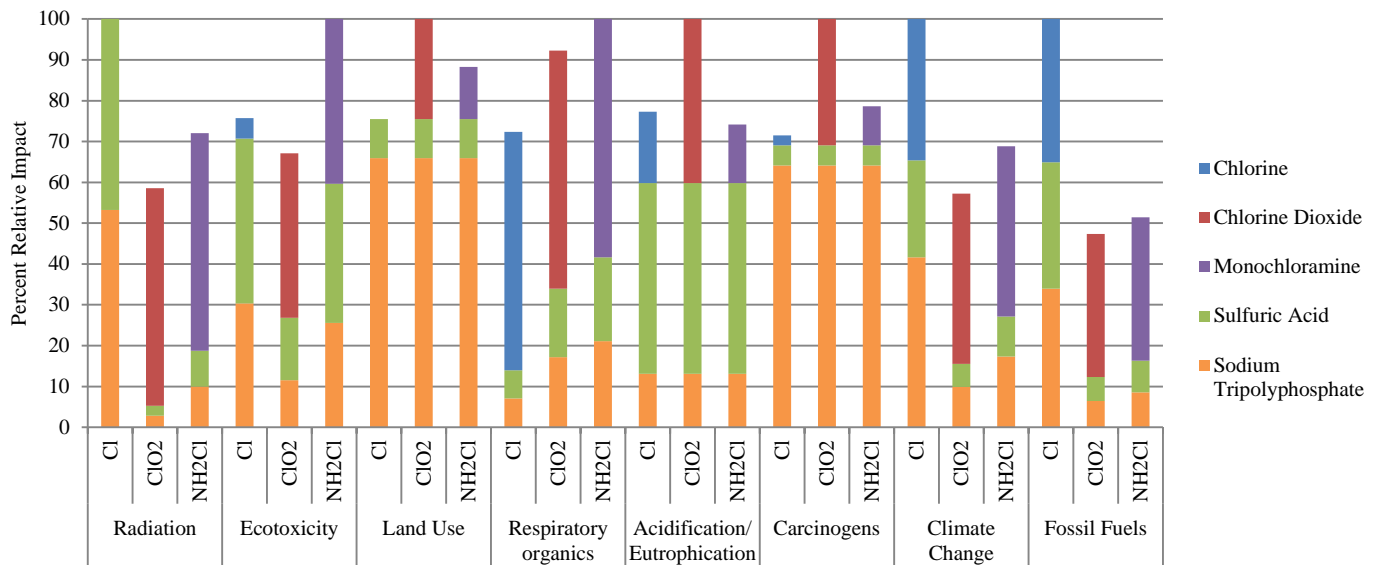
Figure 2-5. Environmental impacts resulting from raw material extraction and chemical production for three treatment scenarios that address biofouling, corrosion, and scaling.

Results normalized to the highest impact in each category. Cl_2 = chlorine scenario (Cl_2, H_2SO_4, $Na_5P_3O_{10}$), ClO_2 = chlorine dioxide scenario (ClO_2, H_2SO_4, $Na_5P_3O_{10}$), NH_2Cl = monochloramine scenario (NH_2Cl, H_2SO_4, $Na_5P_3O_{10}$).

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According to the LCA results presented in Figure 5, no single treatment scenario consistently exhibits the lowest or highest environmental impact in any environmental impact category. There are significant trade-offs, however. For example, while ClO_2 may exhibit, on average, half the impact of Cl with regard to fossil fuel usage and climate change, Cl exhibits a 25 percent greater relative impact than ClO_2 in land use and a 28 percent greater relative impact in carcinogenic potential.

Different impact assessment methods have different emphases and define their categories slightly differently. Eco-indicator 99 defines fossil fuel as oil, gas, or coal. Conventional and unconventional production methods are considered for oil and gas, whereas coal (conventional) for Eco-indicator includes open-pit mining for hard coal or lignite, as well as underground mining. The fossil fuel impact in this study is largely represented by coal and natural gas use at the typical chemical production plant and contributes to climate change via carbon dioxide emissions at the plants. Regarding land use, transformation of fallow land to serve mineral extraction purposes is the primary source of the land use impacts. Most of the carcinogenic potential originates from ionic arsenic, which is a known carcinogen commonly found in degraded sources of water (U.S. Department of Health and Human Services, 2007).

Monochloramine, when used in place of chlorine dioxide or pure chlorine, contributes an average of 10% additional impact to the categories of land use, carcinogenic potential, and acidification and eutrophication. Chlorine gas has long been known as a respiratory irritant (Kennedy, Enarson et al., 1991), so it is hardly a surprise that all three chlorine-based scenarios contribute over 50% to the respiratory organics impact category, largely due to non-methane VOCs and hydrocarbons.

STPP contributes over 60% to the impact categories of total land use and carcinogenic potential. The greatest sulfuric acid impact occurs with respect to the categories of ecotoxicity and acidification and eutrophication. Many different metals used in the production equipment contribute to ecotoxicity, especially chromium and nickel (Wallinder, Bertling et al., 2006). The acidification and eutrophication impacts can be traced back to emission of sulfur dioxide and nitrogen oxides released in the production phase of STPP.

Since this study only considered the raw material extraction and production phases of the chemicals in an effort to show how LCA could be integrated with other sustainability tools, a comprehensive LCA with additional chemical scenarios and risk of leakage would need to be completed to fully understand the system's impacts. Based on the comparative LCA results shown in Figure 5, however, some alternatives for trade-offs can be identified to inform future decisions, especially regarding the use of STPP. To minimize land use or carcinogenic potential, one might look for an alternative to STPP since it contributes the most to these categories. Replacing STPP, however, would involve a trade-off for the category of acidification and eutrophication potential, where impacts from sulfuric acid are nearly as great as those from STPP. Therefore, for the exclusive case of acidification and eutrophication, finding an alternative to sulfuric acid might be more beneficial.

The results in Figure 5 are based on three treatment scenarios; there are potentially many other chemicals and compositions used in cooling water treatment. A plant-specific LCA can help select which chemicals are most appropriate for a particular system. However, LCA should not be mistaken for a full sustainability analysis. Complementary sustainability assessment tools, such as laboratory testing, life-cycle costing, and treatment-effectiveness surveys should be employed in addition to LCA for more comprehensive analyses.

2.4.2 Challenge B: Wastewater Delivery Sustainability Analysis using LCA and Survey

Challenge B, wastewater delivery, can be assessed using survey results to inform the LCA. As illustrated in Figure 6, eighty percent of respondents reported plant-to-plant distances of five or fewer miles. Only two plants reported distances greater than five miles: 7 and 18 miles, respectively. Chien, et al. (2008) calculated an average maximum plant-to-plant distance of 10 miles for 81 percent of proposed U.S. power plants and of 25 miles for 97 percent of proposed U.S. power plants (Chien, 2008). Of existing power plants, approximately 50 percent could use cooling water from wastewater treatment plants within 10 miles and approximately 76 percent could use cooling water within 25 miles (Li, Chien et al., 2011). As the distance between plants increases, however, factors such as piping costs and environmental impacts become more important to consider.
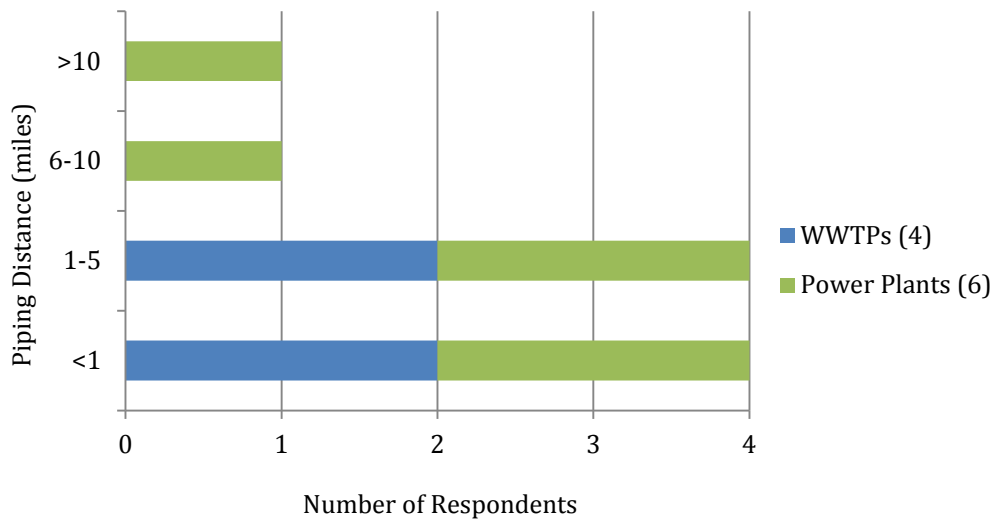
Figure 2-6. Distance between wastewater treatment plants and power plants.

Distances reported by survey respondents who are currently using treated municipal wastewater for cooling makeup water at their facility.

Life cycle assessment can be used to determine the environmental impacts of materials, construction and maintenance of the piping system. Figure 7 shows a sample comparison of environmental impacts resulting from the production of two types of typical pipe material—PVC and concrete—utilizing the average distance of ten miles between plants, which takes both the literature and survey results into consideration. As evident from Figure 7, PVC results in more environmental impacts than concrete in each of the categories shown, particularly with respect to carcinogens. The carcinogenic human health impacts of PVC are widely recognized by the literature and is emphasized through the LCA results (U.S. Department of Health and Human Services, 2005). The environmental impacts of PVC in this scenario range from three times (for minerals, where "minerals" is calculated based on a geostatistical method based on resource availability (Goedkoop and Spriensma, 1999) to 52 times (for respiratory organics) greater than the environmental impacts of concrete.
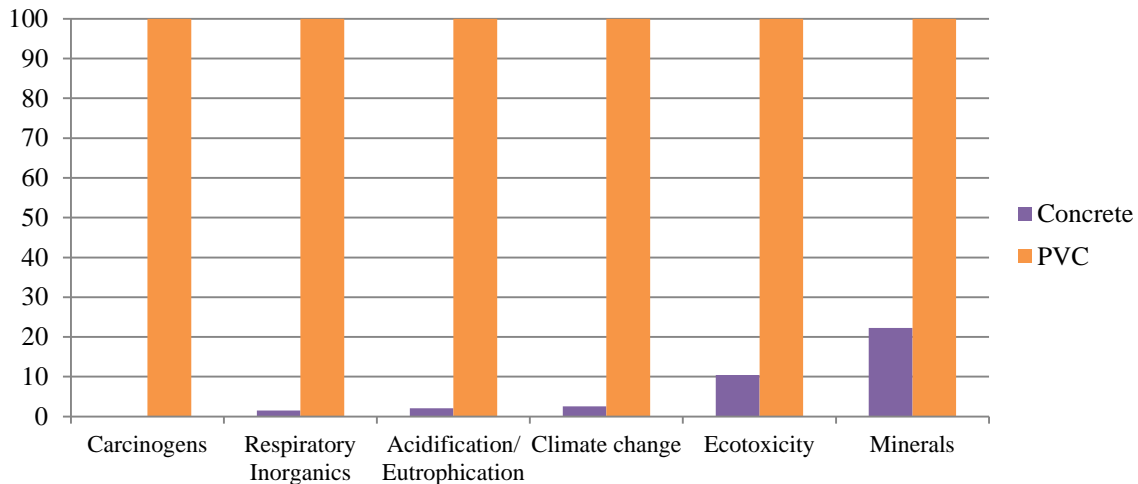
Figure 2-7. Environmental impacts from production of different piping materials.

Results normalized to PVC.

The evaluation of Challenge B—wastewater delivery— does not merely consist of materials selection and distances of piping; factors related to the cost of the materials, the lifetime of the materials, the installation of the system, the maintenance of the piping system, and any necessary energy required for moving the water all contribute to the environmental impacts of wastewater delivery, as well as to the feasibility of wastewater delivery. Life cycle assessment can be used to analyze the environmental impacts of materials selection, as shown in Figure7 as well as installation, maintenance, and energy requirements. Maintenance could vary depending on pipe materials, intensity of use, climatic conditions, and many other factors. Energy and emissions from any pumping required could also vary based on pipe diameters, flow rates, and differences in site elevations. Thus, data related to the expected lifetime of the system, the anticipated maintenance of such a system, and the need for pumping of water must be obtained for the specific systems and incorporated into the LCA. Obtaining the land use rights to install piping in a particular location can also be challenging and costly. If permitting becomes an issue, greater distances for trucking or shipping water may be considered. Life cycle costing (LCC) can also be used to assess the costs of the various piping and transport scenarios.

2.4.3   Challenge C: Public Perception Analysis using a Survey

Challenge C – public perception is one challenge that LCA does not adequately address. Therefore, a survey was used to gather information on plants' experiences related to public perception and outreach activities with respect to utilizing wastewater for power plant cooling at their facilities (Figure 8).
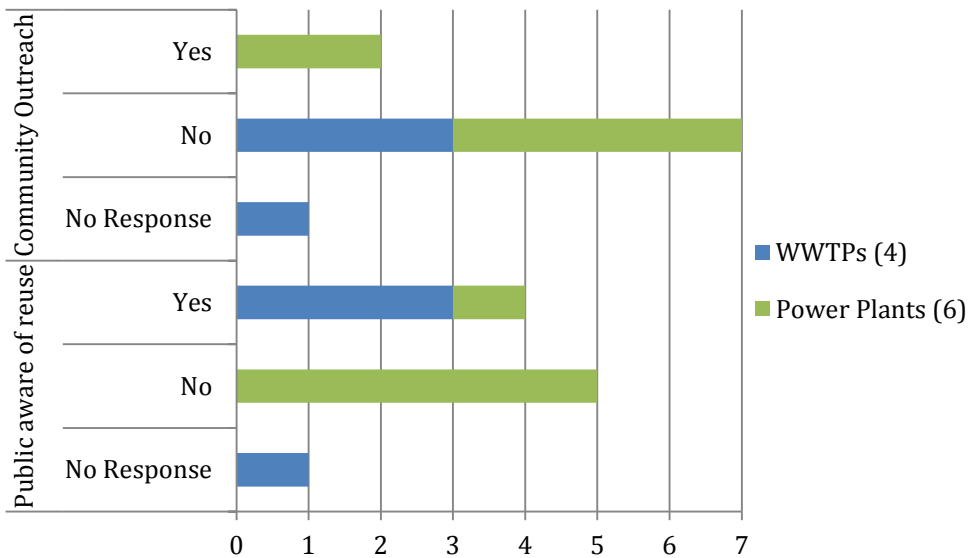
Figure 2-8. Survey responses regarding public perception and community outreach efforts associated with power plants using treated municipal wastewater for cooling makeup water.

Personnel at both the wastewater treatment plants and power plants were asked if the local public was aware that treated wastewater was being sent to or used in the power plant. Personnel at both plants were also asked if the plants hosted any educational outreach events for the community. According to the responses received, some plants allow the public to tour their facilities and other plants inform the public that they are using wastewater to avoid the use of groundwater. Nonetheless, the majority of the survey responses indicated that few respondents were aware of any outreach activities at all at their respective facilities. As described earlier, low public awareness of the processes and technologies used in wastewater reclamation may lead to negative public perception of both the wastewater treatment plants and the power plants engaged in reclamation activities. Further research should be conducted to determine why community involvement is so low and what can be done to improve public awareness and acceptance. Public perception can also be addressed via other tools and metrics described in Table 1, such as surveys directed at the public.

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2.4.4   Challenge D: Valuation of Water Sustainability Analysis using a Survey

Challenge D – valuation of reclaimed water is also inadequately addressed by traditional LCA tools, which have yet to even fully address freshwater consumption (Pfister, Koehler et al., 2009). While current LCIA methods include water quality categories such as eutrophication and ecotoxicity, water withdrawal and consumption categories are largely missing (Goedkoop, Heijungs et al., 2009). Although an LCC code of practice is being developed, the incorporation of water use into LCC still remains to be fully examined as well (Swarr, Hunkeler et al., 2011). The major issue to be examined is that the price paid for water does not reflect the actual costs incurred in reusing treated municipal wastewater, nor does it reflect the economic and environmental savings gained from reusing water that would have otherwise been immediately released to the natural waterways.

Figure 9 shows price paid by power plants to wastewater treatment plants for reuse of wastewater in the power plant cooling system, which was obtained through the survey. The majority of the responses are below $0.66 per 1,000 gallons. For comparison, drinking water in the U.S. typically costs slightly over $2 per 1,000 gallons with treatment accounting for approximately 15 percent of the cost (US EPA Office of Water, 2004). It is interesting to note that one of the wastewater treatment plants did not charge the power plant anything for its wastewater. Additionally, the "Other" response in Figure 9 refers to one dynamic costing scenario. In this case, the power plant paid the wastewater treatment plant a percentage of the cost for potable water, which can vary with broader economic fluctuations, maintenance costs, and any natural events, such as severe storms that require additional treatment of the water.
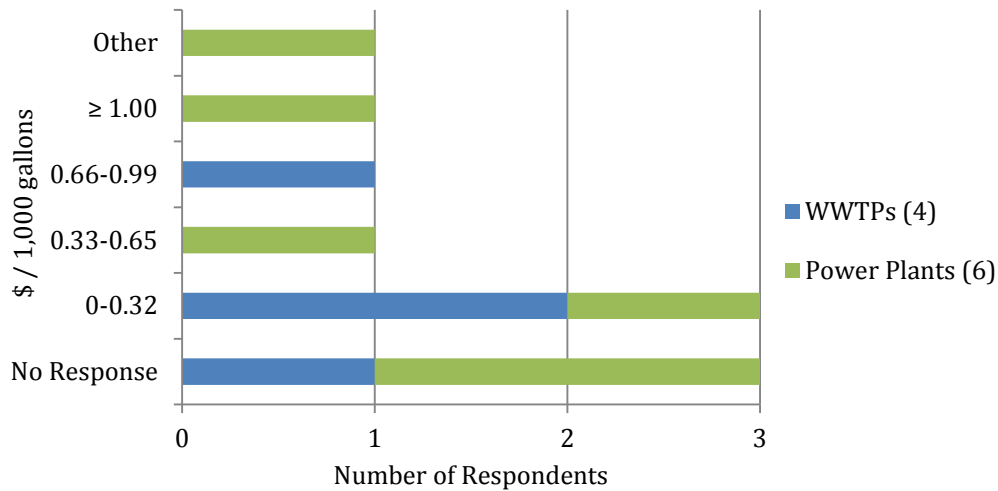
Figure 2-9. Price (in 2009 USD) paid by power plants to wastewater treatment plants for treated municipal wastewater.

The price paid for the wastewater may include the cost of piping, environmental regulation permits, and any internal administrative costs; it does not include the cost of additional chemicals because those are usually handled by the power plants, as reported in Figure 3. When using traditional costing methods such as LCC, wastewater reuse may seem to be more expensive than freshwater withdrawal, since the cost to the environment is not included in LCCs. Interestingly, the primary element that makes such a system seem sustainable, which is the reuse of wastewater, is not adequately captured by existing sustainability tools. LCA does not distinguish between withdrawal of freshwater versus other sources (write about the recipe exception, if it applies), LCC does not place any particular monetary value on freshwater versus wastewater, and the prices paid for freshwater versus wastewater would lead the user to choose free freshwater over wastewater.

Sustainability tools and metrics used in addition to LCA and environmental impacts can be used as complementary approaches. As shown in Table 1, additional sustainability metrics include water volume, cost, and value. Water volume here does not refer to a static quantity, but rather the metric used for an input-output water balance conducted over time to identify changes

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in freshwater levels and potential process improvements. Other possible sustainability metrics for capturing the value of water include water quality and regional ecosystem quality, both of which can be measured using traditional laboratory methods and environmental risk assessment, in addition to LCA.

2.5   CONCLUSIONS

Previous research and industry experience has shown that treated municipal wastewater can be used as makeup water for power plant recirculating cooling systems. With the feasibility established, it is useful to evaluate and optimize the overall sustainability of the system. However, one of the main tools used to evaluate sustainability, life cycle assessment, does not currently address the full complexity of wastewater reuse. Therefore, in addition to traditional LCA methods, other tools and metrics must be considered to analyze the sustainability of such a system.

The study employed a survey of personnel at power plants and wastewater treatment plants engaged in cooperative relationships of using the treated wastewater effluent for power plant cooling to inform the LCA and to investigate the value of avoiding freshwater withdrawal for power plant cooling. While the survey intentionally addressed issues such as chemical treatment and public perceptions, which are not always easily captured through traditional research, the responses also highlighted important issues from the perspectives of the plant personnel.

The survey of power plants and wastewater treatment plants served as a source of inventory data used within the LCA. Survey results regarding biofouling, corrosion, and scaling

showed that wastewater treatment plants generally do not include any special treatment for effluent transported to the power plants, with the exception of additional chlorination. The survey also revealed that power plants are paying relatively low prices for treated wastewater. Other results showed that most plants surveyed were located within five miles of one another. Finally, few plants have conducted community outreach activities; more research should be conducted on community understanding and concerns.

Analysis of the sustainability aspects of the four challenges to wastewater reuse in power plant cooling systems revealed that the sustainability of alternative approaches related to Challenges A and B can be partially assessed using available sustainability tools and metrics, but the available tools and metrics are inadequate to address Challenges C and D. The primary element that makes treated wastewater reuse in power plant cooling systems seem sustainable, which is the reuse of wastewater, is not adequately captured by existing sustainability tools and metrics. Additional tools, such as GIS, and new metrics are needed to assess the sustainability of complex water-energy systems like the one investigated here.

2.6   ACKNOWLEDGEMENTS

3.0 USING GEOGRAPHIC INFORMATION SYSTEMS TO ASSESS POTENTIAL BIOFUEL CROP PRODUCTION ON URBAN MARGINAL LANDS

The following chapter appears as accepted to *Applied Energy* and is in press with the citation:

Niblick, B., Monnell, J.D., Zhao, X., A.E. Landis (2012). "Using geographic information systems to assess potential biofuel crop production on urban marginal lands." Applied Energy. http://dx.doi.org/10.1016/j.apenrgy.2012.09.036. In press.

Chapter 3 examines industrial symbiosis in the context of land reclamation and small-scale sunflower biodiesel production. A GIS framework is created to identify marginal lands on which the sunflower crops could be cultivated and the potential biodiesel contribution to the RFS2 is assessed.

3.1 ABSTRACT

To meet rising energy demands in a sustainable manner, the United States Renewable Fuel Standard 2 (RFS2) mandates the production of 3.78 billion L (1 billion gallons) of biomass-based biodiesel per year by 2020. Urban marginal lands, herein defined as lots with poor agricultural potential and unfit for residential purposes, can be used to cultivate biodiesel feedstock, which can contribute toward the RFS2. GIS is particularly well suited to identify the amount and location of these urban marginal lands. Biofuel crop production is one way for urban neighborhoods to reclaim vacant, blighted properties and also generate green energy for consumption.

Combining soil classification data with urban development data, a GIS framework was developed to determine the amount of urban marginal land available in Pittsburgh, Pennsylvania. This location was chosen because small-scale sunflower crops are already being grown on urban marginal lands for biodiesel production. This paper evaluates two methods for identifying marginal lands for biofuel cultivation. The first is based on NRCS soil classifications derived from previous literature approaches. When compared with the locations of a nonprofit that is actually cultivating marginal lands, the NRCS soil classification method captures less than 35% of the marginal lands being cultivated in Pittsburgh, and 2,400 ha (6,000 acres) of marginal land in total that could be used to grow sunflowers for biodiesel production. We modify the NRCS marginal soil classification method to include certain types of urban commercial lands and lands not currently classified as marginal, and create a framework that identifies almost 90% of the marginal lands currently under cultivation in Pittsburgh, with approximately 3,500 ha (8,700 acres) of available marginal lands. Pittsburgh's marginal lands could be used to produce up to 129,000 L (34,100 gallons) of sunflower-based biodiesel. This could contribute a maximum of

0.1% to Pennsylvania's biofuel mandate and 0.003% to the RFS2. While a city's individual contribution may be incremental on the national scale, multiple cities and regions may be able to contribute to the RFS2. In addition, there is an unquantified social benefit that results from community engagement and revitalization, which is part of the mission of the Pittsburgh nonprofit.

3.2   INTRODUCTION

U.S. cities have an average of 15% vacant, or marginal lands, which produce little to no value and are often considered blights within communities [1]. Without any intervention, these vacant and abandoned properties contribute to urban blight and generate municipal expenses. Marginal lands are herein defined as lots and pastures characterized by poor agricultural potential, ill-suited for residential purposes, and otherwise economically unprofitable [2, 3]. However, urban marginal lands can be reclaimed for beneficial purposes; communities all around the world have turned them into parks, playgrounds, and community food gardens [4, 5].

One seldom explored reclamation activity involves the cultivation of biomass crops on urban marginal lands for the purposes of biofuel production [6-11]. City planners commonly use geographic information systems (GIS) to assess the feasibility and potential of similar projects using urban lands and to more effectively manage these projects once they are underway. While researchers have employed GIS at the regional [12-15], national [10, 16], and global [6, 7] scales to better understand the volumetric yields and land use implications of traditional biomass production, the reclamation of urban marginal lands for biomass production is still a relatively new concept and warrants further investigation.

There is potential for biomass produced on urban marginal lands to directly impact state and national biofuel production targets. The RFS2 requires 1.36×10^{11} L (36 billion gallons) of renewable fuel per year to be blended into all transportation fuel by 2022, 3.78 billion L (1 billion gallons) of which need to be biomass-based biodiesel [17]. Additionally, many states have enacted similar biofuels initiatives, such as Pennsylvania's Act 78, which requires 2% biodiesel to be blended into all gasoline sold at the pump [18]. Given legislative mandates and the opportunities presented by urban marginal land, this study aims to show that cities can use GIS to estimate the amount of marginal land available for site reclamation and biofuel production.

One of the primary challenges in assessing the amount of marginal land available in an area is deciding what qualifies as "marginal" for the region being evaluated. The working definition of "marginal lands" can vary depending on factors such as the quality of other nearby land and the agricultural resources available to the community. This study uses the OECD description of marginal land—"poor agricultural potential and unsuited for residential purposes" [2]—and also incorporates the "Law of Marginality," as defined by Lal (2009), which states that, "Marginal soils cultivated with marginal inputs produce marginal yields and support marginal living" [19]. Taking these two definitions into consideration, marginal land is defined herein as lots or pastures with poor soil as classified by the USDA and with a slope less than 15%, where the 15% slope is used as an upper limit to minimize runoff and erosion.

The City of Pittsburgh maintains a list of vacant lots for sale and offers an online map viewer with data layers including public amenities, demographics, and environmental layers such as floodplains, landslide prone areas, and greenways [20, 21]. This map does not include the vacant lots, one major source of marginal land in urban areas. The Pittsburgh Neighborhood and

Community Information System (PNCIS), based at the University of Pittsburgh, provides an online property information system for community development initiatives and includes vacant lots [22]. The PNCIS also includes greenways, woodlands, and multiple layers of demographic data. PNCIS does not provide data on soil quality, land slope, or farmland classification. While PNCIS does partner with the City of Pittsburgh, differing data availability at each source highlights the site-identification challenge facing organizations attempting to revitalize marginal properties and also highlights the need for increased agency collaboration.

Many community organizations and nonprofits address the reuse and reclamation of vacant and marginal urban lands. One such nonprofit organization, GTECH Strategies (Growth Through Energy and Community Health) reclaims and revitalizes marginal lands in Pittsburgh, Pennsylvania [23]. GTECH uses innovative and resourceful strategies to transform environmental challenges into social and economic opportunities and thereby contributes to the creation of a prosperous and inclusive green economy [24]. One of GTECH's major initiatives created a biomass-to-biofuel community revitalization program. Through an application process, GTECH organizes selected communities to plant sunflowers, canola, and switchgrass on vacant plots of land. Community members plant the crops in the spring, maintain the site throughout the summer, and harvest the seeds in the autumn. After one or two harvests of sunflowers, full responsibility of the site is transitioned to the community. Past sites have become food gardens, rain gardens and playgrounds. In addition to reclaiming vacant land, GTECH also connects marginalized communities to environmentally beneficial economic opportunities through its green economy initiatives. GTECH's partner organizations, ReFuel Pgh and Fossil Free Fuel, also collect waste nonhydrogenated vegetable oil to process into biodiesel for local use.

This paper focuses on GTECH's sunflower-to-biodiesel program and its broader application to other locales, given sunflowers' resiliency to a variety of environments and the comparative ease with which sunflower seeds can be used to produce biodiesel. By developing a framework to identify marginal lands using GIS, and assuming GTECH management practices and yields, we estimate the amount of urban land in Pittsburgh that could be considered marginal and used for biofuel production, and subsequently the total biofuel yield from urban marginal lands. The resulting estimates could inform land management decisions, generate renewable biofuels, and potentially contribute to the RFS2.

3.3   METHODS

Determining the biodiesel yield from urban marginal land is a multi-step process. First, the NRCS marginal soil classification method is defined through Sections 2.1 through 2.2, where soils were first distinguished from developed land using GIS and marginal soils were identified based on soil quality and cultivation requirements. The biofuel production calculations from marginal soils are described in Section 2.3 for sunflower seed, oil, and biodiesel. Figure 1 depicts the steps of the method. After validation of the NRCS marginal soil classification method, the method was updated as a framework to include commercial and vacant urban lands, described in Section 2.4.

We evaluated two methods for identifying marginal lands. The first is based on USDA's Natural Resources Conservation Service (NRCS) soil classifications derived from previous literature approaches [6, 25]. When compared with the locations of a nonprofit that is actually cultivating marginal lands, the NRCS marginal soil classification method captures less

than 35% of the marginal lands that are being cultivated in Pittsburgh. We updated the marginal

NRCS soil classification method and created a framework to include urban commercial lands

with the aim of capturing more sites that the nonprofit GTECH is cultivating.
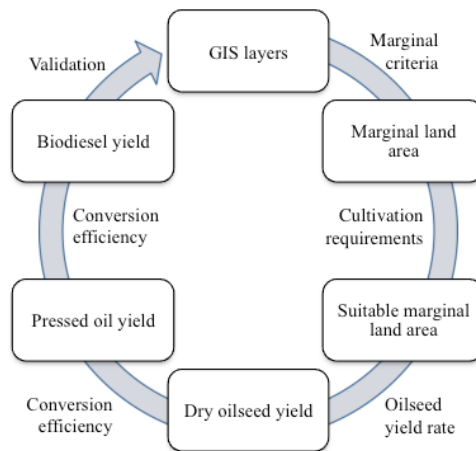
Figure 3-1. Process used to calculate potential biodiesel yield from sunflowers grown on urban

marginal land.

Rectangles with rounded corners represent intermediate results. Calculation steps are shown along the arrow.

3.3.1   Distinguishing soils from developed land

To begin identifying urban marginal lands, the city of Pittsburgh was divided into census tracts,

as shown in Figure 2a. Each census tract contains property parcels, inside of which are building

footprints. Both public and private properties were evaluated. The area of each building footprint

was subtracted from the area of each parcel, leaving the surrounding areas for evaluation (Figure

2b). Building footprints follow the outline of the roof: all parts of the building under the roof

were included as part of the footprint. Driveways and patios that extend beyond the roofline were

not included. Garages greater than 200 square feet were included. After extraction of the building

footprints, streets were layered over the census tracts (Figure 2c) and then subtracted from the total area (Figure 2d), resulting in the total area considered for soil analysis (Figure 2d). A summary of GIS data used is provided in Appendix B.
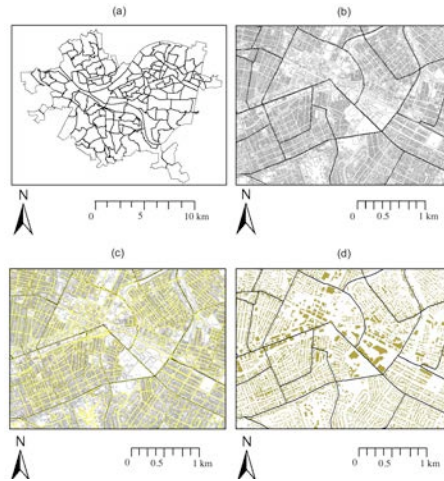
Figure 3-2. Summary of GIS process to calculate area of marginal land.

(a) map of Pittsburgh with census tracts outlined, (b) area of parcels (gray) with building footprints extracted, (c) overlay of streets (yellow) and parcels (gray) with building footprints extracted, (d) land area remaining (brown) after extraction of building footprints and streets.

3.3.2   Identifying marginal soils via NRCS marginal soil classifications

Spatial data for the 92 soil types present in Pittsburgh were obtained from the USDA's NRCS database [26] and imported into the GIS software, *ArcMap 10* [27]. The soil data were evaluated for marginal status and for the suitability of growing sunflowers. Based on GTECH operating practices, the ideal marginal plot would have an area of at least 0.009 ha (1,000 ft^2) and be composed of marginal soils at a slope of 15% or less to minimize runoff and erosion.

Soils were grouped according to the three major NRCS farmland classifications: prime farmland, farmland of statewide importance, and not prime farmland, as well as soil composition,

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as shown in Table 1 [26, 28]. Soils listed as "not prime farmland" were classified as marginal. Prime farmland and farmland of statewide importance were not considered marginal. Greenways are not identified in the NRCS classifications and include areas such as city parks and other recreational areas. These features were added and classified as non-marginal areas [29], leaving urban soils and soils with special industrial uses still to be classified. Urban soils were distinguished from otherwise developed urban areas using the building footprint extraction method described in Section 2.1. Soils not listed as urban, but with particular industrial uses such as stone quarries or coal dumps, were classified as marginal. Table 2 lists all soil categories considered marginal for this study.

Table 3-1. Summary of USDA NRCS soil classification system.

Dash (-) denotes no data listed by NRCS.

USDA NRCS classification	Soil type	Land uses	Slope (%)
Prime farmland	silt loam	-	0-8
	shaly silt loam	-	0-8
	clay loam	-	0-8
	complex	-	0-8
Farmland of statewide importance	silt loam	-	2-15
	shaly silt loam	-	2-15
	clay loam	-	2-15
	complex	-	2-15
Not prime farmland	loam	-	0-35
	silt loam	-	0-35
	shaly silt loam	-	0-35
	silt clay	-	0-35
	silty clay loam	-	0-35
	complex	-	0-35
	-	strip mines	0-75
	-	gullied land	not given
	-	gravel pits	not given
	-	quarries	not given
	-	coal dump	not given
	-	industrial dump	not given
	-	urban	sloping
	-	urban	gently sloping
	-	urban	moderately sloping
	-	urban	moderately steep
	-	urban	steep
	-	urban	very steep

Table 3-2. Selection of marginal soils classified by NRCS as "not prime farmland" or "urban".

Feature category	Marginal characteristics
Slope	less than 15%
	urban - sloping
	urban - gently sloping
	urban - moderately sloping
Special land uses	strip mines
	gullied land
	gravel pits
	quarries
	coal dump
	industrial dump

Pittsburgh's 92 soils were classified into soil quality categories and mapped onto the same census tract map used in Section 2.1. Figures 3a through 3d demonstrate the process of adding each soil layer to the map. Starting with the blank map (Figure 3a), agricultural land, greenways, and land with slopes greater than 15% were added in Figure 3b. Urban soils were added in Figure 3c and marginal soils were added in Figure 3d. The total area of marginal land was then computed using GIS to intersect areas of marginal soil with areas of parcels with building footprints extracted. (For reasons of scale and clarity, parcels are not shown in Figure 3.)
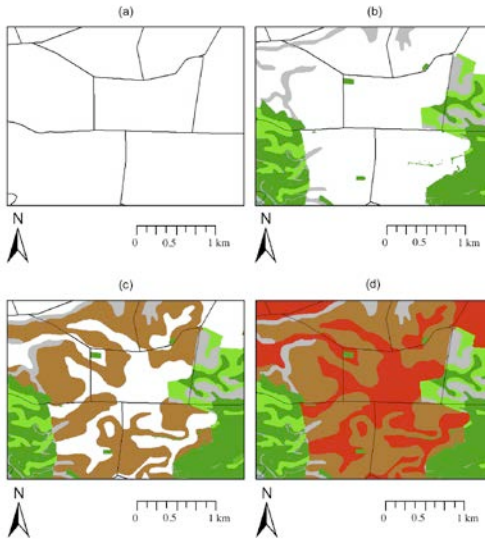
Figure 3-3. Summary of GIS process to map soil types.

Process steps include: (a) selected Pittsburgh area with census tracts outlined, (b) area added with greenways (green), prime agricultural land (dark green), agricultural land of statewide importance (light green), and land with slope greater than 15% (gray), (c) area with urban soils added in brown, and (d) area with marginal soils added in red.

3.3.3   Evaluating potential biofuel production on marginal soils

Once the soils were classified and mapped, production potentials for sunflower seed, oil, and biodiesel were calculated using yields typically obtained by GTECH. Given the area of marginal land suitable for growing sunflowers, as determined by the GIS, the GTECH sunflower oilseed yield (56 kg/ha or 50 lb/acre) was used to calculate the total potential dry oilseed yield (23 L/ha or 2.5 gal/acre, as compared to a prime agricultural average of 580 L/ha) [30]. The typical biodiesel conversion efficiency rate of 99% was used to calculate the biodiesel yield from the pressed oil yield [31].

3.3.4 Validation and framework for identifying marginal sites

The NRCS marginal soil classification method was validated by overlaying the resulting area identified as marginal with the marginal sites currently under cultivation by GTECH. The NRCS marginal soil classification method resulted in poor overlap with marginal sites that were actually being cultivated. The method was updated to capture the marginal sites in Pittsburgh. The urban soils listed in Table 1 not covered by buildings, roads, or pavements were reclassified as "marginal," and building footprints were extracted according to the process described in Figures 1 and 2. In addition, the minimum plot size was decreased from 0.009 ha (1,000 ft^2) to 0.005 ha (500 ft^2) to detect smaller plots not identified by the first method.

3.4   RESULTS AND DISCUSSION

3.4.1   Areas of marginal land

Figure 4 illustrates the soil coverage for the entire city of Pittsburgh. Classifications include greenways, agriculture, developed urban areas, slopes greater than 15%, marginal land, and water. Marginal soils are shown in red and represent urban areas where sunflower crops could be grown. Using the soil classifications presented in Section 2, 2,400 ha (6,000 acres), or 16.7%, of Pittsburgh land was determined to be marginal and suitable for growing sunflowers. Other crops that can tolerate low soil quality, such as switchgrass and miscanthus, could also be grown in these marginal areas. To avoid disease, sunflowers are often grown in two to three year rotations with other crops, such as wheat, sorghum, and barley [32-34].

The method based on the NRCS marginal soil classification system captures only five of GTECH's existing 16 sunflower sites, the results of which are depicted in Figure 4. In order to capture the marginal lands that GTECH has successfully cultivated, the NRCS marginal soil categories were expanded to include urban commercial lands with plot areas half the size of the previously assumed minimum (0.009 ha). GTECH's process for identifying sites to cultivate is based on a public application procedure in which interested communities detail their vision for the site and request assessment, planning, and implementation support from GTECH. GTECH advertises its application process to potential participants through its newsletter, website, and local neighborhood events.

The 11 GTECH sites not classified as marginal using the NRCS marginal soil classification method all fall in areas characterized by commercial urban development and are identified as "developed parcels" in Figures 4 and 5. By employing the updated GIS framework that reclassifies soils (Figure 5), Pittsburgh gains 1,100 ha (2,700 acres) of marginal land in addition to the previously established 2,400 ha (6,000 acres). The individual plots contained within the additional 1,100 ha (2,700 acres), however, would have areas as small as 0.005 ha (500 ft^2), half the size of the currently assumed ideal minimum site size of 0.009 ha (1,000 ft^2). By decreasing the plot size and broadening the definition of marginal to include more commercial lands, the revised GIS framework captures 14 of the 16 GTECH sites, as shown in Figure 5. One of the uncaptured sites is a brownfield, not included in this small-scale marginal lands study, and the other is located near the intersection of urban land, marginal land, and land with a slope greater than 15%. The latter site is a prime example of an area that would benefit from visual verification to determine its marginal status. While in-person verification is feasible at small scales, larger-scale projects may benefit from remote sensing to determine marginal

status and thus only necessitate site visits for groundtruthing, or verifying selected results from the remote sensing process.
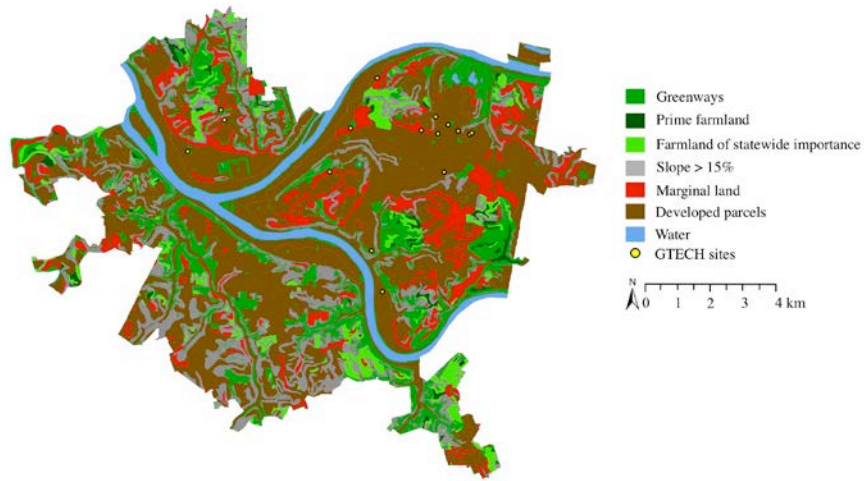
Figure 3-4. Map of Pittsburgh using NRCS marginal soil classification method to identify marginal

lands. showing soil types, waterways, and location of GTECH sites.

Refer to Appendix B for sources of GIS layer data.
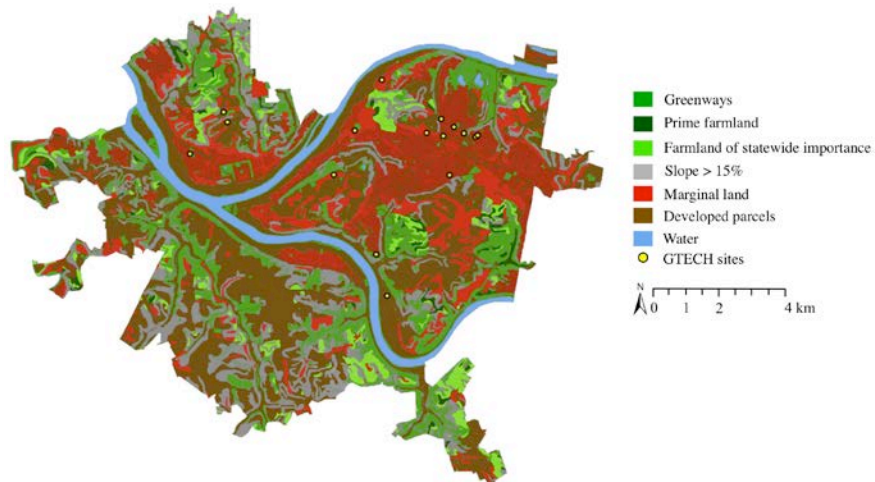
Figure 3-5. Map of Pittsburgh using revised GIS framework,

which captures 14 of 16 GTECH marginal sites. Refer to Appendix B for sources of GIS layer data.

3.4.2   Potential crop and biodiesel yields

Not all marginal land available in a city can, or will, be used to cultivate biofuel crops. Site-specific issues, such as available space, contamination, or zoning, limit the amount of usable marginal land. However, increasing the area of cultivated marginal land also increases the total annual biofuel production. Total production could be increased if the definition of "marginal" were expanded to include more urban commercial land, as described in Section 3.1, which in fact captures more of GTECH's identified and cultivated marginal lands. In addition, more marginal lands could be identified if the minimum size were reduced (here defined as 0.009 ha or 1,000 ft^2). Utilizing a greater number of smaller plots in addition to the current marginal plots could increase the total potential biodiesel production. However, caring for a greater number of plots would also require more person-hours and more organizational support to ensure proper agricultural care to facilitate the biodiesel production.

Another way to increase total biodiesel production is to increase the crop yields. Yields depend largely on environmental conditions and agricultural techniques. For example, birds in Pittsburgh often eat the seeds before they are harvested, therefore crop protection may help provide greater yields. Based on GTECH and national conditions, three yield scenarios were considered for analysis: 1) GTECH baseline, 2) GTECH, i.e. urban, cultivation with additional nitrogen fertilizer, and 3) prime agriculture as exemplified by sunflowers grown in the Northern Midwest of the United States.

GTECH employs very low input agricultural techniques during cultivation and harvest; little to no fertilizers, water, or pesticides are used on their sites. As such, the GTECH yield is significantly lower than that reported by prime agricultural sunflower production. GTECH reports an average sunflower oilseed yield on marginal land of approximately 56 kg/ha (50

lb/acre), resulting in approximately 23 L of sunflower oil per hectare (2.5 gal/acre) [30]. Studies have shown that average-quality land, i.e. not marginal and not prime agricultural land, in the United States can typically produce 560 kg of sunflower oilseed per hectare (500 lb/acre) [35], while productivity in the Northern Midwest and Great Plains prime agricultural regions can produce upwards of 1,330 kg of oilseed per hectare (1,190 lb/acre) [36]. Therefore, one hectare of U.S. agricultural land can produce an average of 580 L of sunflower biodiesel (62 gal/acre), 25 times greater than GTECH's current production rate.

A sensitivity analysis indicates that small changes to crop management could have drastic impacts to the biodiesel yield. Application of 60 to 240 kg of nitrogen fertilizer per hectare could increase the average yield to 37 L of biodiesel (4.0 gal/acre), compared to the current 23 L/ha (2.5 gal/acre) [37, 38]. While higher N rates may decrease the seed oil content, increased N availability has been shown to lead to higher crop yields per hectare and higher oil yields overall [37, 38]. Increased crop yields due to fertilizer could increase Pittsburgh sunflower biodiesel production from 81,500 L (21,500 gallons) per year in the current GTECH scenario to 129,000 L (34,100 gallons) per year in the GTECH fertilizer scenario. However, this still represents only 4% to 6% of the typical sunflower production in U.S. agricultural regions, where sunflower oilseed yields average 1,330 kg per harvested hectare (1,190 lb/acre) and produce 580 L of biodiesel per hectare (62 gal/acre) [39].

Increasing biodiesel technology efficiency does not provide significant improvements since the oil-to-diesel conversion rate is already 99%. Therefore, the greatest improvements in marginal yields can be gained from optimizing the planting and maintenance processes. Regional crop choices, in addition to soil and management issues, should also be considered since certain crops are better suited for certain climatic conditions [40].

3.4.3 Effects on policy: Renewable Fuel Standard and the Pennsylvania Biofuels Mandate

The RFS2 of the Energy Independence and Security Act of 2007 (EISA) calls for 3.78 billion L (1 billion gallons) of biomass-based diesel to be produced by the year 2022 [17]. Sunflower biodiesel produced at current GTECH production rates could contribute 0.001% to the national total. If the current 23 L/ha (2.5 gal/acre) cultivation and production rate were increased to 37 L/ha (4.0 gal/acre) under fertilized conditions, the percent contribution would increase to 0.003% of the national total. If the yield from urban marginal lands were increased to that observed in the Northern Midwest, where yields average 580 L of sunflower biodiesel per hectare (62 gal/acre), Pittsburgh urban marginal lands could contribute an absolute maximum of 0.05% to the RFS2. Of course, the more marginal land that is put into production, the greater the potential to contribute to the RFS2. These production trends and potential contributions to the RFS2 are depicted in Figure 6. These results of using urban marginal lands for contributing to the RFS2 only represent Pittsburgh, which is the nation's 23rd largest city in terms of population, and 15[h] largest city in terms of land area [41, 42].
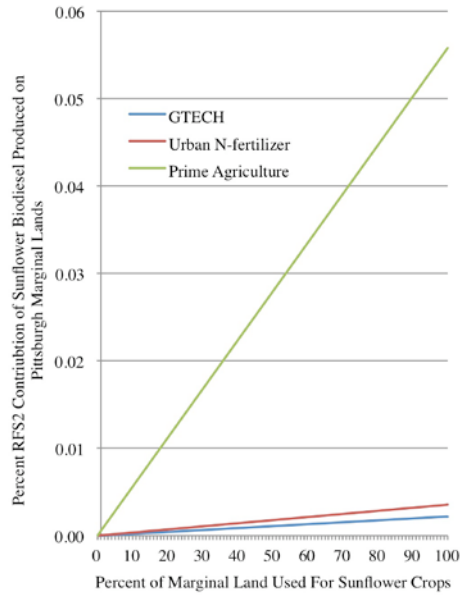
Figure 3-6. Percent potential contribution of sunflower biodiesel produced on Pittsburgh marginal lands to 3.78 billion L (1 billion gal) of biomass-based diesel as stated in the RFS2.

GTECH = 23 L sunflower biodiesel/ha, Urban N-fertilizer = 37 L/ha, Prime Agriculture = 580 L/ha.

Whereas the RFS2 applies to the national scale, other regulations such as Pennsylvania's Act 78, apply to individual states. The state of Pennsylvania produces approximately 151 million L (40 million gallons) of biofuels per year and under Act 78, which provides for the study and mandated content of biofuels, the state is required to include 2% biodiesel (B2) in all diesel sold at the pump as of May 1, 2010 [18]. Once in-state production reaches 379 million L (100 million gallons), the mandate increases to 5% biodiesel (B5); once production reaches 757 million L (200 million gallons), the mandate increases to 10% biodiesel (B10); and once production reaches 1.51 billion L (400 million gallons), the mandate increases to 20% biodiesel (B20). At Pennsylvania's current B2-level, sunflower-based biodiesel produced at GTECH current (unfertilized) rates on Pittsburgh's marginal land could contribute 0.03% biodiesel to the state

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mandate. If the yield were increased to 37 L/ha (4.0 gal/acre) through application of nitrogen fertilizer, sunflower biodiesel in Pittsburgh could contribute 0.1% to the state mandate.

Similar models of biodiesel production potential can be applied to other cities. Take, for example, the five largest cities of the Midwest as shown in Figure 7 and with land areas given in Appendix B: Chicago, Illinois; Indianapolis, Indiana; Columbus, Ohio; Detroit, Michigan; and Milwaukee, Wisconsin [43]. Assuming an equivalent percentage of marginal land in each city as in Pittsburgh (16.7%) and assuming GTECH (no fertilizer) yields of 23 L of pressed oil per hectare (2.5 gal/acre) with 99% conversion efficiency to biodiesel, rates of potential sunflower biodiesel production would range from 97,000 L (26,000 gallons) of sunflower biodiesel in Milwaukee (.002% of the RFS2) to 365,000 L (96,000 gallons) in Indianapolis (.009% of the RFS2). Changing the yield rate from the current GTECH rate to a Midwest agricultural rate of 586 L of pressed oil per hectare (63 gal/acre) and retaining the 99% conversion efficiency, production could range from 2.4 million L (648,000 gallons) of sunflower biodiesel in Milwaukee (0.06% of the RFS2) to 9.2 million L (2.4 million gallons) of sunflower biodiesel in Indianapolis (0.2% of the RFS2). Potential contributions from Chicago, Columbus, and Detroit all fall within this range.

Detailed assessments would need to be conducted for each city. An economically distressed city, such as Detroit, may have a greater percentage of vacant marginal land than a more metropolitan area, such as Chicago. Furthermore, just as Pennsylvania regulates biofuel production through Act 78, many other states have their own biofuel legislation. Using urban marginal land to produce biomass is one way of meeting state biofuel mandates in a locally sustainable manner. Locally produced biomass and bioenergy may also contribute to urban resilience, for example in cases of pipeline disturbance or other impacts to a region's standard

energy supply. Increasing local urban biofuel production on marginal lands may also result in the need for siting biodiesel production facilities in cities with large quantities of marginal land. In addition, locally produced biodiesel can be used locally and thus minimize impacts from distribution. Biodiesel cultivated in Pittsburgh, for example, could be used to run city-owned vehicles. Pittsburgh owns approximately 1,000 vehicles, 500 of which operate on diesel. These 500 vehicles consume approximately 2,650,000 L (700,000 gallons) of diesel per year [44]. Biodiesel produced on Pittsburgh marginal lands could therefore fulfill 3 to 5 % (5% with fertilizer) of the City's diesel vehicle demand. Depending on the amount of land available, however, the monetary and energy costs associated with feedstock and diesel distribution may negate any environmental or economic gains from the marginal biodiesel production. In these cases, social benefits such as community education and youth involvement become the real profits from these endeavors.
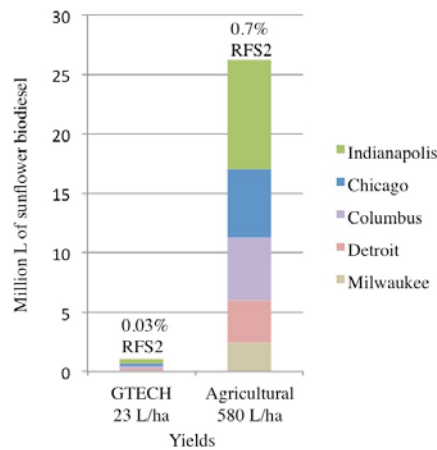
Figure 3-7. Potential production volume and RFS2 contribution of sunflower biodiesel produced

from marginal lands in five Northern Midwestern cities.

Prime U.S. agricultural sunflower biodiesel yield (580 L/ha) is compared to Pittsburgh GTECH biodiesel

yield (23 L/ha).

3.5   CONCLUSIONS

This study demonstrates the feasibility and GIS-informed process for identifying urban marginal lands and calculating potential biodiesel production from sunflowers grown on urban marginal land using Pittsburgh, Pennsylvania as an example. While the data show that biodiesel produced through a Pittsburgh community development initiative currently has little impact on the RFS2 and Pennsylvania's Act 78 requirements (0.001% and 0.03%, respectively), Pittsburgh is only one city among thousands across the U.S. Combined efforts would have a greater impact on the RFS2.

There is a profound social benefit evident from GTECH's sunflower-to-biodiesel programs in that they unite individuals in a neighborhood, create community engagement, enhance community members' agricultural and organizational skills, and revitalize otherwise blighted communities. Future research should consider ways of quantifying these benefits through social LCA and other methods, in addition to evaluating life-cycle environmental impacts. For urban areas dominated by vacant lots, the framework described herein can be reproduced to identify marginal lands for deployment of programs like GTECH's.

3.6   ACKNOWLEDGEMENTS

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4.0   ASSESSING RENEWABLE ENERGY POTENTIAL OF UNITED STATES

MARGINAL LANDS

Chapter 4 expands upon Chapter 3 by mapping land cover across the continental United States. Contaminated sites, including brownfields, closed landfills, and abandoned mine lands, were identified via GIS and considered as cultivation sites for soybean and sunflower feedstocks and as construction sites for algae production facilities.

4.1   ABSTRACT

The United States has 27.8 million hectares of marginal land that could be used to produce renewable energy. This study constructs a GIS model to evaluate a range of site-specific feedstock yields on brownfields, closed landfills, and abandoned mine lands. Using soybeans, sunflowers, and algae, the United States could produce 9.2×10^3 to 25.6×10^3 TJ of renewable energy per year. The low end of the range represents low crop yields as expected under marginal conditions. The high end of the range represents prime agricultural conditions and is used for comparison. In addition to considering other feedstocks, future studies should evaluate solar and wind farms on marginal sites, where the production of energy does not rely on the quality of the soil but rather on other climate conditions and the space available.

4.2   INTRODUCTION

4.2.1   Motivation and Background

Recent studies have highlighted irreversible impacts of food-grade agriculture as well as direct and indirect land use change related to biofuel production (Dupouey, Dambrine et al., 2002; Searchinger, Heimlich et al., 2008; Bailis and McCarthy, 2011; Smith, Cleveland et al., 2012). Searchinger et al. (2008) found that inclusion of land use change in the life-cycle emissions from corn-based ethanol (a first-generation biofuel) results in a 93 percent increase in total GHGs in

comparison to conventional gasoline while the same calculation for switchgrass-based ethanol (a second-generation biofuel) results in a 50 percent total increase in GHGs compared to gasoline (Searchinger, Heimlich et al., 2008). Both the type of fuel and the land used to produce the fuel are important when considering the entire life cycle. Biofuels produced on marginal lands are one useful method for decreasing inputs required for producing renewable energy. Other renewable energy technologies can be built on marginal lands, such as solar, wind, geothermal, or hydropower. Interest in this co-location strategy is growing, as evidenced by the newly funded EPA program: "RE-Powering America's Land", which encourages renewable energy projects on currently and formerly contaminated lands and provides resources to communities engaging in such projects (USEPA, 2012). This chapter evaluates the energy that can be produced on marginal lands by cultivating soybeans, sunflowers, and algae for biodiesel production.

One of the primary challenges in assessing the amount of marginal land available in an area is deciding what qualifies as "marginal" for the region being evaluated. Definitions of marginal land can vary on the global, national, and regional scales. A wide variety of marginal land definitions exist in the literature, as shown in Table 1.

Table 4-1. Definitions of marginal lands.

Source	Year	Definition
Peterson and Galbraith[a]	1932	Land on the margin of cultivation; the poorest land that can be remuneratively operated under given price, cost, and other conditions.
Dangerfield and Harwell, U.S. Soil Conservation Service [b]	1990	Lands have serious, excessive erosion, with additional lands having erosion protection only because they are in pasture, idle, or in uses other than row crops. (U.S. South)
USDA-NRCS[c]	1995	Land is restricted by various soil physical/chemical properties, or environmental factors, for crop production. Class 4-8 defined as the marginal land based on NRCS State Soil Geographic database.
OECD[d]	2001	Land of poor quality with regard to agricultural use and unsuitable for housing and other uses.
Campbell et al. [e]	2008	Has limited potential for food production.
Gopalakrishnan et al[f]	2009	Land resources that are neither part of existing protected ecosystems nor used for food, fiber, or feed production.
Cai et al[g]	2010	Marginal agricultural land - low productivity for agriculture, is susceptible to degradation, and is high-risk for agricultural production.
Goapalakrishnan et al.[h]	2011	Defined by soil health criteria: land that is eroded, frequently flooded, poorly drained, highly sloped, and low productivity for the main grain crop.
Swinton et al.[i]	2011	Non-crop lands; farmers choose to convert to produce bioenergy.

[a] (Peterson and Galbraith, 1932)
[b] (Dangerfield and Harwell, 1990)
[c] (USDA NRCS, 2010)
[d] (OECD, 2008)
[e] (Campbell, Lobell et al., 2008)
[f] (Gopalakrishnan, Negri et al., 2009)
[g] (Cai, Zhang et al., 2011)
[h] (Gopalakrishnan, Cristina Negri et al., 2011)
[i] (Swinton, Babcock et al., 2011)

The definitions in Table 1 include common terms describing poor quality, susceptibility to erosion, not protecting any ecosystem, low productivity, and limited potential for food production. Swinton et al. (2011) even includes in the definition the decision to convert marginal land to produce bioenergy.

4.3   METHODS

Marginal land is defined in this study as land unfit for food-grade agriculture and not otherwise fulfilling conservational purposes or ecosystem services. This land is described in Class VIII of the USDA NRCS's classification system as "soils and miscellaneous areas [that] have limitations that preclude their use for commercial plant production and limit their use to recreation, wildlife, or water supply or for aesthetic purposes" (USDA NRCS, 2010). NRCS lists eight classes, I through VIII. While Classes IV through VIII are generally considered marginal for agricultural purposes, only Class VIII was included in this study as being marginal for renewable energy purposes.

4.3.1   Land Data

GIS was used to map the data for the lower 48 states. Two maps were created: one with a base layer of soil types and another with a base layer of solar insolation (Perez, Ineichen et al., 2002). The soil layer was imported from the National Land Cover Dataset, shown in Figure 1 and listed in Table 2. The soil layer includes information that was grouped into five categories: agriculture, water, vegetation, barren, and developed land. The solar map, illustrated in Figure 2, uses rates of Global Horizontal Irradiance (GHI) to calculate potential algae production on brownfields, landfills, and abandoned mine lands (AMLs).

Table 2 lists the sources and feature data types of GIS data layers used in the analysis. Each of the three marginal site types—brownfields, landfills, and abandoned mine lands—were imported as XY data and projected into a geographic map projection using the NAD83 datum. Since no shapefiles, or polygons, of the marginal sites were available, additional research was

conducted to determine the area of each site. The AML site area was extracted from the Abandoned Mine Land Inventory System for each mine where the status was listed as complete (Office of Surface Mining Reclamation and Enforcement, 2011). The site areas for both closed landfills and brownfields were extracted from the EPA's RE-Powering database and matched by site name and location to the mapped points (USEPA, 2012).

Table 4-2. GIS layers, data types, and sources for land cover and marginal sites.

Site Type	GIS Data Source	Data Type	Year
Brownfield	EPA ACRES database	Point	2012
Landfill	EPA Landfill Methane Outreach Program	Point	2012
AML	OSMRE Abandoned Mine Land Inventory System	Point	2012
Land Cover	National Land Cover Dataset	Raster image	2006

4.3.1.1 Feedstock and Yield Data

Soybean, sunflower, and algae were evaluated as feedstocks on the marginal sites. Soybean and sunflower yields, shown in Table 3, were calculated based on high and low yields provided by annual USDA statistical records (USDA Economic Research Service, 2011). The low yields were used to model growth potential on marginal land. The high yields were used for comparison to model growth on prime agricultural land, such as that in the Corn Belt of the Midwest.

Table 4-3. Oilseed feedstocks and harvested yields

(USDA ERS 2011)

Feedstock	Low yield (kg/ha)	High yield (kg/ha)
Sunflower	1121	2018
Soybean	1009	3699

Algae yields were calculated based on rates of solar insolation, which directly influence rates of algae growth. Detailed calculations of the algae growth rates can be found in Appendix

A. This study assumes that the marginal site facilities cultivate the algae strain *Chlorella vulgaris* in flat-plate photobioreactors (PBRs), as is common practice in the algae biodiesel industry (Schenk, Thomas-Hall et al., 2008; Posten, 2009). Whereas soybean and sunflower crops can use the entire available land area, the final algal yields depend on the surface area of the PBRs. This study assumes that the PBRs occupy 80% of the marginal site and that the PBR geometry has a surface-to-volume ratio of 80.1 m^2/m^3, where 80 to 100 m^2/m^3 is considered optimal for production (Posten, 2009). The PBR dimensions are 50 m long by 20 m high by 0.025 m wide.

A GIS model used to calculate the algae growth rates on marginal sites was constructed in *ModelBuilder* in *ArcGIS 10*. *ModelBuilder* allows the user to automate complex GIS processes and describe geoprocessing procedures in a visual manner. The solar-based algae growth rate layer, the calculations for which can be found in Appendix A, was spatially joined to each of the marginal site layers: brownfields, closed landfills, and abandoned mine lands. The spatial join resulted in algae growth rates specific to each marginal land site, based on the amount of solar insolation received at the site. The growth rates were multiplied by the site areas to determine the total potential algae production at each site. Only sites with algae growth rates greater than or equal to 18 g/m^2day, which occur predominantly in the Southwestern United States, were included in the final yield calculation.
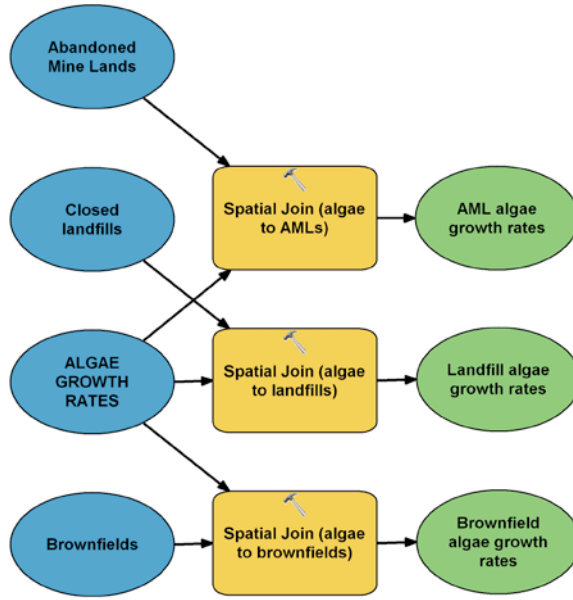
Figure 4-1. GIS model used to calculated solar-based algae growth rates on marginal sites.

Blue ovals represent data layers; yellow rounded rectangles represent tools used and analyses performed;

green ovals represent layer outputs.

4.4 RESULTS AND DISCUSSION

Figure 2 shows the marginal sites—brownfields, landfills, and AMLs—mapped on U.S. land cover, as adapted from the NLCD soil and water categorizations described in the Methods. After removing landfill and AML sites with areas given as zero or null, 15,893 brownfields, 406 (of 671) landfills, and 25,114 (of 50,483) abandoned mine lands remained. In Figure 2, brownfields are shown in orange and closed landfills are shown in pink. Both site types appear largely in the Northeastern and Mid-Atlantic states and extend toward the Midwest, with some notable clusters near the West Coast. Abandoned mine lands are shown in gray and appear as expected along the Appalachian Mountains in the East, Rocky Mountains in the West, and are also scattered throughout other mountainous regions.
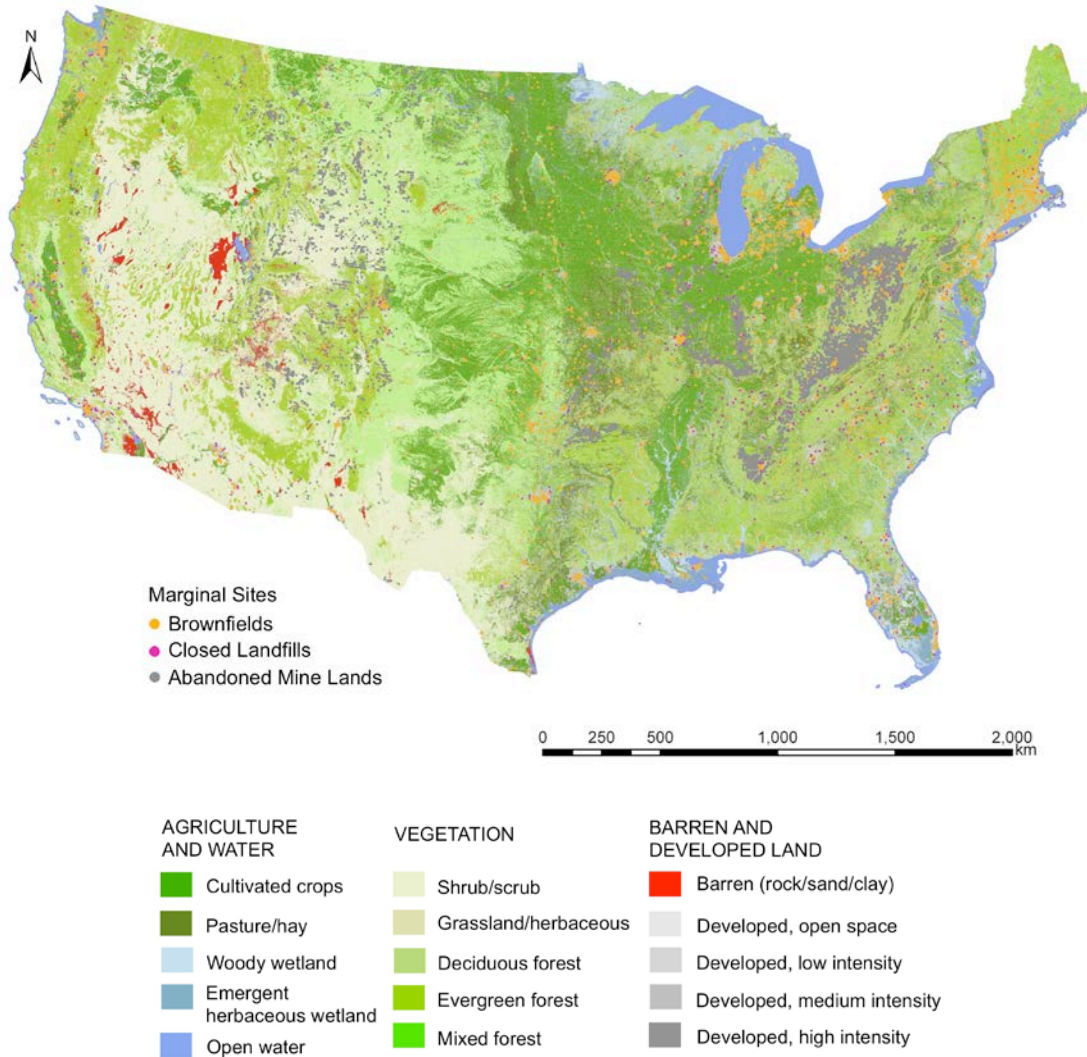
Figure 4-2. Map of U.S. land cover and marginal sites.

Table 4 lists the total areas of the marginal sites nationally and their potential sunflower and soybean biodiesel yields. Biodiesel volumes were calculated based on the high and low yields given by the USDA and as listed in the Methods section. High yields represent prime agricultural production rates while low yields represent marginal production rates. When considering specific sites for implementation, a range of yields should be considered as soil quality varies from site to site. According to the results, there is twice as much marginal land available on closed landfills as there is on brownfields and 35 times as much land on AMLs as there is on both landfills and brownfields combined.

Table 4-4. Areas of marginal land and potential sunflower and soybean biodiesel yields.

High yields as reported by the USDA are marked with (H); low reported yields are marked with (L).

	Area (ha)	Sunflower (10^6 L)	Soybean (10^6 L)
Landfill (L)	28,116	5.6	6.0
Landfill (H)	28,116	10.1	22.1
Brownfield (L)	14,918	3.0	3.2
Brownfield (H)	14,918	5.4	11.7
AML (L)	1,505,252	301.4	322.7
AML (H)	1,505,252	542.5	1183.2

Given a soybean biodiesel energy content of 35.9 MJ/L and a sunflower biodiesel energy content of 33.7 MJ/L, marginal sites including landfills, brownfields, and AMLs could produce between 10.4×10^3 TJ to 18.8×10^3 TJ of sunflower biodiesel or between 11.9×10^3 TJ and 43.7×10^3 TJ of soybean biodiesel. If half the marginal sites were used for soybean biodiesel and the other half for sunflower biodiesel, the U.S. could produce 11.1×10^3 TJ on marginal lands (low-yield), compared to 31.2×10^3 TJ for high-yield quality lands.

Figure 3 illustrates the algae growth rates at each site according to geographic solar insolation. Due to economic feasibility, the PBRs should be located on sites with enough solar insolation conducive to commercial algae production. Therefore, only sites with algal biomass yields greater than or equal to 18 g/m^2-day were considered for marginal algae production. Under these conditions, the United States could produce 1.8 billion tonnes of algal biomass per year. Given an energy content of 41 MJ/kg, this is equivalent to 48.4 TJ of energy per year.
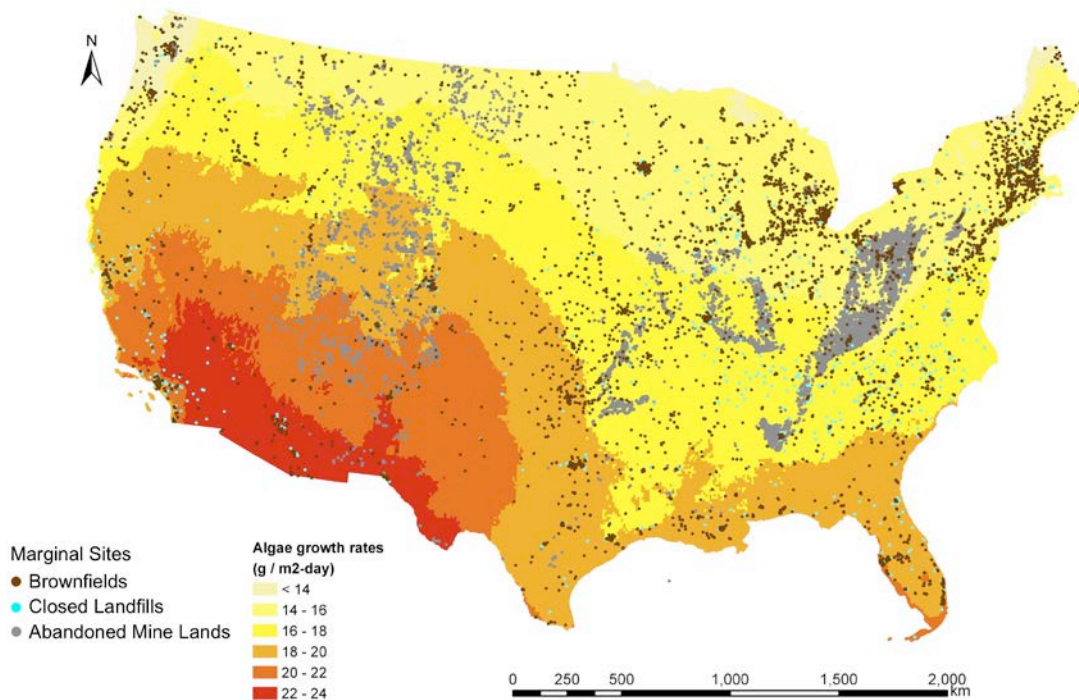
Figure 4-3. Marginal sites mapped against solar-based algae growth rates.

Ideally the algae production facilities would be sited on the most contaminated lands where sunflower and soybean feedstocks would otherwise exhibit the lowest yields. If the 7,421 marginal sites with algae growth rates above 18 g/m^2day were reserved for algae production and the other 33,992 sites were split evenly between soybean and sunflower production, 18% of the marginal sites would be devoted to algae and 41% of the remaining marginal sites would be devoted each to sunflower and soybean. This allocation by area and feedstock would produce 9.2 $\times 10^3$ to 25.6 $\times 10^3$ TJ of renewable energy per year, depending on feedstock yields.

4.5   CONCLUSIONS

The United States has 27.8 million hectares of marginal land that could be used to produce renewable energy. Using soybeans, sunflowers, and algae as biodiesel feedstocks, the United States could produce 9.2×10^3 to 25.6×10^3 TJ of renewable energy per year based on low and high yields, respectively. Both low and high yields were calculated in order to provide a range of possible biofuel production on marginal lands. However, it is likely that marginal lands will have a lower soil quality and thus result in lower yields than USDA high yield records. Future studies should include other types of marginal land, such as RCRA sites, and additional feedstocks, including camelina, switchgrass, and other perennial grasses. Wind and solar technologies should also be evaluated for siting on marginal lands. Solar and wind farms can also utilize marginal lands to produce energy and their energy production potential does not rely on the quality of soil.

4.6   ACKNOWLEDGEMENTS

5.0 USING GIS TO HIGHLIGHT INDUSTRIAL SYMBIOSIS POTENTIAL FOR MICROALGAL BIODIESEL PRODUCTION IN THE UNITED STATES

Chapter 5 creates and demonstrates a framework using GIS to identify industrial symbiosis opportunities for producing microalgal biodiesel. Photobioreactors in this study are co-located with coal, natural gas, and cement plants for CO_2 acquisition. The required nitrogen (N) and phosphorus (P) nutrients for algae production are obtained from municipal wastewater treatment plants and supplemented with synthetic N-P fertilizer when necessary. Contributions to the RFS2 are assessed and vary according to facility size and the level of wastewater treatment (untreated, secondary, or tertiary).

5.1 ABSTRACT

In 2010, the United States consumed 1.03×10^{11} GJ of energy and emitted 5.4 billion tons CO_2 from fossil fuels. As energy demands increase, microalgal biodiesel is being developed for the market as a high-energy fuel with low carbon emissions. Since microalgae need CO_2, as well as N and P for cultivation, there is a unique opportunity to co-locate algal photobioreactors (PBRs) next to CO_2-emitting facilities, such as power plants and cement plants, and to utilize N and P from nearby wastewater treatment plants. This paper uses GIS to evaluate the microalgal strain, *Chlorella vulgaris*, in terms of total biomass production capacity under these industrial symbiotic conditions. Given a 0.2-m^3 tubular photobioreactor co-located at the CO_2 facility, results indicate that untreated wastewater could meet 34% of the RFS2's 2013 requirement of 1.28 billion gallons of biomass-based diesel per year.

5.2 INTRODUCTION

The Renewable Fuel Standard (RFS2) under the U.S. Energy Independence and Security Act of 2007 mandates 15.2 billion gallons of domestic alternative fuels per year, 1.28 billion gallons of which need to be biomass-based biodiesel by the year 2013 (US EPA, 2011). Microalgal biodiesel can contribute to meeting the requirements of the RFS2, purportedly with minimal environmental impacts since it requires less land than soybean biodiesel and can utilize waste CO_2 for enhancing biomass growth.

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Current research suggests the success of algal biofuels relies not only on their scale-up potential to meet growing widespread demands but also on their ability to implement advanced environmental performance practices (Sheehan, Dunahay et al., 1998; Benemann, 2003; Chisti, 2008; Borowitzka and Moheimani, 2010; Mata, Martins et al., 2010). Synergies with existing industries have been shown to benefit algal biofuel production by providing the necessary production inputs while thus lessening the burden placed on raw materials, effectively enhancing environmental performance (Benemann, 1997; Clarens, Resurreccion et al., 2010; Soratana and Landis, 2011). Few studies, however, have examined the co-location of algal production systems with industrial facilities for supply of nutrients (Martin and Eklund, 2009; Martin, Ivner et al., 2011; McGinn, Dickinson et al., 2011). Even fewer studies have implemented geographic information system (GIS) techniques to facilitate the co-location assessment (Pate, Klise et al., 2011; Quinn, Catton et al., 2011). This study employs GIS to map three key parameters to enable microalgal production: solar insolation for photosynthesis, wastewater treatment plants for N and P, and CO_2 from coal, natural gas, and cement plants.

Studies have demonstrated the technical feasibility and benefits of co-locating microalgal cultivation systems with CO_2-producing industries, such as electrical power plants (Kadam, 2001; Kadam, 2002; Schenk, Thomas-Hall et al., 2008; Lardon, Helias et al., 2009; Rodolfi, Zittelli et al., 2009; Batan, Quinn et al., 2010; Greenwell, Laurens et al., 2010; Mata, Martins et al., 2010). Co-location with power plants is useful since microalgae can tolerate 5-15% of CO_2 concentration in flue gas, which is about 250 times higher than terrestrial crops (Negoro, Shioji et al., 1992). However, the reduction of CO_2 is also climate-dependent. On a cloudy day, microalgae can reduce between $50.1 \pm 6.5\%$ of CO_2 emissions, which is 26% - 38% less than the potential CO_2 reduction on a sunny day (Li, Horsman et al., 2008). Not only can a microalgal

biomass production system reduce CO_2 emissions, but it can also reduce up to 86% of NO_x in flue gas (Avagyan, 2008). In addition, residual N_2O and NO in flue gas does not affect microalgal growth, therefore flue gas pre-treatment is not required (Li, Horsman et al., 2008).

Nutrients are also essential to algae growth, however P scarcity and water quality degradation, such as eutrophication caused by N and $P_{(aq)}$ emissions have become important factors for the growth of algae biorefineries. Wastewater can be used to provide N and P for microalgal production (Pittman, Dean et al., 2011; Rawat, Ranjith Kumar et al., 2011; Soratana and Landis, 2011). Microalgae can also be used to remove nutrients from wastewater directly (Mallick, 2002; Rawat, Ranjith Kumar et al., 2011). This study assumes N and P are obtained from untreated domestic wastewater since insufficient nutrients are present in secondary and tertiary treated wastewater and thus would require supplemental fertilizer. A sensitivity analysis was conducted to evaluate nutrient concentrations at the secondary and tertiary treatment levels. If untreated wastewater is used, issues related to treatment of pathogens and logistical issues such as infrastructure maintenance and replacement must be taken into special consideration.

This study evaluates the use of untreated wastewater as a best-case nutrient scenario and the feasibility of co-siting algae production facilities at power plants and cement plants for access to low-cost waste CO_2. Nutrient needs and availabilities were assessed for the geographic region surrounding each algae production facility. An energy balance was designed and a sample calculation was conducted to compare the energy required to produce and deliver nutrients to the system via synthetic N-P fertilizers vs. the symbiotic use of untreated wastewater.

5.3 METHODS

GIS is employed in this study to identify the locations of waste CO_2 sources from coal power plants, natural gas power plants, and cement production plants and their proximity to waste nutrient sources from municipal wastewater treatment plants for producing algal biomass. The total potential biomass production of the microalgal strain, *Chlorella vulgaris* under these industrial symbiotic conditions is modeled in a vertical tubular photobioreactor (PBR). The biomass volume is converted to biodiesel volume to assess potential contribution to the RFS2.

5.3.1 Algal biomass production using *Chlorella vulgaris*

The microalgal strain *Chlorella vulgaris* was chosen for its common usage in the literature and thus wealth of data (Avagyan, 2008; Lardon, Helias et al., 2009; Lehr and Posten, 2009; Brennan and Owende, 2010; Singh and Dhar, 2011; Soratana and Landis, 2011). An assumed composition of 30% lipids, 33% protein, and 37% carbohydrates was used and then varied in the sensitivity analysis. Nutrient requirements per kg algae were assumed to be 1.5kg CO_2, 0.0812 kg N, and 0.0176 kg P (Soratana, Harper Jr. et al., 2012).

In accordance with prior literature, the microalgae cultivation system was modeled in a 0.2-m^3 vertical tubular PBR with a surface area of 15.7 m^2 (Soratana, Harper Jr. et al., 2012). Efficiency factors associated with photosynthesis, reflection, geometric structure, and environmental conditions were calculated and are included in Appendix C. Biodiesel production volumes were calculated using the density conversion of 870 kg microalgal biodiesel/m^3 and energy content conversion of 41 MJ/kg microalgal biodiesel (Huang, Chen et al., 2010; Sander and Murthy, 2010).

Table 5-1. Composition of *Chlorella vulgaris*.

Fraction	Percent Composition	Molecular Composition
Protein	33	$C_{4.43}H_7O_{1.44}N_{1.16}$
Carbohydrate	37[a,b]	$C_6H_{12}O_6$
Lipid	30[c,d,e]	$C_{40}H_{74}O_5$

[a] Brennan & Owende, 2010
[b] Singh & Dhar, 2011
[c] Soratana, 2011
[d] Avagyan, 2008
[e] Lehr & Posten, 2009

Table 5-2. Nutrient requirements for *Chlorella vulgaris*

(Soratana, Harper Jr. et al., 2012)

Nutrient requirement	Concentration (kg/kg)
CO_2 required for microalgae	1.5
N required for microalgae	0.0812
P required for microalgae	0.0176

5.3.2 Using GIS to identify industrial symbiosis opportunities

The industrial symbiosis potential for utilizing waste CO_2 and waste nutrients was evaluated using GIS. Two models were constructed using *ModelBuilder* in *ArcGIS 10:* one model for depicting the process used to obtain biomass production rates based on location-specific volumes of CO_2 available at natural gas, coal, and cement plants, and a second model depicting the process used to obtain the potential biomass production rates based on the nutrients N and P, which were acquired from nearby wastewater treatment plants. A complete description of the models can be found in Appendix C.

A basemap of the United States from the U.S. Census Bureau (U.S. Census Bureau, 2010) and solar insolation values in terms of Global Horizontal Irradiance (kWh/m^2-day) at a 10km resolution (Perez, Ineichen et al., 2002) were imported into *ArcGIS* as two different

shapefiles. Alaska and Hawaii were removed from the 50-state basemap and the solar insolation values were clipped to the map of the lower 48 states. The resulting 48-state map with Global Horizontal Irradiance is labeled "Solar48" in Figure 1.

CO$_2$-emitting sources—coal, natural gas, and cement—were added to the GIS as point features; 575 coal-fired power plants and 1,435 natural gas-fired power plants were imported from the Emissions and Generation Resource Integrated Database 2010 (eGRID), which catalogues U.S. electric power sources and their point source emissions, such as carbon dioxide, sulfur dioxide, and methane (US EPA, 2011). Cement plants (111 in total) were imported from the National Carbon Sequestration Database (NATCARB), which lists U.S. stationary CO$_2$ sources among other data related to carbon sequestration (National Energy Technology Laboratory (NETL), 2011).
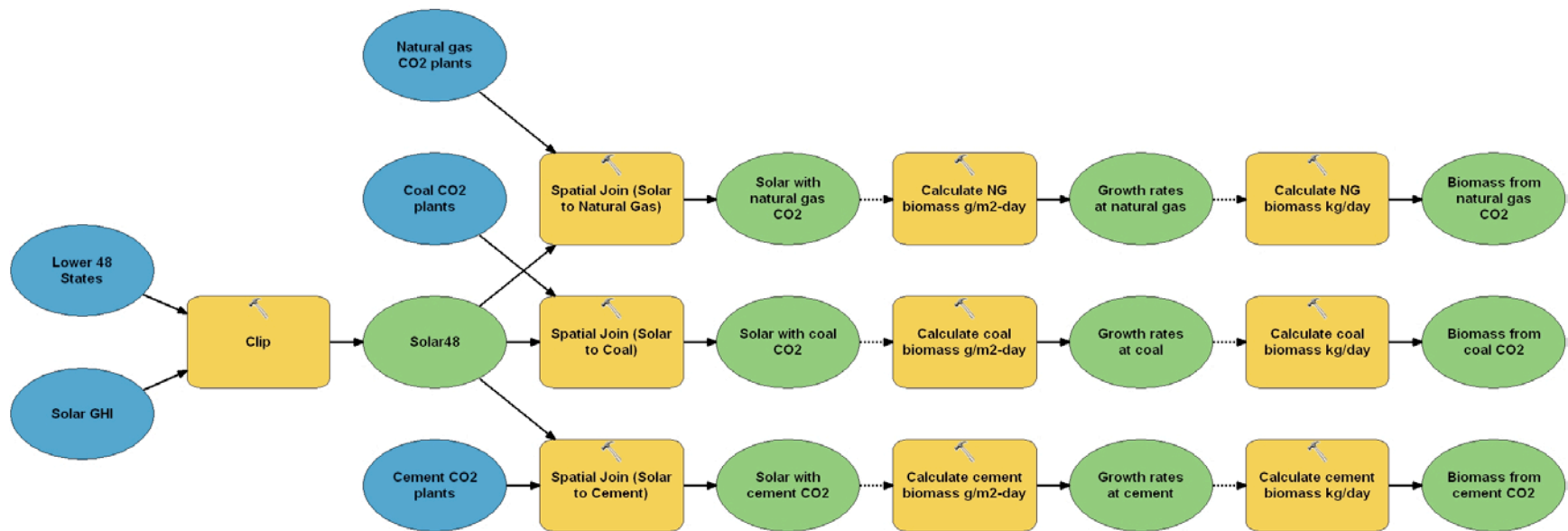
Figure 5-1. GIS process model for calculating microalgal biomass production potential based on CO_2 emissions from coal, natural gas, and cement plants.

Blue ovals represent data layers. Yellow rounded rectangles represent tools used (hammer icon) and analyses performed. Green ovals represent layer outputs.
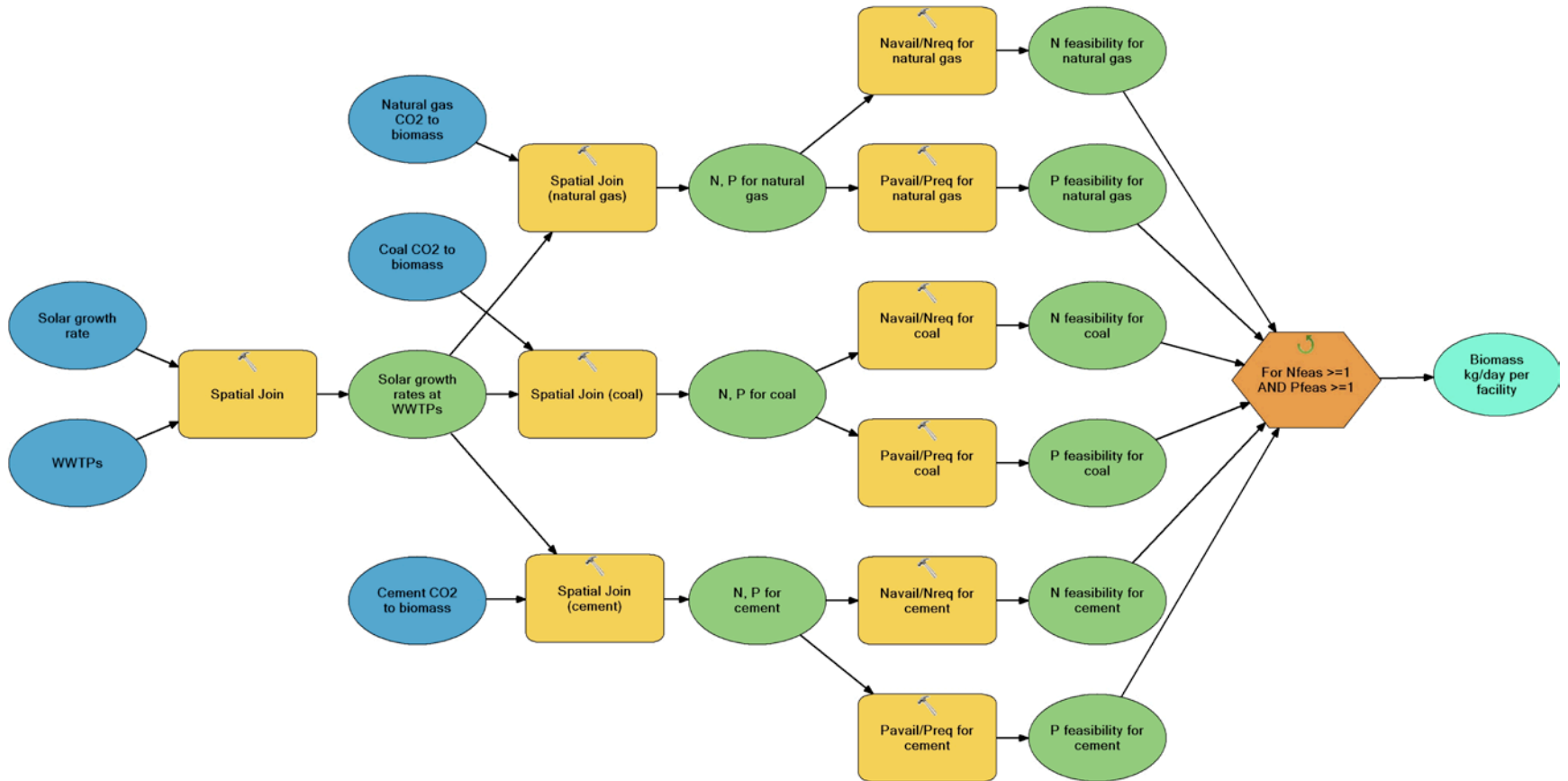
Figure 5-2. GIS process model for calculating microalgal biomass production potential based on the availability of N and P from nearby wastewater treatment plants.

Blue ovals represent data layers. Yellow rounded rectangles represent tools used (hammer icon) and analyses performed. Green ovals represent layer outputs. Orange pentagon represents IF operator and teal oval represents output of IF operator.

Each of the three CO_2 layers were spatially joined with the solar insolation layer to create a new layer with access to both solar and CO_2 data. Microalgal biomass growth rates based on solar insolation values were computed in the attribute table of each of the three joined layers. These growth rates were measured in g/m^2-day and spatially located at the site of each CO_2 plant. Based on the amount of CO_2 emitted by each plant, potential biomass production values were calculated in kg/day, which is the final output shown in Figure 1.

Figure 2 shows the process for calculating biomass yields based on wastewater concentrations of N and P. For this calculation, 33,445 wastewater treatment plants were imported from the U.S. EPA Clean Watersheds Needs Survey 2008 (CWNS) (EPA, 2010). CWNS is a database that was created to monitor the water quality goals set by the Clean Water Act. The wastewater treatment layer and the solar insolation layer were spatially joined so that data from the layers would be matched based on spatial location. Another spatial join was performed to add the quantity of biomass produced from CO_2 (Figure 1 output). The nutrients available from wastewater treatment plants in million gallons per day (MGD) were calculated based on the size of the wastewater treatment plant. Given typical bioavailable nitrogen content of 40 mg/L and bioavailable phosphorus content of 8 mg/L (Sedlak, 1991), the total bioavailable N and P per treatment facility was divided by the total required N and P for the algae (Table 2). Results greater or equal to one indicate sufficient nutrient content. If both N and P return results greater than one, the potential biomass production volume was calculated and converted to volume of biodiesel.

Figure 3 illustrates the potential volumes of biomass production if all PBRs had sufficient access to N and P, and if the only limiting factor were the rate of solar insolation. For this

scenario, the greatest algae yields are found in the areas with the highest rates of solar insolation, namely in the southwestern region of the country.
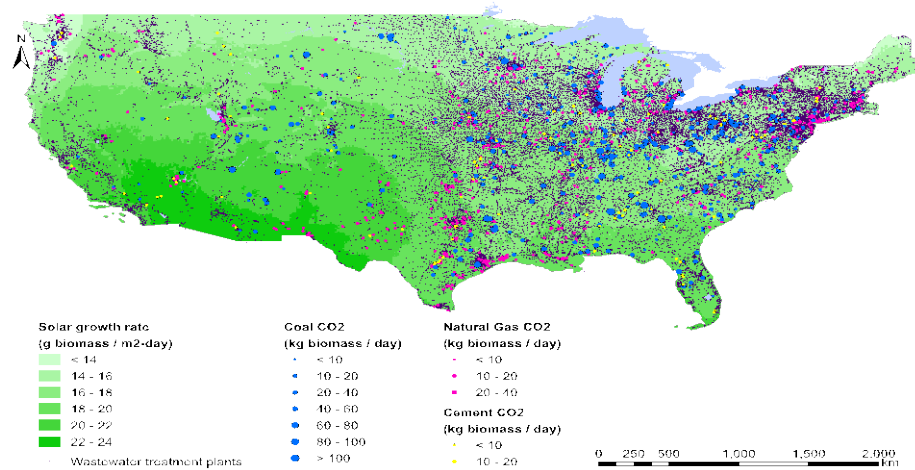
Figure 5-3. Map of solar-based and CO$_2$-based microalgal growth rates.

Wastewater treatment plants shown by location, not size, and before spatial join of CO$_2$ data layer.

5.3.3 Nutrient-transport energy balance

Engaging in industrial symbiosis is only beneficial when it reduces the system's net impact. Therefore, the system's net energy balance was computed by comparing life-cycle energy consumed or expended due to wastewater treatment plant operations, production of synthetic nutrients for instances when levels of wastewater N and P were insufficient, and transportation between the wastewater treatment plant or fertilizer warehouse and the CO$_2$ plant. No minimum or maximum distance was assumed between wastewater treatment plants and CO$_2$ plants. Instead the *ArcGIS* "Near" tool in the Proximity toolset of the Analysis toolbox was used

to compute the point-to-point distance between each wastewater treatment plant and the closest CO_2 plant. The average point-to-point distance was 43 km; the median was 26 km.

The fuel consumed to transport wastewater between plants was calculated and incorporated into the model. The energy required to produce and deliver nutrients to the system was modeled via synthetic N-P fertilizers or via symbiotic use of untreated wastewater, in which N and P are already present. The wastewater nutrients were assumed to be transported via a single-unit diesel truck from the fertilizer distribution facility or wastewater treatment plant to the CO_2 source. The truck is assumed to be loaded to full capacity when it leaves the distribution facility and is empty on the return trip. Transport energy includes the energy content of the diesel fuel as well as the life-cycle energy of the fuel's production. Net energy of at least zero indicates that the system avoids or saves as much or more energy as it consumes. Negative net energy indicates that the system consumes more energy than it avoids.

Equations (1) through (3) describe the basic procedure for calculating net energy. Equation (1) computes the total energy avoided at the wastewater treatment plant by sending the untreated wastewater to the CO_2 facility and thus not having to treat for N and P.

$$E_{WWTP\_av} = E_{Nrem} + E_{Prem} \tag{1}$$

where E_{WWTP_av} is the total energy avoided in MJ/kg, E_{Nrem} is the energy avoided in MJ/kg N by not treating for N, and E_{Prem} is the energy avoided in MJ/kg P by not treating for P.

Equation (2), E_1, represents the scenario in which the waste nutrients are obtained from the wastewater treatment plant and transported to the closest CO_2 plant.

$$E_1 = E_{trans:WWTP \rightarrow CO2} - E_{Nrem} - E_{P\_rem} \tag{2}$$

where $E_{trans:WWTP \rightarrow CO_2}$ represents the life-cycle transportation energy, including combusted diesel fuel, from the wastewater treatment plant to the closest CO_2 plant.

Equation (3), E_2, represents the scenario in which the nutrients are obtained from a fertilizer warehouse assumed to be located a radial distance of 25 km from the CO_2 site.

$$E_2 = E_{trans:warehouse \to CO_2} + E_{N_{prod}} + E_{P_{prod}} \tag{3}$$

where $E_{trans:warehouse \to CO2}$ is the life-cycle energy, including combusted diesel fuel, consumed by a single-unit truck traveling from the fertilizer warehouse to the CO_2 site, $E_{N_{prod}}$ is the life-cycle energy required to produce synthetic nitrogen fertilizer, and $E_{P_{prod}}$ is the life-cycle energy required to produce synthetic phosphorus fertilizer.

If $E_1 < E_2$, the waste nutrient scenario uses less life-cycle energy than the fertilizer nutrient scenario and therefore synergy between wastewater treatment plants and PBRs located at CO_2 facilities is possible. Site-specific energy balances will be conducted in future versions of this study.

5.4   RESULTS AND DISCUSSION

Figure 4 shows coal, cement, and natural gas plants mapped according to metric tons of CO_2 emitted: the larger the circle, the greater the point-source CO_2 emission. If the PBRs at these CO_2 sources were supplied with sufficient N and P from either wastewater treatment plants or from synthetic fertilizers, algal biodiesel produced from the CO_2 available could meet the 1.28 billion gallon requirement of the RFS2.
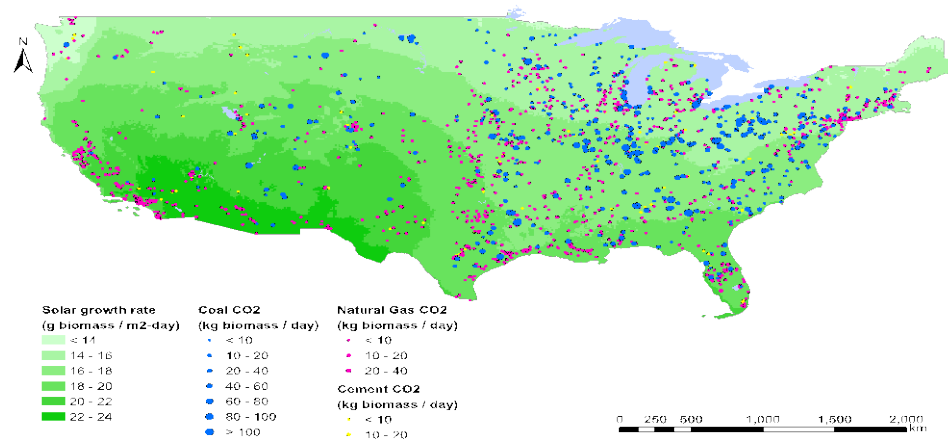
Figure 5-4. Microalgal growth rates and production volumes according to solar insolation and CO$_2$ inputs from coal, natural gas, and cement plants.
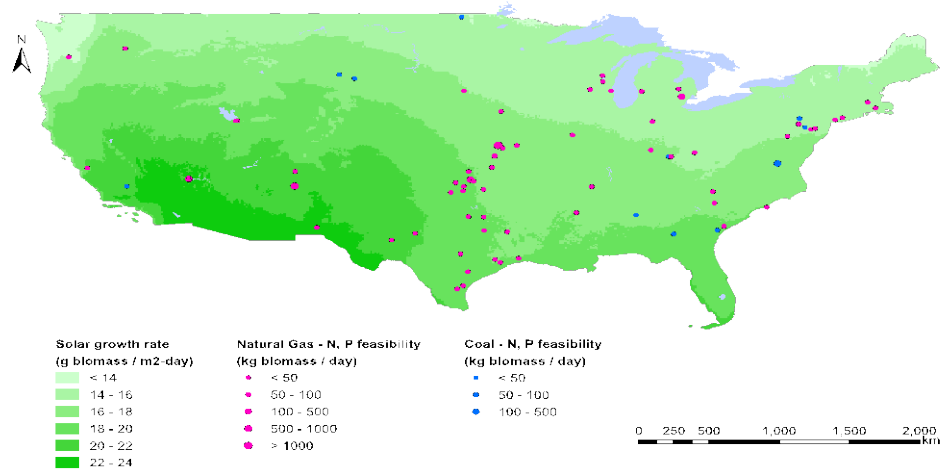
Figure 5-5. Potential microalgal production at 11 coal and 65 natural gas plants according to N and P availability from nearby wastewater treatment plants.

Cement plants not shown due to insufficient nutrient availability.

Figure 5 depicts the results of an industrial symbiosis network providing N and P nutrients from municipal wastewaters and CO_2 from either coal or natural gas power plants to cultivate algal biomass at the waste CO_2 site. Eleven coal plants and 65 natural gas plants have access to enough N and P to fully meet the nutrient requirements of the biomass produced at the CO_2 facilities, as shown in Table 1. These 76 facilities together could produce 4.36×10^8 gallons of biodiesel per year and contribute 34% to the RFS2. This volume is less promising than other studies that claim that microalgal biodiesel could meet 2030 DOE alternative fuel goals of displacing 30% of gasoline demand, however these studies do not consider full synergy with wastewater treatment plants and thus are not limited by nutrient availability (Quinn, Catton et al., 2012).

A sensitivity analysis was conducted to compare potential biodiesel production volumes based on N and P available in raw wastewater and in wastewater treated at the secondary or tertiary level. Wastewater treated at the secondary level can produce a total biodiesel volume of 119 million gallons per year across the 48 states (118 million gallons from natural gas CO_2 and 1.3 million from coal CO_2). This is equivalent to 77% of what could be produced using untreated wastewater. If effluent were used from wastewater treatment plants treating at the tertiary level, 3.2 million gallons of biodiesel could be produced per year.
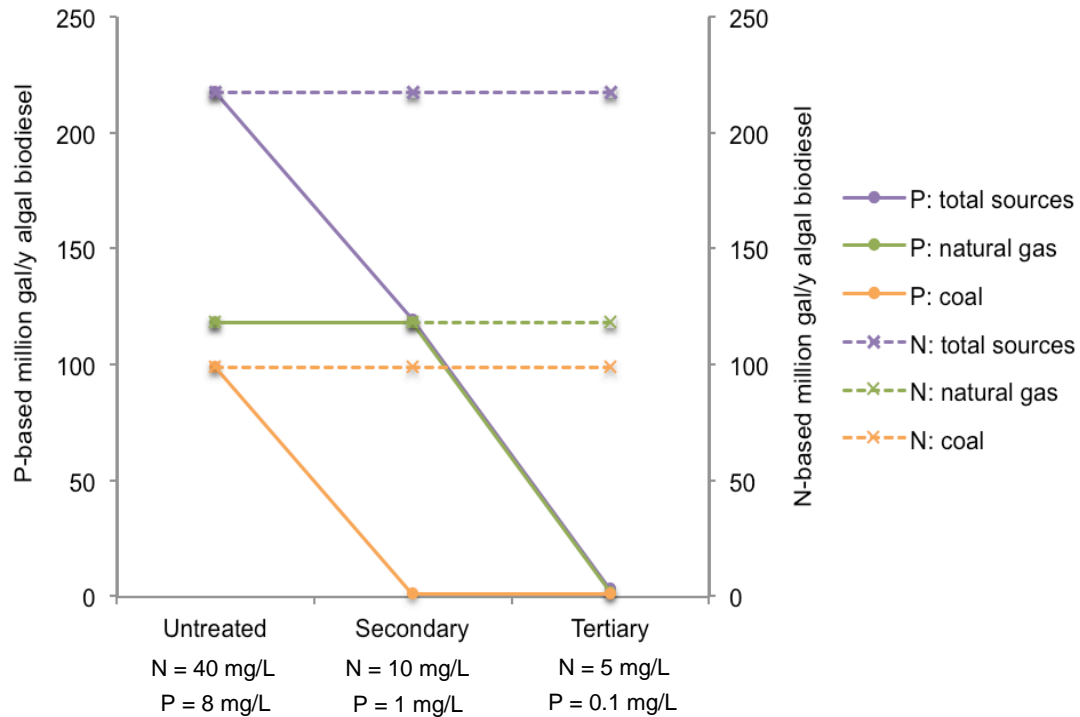
Figure 5-6. Ranges of total potential biodiesel volumes from *Chlorella vulgaris* production at coal and natural gas plants using raw wastewater or wastewater treated at the secondary or tertiary level.

Annual national production rates based on availability of N or P from the wastewater treatment plant closest to each CO_2 facility. Cement plants are not shown due to insufficient nutrient availability.

The flat horizontal lines in Figure 6 indicate that there is always sufficient N available and that P is the limiting wastewater nutrient. If it were possible to reduce the P requirement of *Chlorella vulgaris*, identify another equally productive strain that requires less P, or obtain more bioavailable P from wastewaters, the number of industrial symbiosis opportunities and the resulting annual biodiesel production volume could increase.

There are several additional challenges to utilizing untreated wastewaters that were not examined in this study. Such challenges include the potential contamination of algae cultivation systems by pathogens from untreated wastewater, transportation logistics, and other

infrastructure-related concerns. Untreated wastewater was modeled to evaluate the highest possible amount of available nutrients from wastewaters to produce the maximum amount of biodiesel to contribute to the RFS. Treated wastewater provides even fewer nutrients to the system, and will either reduce the number of industrial symbiosis opportunities established using the scenario in Figure 2, or will necessitate increased supplement of synthetic nutrients to meet the utilization demand of all the waste CO_2 from the scenario in Figure 2. Lastly, the distance between the CO_2 plants and the wastewater treatment plants affects the overall sustainability of the system as greater distances lead to greater energy emissions and greater transportation expenses.

5.5   CONCLUSIONS AND FUTURE WORK

Co-location of microalgal production systems with CO_2-emitting facilities has been shown to be feasible based on plant-to-plant distance and nutrient availability. While using waste resources for nutrient inputs often saves energy, using untreated wastewater for its high N and P content is unlikely; secondary or tertiary treated wastewater, both of which have lower nutrient concentrations, would likely be used instead. To maintain biomass production levels while using secondary or tertiary treated wastewater, greater quantities of wastewater or synthetic fertilizers would be needed. Using secondary treated wastewater would allow the U.S. to produce 119 million gallons of algal biodiesel per year. Tertiary treated wastewater would allow for 3.2 million gallons per year. Future versions of this study will include additional nutrient-based sensitivity analyses, site-specific net energy balances, and model validation using facilities currently in operation.

5.6   ACKNOWLEDGEMENTS

6.0   CONCLUSIONS

6.1   SUMMARY

The goal of this dissertation was to evaluate industrial symbiosis as a sustainable approach to U.S. biofuel production by creating a framework that integrates the spatial implications of land and nutrient supply. First, the feasibility of using wastes as a resource for energy production systems was demonstrated via a coupled wastewater-power plant system. Sustainability metrics were evaluated, the results of which highlighted the need for systems analysis and spatially explicit tools to address the unique sustainability challenges associated with industrial symbiosis.

A land-identification framework using GIS was created and demonstrated to identify regional and national "waste" lands, or marginal lands, for potential biofuel crop production. A nutrient-availability framework for algal biodiesel was created and shown to identify synergistic production opportunities, regardless of land type, using waste CO_2 and wastewater for nutrients. While urban marginal biodiesel production in Pittsburgh demonstrated trivial contributions to the RFS2 (0.003%), marginal sites at the national level could potentially meet 7 to 19% of the RFS2, depending on the distribution of feedstocks and associated yields. Algal biodiesel produced from waste CO_2 and wastewater could meet up to 17% of the RFS2, depending on the nutrient concentration of the wastewater.

Resource reclamation through industrial symbiosis is generally a sustainable practice, however spatial implications must be taken into consideration when translating design into reality. Knowing what resources are available in an area and the distance between resources and production facilities is crucial to maximizing the sustainability of a given system. As energy and monetary costs increase, social benefits become more important to the sustainability analysis. GIS can identify opportunities for sustainable industrial symbiosis and can be used throughout the design phase to ensure that the performance of the model accurately predicts the performance of the physical system.

6.2   RECOMMENDATIONS FOR FUTURE WORK

The U.S. marginal lands (Chapter 4) and algal biodiesel (Chapter 5) studies would benefit from further sustainability analyses. Chapter 4 could include wind and solar technologies on marginal lands, in addition to the sunflower, soybean, and algae feedstocks already evaluated. The energy results and calculation methods should be compared with similar data and analyses from the EPA RE-Powering Initiative. Chapter 5 would benefit from further nutrient-based sensitivity analyses and life-cycle energy balances. Results should be validated through a sample of currently operating facilities or industry standard values.

This dissertation has shown that GIS is an appropriate tool for evaluating spatial implications from a life-cycle perspective. Until the LCA community creates a standardized land use impact assessment category, addressing land use within LCA will require a combination of life-cycle systems approaches, as demonstrated. Even after a land use category is established, there will still be a need for GIS-informed studies in LCA when considering land-industry

systems located at particular geographic points as opposed to theoretical systems that could be located anywhere. Furthermore, GIS can enhance communication with decision-makers since decision-makers are usually not trained in the interpretation of life-cycle impact assessment results. GIS provides an intuitive visual tool to aid the communication process.

Future biofuels studies in LCA must continue to incorporate direct and indirect land use change, particularly at the regional levels. Economic and social benefits resulting from community engagement in local agriculture and biodiesel production efforts should also be quantified. System boundaries and scope should be varied to assess different levels of the system.

Additional waste resources can benefit from industrial symbiosis. This study included marginal land, wastewater, CO_2, N, and P. Other studies might consider alternative methods of heat exchange, particularly for the algae drying process, and the feasibility of feeding surplus energy back to the grid, as is commonly done with sugarcane ethanol production in Brazil. New input, output, and performance data should be collected from biofuel-related facilities currently engaging in industrial symbiosis to continually improve the models' representations of current industry operations and to best guide the future direction of the field.

APPENDIX A

CHEMICAL TREATMENT FOR BIOFOULING, CORROSION, AND SCALING

Table A1. Chemical treatment concentrations used in LCA of recycling treated municipal wastewater as cooling makeup water in power plants.

Scenario	Compound	LCI Database	Dose (mg/1000 gal)	References
1ppm Chlorine (Cl$_2$)	Chorine (Cl$_2$), pure	BUWAL 250	3,785	[1, 2]
	Sulfuric acid (H$_2$SO$_4$), liquid	Ecoinvent 2.0	473,125	125 average ppm assumption [3]
	Sodium tripolyphosphate (Na$_5$P$_3$O$_{10}$ or STPP)	Ecoinvent 2.0	18,925	5 ppm assumption [4]
1 ppm Chlorine dioxide (ClO$_2$)	Chlorine dioxide (ClO$_2$)	Ecoinvent 2.0	3,785	[1]
	Sulfuric acid (H$_2$SO$_4$), liquid	Ecoinvent 2.0	473,125	125 average ppm assumption [3]
	Sodium tripolyphosphate (Na$_5$P$_3$O$_{10}$ or STPP)	Ecoinvent 2.0	18,925	5 ppm assumption [4]
3 ppm Monochloramine (NH$_2$Cl)	Sodium hypochlorite (NaClO), 15% in H$_2$O	Ecoinvent 2.0	9,063	[5] supplemented with experimental data
	Ammonia (NH$_3$)	Industry data 2.0	2,266	[5] supplemented with experimental data
	Sodium hydroxide (NaOH)	USLCI	26.8	[5] supplemented with experimental data
	Sulfuric acid (H$_2$SO$_4$), liquid	Ecoinvent 2.0	473,125	125 average ppm
	Sodium tripolyphosphate (Na$_5$P$_3$O$_{10}$ or STPP)	Ecoinvent 2.0	18,925	5 ppm assumption [4]

[1] Frayne, C. (1999). [2] Harston, J.D. and Ropital, F. (2004).
[3] Li, H. (Personal communication, 17 March 2010). [4] Li, H. (Personal communication, 16 March 2010).
[5] Vidic, R.D., Dzombak, D.A., Hsieh, M.-K., Li, H., Chien, S.-H., Feng, Y., Chowdhury, I. Monnell, J.D. (2009).

APPENDIX B

DATA SOURCES FOR URBAN MARGINAL LANDS

Table B1. Layers and sources used for compiling GIS map of Pittsburgh, Pennsylvania.

GIS layer	Source	Year	Reference
Soil type	NRCS	2006	(a)
Slope	NRCS	2006	(a)
Water	NRCS	2006	(a)
Greenways	PASDA	2000	(b)
Census tracts	TIGER/Line	2011	(c)
Property parcels	PASDA	2008	(d)
Building footprints	PASDA	2006	(e)
Streets	PASDA	2006	(f)

a (USDA Natural Resources Conservation Service, 2008)
b (PASDA, 2000)
c (U.S. Census Bureau, 2009)
d (PASDA, 2008)
e (PASDA, 2006)
f (PASDA, 2006)

Table B2. Largest U.S. Midwestern states by land area (U.S. Census Bureau, 2010).

City	Land Area (ha)
Indianapolis	93,610
Chicago	58,956
Columbus	56,247
Detroit	35,936
Milwaukee	24,895

APPENDIX C

SUPPORTING INFORMATION FOR CHAPTER 5: USING GIS TO HIGHLIGHT INDUSTRIAL SYMBIOSIS POTENTIAL FOR MICROALGAL BIODIESEL PRODUCTION IN THE UNITED STATES

1. MODEL OVERVIEW

1.1. RESEARCH OBJECTIVES

This paper has two main research objectives:

1. Determine feasibility of producing *Chlorella vulgaris* via industrial symbiosis by siting PBRs at CO_2-emitting sources and obtaining N and P from wastewater treatment plants.

2. Determine U.S. potential production of microalgal biodiesel under these industrial symbiotic conditions and compare to volumes mandated by the RFS2.

2. COMPOSITION OF CHLORELLA VULGARIS

Table C1. Algal composition (Lardon et al., 2009)

Fraction	Percent Composition	Molecular Composition	Molar Mass (g/mol)	Net Calorific Value (MJ/g biomass)
Protein	33	$C_{4.43}H_7O_{1.44}N_{1.16}$	100.1	15.5 x 10^{-3}
Carbohydrate	37[a,b]	$C_6H_{12}O_6$	180	13 x 10^{-3}
Lipid	30[c,d,e]	$C_{40}H_{74}O_5$	634	38.3 x 10^{-3}

[a] (Brennan and Owende, 2010)
[b] (Singh and Dhar, 2011)
[c] (Soratana and Landis, 2011)
[d] (Avagyan, 2008)
[e] (Lehr and Posten, 2009)

3. EFFECTS OF SOLAR INSOLATION ON MICROALGAL GROWTH RATE

3.1 MICROALGAL GROWTH RATES

Table C2. Efficiency factors affecting microalgal growth

	Efficiency factor	Value
1	Photosynthetic efficiency: 0.267	0.267
2	Losses due to reflection [a]	0.95
3	Losses due to PBR geometry [b]	0.99
4	Photon utilization efficiency [c]	0.50
5	Biomass accumulation efficiency	0.72
6	Sub-optimal environmental conditions	0.95
P	**Product of efficiency factors**	**0.086**

[a] Assuming PBR constructed from HDPE
[b] PBR tilted at 80 degrees
[c] (Weyer, Bush et al., 2010)

$$H = \sum_{i=1}^{i=3}(\% \; composition)_i * (net \; calorific \; value)_i \tag{1}$$

where H represents biomass lower heating value in MJ/g-biomass.

$$H = 21.4 \frac{MJ}{kg \; biomass} \tag{2}$$

$$R = S * \frac{P}{H}, \tag{3}$$

where R represents microalgal growth rate in g-biomass/m^2-day,
S represents solar insolation in MJ/m^2-day,
and P represents product of efficiency factors.

$$R = S * \frac{0.086}{21.4 \; MJ/kg} \tag{4}$$

To calculate R, the GIS layer with plant information and the GIS layer with solar insolation were spatially joined so both sets of data would be accessible in one database table.

4. STOICHIOMETRIC CO_2 REQUIREMENTS

Table S1 lists the composition of *Chlorella vulgaris* for this study.

$$M = \sum_{i=1}^{i=3}(\% \; composition)_i * (molar \; mass)_i, \tag{5}$$

where M represents total molecular mass.

$$M = 0.33 * 100.1 \frac{g}{mol} + 0.37 * 180 \frac{g}{mol} + 0.30 * 634 \frac{g}{mol} \tag{6}$$

$$M = 289.8 \; g \; biomass$$

$$C = \sum_{i=1}^{i=3}(mol\;C) * \left(12.011 \frac{g}{mol\;C}\right) * (\%\;composition), \tag{7}$$

where C represents the carbon fraction of the molecular mass.

$$C = 12.011 \frac{g}{mol\;C} \; [(4.43\;mol\;C) * (0.33) + (6\;mol\;C) * (0.37) + (40\;mol\;C) * (0.30)] \tag{8}$$

$$C = 188.4 \; g \; C$$

Converting g C to g CO_2:
$$C \; as \; CO_2 = (188.4 \; g \; C) * \frac{44 \frac{g}{mol\;CO2}}{12.011 \frac{g}{mol\;C}} \tag{9}$$

$$C \; as \; CO_2 = 690.2 \; g \; CO_2$$

$$CO_{2-req} = \frac{C \; as \; CO_2}{M}, \tag{10}$$

where $CO_{2\text{-}req}$ represents the CO_2 requirement per kg biomass.

$$CO_{2-req} = \frac{690.2 \; g \; CO2}{289.8 \; g \; biomass} \tag{11}$$

$$CO_{2-req} = \frac{g \; CO_2}{g \; biomass}$$

Since g/g = kg/kg:

$$CO_{2-req} = 2.38 \frac{kg \; CO_2}{kg \; biomass} \tag{12}$$

5. CO₂ REQUIREMENTS FOR PHOTOBIOREACTOR

Table C3. Design dimensions of vertical tubular PBR (Carvalho, Meireles et al., 2006; Posten, 2009)

Dimension	Value
Radius	0.025 m
Height	100 m
Volume	0.2 m^3
Surface area	15.7 m^2
Surface area to volume ratio	78.6 m^2/m^3

$$CO_{2-req/PBR} = (PBR\;surface\;area)(R)(CO_{2-req}), \tag{13}$$

where $CO_{2\text{-req/PBR}}$ represents CO_2 required per PBR per day, given growth rate, R, in $\frac{\text{g biomass}}{m^2 * \text{day}}$.

$$CO_{2-req/PBR} = (15.7m^2)\left(R \frac{g\ biomass}{m^2*day}\right)\left(\frac{2.38\ g\ CO_2}{g\ biomass}\right) \tag{14}$$

Simplifying:
$$CO_{2-req/PBR} = \left(\frac{37.4\ g\ CO_2}{PBR*day}\right)R \tag{15}$$

$$CO_{2-em} = \frac{tonne\ CO_2}{facility*365day}, \tag{16}$$

where $CO_{2\text{-em}}$ represents tonnes CO_2 emitted from CO_2 source, converted to kg CO_2/day.

$$B = \left(\frac{CO_{2-em}}{CO_{2-req}}\right), \tag{18}$$

where B represents biomass production potential in kg / day.

$$B = \frac{\left(\frac{tonnes\ CO_2}{facility*365\ day}\right)}{\left(R*\frac{37.4\ g\ CO_2}{PBR*day}\right)} \tag{19}$$

Simplifying:

$$B = \frac{tonnes\ CO_2}{365*37.4*R} \tag{20}$$

$$B = \frac{tonnes\ CO_2}{13651*R} \tag{21}$$

6. N AND P REQUIREMENTS FOR WASTEWATER TREATMENT PLANTS

Given a 0.2m³ PBR at each CO_2-emitting facility, how much nitrogen and phosphorus would be required per day from the nearest wastewater treatment plant to enable microalgal production at the CO_2-emitting facility?

6.1. N REQUIREMENTS AND AVAILABILITIES

Table C4. Nitrogen requirements and availabilities

Nitrogen parameters	Value
N required for biomass (kg N/kg)	0.0812 [a]
Average bioavailable N (ammonia) in domestic sewage (kg N/MGD)	110 [b]

[a] (Soratana, Harper Jr. et al., 2012)
[b] Converted from 29 mg N/L as given in (Sedlak, 1991)

$N_{req/WWTP}$ represents N *required* for WWTP to supply PBR at the closest CO_2 source.

$N_{avail/WWTP}$ represents N *available* for WWTP to supply PBR at the closest CO_2 source.

$$N_{req/WWTP} = \frac{Biomass\ production\ at\ CO2\ source}{N\ required\ per\ kg\ biomass} \tag{22}$$

$$N_{req/WWTP} = \frac{B}{0.0812\ kg\ N/kg\ biomass}\ ,\ \text{where } B \text{ is biomass production field in GIS.} \tag{23}$$

$IFF\ \frac{N_{avail/WWTP}}{N_{req/WWTP}} \geq 1$, WWTP can sufficiently supply PBR with N at CO_2 facility.

$$\frac{N_{avail/WWTP}}{N_{req/WWTP}} = N_{feas} \tag{24}$$

6.2. P REQUIREMENTS AND AVAILABILITIES

Table C5. Phosphorus requirements and availabilities

Phosphorus parameters	Value
P required for biomass (kg P/kg)	0.0176 [a]
Average bioavailable P (orthophosphate and condensed phosphates as P) in domestic sewage (kg P/MGD)	22.6 [b]

[a] Soratana et al., 2012
[b] Converted from 6 mg P/L as given in Sedlak 1991.

Given a $0.2m^3$ PBR at each CO_2-emitting facility, how much phosphorus would be required per day from the nearest wastewater treatment plant to enable microalgal production?

$P_{req/WWTP}$ represents P *required* for WWTP to supply PBR at the closest CO_2 source.

$P_{avail/WWTP}$ represents P *available* for WWTP to supply PBR at the closest CO_2 source.

$$P_{req/WWTP} = \frac{Biomass\ production\ at\ CO2\ source}{P\ required\ per\ kg\ biomass} \tag{25}$$

$$P_{req/WWTP} = \frac{B}{0.0176\ kg\ P/kg\ biomass}\ ,\ \text{where } B \text{ is biomass production field in GIS.} \tag{26}$$

$IFF\ \frac{P_{avail/WWTP}}{P_{req/WWTP}} \geq 1$, WWTP can sufficiently supply PBR with P at CO_2 facility.

$$\frac{P_{avail/WWTP}}{P_{req/WWTP}} = P_{feas} \tag{27}$$

7. SENSITIVITY ANALYSIS: ALGAL COMPOSITION AND NUTRIENTS

Three parameters were examined in the sensitivity analysis: lipid content, nitrogen (N) availability, and phosphorus (P) availability. The lipid content was increased from 30% to a currently feasible 50% to a realistic projected feasibility of 70%. Sensitivity to concentrations of N and P was examined in the main body of this paper. Total biomass production in the lower 48 states was computed for each parameter.

Lipid Content

Algae's basic composition can be described using fractions of lipids ($C_{40}H_{74}O_5$), protein ($C_{4.43}H_7O_{1.44}N_{1.16}$), and carbohydrates ($C_6H_{12}O_6$). The composition scenarios evaluated in the sensitivity analysis were based on current literature for *Chlorella vulgaris* and are listed in Table A1.(Chisti, 2007; Gouveia and Oliveira, 2009; Batan, Quinn et al., 2010; Mata, Martins et al., 2010; Menetrez, 2012) Algae with different lipid contents require different amounts of CO_2 for growth. For the modeled scenarios, algae with 30% lipid content require 2.38 kg CO_2 per kg biomass, 2.52 kg CO_2 for 50% lipid content, and 2.65 kg CO_2 for 70% lipid content.

Table C6. Percent lipid, protein, and carbohydrate scenarios modeled for *Chlorella vulgaris*.

component	composition1 (%)	composition2 (%)	composition3 (%)
Lipid	30	50	70
Protein	33	10	5
Carbohydrate	37	40	25

Each of the CO_2 sites where the PBRs are co-located—coal, natural gas, and cement facilities—provide differing amounts of CO_2 required for lipid production and algae growth. The original 30% lipid content yields a national biomass production of 10.6 tonnes of biomass per

day. Increasing the lipid content to 50% increases the biomass output to 10,000 tonnes/day, as shown in Figure S1. A further increase to 70% lipid content decreases the national output to 9,500 tonnes per day. Generally, biomass production increases as the lipid content increases. However, as is evident in the 70% scenario, increasing the lipid content beyond a certain point causes a decrease in both protein and carbohydrate content, both of which can affect the overall biomass production.
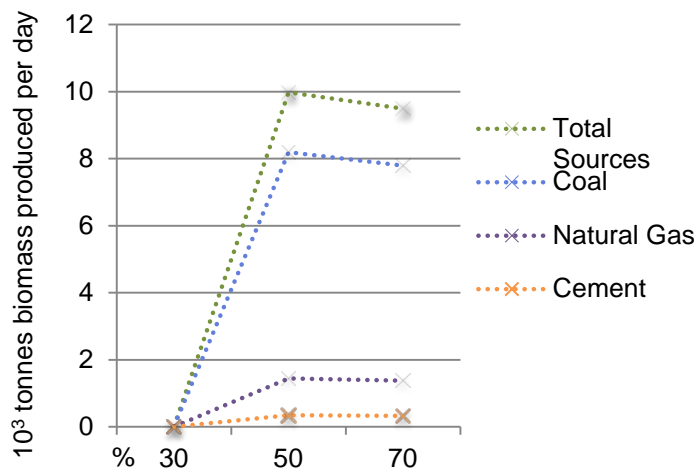
Figure C1. *Chlorella vulgaris* **biomass production for the lower 48 states based on 30%, 50%, and 70% algae lipid content with CO_2 contributions from coal, natural gas, and cement facilities.**

8. NUTRIENT-TRANSPORT ENERGY BALANCE

Table C7. Concentration of nutrients for *Chlorella vulgaris.*

Nutrient Parameter	Concentration (kg/kg)
CO_2 required for microalgae	1.5
N required for microalgae	0.0812
P required for microalgae	0.0176

Table C8. Life-cycle energy content of nutrients for *Chlorella vulgaris.*

Nutrient Parameter	Energy (MJ/kg)
Energy from N-removal avoided by WWTP	14
Energy from P-removal avoided by WWTP	24
Energy to produce synthetic N (urea)	24.7
Energy to produce synthetic P (superphosphate)	62.1

Table C9. Input parameters to calculate energy required for transport of nutrients, N and P, to CO_2 sources co-located with tubular PBRs.

Parameter	Value
Average energy content of diesel fuel	38.6 MJ/L[a]
Average fuel economy for single-unit diesel truck	3.1 km/L[b]
Diesel energy combusted by single-unit diesel truck	12.46 MJ/km
Life-cycle energy consumption of single-unit diesel truck	2.71 MJ/tkm
Typical weight of fully loaded single-unit diesel truck	32 tonnes
Typical single-unit truck storage capacity	20 tonnes

[a] Converted from 138,690 Btu/gal
[b] Converted from 7.3 mi/gal

8.1. ENERGY BALANCE FOR PRODUCING BIOMASS AND TRANSPORTING N AND P

Two scenarios were modeled. Twenty tonnes of N and P fertilizers were transported to the CO_2 sites from either: 1) the closest wastewater treatment plant or 2) from a fertilizer warehouse assumed to be 25 km from the CO_2 site (Lundin, Bengtsson et al., 2000; Remy and Jekel, 2008).

The following calculations describe the life-cycle energy balance of the nutrients and of the transportation for the two scenarios modeled.

$$E_{trans\ WWTP \rightarrow CO2} = (E_{diesel} + E_{truck})(w)(x), \tag{28}$$

where E_{diesel} is the life-cycle energy combusted by a single-unit diesel truck,
E_{truck} is the life-cycle energy consumption of a single-unit diesel truck,
w is the weight of the fully loaded truck,
and x is the distance traveled to the CO_2 site.

Substituting the values from Table S8:

$$E_{trans\ WWTP \rightarrow CO_2} = (12.46 \frac{MJ}{t \cdot km} + 2.71 \frac{MJ}{t \cdot km})(32\ t)x \tag{29}$$

$$E_{trans\ WWTP \rightarrow CO_2} = 485.44\ x \tag{30}$$

The plant-to-plant distance x is stored in the GIS attribute table for each pairing of wastewater treatment plants and CO_2 plants.

For the second scenario, in which the fertilizer warehouse is assumed to be 25 km from the CO_2 site, $x = 25$.

$$E_{trans\ FERT \rightarrow CO_2} = (485.44)(25) \tag{31}$$
$$E_{trans\ FERT \rightarrow CO2} = 12,136\ MJ$$

APPENDIX D

PYTHON SCRIPT FOR CHAPTER 4 AND CHAPTER 5 GIS MODELS

D.1   PYTHON SCRIPT FOR CHAPTER 4 GIS MODEL

D.1.1   Python Script for Chapter 4: Figure 1.

The following Python script describes the process used to produce Figure 1: GIS model used to calculate solar-based algae growth rates on marginal sites.

```
# ---------------------------------------------------------------------------
# Figure 1 - algae potential on USML.py
# Created on: 2012-11-24 00:01:51.00000
#   (generated by ArcGIS/ModelBuilder)
# Description:
# Figure 1 (in dissertation). GIS model used to calculate solar-based algae growth rates on U.S.
marginal sites.
# ---------------------------------------------------------------------------
# Import arcpy module
import arcpy
```

Local variables:

Brownfields = "Marginal Sites\\ACRES Brownfields\\Brownfields"

ALGAE_GROWTH_RATES = "Algae growth rates"

Closed_landfills = "Marginal Sites\\Closed landfills"

Abandoned_Mine_Lands = "Marginal Sites\\Abandoned Mine Lands"

Brownfield_algae_growth_rates = "\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Points_SpatialJoin"

Landfill_algae_growth_rates = "\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\LF_closed$_Features_SpatialJ"

AML_algae_growth_rates = "\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\ShapeFile-wdpqpg55xhmgof55zw"

Process: Spatial Join (algae to brownfields)

arcpy.SpatialJoin_analysis(Brownfields, ALGAE_GROWTH_RATES, Brownfield_algae_growth_rates, "JOIN_ONE_TO_ONE", "KEEP_ALL", "Name \"Name\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\US-BML EPA data\\acres_frs(1).gdb\\Placemarks\\Points,Name,-1,-1;FolderPath \"FolderPath\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\US-BML EPA data\\acres_frs(1).gdb\\Placemarks\\Points,FolderPath,-1,-1;SymbolID \"SymbolID\" true true false 4 Long 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\US-BML EPA data\\acres_frs(1).gdb\\Placemarks\\Points,SymbolID,-1,-1;AltitudeMode \"AltitudeMode\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\US-BML EPA data\\acres_frs(1).gdb\\Placemarks\\Points,AltitudeMode,-1,-1;Snippet \"Snippet\" true true false 268435455 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\US-BML EPA data\\acres_frs(1).gdb\\Placemarks\\Points,Snippet,-1,-1;PopupInfo \"PopupInfo\" true true false 268435455 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\US-BML EPA data\\acres_frs(1).gdb\\Placemarks\\Points,PopupInfo,-1,-1;ID \"ID\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,ID,-1,-1;GRIDCODE \"GRIDCODE\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GRIDCODE,-1,-1;LON \"LON\" true true false 4 Float 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LON,-1,-1;LAT \"LAT\" true true false 4 Float 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LAT,-1,-1;GHIANN \"GHIANN\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHIANN,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Length,-1,-1;Shape_Area \"Shape_Area\" false true true 8 Double 0 0

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,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Area,-1,-1;AgrowthRate_kg_per_m2day \"AgrowthRate_kg_per_m2day\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,AgrowthRate_kg _per_m2day,-1,-1", "INTERSECT", "", "")

Process: Spatial Join (algae to landfills)

arcpy.SpatialJoin_analysis(Closed_landfills, ALGAE_GROWTH_RATES, Landfill_algae_growth_rates, "JOIN_ONE_TO_ONE", "KEEP_ALL", "OID \"OID\" true true false 8 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,OID,-1,-1;FID \"FID\" true true false 8 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,FID,-1,-1;Ref \"Ref\" true true false 8 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Ref,-1,-1;Site \"Site\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Site,-1,-1;LF_OWN \"LF_OWN\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,LF_OWN,-1,-1;OWN_TYPE \"OWN_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,OWN_TYPE,-1,-1;City \"City\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,City,-1,-1;State \"State\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,State,-1,-1;Acres_Map \"Acres_Map\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Acres_Map,-1,-1;LF_Status \"LF_Status\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,LF_Status,-1,-1;YR_OPEN \"YR_OPEN\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,YR_OPEN,-1,-1;YR_CLOSE \"YR_CLOSE\" true true false 8 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,YR_CLOSE,-1,-1;DESIGN_ACRES \"DESIGN_ACRES\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,DESIGN_ACRES,-1,-1;CURRENT_ACRES \"CURRENT_ACRES\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,CURRENT_ACRES,-1,-1;TOTAL_ACRES \"TOTAL_ACRES\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,TOTAL_ACRES,-1,-1;TONS_CAPAC \"TONS_CAPAC\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\US Marginal

Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,TONS_CAPAC,-1,-1;TONS_WASTE_INPLACE \"TONS_WASTE_INPLACE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,TONS_WASTE_INPLACE,-1,-1;ANNUAL_INPLACE \"ANNUAL_INPLACE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,ANNUAL_INPLACE,-1,-1;State_RPS \"State_RPS\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,State_RPS,-1,-1;Renew_Types \"Renew_Types\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Renew_Types,-1,-1;Non_Grid_PV \"Non_Grid_PV\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Non_Grid_PV,-1,-1;Biopower \"Biopower\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Biopower,-1,-1;Biorefinery \"Biorefinery\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Biorefinery,-1,-1;Latitude \"Latitude\" true true false 8 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Latitude,-1,-1;Longitude \"Longitude\" true true false 8 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Longitude,-1,-1;Crop_res \"Crop_res\" true true false 8 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Crop_res,-1,-1;Landfill_tonnes_yr \"Landfill_tonnes_yr\" true true false 8 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Landfill_tonnes_yr,-1,-1;WWtreat \"WWtreat\" true true false 8 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,WWtreat,-1,-1;Landfill_TJ_yr \"Landfill_TJ_yr\" true true false 8 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\USML GIS data\\Landfills from EPA Repowering.xls\\LF_closed$_Features,Landfill_TJ_yr,-1,-1;ID \"ID\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,ID,-1,-1;GRIDCODE \"GRIDCODE\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GRIDCODE,-1,-1;LON \"LON\" true true false 4 Float 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LON,-1,-1;LAT \"LAT\" true true false 4 Float 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LAT,-1,-1;GHIANN \"GHIANN\" true true false 2 Short 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHIANN,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Length,-

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1,-1;Shape_Area   \"Shape_Area\"   false   true   true   8   Double   0   0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Area,-1,-1;AgrowthRate_kg_per_m2day \"AgrowthRate_kg_per_m2day\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,AgrowthRate_kg_per_m2day,-1,-1", "INTERSECT", "", "")

Process: Spatial Join (algae to AMLs)

arcpy.SpatialJoin_analysis(Abandoned_Mine_Lands,   ALGAE_GROWTH_RATES, AML_algae_growth_rates,   "JOIN_ONE_TO_ONE",   "KEEP_ALL",   "AMLIS_KEY \"AMLIS_KEY\" true true false 8 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,AMLIS_KEY,-1,-1;STATE_KEY \"STATE_KEY\" true true false 2 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,STATE_KEY,-1,-1;COUNTY \"COUNTY\" true true false 20 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,COUNTY,-1,-1;LATITUDE \"LATITUDE\" true true false 15 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,LATITUDE,-1,-1;LONGITUDE \"LONGITUDE\" true true false 17 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,LONGITUDE,-1,-1;PROGRAM \"PROGRAM\" true true false 3 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PROGRAM,-1,-1;PA_NAME \"PA_NAME\" true true false 35 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PA_NAME,-1,-1;PA_NUMBER \"PA_NUMBER\" true true false 6 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PA_NUMBER,-1,-1;PU_NAME \"PU_NAME\" true true false 28 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PU_NAME,-1,-1;PU_NUMBER \"PU_NUMBER\" true true false 8 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PU_NUMBER,-1,-1;PRIORITY \"PRIORITY\" true true false 1 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PRIORITY,-1,-1;PROB_TY_CD \"PROB_TY_CD\" true true false 4 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,PROB_TY_CD,-1,-1;MINE_TYPE \"MINE_TYPE\" true true false 1 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,MINE_TYPE,-1,-1;ORE_TYPES \"ORE_TYPES\" true true false 23 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,ORE_TYPES,-1,-1;DATE_PREPA \"DATE_PREPA\" true true false 22 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,DATE_PREPA,-1,-1;DATE_REVIS \"DATE_REVIS\" true true false 22 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,DATE_REVIS,-1,-1;UNFD_UNITS \"UNFD_UNITS\" true true false 17 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,UNFD_UNITS,-1,-1;UNFD_GPRA \"UNFD_GPRA\" true true false 16 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal

Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,UNFD_GPRA,-1,-1;UNFD_METER \"UNFD_METER\" true true false 17 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,UNFD_METER,-1,-1;FUND_UNITS \"FUND_UNITS\" true true false 16 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,FUND_UNITS,-1,-1;FUND_GPRA \"FUND_GPRA\" true true false 15 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,FUND_GPRA,-1,-1;FUND_METER \"FUND_METER\" true true false 16 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,FUND_METER,-1,-1;COMP_UNITS \"COMP_UNITS\" true true false 20 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,COMP_UNITS,-1,-1;COMP_GPRA \"COMP_GPRA\" true true false 20 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,COMP_GPRA,-1,-1;COMP_METER \"COMP_METER\" true true false 20 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,COMP_METER,-1,-1;Comp_Acres \"Comp_Acres\" true true false 19 Double 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\US Marginal Lands\\ShapeFile-wdpqpg55xhmgof55zwriooz3.shp,Comp_Acres,-1,-1;ID \"ID\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,ID,-1,-1;GRIDCODE \"GRIDCODE\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GRIDCODE,-1,-1;LON \"LON\" true true false 4 Float 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LON,-1,-1;LAT \"LAT\" true true false 4 Float 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LAT,-1,-1;GHIANN \"GHIANN\" true true false 2 Short 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHIANN,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Length,-1,-1;Shape_Area \"Shape_Area\" false true true 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Area,-1,-1;AgrowthRate_kg_per_m2day \"AgrowthRate_kg_per_m2day\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,AgrowthRate_kg_per_m2day,-1,-1", "INTERSECT", "", "")

D.2   PYTHON SCRIPT FOR CHAPTER 5 GIS MODELS

D.2.1   Python Script for Chapter 5: Figure 1

The following Python script describes the process used to produce Figure 1: GIS process model for calculating microalgal biomass production potential based on CO_2 emissions from coal, natural gas, and cement plants.

```
# ----------------------------------------------------------------------------
# Algae figure 1 - solar and CO2.py
# Created on: 2012-11-23 18:59:25.00000
#   (generated by ArcGIS/ModelBuilder)
# Description:
# Figure 1 (in dissertation). GIS process model for calculating U.S. microalgal biomass
production potential based on CO2 emissions from coal, natural gas, and cement plants.
# ----------------------------------------------------------------------------
# Import arcpy module
import arcpy
# Local variables:
Cement_CO2_plants = "CO2 Sources\\Cement plants"
Coal_CO2_plants = "CO2 Sources\\Coal plants"
Natural_gas_CO2_plants = "CO2 Sources\\Natural gas plants"
Solar_GHI = "l48_ghi_10km"
```

Lower_48_States = "not always water"

Solar48 = "\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48"

Solar_with_cement_CO2   =

"\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48_SpatialJoin"

Solar_with_coal_CO2   =

"\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48_SpatialJoin2"

Solar_with_natural_gas_CO2   =

"\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48_SpatialJoin1"

Process: Clip

arcpy.Clip_analysis(Solar_GHI, Lower_48_States, Solar48, "")

Process: Spatial Join (Solar to Natural Gas)

arcpy.SpatialJoin_analysis(Solar48, Natural_gas_CO2_plants, Solar_with_natural_gas_CO2, "JOIN_ONE_TO_ONE", "KEEP_ALL", "ID \"ID\" true false false 10 Double 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,ID,-1,-1;GRIDCODE \"GRIDCODE\" true false false 10 Double 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GRIDCODE,-1,-1;LON \"LON\" true false false 7 Float 2 6 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,LON,-1,-1;LAT \"LAT\" true false false 5 Float 2 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,LAT,-1,-1;GHI01 \"GHI01\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI01,-1,-1;GHI02 \"GHI02\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI02,-1,-1;GHI03 \"GHI03\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI03,-1,-1;GHI04 \"GHI04\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI04,-1,-1;GHI05 \"GHI05\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI05,-1,-1;GHI06 \"GHI06\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI06,-1,-1;GHI07 \"GHI07\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI07,-1,-1;GHI08 \"GHI08\" true false false 4 Short 0 4

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,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI08,-1,-1;GHI09
\"GHI09\"   true   false   false   4   Short   0   4
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI09,-1,-1;GHI10
\"GHI10\"   true   false   false   4   Short   0   4
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI10,-1,-1;GHI11
\"GHI11\"   true   false   false   4   Short   0   4
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI11,-1,-1;GHI12
\"GHI12\"   true   false   false   4   Short   0   4
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI12,-1,-1;GHIANN
\"GHIANN\"   true   false   false   4   Short   0   4
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHIANN,-1,-1;Shape_length
\"Shape_length\"   true   true   false   0   Double   0   0
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,Shape_length,-1,-
1;Shape_area   \"Shape_area\"   true   true   false   0   Double   0   0
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,Shape_area,-1,-1;SEQPLT07
\"SEQPLT07\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\eGRID 2007\\coalgas3.shp,SEQPLT07,-1,-1;PSTATABB \"PSTATABB\" true true false
254   Text   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID
2007\\coalgas3.shp,PSTATABB,-1,-1;PNAME \"PNAME\" true true false 254 Text 0 0
,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PNAME,-1,-1;LAT_1
\"LAT_1\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID
2007\\coalgas3.shp,LAT,-1,-1;LON_1   \"LON_1\"   true   true   false   16   Double   6   15
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID   2007\\coalgas3.shp,LON,-1,-
1;PLFUELCT   \"PLFUELCT\"   true   true   false   254   Text   0   0
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID   2007\\coalgas3.shp,PLFUELCT,-1,-
1;PLCO2AN   \"PLCO2AN\"   true   true   false   16   Double   6   15
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID   2007\\coalgas3.shp,PLCO2AN,-1,-
1;PLCO2RTA   \"PLCO2RTA\"   true   true   false   16   Double   6   15
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID   2007\\coalgas3.shp,PLCO2RTA,-1,-
1;CO2_TONNE   \"CO2_TONNE\"   true   true   false   19   Double   0   0
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID   2007\\coalgas3.shp,CO2_TONNE,-1,-
1;CO2biomass   \"CO2biomass\"   true   true   false   19   Double   0   0
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\eGRID   2007\\coalgas3.shp,CO2biomass,-1,-1",
"INTERSECT",   "",   "")

Process: Calculate NG biomass g/m2-day

arcpy.CalculateValue_management("Solar48_SpatialJoin1*0.086/21.4", "", "Variant")

Process: Calculate NG biomass kg/day

arcpy.CalculateValue_management("Natural   gas   CO2   plants   /(13651*output_value)", "",

"Variant")

Process: Spatial Join (Solar to Coal)

arcpy.SpatialJoin_analysis(Solar48, Coal_CO2_plants, Solar_with_coal_CO2, "JOIN_ONE_TO_ONE", "KEEP_ALL", "ID \"ID\" true false false 10 Double 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,ID,-1,-1;GRIDCODE \"GRIDCODE\" true false false 10 Double 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GRIDCODE,-1,-1;LON \"LON\" true false false 7 Float 2 6 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,LON,-1,-1;LAT \"LAT\" true false false 5 Float 2 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,LAT,-1,-1;GHI01 \"GHI01\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI01,-1,-1;GHI02 \"GHI02\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI02,-1,-1;GHI03 \"GHI03\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI03,-1,-1;GHI04 \"GHI04\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI04,-1,-1;GHI05 \"GHI05\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI05,-1,-1;GHI06 \"GHI06\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI06,-1,-1;GHI07 \"GHI07\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI07,-1,-1;GHI08 \"GHI08\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI08,-1,-1;GHI09 \"GHI09\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI09,-1,-1;GHI10 \"GHI10\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI10,-1,-1;GHI11 \"GHI11\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI11,-1,-1;GHI12 \"GHI12\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI12,-1,-1;GHIANN \"GHIANN\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHIANN,-1,-1;Shape_length \"Shape_length\" true true false 0 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,Shape_length,-1,-1;Shape_area \"Shape_area\" true true false 0 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,Shape_area,-1,-1;SEQPLT07 \"SEQPLT07\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,SEQPLT07,-1,-1;PSTATABB \"PSTATABB\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PSTATABB,-1,-1;PNAME \"PNAME\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PNAME,-1,-1;LAT_1

\"LAT_1\" true true false 16 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,LAT,-1,-1;LON_1 \"LON_1\" true true false 16 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,LON,-1,-1;PLFUELCT \"PLFUELCT\" true true false 254 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLFUELCT,-1,-1;PLCO2AN \"PLCO2AN\" true true false 16 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLCO2AN,-1,-1;PLCO2RTA \"PLCO2RTA\" true true false 16 Double 6 15 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLCO2RTA,-1,-1;CO2_TONNE \"CO2_TONNE\" true true false 19 Double 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,CO2_TONNE,-1,-1;CO2biomass \"CO2biomass\" true true false 19 Double 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,CO2biomass,-1,-1", "INTERSECT", "", "")
Process: Calculate coal biomass g/m2-day

arcpy.CalculateValue_management("Solar48_SpatialJoin2*0.086/21.4", "", "Variant")

Process: Calculate coal biomass kg/day

arcpy.CalculateValue_management("Coal CO2 plants /(13651*output_value (2))", "", "Variant"

Process: Spatial Join (Solar to Cement)

arcpy.SpatialJoin_analysis(Solar48, Cement_CO2_plants, Solar_with_cement_CO2, "JOIN_ONE_TO_ONE", "KEEP_ALL", "ID \"ID\" true false false 10 Double 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,ID,-1,-1;GRIDCODE \"GRIDCODE\" true false false 10 Double 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GRIDCODE,-1,-1;LON \"LON\" true false false 7 Float 2 6 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,LON,-1,-1;LAT \"LAT\" true false false 5 Float 2 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,LAT,-1,-1;GHI01 \"GHI01\" true false false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI01,-1,-1;GHI02 \"GHI02\" true false false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI02,-1,-1;GHI03 \"GHI03\" true false false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI03,-1,-1;GHI04 \"GHI04\" true false false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI04,-1,-1;GHI05 \"GHI05\" true false false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI05,-1,-1;GHI06 \"GHI06\" true false false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI06,-1,-1;GHI07 \"GHI07\" true false false 4 Short 0 4

,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI07,-1,-1;GHI08 \"GHI08\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI08,-1,-1;GHI09 \"GHI09\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI09,-1,-1;GHI10 \"GHI10\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI10,-1,-1;GHI11 \"GHI11\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI11,-1,-1;GHI12 \"GHI12\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHI12,-1,-1;GHIANN \"GHIANN\" true false false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,GHIANN,-1,-1;Shape_length \"Shape_length\" true true false 0 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,Shape_length,-1,-1;Shape_area \"Shape_area\" true true false 0 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Solar48,Shape_area,-1,-1;ORIS \"ORIS\" true true false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ORIS,-1,-1;LONG_NAD83 \"LONG_NAD83\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,LONG_NAD83, -1,-1;LAT_NAD83 \"LAT_NAD83\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,LAT_NAD83,- 1,-1;SOURCENAME \"SOURCENAME\" true true false 250 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,SOURCENAME ,-1,-1;OPERATOR \"OPERATOR\" true true false 150 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,OPERATOR,-1,- 1;ADDRESS \"ADDRESS\" true true false 150 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ADDRESS,-1,- 1;CITY \"CITY\" true true false 35 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,CITY,-1,- 1;ST_PROV_OR \"ST_PROV_OR\" true true false 20 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ST_PROV_OR,- 1,-1;SRC_TYPE \"SRC_TYPE\" true true false 50 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,SRC_TYPE,-1,- 1;SRCTYPECOM \"SRCTYPECOM\" true true false 25 Text 0 0

,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,SRCTYPECOM, -1,-1;FUEL \"FUEL\" true true false 50 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,FUEL,-1,- 1;CO2_TONNE \"CO2_TONNE\" true true false 9 Long 0 9 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,CO2_TONNE,- 1,-1;YEAR \"YEAR\" true true false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,YEAR,-1,- 1;PARTNRSHIP \"PARTNRSHIP\" true true false 50 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,PARTNRSHIP,- 1,-1;ST_PROV_NM \"ST_PROV_NM\" true true false 50 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ST_PROV_NM, -1,-1;ST_PROV_AB \"ST_PROV_AB\" true true false 2 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ST_PROV_AB,- 1,-1;COMMENTS \"COMMENTS\" true true false 150 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,COMMENTS,- 1,-1;CO2biomass \"CO2biomass\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,CO2biomass,-1,- 1;GrowthRate \"GrowthRate\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,GrowthRate,-1,- 1", "INTERSECT", "", "")

Process: Calculate cement biomass g/m2-day

arcpy.CalculateValue_management("Solar48_SpatialJoin3*0.086/21.4", "", "Variant")

Process: Calculate cement biomass kg/day

arcpy.CalculateValue_management("Cement CO2 plants /(13651*output_value (3))", "", "Variant")

D.2.2 Python Script for Chapter 5: Figure 2

The following Python script describes the process used to produce Figure 2: GIS process model for calculating microalgal biomass production potential based on the availability of N and P from nearby wastewater treatment plants.

```
# -------------------------------------------------------------------------
# Algae figure 2 - N and P.py
# Created on: 2012-11-23 23:56:57.00000
#   (generated by ArcGIS/ModelBuilder)
# Description:
# Figure 2 (in dissertation). GIS process model for calculating microalgal biomass prodcution
potential based on the availability of N and P from nearby wastewater treatment plants.
# -------------------------------------------------------------------------

# Import arcpy module
import arcpy
# Load required toolboxes
arcpy.ImportToolbox("Model Functions")
# Local variables:
WWTPs = "Wastewater treatment plants"

Solar_growth_rate = "Solar growth rate"

Cement_CO2_to_biomass = "CO2 to biomass\\Cement CO2 to biomass"

Coal_CO2_to_biomass = "CO2 to biomass\\Coal CO2 to biomass"

Natural_gas_CO2_to_biomass = "CO2 to biomass\\Natural gas CO2 to biomass"

Solar_growth_rates_at_WWTPs                                    =
"\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps"
```

N__P_for_cement   =
"\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\NATCARB_Sources_v1104_Spatia"

N__P_for_coal = "\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\coalgas3_SpatialJoin"

N__P_for_natural_gas   =
"\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\coalgas3_SpatialJoin1"

N_feasibility_for_natural_gas = "1"

P_feasibility_for_cement = "1"

Process: Spatial Join

arcpy.SpatialJoin_analysis(WWTPs,   Solar_growth_rate,   Solar_growth_rates_at_WWTPs,
"JOIN_ONE_TO_ONE", "KEEP_ALL", "FID \"FID\" true true false 4 Long 0 10
,First,#,\\\\.psf\\Home\\Desktop\\Algae   paper\\WWTPs\\USwwtps.csv_Features,FID,-1,-
1;CWNS_NUMBER   \"CWNS_NUMBER\"   true   true   false   4   Long   0   10
,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,CWNS_NUMBER,-1,-1;LATITUDE   \"LATITUDE\"
true   true   false   8   Double   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,LATITUDE,-1,-1;NoName \"NoName\" true true false
255   Text   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,NoName,-1,-1;NoName_1 \"NoName_1\" true true
false   8   Double   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,NoName,-1,-1;LONGITUDE \"LONGITUDE\" true
true   false   8   Double   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,LONGITUDE,-1,-1;NoName_12 \"NoName_12\" true
true   false   255   Text   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,NoName,-1,-1;REGION \"REGION\" true true false 4
Long   0   10   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,REGION,-1,-1;STATE \"STATE\" true true false 255
Text   0   0   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,STATE,-1,-1;PRIMARY_COUNTY
\"PRIMARY_COUNTY\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,PRIMARY_COUNTY,-1,-1;AUTHORITY
\"AUTHORITY\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,AUTHORITY,-1,-1;FACILITY_NAME
\"FACILITY_NAME\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,FACILITY_NAME,-1,-1;OWNER_TYPE
\"OWNER_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,OWNER_TYPE,-1,-
1;PRIMARY_WATERSHED_HUC \"PRIMARY_WATERSHED_HUC\" true true false 4 Long
0   10   ,First,#,\\\\.psf\\Home\\Desktop\\Algae
paper\\WWTPs\\USwwtps.csv_Features,PRIMARY_WATERSHED_HUC,-1,-
1;PRIMARY_WATERSHED_NAME \"PRIMARY_WATERSHED_NAME\" true true false

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255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PRIMARY_WATERSHED_NAME,-1,-1;SECONDARY_WATERSHEDS \"SECONDARY_WATERSHEDS\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SECONDARY_WATERSHEDS,-1,-1;PRIMARY_CONGRESSIONAL_DISTRICT \"PRIMARY_CONGRESSIONAL_DISTRICT\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PRIMARY_CONGRESSIONAL_DISTRICT,-1,-1;SECONDARY_CONGRESSIONAL_DIST \"SECONDARY_CONGRESSIONAL_DIST\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SECONDARY_CONGRESSIONAL_DIST,-1,-1;NPDES_PERMIT_NUMBER \"NPDES_PERMIT_NUMBER\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,NPDES_PERMIT_NUMBER,-1,-1;PERMIT_TYPE \"PERMIT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PERMIT_TYPE,-1,-1;FACILITY_STREET_1 \"FACILITY_STREET_1\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_STREET_1,-1,-1;FACILITY_STREET_2 \"FACILITY_STREET_2\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_STREET_2,-1,-1;FACILITY_CITY \"FACILITY_CITY\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_CITY,-1,-1;FACILITY_STATE \"FACILITY_STATE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_STATE,-1,-1;FACILITY_ZIP \"FACILITY_ZIP\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_ZIP,-1,-1;SYSTEM_NAME \"SYSTEM_NAME\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SYSTEM_NAME,-1,-1;FACILITY_DESCRIPTION \"FACILITY_DESCRIPTION\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_DESCRIPTION,-1,-1;MILITARY_IND \"MILITARY_IND\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,MILITARY_IND,-1,-1;TMDL_IND \"TMDL_IND\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,TMDL_IND,-1,-1;SOURCE_WATER_PROTECTION_IND \"SOURCE_WATER_PROTECTION_IND\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SOURCE_WATER_PROTECTION_IND,-1,-1;SMALL_COMMUNITY_EXCEPTION_IND \"SMALL_COMMUNITY_EXCEPTION_IND\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SMALL_COMMUNITY_EXCEPTION_IND,-1,-1;PRES_FACILITY_TYPE \"PRES_FACILITY_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae

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paper\\WWTPs\\USwwtps.csv_Features,PRES_FACILITY_TYPE,-1,-1;PRES_FACILITY_OVERALL_TYPE \"PRES_FACILITY_OVERALL_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PRES_FACILITY_OVERALL_TYPE,-1,-1;PRES_TREATMENT_PLANT_TYPE \"PRES_TREATMENT_PLANT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PRES_TREATMENT_PLANT_TYPE,-1,-1;PROJ_FACILITY_TYPE \"PROJ_FACILITY_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PROJ_FACILITY_TYPE,-1,-1;PROJ_FACILITY_OVERALL_TYPE \"PROJ_FACILITY_OVERALL_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PROJ_FACILITY_OVERALL_TYPE,-1,-1;PROJ_TREATMENT_PLANT_TYPE \"PROJ_TREATMENT_PLANT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,PROJ_TREATMENT_PLANT_TYPE,-1,-1;COORDINATE_TYPE \"COORDINATE_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,COORDINATE_TYPE,-1,-1;LOCATION_DESCRIPTION \"LOCATION_DESCRIPTION\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,LOCATION_DESCRIPTION,-1,-1;HORIZONTAL_COORDINATE_DATUM \"HORIZONTAL_COORDINATE_DATUM\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,HORIZONTAL_COORDINATE_DATUM,-1,-1;HORIZONTAL_COLLECTION_METHOD \"HORIZONTAL_COLLECTION_METHOD\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,HORIZONTAL_COLLECTION_METHOD,-1,-1;SCALE \"SCALE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SCALE,-1,-1;GEOGRAPHIC_LOCATION_SOURCE \"GEOGRAPHIC_LOCATION_SOURCE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,GEOGRAPHIC_LOCATION_SOURCE,-1,-1;MEASUREMENT_DATE \"MEASUREMENT_DATE\" true true false 16 Date 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,MEASUREMENT_DATE,-1,-1;TRIBE_IND \"TRIBE_IND\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,TRIBE_IND,-1,-1;SPECIAL_PROGRAM_AREAS \"SPECIAL_PROGRAM_AREAS\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,SPECIAL_PROGRAM_AREAS,-1,-1;FACILITY_ID \"FACILITY_ID\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,FACILITY_ID,-1,-1;REVIEW_STATUS \"REVIEW_STATUS\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,REVIEW_STATUS,-1,-1;NoName_12_13

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\"NoName_12_13_14\" true true false 255 Text 0 0 ,First,#,\\\\\\.psf\\Home\\Desktop\\Algae paper\\WWTPs\\USwwtps.csv_Features,NoName,-1,-1;ID \"ID\" true true false 8 Double 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,ID,-1,-1;GRIDCODE \"GRIDCODE\" true true false 8 Double 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GRIDCODE,-1,-1;LON \"LON\" true true false 4 Float 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LON,-1,-1;LAT \"LAT\" true true false 4 Float 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,LAT,-1,-1;GHI01 \"GHI01\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI01,-1,-1;GHI02 \"GHI02\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI02,-1,-1;GHI03 \"GHI03\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI03,-1,-1;GHI04 \"GHI04\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI04,-1,-1;GHI05 \"GHI05\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI05,-1,-1;GHI06 \"GHI06\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI06,-1,-1;GHI07 \"GHI07\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI07,-1,-1;GHI08 \"GHI08\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI08,-1,-1;GHI09 \"GHI09\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI09,-1,-1;GHI10 \"GHI10\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI10,-1,-1;GHI11 \"GHI11\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI11,-1,-1;GHI12 \"GHI12\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHI12,-1,-1;GHIANN \"GHIANN\" true true false 2 Short 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,GHIANN,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Length,-1,-1;Shape_Area \"Shape_Area\" false true true 8 Double 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,Shape_Area,-1,-1;AgrowthRate_kg_per_m2day \"AgrowthRate_kg_per_m2day\" true true false 8 Double 0 0 ,First,#,\\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\l48_ghi_10km_Clip1,AgrowthRate_kg_per_m2day,-1,-1", "INTERSECT", "", "")

Process: Spatial Join (natural gas)

arcpy.SpatialJoin_analysis(Natural_gas_CO2_to_biomass, Solar_growth_rates_at_WWTPs, N__P_for_natural_gas, "JOIN_ONE_TO_ONE", "KEEP_ALL", "SEQPLT07 \"SEQPLT07\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,SEQPLT07,-1,-1;PSTATABB \"PSTATABB\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PSTATABB,-1,-1;PNAME \"PNAME\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PNAME,-1,-1;LAT \"LAT\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,LAT,-1,-1;LON \"LON\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,LON,-1,-1;PLFUELCT \"PLFUELCT\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLFUELCT,-1,-1;PLCO2AN \"PLCO2AN\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLCO2AN,-1,-1;PLCO2RTA \"PLCO2RTA\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLCO2RTA,-1,-1;CO2_TONNE \"CO2_TONNE\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,CO2_TONNE,-1,-1;CO2biomass \"CO2biomass\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,CO2biomass,-1,-1;Join_Count \"Join_Count\" true true false 0 Long 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Join_Count,-1,-1;TARGET_FID \"TARGET_FID\" true true false 0 Long 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TARGET_FID,-1,-1;FID \"FID\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FID,-1,-1;CWNS_NUMBER \"CWNS_NUMBER\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,CWNS_NUMBER,-1,-1;LATITUDE \"LATITUDE\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LATITUDE,-1,-1;NoName \"NoName\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName,-1,-1;NoName_1 \"NoName_1\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_1,-1,-1;LONGITUDE \"LONGITUDE\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LONGITUDE,-1,-1;NoName_12 \"NoName_12\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_12,-1,-1;REGION \"REGION\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,REGION,-1,-1;STATE \"STATE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,STATE,-1,-1;PRIMARY_COUNTY \"PRIMARY_COUNTY\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_COUNTY,-

1,-1;AUTHORITY \"AUTHORITY\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,AUTHORITY,-1,-1;FACILITY_NAME \"FACILITY_NAME\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_NAME,-1,-1;OWNER_TYPE \"OWNER_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,OWNER_TYPE,-1,-1;PRIMARY_WATERSHED_HUC \"PRIMARY_WATERSHED_HUC\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_WATERSHED_HUC,-1,-1;PRIMARY_WATERSHED_NAME \"PRIMARY_WATERSHED_NAME\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_WATERSHED_NAME,-1,-1;SECONDARY_WATERSHEDS \"SECONDARY_WATERSHEDS\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SECONDARY_WATERSHEDS,-1,-1;PRIMARY_CONGRESSIONAL_DISTRICT \"PRIMARY_CONGRESSIONAL_DISTRICT\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_CONGRESSIONAL_DISTRICT,-1,-1;SECONDARY_CONGRESSIONAL_DIST \"SECONDARY_CONGRESSIONAL_DIST\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SECONDARY_CONGRESSIONAL_DIST,-1,-1;NPDES_PERMIT_NUMBER \"NPDES_PERMIT_NUMBER\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NPDES_PERMIT_NUMBER,-1,-1;PERMIT_TYPE \"PERMIT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PERMIT_TYPE,-1,-1;FACILITY_STREET_1 \"FACILITY_STREET_1\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_STREET_1,-1,-1;FACILITY_STREET_2 \"FACILITY_STREET_2\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_STREET_2,-1,-1;FACILITY_CITY \"FACILITY_CITY\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_CITY,-1,-1;FACILITY_STATE \"FACILITY_STATE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_STATE,-1,-1;FACILITY_ZIP \"FACILITY_ZIP\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_ZIP,-1,-1;SYSTEM_NAME \"SYSTEM_NAME\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SYSTEM_NAME,-1,-1;FACILITY_DESCRIPTION \"FACILITY_DESCRIPTION\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_DESCRIPTION,-1,-1;MILITARY_IND \"MILITARY_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,MILITARY_IND,-1,-1;TMDL_IND \"TMDL_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TMDL_IND,-1,-1;SOURCE_WATER_PROTECTION_IND \"SOURCE_WATER_PROTECTION_IND\" true

true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SOURCE_WATER_PRO TECTION_IND,-1,-1;SMALL_COMMUNITY_EXCEPTION_IND \"SMALL_COMMUNITY_EXCEPTION_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SMALL_COMMUNITY_ EXCEPTION_IND,-1,-1;PRES_FACILITY_TYPE \"PRES_FACILITY_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRES_FACILITY_TYPE ,-1,-1;PRES_FACILITY_OVERALL_TYPE \"PRES_FACILITY_OVERALL_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRES_FACILITY_OVER ALL_TYPE,-1,-1;PRES_TREATMENT_PLANT_TYPE \"PRES_TREATMENT_PLANT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRES_TREATMENT_PL ANT_TYPE,-1,-1;PROJ_FACILITY_TYPE \"PROJ_FACILITY_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PROJ_FACILITY_TYPE, -1,-1;PROJ_FACILITY_OVERALL_TYPE \"PROJ_FACILITY_OVERALL_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PROJ_FACILITY_OVER ALL_TYPE,-1,-1;PROJ_TREATMENT_PLANT_TYPE \"PROJ_TREATMENT_PLANT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PROJ_TREATMENT_PL ANT_TYPE,-1,-1;COORDINATE_TYPE \"COORDINATE_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,COORDINATE_TYPE,- 1,-1;LOCATION_DESCRIPTION \"LOCATION_DESCRIPTION\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LOCATION_DESCRIPTI ON,-1,-1;HORIZONTAL_COORDINATE_DATUM \"HORIZONTAL_COORDINATE_DATUM\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,HORIZONTAL_COORD INATE_DATUM,-1,-1;HORIZONTAL_COLLECTION_METHOD \"HORIZONTAL_COLLECTION_METHOD\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,HORIZONTAL_COLLE CTION_METHOD,-1,-1;SCALE \"SCALE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SCALE,-1,- 1;GEOGRAPHIC_LOCATION_SOURCE \"GEOGRAPHIC_LOCATION_SOURCE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GEOGRAPHIC_LOCATI ON_SOURCE,-1,-1;MEASUREMENT_DATE \"MEASUREMENT_DATE\" true true false 16 Date 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,MEASUREMENT_DAT E,-1,-1;TRIBE_IND \"TRIBE_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TRIBE_IND,-1,- 1;SPECIAL_PROGRAM_AREAS \"SPECIAL_PROGRAM_AREAS\" true true false 255 Text

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,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI09,-1,-1;GHI10
\"GHI10\"   true   true   false   2   Short   0   0
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI10,-1,-1;GHI11
\"GHI11\"   true   true   false   2   Short   0   0
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI11,-1,-1;GHI12
\"GHI12\"   true   true   false   2   Short   0   0
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI12,-1,-1;GHIANN
\"GHIANN\"   true   true   false   2   Short   0   0
,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHIANN,-1,-
1;Shape_Length   \"Shape_Length\"   false   true   true   8   Double   0   0

133

,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Shape_Length,-1,-1;Shape_Area \"Shape_Area\" false true true 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Shape_Area,-1,-1;AgrowthRate_kg_per_m2day \"AgrowthRate_kg_per_m2day\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,AgrowthRate_kg_per_m2day,-1,-1", "INTERSECT", "", "")

Process: Navail/Nreq for natural gas

arcpy.CalculateValue_management("N available / N required", "", "Variant")

Process: Spatial Join (cement)

arcpy.SpatialJoin_analysis(Cement_CO2_to_biomass, Solar_growth_rates_at_WWTPs, N__P_for_cement, "JOIN_ONE_TO_ONE", "KEEP_ALL", "ORIS \"ORIS\" true true false 4 Short 0 4 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ORIS,-1,-1;LONG_NAD83 \"LONG_NAD83\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,LONG_NAD83,-1,-1;LAT_NAD83 \"LAT_NAD83\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,LAT_NAD83,-1,-1;SOURCENAME \"SOURCENAME\" true true false 250 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,SOURCENAME,-1,-1;OPERATOR \"OPERATOR\" true true false 150 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,OPERATOR,-1,-1;ADDRESS \"ADDRESS\" true true false 150 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ADDRESS,-1,-1;CITY \"CITY\" true true false 35 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,CITY,-1,-1;ST_PROV_OR \"ST_PROV_OR\" true true false 20 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ST_PROV_OR,-1,-1;SRC_TYPE \"SRC_TYPE\" true true false 50 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,SRC_TYPE,-1,-1;SRCTYPECOM \"SRCTYPECOM\" true true false 25 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,SRCTYPECOM,-1,-1;FUEL \"FUEL\" true true false 50 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS

data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,FUEL,-1,-1;CO2_TONNE \"CO2_TONNE\" true true false 9 Long 0 9 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,CO2_TONNE,-1,-1;YEAR \"YEAR\" true true false 4 Short 0 4 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,YEAR,-1,-1;PARTNRSHIP \"PARTNRSHIP\" true true false 50 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,PARTNRSHIP,-1,-1;ST_PROV_NM \"ST_PROV_NM\" true true false 50 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ST_PROV_NM, -1,-1;ST_PROV_AB \"ST_PROV_AB\" true true false 2 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,ST_PROV_AB,-1,-1;COMMENTS \"COMMENTS\" true true false 150 Text 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,COMMENTS,-1,-1;CO2biomass \"CO2biomass\" true true false 19 Double 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,CO2biomass,-1,-1;GrowthRate \"GrowthRate\" true true false 19 Double 0 0 ,First,#,\\\\\.psf\\Home\\Desktop\\Algae paper\\Algae co-location GIS data\\NATCARB\\NATCARB_v1104_shape\\NATCARB_Sources_v1104.shp,GrowthRate,-1,-1;Join_Count \"Join_Count\" true true false 0 Long 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Join_Count,-1,-1;TARGET_FID \"TARGET_FID\" true true false 0 Long 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TARGET_FID,-1,-1;FID \"FID\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FID,-1,-1;CWNS_NUMBER \"CWNS_NUMBER\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,CWNS_NUMBER,-1,-1;LATITUDE \"LATITUDE\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LATITUDE,-1,-1;NoName \"NoName\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName,-1,-1;NoName_1 \"NoName_1\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_1,-1,-1;LONGITUDE \"LONGITUDE\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LONGITUDE,-1,-1;NoName_12 \"NoName_12\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_12,-1,-1;REGION \"REGION\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,REGION,-1,-1;STATE

\"STATE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,STATE,-1,-1;PRIMARY_COUNTY \"PRIMARY_COUNTY\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_COUNTY,-1,-1;AUTHORITY \"AUTHORITY\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,AUTHORITY,-1,-1;FACILITY_NAME \"FACILITY_NAME\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_NAME,-1,-1;OWNER_TYPE \"OWNER_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,OWNER_TYPE,-1,-1;PRIMARY_WATERSHED_HUC \"PRIMARY_WATERSHED_HUC\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_WATERSHED_HUC,-1,-1;PRIMARY_WATERSHED_NAME \"PRIMARY_WATERSHED_NAME\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_WATERSHED_NAME,-1,-1;SECONDARY_WATERSHEDS \"SECONDARY_WATERSHEDS\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SECONDARY_WATERSHEDS,-1,-1;PRIMARY_CONGRESSIONAL_DISTRICT \"PRIMARY_CONGRESSIONAL_DISTRICT\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_CONGRESSIONAL_DISTRICT,-1,-1;SECONDARY_CONGRESSIONAL_DIST \"SECONDARY_CONGRESSIONAL_DIST\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SECONDARY_CONGRESSIONAL_DIST,-1,-1;NPDES_PERMIT_NUMBER \"NPDES_PERMIT_NUMBER\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NPDES_PERMIT_NUMBER,-1,-1;PERMIT_TYPE \"PERMIT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PERMIT_TYPE,-1,-1;FACILITY_STREET_1 \"FACILITY_STREET_1\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_STREET_1,-1,-1;FACILITY_STREET_2 \"FACILITY_STREET_2\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_STREET_2,-1,-1;FACILITY_CITY \"FACILITY_CITY\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_CITY,-1,-1;FACILITY_STATE \"FACILITY_STATE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_STATE,-1,-1;FACILITY_ZIP \"FACILITY_ZIP\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_ZIP,-1,-1;SYSTEM_NAME \"SYSTEM_NAME\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SYSTEM_NAME,-1,-1;FACILITY_DESCRIPTION \"FACILITY_DESCRIPTION\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_DESCRIPTION,-1,-1;MILITARY_IND \"MILITARY_IND\" true true false 255 Text 0 0

,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,MILITARY_IND,-1,-1;TMDL_IND \"TMDL_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TMDL_IND,-1,-1;SOURCE_WATER_PROTECTION_IND \"SOURCE_WATER_PROTECTION_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SOURCE_WATER_PROTECTION_IND,-1,-1;SMALL_COMMUNITY_EXCEPTION_IND \"SMALL_COMMUNITY_EXCEPTION_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SMALL_COMMUNITY_EXCEPTION_IND,-1,-1;PRES_FACILITY_TYPE \"PRES_FACILITY_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRES_FACILITY_TYPE,-1,-1;PRES_FACILITY_OVERALL_TYPE \"PRES_FACILITY_OVERALL_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRES_FACILITY_OVERALL_TYPE,-1,-1;PRES_TREATMENT_PLANT_TYPE \"PRES_TREATMENT_PLANT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRES_TREATMENT_PLANT_TYPE,-1,-1;PROJ_FACILITY_TYPE \"PROJ_FACILITY_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PROJ_FACILITY_TYPE,-1,-1;PROJ_FACILITY_OVERALL_TYPE \"PROJ_FACILITY_OVERALL_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PROJ_FACILITY_OVERALL_TYPE,-1,-1;PROJ_TREATMENT_PLANT_TYPE \"PROJ_TREATMENT_PLANT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PROJ_TREATMENT_PLANT_TYPE,-1,-1;COORDINATE_TYPE \"COORDINATE_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,COORDINATE_TYPE,-1,-1;LOCATION_DESCRIPTION \"LOCATION_DESCRIPTION\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LOCATION_DESCRIPTION,-1,-1;HORIZONTAL_COORDINATE_DATUM \"HORIZONTAL_COORDINATE_DATUM\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,HORIZONTAL_COORDINATE_DATUM,-1,-1;HORIZONTAL_COLLECTION_METHOD \"HORIZONTAL_COLLECTION_METHOD\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,HORIZONTAL_COLLECTION_METHOD,-1,-1;SCALE \"SCALE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SCALE,-1,-1;GEOGRAPHIC_LOCATION_SOURCE \"GEOGRAPHIC_LOCATION_SOURCE\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GEOGRAPHIC_LOCATION_SOURCE,-1,-1;MEASUREMENT_DATE \"MEASUREMENT_DATE\" true true false 16 Date 0 0

,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,MEASUREMENT_DAT E,-1,-1;TRIBE_IND \"TRIBE_IND\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TRIBE_IND,-1,- 1;SPECIAL_PROGRAM_AREAS \"SPECIAL_PROGRAM_AREAS\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SPECIAL_PROGRAM_ AREAS,-1,-1;FACILITY_ID \"FACILITY_ID\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_ID,-1,- 1;REVIEW_STATUS \"REVIEW_STATUS\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,REVIEW_STATUS,-1,- 1;NoName_12_13 \"NoName_12_13\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_12_13,-1,- 1;NoName_12_13_14 \"NoName_12_13_14\" true true false 255 Text 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_12_13_14,-1,- 1;ID \"ID\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,ID,-1,-1;GRIDCODE \"GRIDCODE\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GRIDCODE,-1,-1;LON \"LON\" true true false 4 Float 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LON,-1,-1;LAT \"LAT\" true true false 4 Float 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LAT,-1,-1;GHI01 \"GHI01\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI01,-1,-1;GHI02 \"GHI02\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI02,-1,-1;GHI03 \"GHI03\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI03,-1,-1;GHI04 \"GHI04\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI04,-1,-1;GHI05 \"GHI05\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI05,-1,-1;GHI06 \"GHI06\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI06,-1,-1;GHI07 \"GHI07\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI07,-1,-1;GHI08 \"GHI08\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI08,-1,-1;GHI09 \"GHI09\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI09,-1,-1;GHI10 \"GHI10\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI10,-1,-1;GHI11 \"GHI11\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI11,-1,-1;GHI12 \"GHI12\" true true false 2 Short 0 0

,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHI12,-1,-1;GHIANN \"GHIANN\" true true false 2 Short 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,GHIANN,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Shape_Length,-1,-1;Shape_Area \"Shape_Area\" false true true 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Shape_Area,-1,-1;AgrowthRate_kg_per_m2day \"AgrowthRate_kg_per_m2day\" true true false 8 Double 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,AgrowthRate_kg_per_m2day,-1,-1", "INTERSECT", "", "")

Process: Pavail/Preq for cement

arcpy.CalculateValue_management("P available / P required", "", "Variant")

Process: Pavail/Preq for natural gas

arcpy.CalculateValue_management("P available / P required", "", "Variant")

Process: Spatial Join (coal)

arcpy.SpatialJoin_analysis(Coal_CO2_to_biomass, Solar_growth_rates_at_WWTPs, N__P_for_coal, "JOIN_ONE_TO_ONE", "KEEP_ALL", "SEQPLT07 \"SEQPLT07\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,SEQPLT07,-1,-1;PSTATABB \"PSTATABB\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PSTATABB,-1,-1;PNAME \"PNAME\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PNAME,-1,-1;LAT \"LAT\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,LAT,-1,-1;LON \"LON\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,LON,-1,-1;PLFUELCT \"PLFUELCT\" true true false 254 Text 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLFUELCT,-1,-1;PLCO2AN \"PLCO2AN\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLCO2AN,-1,-1;PLCO2RTA \"PLCO2RTA\" true true false 16 Double 6 15 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,PLCO2RTA,-1,-1;CO2_TONNE \"CO2_TONNE\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,CO2_TONNE,-1,-1;CO2biomass \"CO2biomass\" true true false 19 Double 0 0 ,First,#,\\\\.psf\\Home\\Desktop\\Algae paper\\eGRID 2007\\coalgas3.shp,CO2biomass,-1,-1;Join_Count \"Join_Count\" true true false 0 Long 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,Join_Count,-1,-1;TARGET_FID \"TARGET_FID\" true true false 0 Long 0 0 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,TARGET_FID,-1,-1;FID \"FID\" true true false 4 Long 0 10 ,First,#,\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FID,-1,-

1;CWNS_NUMBER \"CWNS_NUMBER\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,CWNS_NUMBER,-1,-1;LATITUDE \"LATITUDE\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LATITUDE,-1,-1;NoName \"NoName\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName,-1,-1;NoName_1 \"NoName_1\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_1,-1,-1;LONGITUDE \"LONGITUDE\" true true false 8 Double 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,LONGITUDE,-1,-1;NoName_12 \"NoName_12\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NoName_12,-1,-1;REGION \"REGION\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,REGION,-1,-1;STATE \"STATE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,STATE,-1,-1;PRIMARY_COUNTY \"PRIMARY_COUNTY\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_COUNTY,-1,-1;AUTHORITY \"AUTHORITY\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,AUTHORITY,-1,-1;FACILITY_NAME \"FACILITY_NAME\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,FACILITY_NAME,-1,-1;OWNER_TYPE \"OWNER_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,OWNER_TYPE,-1,-1;PRIMARY_WATERSHED_HUC \"PRIMARY_WATERSHED_HUC\" true true false 4 Long 0 10 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_WATERSHED_HUC,-1,-1;PRIMARY_WATERSHED_NAME \"PRIMARY_WATERSHED_NAME\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_WATERSHED_NAME,-1,-1;SECONDARY_WATERSHEDS \"SECONDARY_WATERSHEDS\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SECONDARY_WATERSHEDS,-1,-1;PRIMARY_CONGRESSIONAL_DISTRICT \"PRIMARY_CONGRESSIONAL_DISTRICT\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PRIMARY_CONGRESSIONAL_DISTRICT,-1,-1;SECONDARY_CONGRESSIONAL_DIST \"SECONDARY_CONGRESSIONAL_DIST\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,SECONDARY_CONGRESSIONAL_DIST,-1,-1;NPDES_PERMIT_NUMBER \"NPDES_PERMIT_NUMBER\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,NPDES_PERMIT_NUMBER,-1,-1;PERMIT_TYPE \"PERMIT_TYPE\" true true false 255 Text 0 0 ,First,#,\\\\\.psf\\Home\\Documents\\ArcGIS\\Default.gdb\\Join_wwtps,PERMIT_TYPE,-1,-1;FACILITY_STREET_1 \"FACILITY_STREET_1\" true true false 255 Text 0 0

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Process: Navail/Nreq for coal

arcpy.CalculateValue_management("N available / N required", "", "Variant")

Process: Pavail/Preq for coal

arcpy.CalculateValue_management("P available / P required", "", "Variant")

Process: Navail/Nreq for cement

arcpy.CalculateValue_management("N available / N required", "", "Variant")

Process: For Nfeas >=1 AND Pfeas >=1

arcpy.IterateCount_mb(N_feasibility_for_natural_gas, P_feasibility_for_cement, "1")

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