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2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

A Study Sponsored by U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

Volume 1:
Economic Availability of Feedstocks

July 2016

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for the
U.S. DEPARTMENT OF ENERGY

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Additional Information

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

energy.gov
eere.energy.gov
bioenergy.energy.gov
web.ornl.gov/sci/transportation/research/bioenergy/

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07 | Microalgae

7.1 Introduction

Algae can be single-celled or filamentous bacteria, or they can be single-celled or multicellular eukaryotes. Algae include microalgae, macroalgae (seaweeds), and cyanobacteria (historically known as blue-green algae). They typically live in aquatic environments and are capable of photosynthesis, although this is not always the case. In this chapter, we model only the cultivation of microalgae and define them as photosynthetic organisms that use sunlight and nutrients (CO_2, nitrogen, phosphorus, and other elements) to create biomass. Algal biomass contains lipids, proteins, and carbohydrates that, in turn, can be converted and upgraded to a variety of biogas and biofuel end products. These end products include but are not limited to hydrogen, methane, renewable diesel, jet fuel, and ethanol. Owing to their diverse characteristics, the type and strain of algae cultivated will ultimately affect every step of the algal biofuels supply chain.

Algae are an attractive feedstock for many locations in the United States because of their high biomass yield and lipid content per unit of area per unit of time. Depending on the strain, algae can be grown using fresh, saline, and/or brackish media from a variety of "clean" surface freshwater sources, groundwater, or seawater; additionally, they can grow in water from second-use sources such as treated industrial wastewater; municipal, agricultural, and/or aquaculture wastewater; or produced water generated from oil and gas drilling operations. Microalgae require ammonia and/or nitrates, phosphates, trace metals (i.e., iron, manganese, zinc), and CO_2 as nutrients and have the potential to provide beneficial use of waste streams and provide significant co-benefits to municipalities, industry, and the environment. Research and development on algal biofuels, moving toward commercial applications, is ongoing in states including Hawaii, California, New Mexico, Arizona, Florida, Texas, and Iowa.

Depending on conversion and upgrading pathways, residual biomass can be used for high-value coproducts such as livestock and aquaculture feed, for biofertilizers. or as recycled nutrients that are processed and reintroduced to the cultivation system. Until now, more than 90% of all algae production globally has been used for nutritional products. A rough estimate of total biomass production is 15,000 tons/year, of which about two-thirds is *Spirulina*, one-fourth is *Chlorella*, and the rest is *Duniella* and *Haematococcus* (Benemann 2013; Benemann 2016).

7.1.1 Goals of Analysis

As is the case for terrestrial feedstocks, important resource analysis questions for algae include not only how much of the crop may be available but also what price might be needed to procure that supply. Identifying resource co-location opportunities for algal biofuel facilities has the potential to reduce costs, utilize waste resources, and focus attention on appropriate technologies and locations for commercialization.

This chapter provides an estimate of biomass potential from open-pond production at given minimum selling prices. This is not a projection of actual measured biomass or a simulation of commercial projects. Biomass potential is estimated based on 30 years of hourly local climate and strain-specific biophysical characteristics using the Biomass Assessment Tool (BAT) (Wigmosta et al. 2011), assuming sufficient available nutrients (including CO_2).

The economic availability of biomass resources is influenced by variables including but not limited to biomass market development, land values, rate of adoption, and the profitability of alternative land uses (see text box 7.1). For example, in chapter 5, the economic availability of switchgrass is quantified by assessing the potential profitability of switchgrass production compared with other crop alternatives from the farmer's perspective. Switchgrass is assumed to be economically available if results suggest it is the most profitable crop option. Lacking a comparable framework to evaluate the opportunity cost of land that could be allocated to algae production, we use nutrient co-locating strategies as a proxy to quantify the most likely locations and quantities of algae resource production. These most likely locations may well change in the future, as new technologies determine the least-cost algae production methods.

Exogenous CO_2 is a requirement for viable commercial production of algal biofuels and one of the major costs of production (Campbell, Beer, and Batten 2011, Rogers et al. 2014). As a consequence, a better understanding of the costs associated with transport and delivery of CO_2 is needed (Davis et al. 2014, Quinn et al. 2013).

The goal of this chapter is to estimate the site-specific and national economic availability of algae biomass under co-location scenarios, (i.e., locating algal biomass production with coal-fired electric gener-

Text Box 7.1 | Algae Resource Analysis

A limited number of studies have analyzed the potential supply of algae biomass and biofuel in different geographic regions in the United States.

- Benemann et al. (1982); Vigon et al. (1982); Maxwell, Folger, and Hogg (1985); and Lundquist et al. (2010) provided a foundational basis for later resource assessment works, defining general criteria and offering more detailed analyses for the state of California.
- Wigmosta et al. (2011) investigated the potential national U.S. supply of algal biofuels produced from open-pond facilities while optimizing production on the basis of water use efficiency.
- Biofuel potential from microalgae cultivated in photobioreactors (PBRs) (i.e., closed reactors providing a controlled environment) in regions of the United States was estimated by Quinn et al. (2012) using *Nannochloropsis*. Quinn et al. (2013) also conducted resource sensitivity analyses related to land and CO_2 resource assumptions for the conterminous United States (CONUS) on a state-by-state basis.
- Pate (2013) reviewed current and future resource demand challenges associated with commercial scale-up of algal biofuel production in the United States. ANL, NREL, and PNNL (2012) reconciled assumptions related to algae biomass production from techno-economic analysis and life-cycle analysis models, creating a performance baseline and prioritizing the most favorable group of sites that would support a production target of 5 billion gallons per year of renewable diesel. This work was further evaluated in Davis et al. (2014).
- Bennett, Turn, and Chan (2014) identified priority lands available for open-pond algae production in Hawaii and estimated yields for the state.
- Orfield, Keoleian, and Love (2014) evaluated potential biomass and associated lipid yields in the CONUS, considering co-location with CO_2 flue gas and wastewater sources. Several scenarios dictated by available resource trade-offs were used to estimate biomass and associated fuel production by multiple processing pathways in the CONUS (Venteris, Skaggs et al. 2014a).
- Moody, McGinty, and Quinn (2014) estimated global biofuel potential from microalgae in PBRs on non-arable land. Langholtz et al. (2016) assessed potential land competition between algal and terrestrial feedstocks for pastureland in the United States and found little competition for production sites.

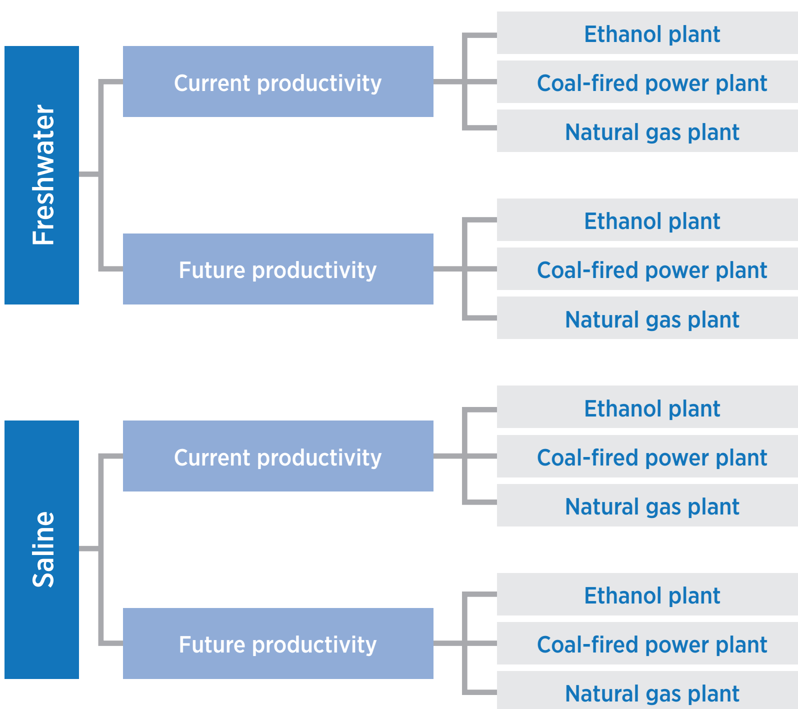
ating units [EGUs], natural gas EGUs, or ethanol production facilities that produce waste CO_2). We evaluate the potential economic benefit of the three CO_2 co-location scenarios with a defined cost limit of $40/ton of CO_2 to avoid exceeding commercial supply costs. In combination with the CO_2 co-location sources, a current productivity rate scenario and a future high-productivity scenario are presented for both freshwater and saline water algae strains. For saline scenarios, both fully lined ponds and minimally lined ponds are considered because of the substantial costs of pond liners and uncertainty as to where they are needed. Key variables in the algae analyses are depicted in figure 7.1.

This chapter provides the first estimate of the national algae biomass supply available for fuel in a billion-ton biomass supply and price report. The analysis of potential supply moves toward DOE's goal of modeling a sustainable supply of 1 million metric tonnes (1.1 million tons) of ash-free dry weight (AFDW) cultivated algal biomass by 2017 and 20 million metric tonnes (22 million tons) by 2022. However, as in the other chapters, the potential biomass reported has not been produced; and even for future projections, a viable market would be needed to achieve the potential.

7.2 Scope of Analysis

The scope of the chapter focuses on microalgae. It does not reflect the full range of algal biomass production systems, but rather, the systems for which we have sufficient engineering and cost data. We consider only the well-established open-pond/raceway production systems in the current analysis, largely because costs of PBRs have not been well quantified in the literature, and there are many different types of PBR systems (e.g., flat plate systems, hanging bags, vertical tubes, horizontal tubes).

Figure 7.1 | Key variables in the algae analyses



Representative freshwater and saline algal strains, *Chlorella sorokiniana* (DOE strain 1412) and *Nannochloropsis salina*, respectively, were selected because these strains offer good growth potential in outdoor ponds under varying environmental conditions, are well studied, and have been parameterized in several different biomass growth models; see for example, NAABB (2010); Bechet et al. (2011); Huesemann et al. (2013); Dong et al. (2014); Orfield, Keoleian, and Love (2014); Venteris, Wigmosta, et al. (2014); and Huesemann et al. (2016). Heterotrophic production pathways are not considered. The analysis incorporates direct consideration of water resource availability for both freshwater—following the DOE algae model harmonization study described in ANL, NREL, and PNNL (2012)—and brackish/saline water within a salinity range of 2–70 practical salinity units (PSU).

Co-location strategies were investigated for the potential use of waste CO_2 from natural gas and coal EGUs and ethanol production plants. The analysis required (1) site-specific spatial routing analysis and biomass production estimates, (2) site-specific techno-economics to estimate the cost of delivering waste CO_2 to the algae facility, (3) aggregation to county-level production and cost estimates, and (4) the comparative cost of algae biomass production without co-located resources. The chapter considers productivity and cost estimates for 2014 and a non-specific future year.

The chapter focuses on fuel pathways that require use of the lipid fraction or whole algae and that can result in a variety of fuels and coproducts; however, non-destructive algae pathways such as ethanol secretion are not currently considered. The biomass endpoint for the resource analysis and supply curves is a 20 wt % solids content that is agnostic to the eventual fuel pathway. With respect to the biofuel supply chain, this endpoint is beyond the production “pondgate” (analogous to the farmgate in previous chapters); it includes dewatering processes and costs and allows an optimum starting concentration for downstream conversion processes such as algal lipid extraction and upgrading or whole algae hydrothermal liquefaction and the production of coproducts. Low-cost drying strategies for stabilizing wet algae for storage and transport are also of interest for further development after initial concentration to 20% solids content. The analysis endpoint is consistent with the recent cultivation design case report that was used to estimate minimum selling prices for algae biomass in the analyses in this chapter (Davis et al. 2016).

The following are some of the questions that are addressed:

- Can waste CO_2 be transported cost-effectively, and under what conditions are the greatest cost savings projected?
- How much suitable land is available near CO_2 sources?
- What are the production potential and associated costs from freshwater and saline water sources?
- What effect does increased future productivity have on potential biomass and minimum selling price estimates?
- Can existing CO_2 waste streams meet future productivity demands?

7.3 Algae Biomass Resource

7.3.1 Differences between Algae and Terrestrial Feedstocks and Biofuel Pathways

Earlier chapters focus on terrestrial bioenergy feedstocks (i.e., vascular plants that grow in soil). This chapter considers the production of biomass from microalgae and elements of the biofuel supply chain, which are well integrated with the production step.

Table 7.1 | Major Differences between Terrestrial and Algal Biomass Production Systems

	Algal biomass	Terrestrial biomass
Growth medium	Aqueous nutrient media	Soil
Water used	Freshwater, brackish, saline, or otherwise non-potable water	Rainwater
Resource requirements	CO_2, nitrogen, phosphorus, and other supplements such as iron, manganese, and zinc	Nitrogen, phosphorus, and other agricultural supplements (e.g., potassium and lime)
Infrastructure and equipment for production and harvesting	Pond liners, photobioreactors, paddlewheels, pumps, and others	Farm equipment
Harvesting	Frequent (i.e., daily, weekly, or monthly)	Annual or less frequently than annual, depending on maturity
Storage duration	Short-term (days) unless dried	Long-term (months)
Dewatering	Low solid concentration in water for some applications	Relatively dry
Location of biorefinery	Onsite (except when biomass is dried) with offsite potential	Usually offsite
Recycling of water and nutrients during production	Yes, potential for ~90% nutrient recycle	No, nutrient losses through erosion and runoff

Some of the important differences between algae and terrestrial feedstocks are described in table 7.1. All of these differences affect estimates of the potential supply, costs, and geography of algal biofuel production.

Algal feedstocks discussed in this chapter are unicellular aquatic species cultivated in engineered open ponds. Hundreds of thousands of different natural algal strains have adapted to local environmental conditions and can flourish across a massive range of diverse conditions. Tens of thousands of these species have been characterized and cultured (see for example ncma.bigelow.org and utex.org). Some species grow in media containing freshwater (e.g., BG-11 medium at a pH of 7.0 containing NO_3 and PO_4) and others grow in brackish or saline- or hypersaline-based media from groundwater resources or seawater (e.g., pH of 7.5 in f/2–Si medium at 35 PSU salinity, and pH of 7.5 containing NO_3 and PO_4) (Crowe et al. 2012, Huesemann et al. 2016). Exogenous CO_2 is required for viable commercial production of algal biofuels. Unlike in terrestrial crop production, water and nutrients can be recycled through the algal cultivation process.

Algae have some distinct advantages compared with terrestrial crops. Because algae are cultivated in engineered systems, they do not require arable lands and thus do not typically compete for land resources with cultivated agriculture. Also, the areal productivities of algae are substantially higher than those for terrestrial crops. The use of non-potable water from wastewater treatment facilities and brackish, saline, or hypersaline water from groundwater or seawater is also an option in some locations (Craggs et al. 2011). Co-location with wastewater resources is not considered.

In most algal biofuel systems, biomass is harvested much more frequently than are terrestrial crops; however, in contrast to long-term storage of terrestrial feedstocks, downstream processing of algae needs to be completed within days to prevent feedstock deterioration. Drying of the algae feedstock can overcome this storage limitation, but strategies need to be developed to reduce the costs associated with thermal drying. Because algae are highly responsive to temperature and light fluctuations, seasonal growth patterns are evident and impact downstream processing and design (Coleman et al. 2014; Huesemann et al. 2016). The combination of the seasonal variability of biomass production and the need for consistent volumes of feedstock supply are challenges for the design of downstream conversion equipment. Consider that most terrestrial biorefineries require a fixed feed rate over a full year to remain economically viable. The challenges can be partly alleviated by microalgae crop rotation, which is not considered here, as well as by feedstock blending.

Because most algal biofuel pathways are in an earlier state of commercialization than most terrestrial biofuel pathways, the production model parameters and results are more uncertain for algae than for terrestrial crops. For many pathways, coproducts may drive the economics of the production system.

7.3.2 Cultivation

Algae cultivation must account for aspects of strains selection, solar radiation, temperature, pond and/or growth medium design, and nutrient and CO_2 availability. Following is a description as applicable to open-pond production.

Photosynthesis and Algal Strains

Photoautotrophic microalgae grow by converting solar energy to chemical storage in the form of biomass via photosynthesis. With adequate nutrients, the growth rate of microalgae is predominantly influenced by the intensity of specific wavelengths of incident solar radiation and the corresponding water temperature of the growth media. In particular, solar radiation in the form of photosynthetically active radiation (which operates at the 0.4–0.7 µm portion of the electromagnetic spectrum) provides available light for photosynthesis; whereas shortwave radiation, operating at 0.285–2.8 µm, has a dominant influence on heating water within the open cultivation ponds and closed PBRs. For any photosynthesizing plant, available light intensity below or above the optimum range causes a decline in biomass productivity (Bechet, Shilton, and Benoit 2013, Rubio et al. 2003, Weyer et al. 2010). Photosynthetically active radiation is limited by normal diurnal and seasonal fluctuations as a function of the sun's changing zenith angle throughout the year. Consequently, algae cultivation sites at lower latitudes experience less change in solar insolation (outside of monsoonal zones) and will generally have a more consistent daily availability of photosynthetically active radiation due to a limited change in solar insolation. Cloud cover and storms have a significant impact on available photosynthetically active radiation; however, photosynthesis still occurs at a reduced rate using available diffuse radiation (Churkina and Running 1998). Although areas within the United States, such as the Southwest, receive high percentages of available and uninhibited photosynthetically active radiation, the lack of cloud cover and low relative humidity can also present issues with thermal energy loss from open ponds at night due to low nighttime temperatures. Thus, from a climate-resource perspective, areas where strain-specific optimal temperature ranges exist, and have limited variability within the diurnal and seasonal air temperature regimes, tend to be more suitable locations for growth.

The water temperature within shallow microalgae cultivation ponds is bounded by the principle of conservation of energy to a fluid volume and is thus influenced by pond water depth; water density (which varies by level of salinity); the specific heat of water; and net surface heat-flux, including net solar short-wave radiation, downward atmospheric longwave radiation, longwave back radiation, and heat flux due to evaporation and conduction. All of these are driven by meteorological variables, including air temperature, wind, and relative humidity. Thus, open-pond systems are subject to dominant control from environmental conditions, barring engineered solutions such as the use of industrial waste heat during cool-temperature months or the introduction of cool makeup water during warm-temperature months. The water temperature in an open pond will be impacted by large diurnal swings in air temperature and the degree of evaporative cooling. Because of the thermal properties of water, the water temperature will respond to air temperatures with varying degrees of latency and dampening.

Optimal media temperatures vary among types and strains of microalgae (Christi 2007, Pate 2013, Sheehan et al. 1998). Many microalgae can tolerate temperatures down to 15°C below their optimal, but exceeding the optimal temperature range by 2°–4°C can cause total culture loss (Mata, Martins, and Caetano 2010). Photosynthetic reactions become limiting outside the optimal temperature range and, if the minimum temperature is not reached or maximum temperature is exceeded, the suboptimal temperatures will more than likely lead to reduced cell viability. Understanding the basic growth characteristics of specific strains of microalgae is fundamental to determining what and where to grow to maximize biomass production potential.

Open-Pond Production System

Production in open ponds, generally taking the form of raceways (fig. 7.2) or circular ponds, is well established and represents the cultivation design of choice for the vast majority of commercial algae biomass production globally. A major incentive for the use of open ponds, and in particular mixed raceway ponds, is that they are less expensive to build, scale up, and operate than their PBR counterparts (Davis, Aden, and Pienkos 2011, Amer, Adhikari, and Pellegrino 2011, Sun et al. 2011). In addition, open ponds have demonstrated commercial success in scale-up, e.g., several hectares for individual ponds. For example, the Hutt Lagoon in western Australia contains ~7,000 acres of food-grade algae, and EarthRise Nutritionals exemplifies sustainable large-scale operation in California's Imperial Valley. However, CO_2 loss is generally higher from algal ponds than from PBRs. It is not uncommon for both research and commercial cultivation systems to include a hybrid system, where single or multiple-scale PBR systems are used for algae culture scale-up and inoculation to the open pond.

Figure 7.2 | Traditional open-pond raceway design used in the current analysis

The selection of algal strains for use in open ponds must be considered carefully to meet location-specific primary environmental conditions (light and temperature) and suitability for survival in the local pond water ecosystem. Local, natural strains have an advantage, as they have adapted to predators and diseases found in the locale. Strains may also be rotated to adapt to seasonal environmental conditions to help ensure the highest possible production performance.

For open ponds, a significant capital cost is pond construction, particularly pond liners, which can comprise 20%–35% of the capital costs (Abodeely et al. 2014, Davis et al. 2012, Coleman et al. 2014). For freshwater systems, eliminating pond liners through construction with clay soil compaction or biological sealants would reduce capital costs and improve profitability, but it would be dependent upon local and state regulations and potential water quality effects (Venteris, McBride, et al. 2014). For some saline water systems, soil plugging approaches without plastic liners may not be permissible under local and state environmental regulations; however, there are existing cases in which saline aquaculture facilities were repurposed for microalgae production and do not have liner requirements.

Resource Requirements

Land and water are the primary resources needed to grow algae. However, to enhance algae productivities over those observed in natural environments, extra quantities of CO_2, nitrogen, and phosphorus are provided. Some nutrients can be recycled, depending on the downstream process method, but "fresh" nutrients also need to be procured. If nutrients were available as a result of co-locating with waste stream resources near the algae facility, the purchase of consumables for biofuel production could be reduced. The cost reduction in biofuel production will largely depend on the nutrient; nutrient source; required processing for utilization; and distance, method, and subsequent expense for transportation.

7.3.3 Logistics

In chapter 6, the quantified potential biomass supply is the amount delivered to the refinery, which is an advance over previous billion-ton reports. The advanced logistics operations for supply of terrestrial feedstocks consist of transporting biomass to intermediate preprocessing centers (depots) where the biomass is modified to meet the biorefinery specifications. At the depot, the biomass may have to be dried to become stable in storage and densified for economical transport and storage.

In the context of this chapter, we define "logistics" as all operations to dewater algae and recover it from its growth media in open ponds. A wide range of methods and equipment have been proposed and tested for collecting and thickening microalgae, with the range of output concentrations and costs depending on the technology. For example, at the beginning of the harvest, the dispersed small particles of microalgae at a concentration of 0.5 g/L (0.05% dry matter content) are removed through sedimentation, filtration, and centrifugation. Then algae are subjected to various additional pathway steps, including possible extraction and conversion processes to make fuel and coproducts (Laurens et al. 2015). Considerations of logistical operations become important, especially when the production of higher-value coproducts like animal feed becomes an integral part of biofuels for algae.

Post-production processes for algae can include harvesting, dewatering, drying, densification (e.g., granulation), storage, and transport, although the exact processes depend on the conversion technology, the location of the biorefinery, and cost (Chen et al. 2009). Drying and densification operations for large-scale volumes of algae biomass have not been developed and costed yet, and conventional heated air-drying methods could make GHG and energy balances more challenging. In this chapter, the endpoint for which we evaluate minimum selling prices is dewatering to 20 wt % solids, which makes the biomass available for potential extraction, conversion, and transport to the biorefinery. Some conversion processes, such as pyrolysis, would require additional dewatering (Bennion et al. 2015).

7.3.4 Conversion to Fuel

Algae can be processed into a variety of fuel products. A strong emphasis has been placed on developing drop-in fuels for major liquid transportation fuel sectors, including diesel (biodiesel or renewable diesel/green diesel[1]) and kerosene (jet fuel/aviation biofuel), although processes have also been developed for the production of ethanol, methane gas, butanol (biobutanol; higher energy density than ethanol), gasoline (biogasoline), hydrogen (biohydrogen), crude oil, and syngas.

Likely conversion options include lipid extraction (in which "algae lipid upgrading" may enable sugars and potentially proteins to be converted to other fuel products), hydrothermal liquefaction, catalytic hydrothermal gasification, and direct ethanol or hydrocarbon secretion. The ultimate conversion process has a significant impact on the production/resource co-location strategy, particularly the sources and demands for nutrients and CO_2 (Venteris, Skaggs, et al. 2014b). For example, if a lipid extraction pathway is the goal, anaerobic digestion or catalytic hydrothermal gasification could be used in the site design to recycle biomass for nutrients and generated methane, thus reducing the overall consumptive resource demands. Alternatively, the remaining biomass could be sold to a coproduct market, and no nutrient recycling would be possible. If hydrothermal liquefaction is the pathway, all of the biomass may be used—or coproduct compounds such as polysaccharides may be separated in a preparatory step (Chakraborty et al. 2012)—and anaerobic digestion is not included. For all pathways, the selected strain(s) is a critical factor to optimize for the intended pathway requirements (i.e., biomass production, lipid content).

One conversion process pertinent to algae that is different from terrestrial processes is the direct secretion of ethanol or other fuel products by live algae (Luo et al. 2010). This process is not currently evaluated in this study because few peer-reviewed publications on the topic exist, and no DOE techno-economic assessments or design case reports detail the process costs and production rate outcomes. Also, the billion-ton reports present biomass quantities, because they are related to the quantity of biofuel that can be produced. In ethanol secretion processes, the quantity of biomass may not be closely related to the amount of fuel: while there is turnover, each algae cell produces ethanol continuously without harvest until it dies. In future analyses, this process will receive more attention.

7.3.5 Coproducts

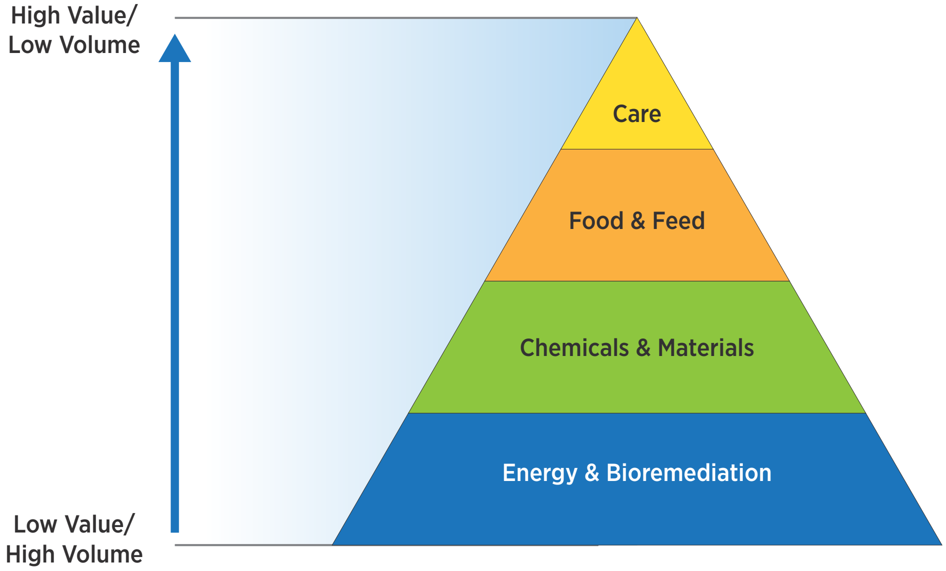
Coproducts are currently required for the commercial viability of most algal biofuel systems (Zhu 2015, NRC 2012). In the past year, some algal biofuel companies in the United States have announced an increasing focus on non-fuel products, with biofuels produced from remaining biomass. In an example from one company, 10% of the biomass drives 80%–90% of the product value, with biomass destined for fuel oils and feed making up the rest (Schultz 2013).

Example coproducts include nutraceuticals; defatted, high-protein livestock (swine and poultry) feed; aquaculture food; polyunsaturated fatty acids; and recombinant products such as astaxanthin (Austic et al. 2013, Brennan and Owende 2010, Kiron et al. 2012, NRC 2012). Except for animal feedstuffs, all of these potential coproducts have small volumes, with market saturation at hundreds to thousands of tons of biomass.

The coproducts with large commercial markets are animal feedstuffs (NRC 2012). In addition, algae biomass remaining after lipid extraction can be anaerobically digested and applied to land as a fertilizer (Frank et al. 2012), a use that may improve the energy balance more than does using it as animal feed (Sills et al. 2012).

[1] Biodiesel is a fuel consisting of mono-alkyl esters of long-chain fatty acids, also referred to as FAME (fatty acid methyl ester). Renewable diesel refers to biomass-derived diesel fuels that are not mono-alkyl esters.

Figure 7.3 | Value and volume pyramid for possible biofuel coproducts from microalgae; "Care" indicates personal care products



Source: Modified from van der Voort et al. (2015).

Figure 7.3 is a qualitative representation of the value and volume of products that can be obtained from algae. The lowest value and largest volume are associated with energy and environmental products. Bioremediation applications for wastewater treatment belong to this group as well. Personal care products, including pharmaceuticals, have the lowest volume but the highest value. Nutraceuticals from microalgae are classed as foods and include ingredients for animal feed. Bioplastics are grouped with chemicals.

7.4 Co-Location

Co-location strategies involve pairing an algae production system (e.g., open pond) with an existing industrial facility (e.g., EGU, ethanol plant, wastewater treatment plant) for the purpose of utilizing available waste products (e.g., CO_2, nutrients, process heat) to provide benefits to either or both co-located operations. Co-location of an algae facility with waste resources provides an opportunity to reduce the cost of those resources and potentially reduce the cost of the disposal or other disposition of the waste materials.

Carbon dioxide is a waste product from many industrial processes, each a potential source for inexpensive CO_2 for algae, especially where federal and state policies have put a policy restriction or price on carbon emissions. Waste CO_2 is also generated by ethanol, cement, and ammonia production, in addition to many refinery and other industrial chemical processes. Other nutrients (nitrogen, phosphorus) are generated in the waste processing from confined animal-feeding operations, dairies, and other farm operations, as well as in municipal wastewater treatment plants. These are potential sources of nutrients for algae that may be co-located with algae cultivation facilities.

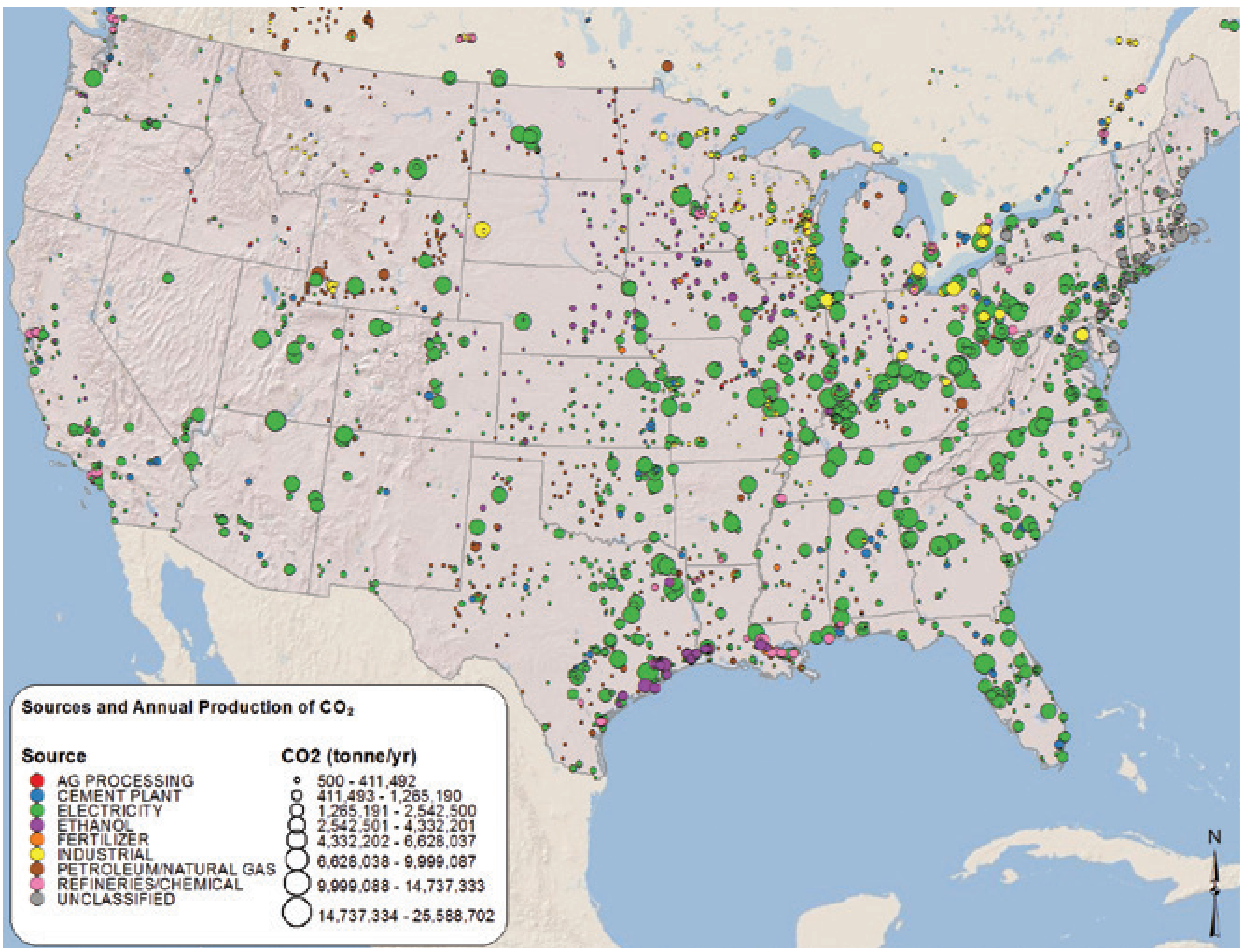
The United States currently emits 6.4 billion tons of CO_2 per year from all sources (point and non-point sources). More than 3.3 billion tons of these emissions are from point sources that can potentially be used for algal biomass production (fig. 7.4) (NATCARB 2015, Middleton et al. 2014). Generally speaking, with the total amount of waste CO_2 that is available, approximately 1.4 billion tons of algal biomass could be produced. However, these numbers are irrespective of the spatial relationships between the CO_2 point sources and the potential cultivation sites identified, and of the economic constraints of transport. In general, for algae cultivation operational expenses, CO_2 supply is a significant cost factor, contributing approximately 20%–25% of the costs. The co-location with point sources of waste CO_2 has been demonstrated in both research and commercial industry environments.

7.4.1 Transport and Purity of CO_2

The biggest constraint in CO_2 co-location is cost-effective delivery, which is limited by the concentration of gases other than CO_2 in the waste stream, which in turn, impacts the distance over which CO_2 can be transported. The purer the CO_2 stream, the less expensive is the transport system.

The most important distinction between sources is those that provide a nearly pure CO_2 stream (>95% CO_2) and those that provide CO_2 mixed with other

Figure 7.4 | General categories of CO_2 point-source emissions and associated total annual output for 2012–2013



Source: Data from NATCARB (2015) and Middleton et al. (2014).

gases (mainly N_2), typically the result of air combustion. When the waste stream is essentially pure CO_2, such as the emissions from ethanol (~99%), ammonia, or hydrogen production plants, delivery to the algae facility is similar to the simple purchase of CO_2 from an industrial supplier (Middleton et al. 2014). Distribution is handled similarly. Ethanol plant flue gas, containing a nearly pure stream of CO_2, is ideal for transport, in terms of volume, capital, and operating expenses.

When flue gas from an EGU is used, the composition of the gas is variable, and the CO_2 fraction may not be high enough to provide the enhanced productivity desired. For example, carbon-rich fuels such as coal produce a waste gas with a concentration of ~14% CO_2 (by volume), whereas natural gas EGUs produce a lower concentration of ~5% CO_2. In a dilute mixture, most of the gas being transported (N_2) is not valuable to the algae, but the pipes and compressors still need to be sized and costed to move the unwanted extra components. These diluents increase not only capital cost but also operating (electricity) costs. While CO_2 flue gas can be used directly (see for example, Wilson et al. (2014)), there are technologies available to strip CO_2 from lower-concentration CO_2 streams (e.g., amine scrubbers), allowing for CO_2 storage and making for more cost-effective transport.

Table 7.2 provides several CO_2 sources, their associated CO_2 concentrations, and total annual reported emissions. Note that under the EPA Greenhouse Gas Reporting Rule (74 FR 56260), only large facilities exceeding emissions of 25 kt of CO_2 or CO_2 equivalents (CO_2e) are reported. For this study, smaller CO_2 sources are also identified and considered for co-location (see section 7.5.4, CO_2 Co-Location Model).

7.4.2 Three Sources of CO_2

Three significant sources of waste CO_2 were selected, representing a range of purities and geographic distributions: natural gas EGUs, coal EGUs, and ethanol production facilities. These three classes of point-source CO_2 represent approximately 86.6% of CO_2 emissions in the CONUS and thus represent the major portion of the U.S. waste CO_2 supply. Table 7.3 provides the three sources of waste CO_2 considered in this study along with the assumed concentration, the

Table 7.2 | Sources of CO_2, Including Percent of CO_2 in Output Stream and Total National Emissions for Large Facilities

CO_2 source	Percent CO_2 in output stream	2013 U.S. CO_2 emissions (million tons)[a]
EGUs	4%–15%, depending on fuel	2,316
Cement plants	~24%	122
Fertilizer/ ammonia plants	~97%	28
Ethanol plants	>99%	19
Hydrogen plants	~99%	46
Refineries, chemical plants	Varies; as high as 99% for steam methane reformers	525

[a]From www.epa.gov/ghgreporting for sites > 25 kt/year CO_2 or CO_2e.

Table 7.3 | Sources of Point-Source CO_2, Concentrations, Total Output, Percentage Contribution, and Number of Individual Sites

CO_2 source	CO_2 concentration	Estimated annual output (million tons)	Total CONUS CO_2 (%)	Number of sites in CONUS
Ethanol	99	140.8	3.8	317
Coal EGU	14	2,677.3	72.2	1,339
Natural gas EGU	5	394.5	10.6	1,774

EGU = electric generating unit.
CONUS = Conterminous United States.

total CONUS annual CO_2 output (including smaller sites with <25 kt CO_2/year not reporting to the EPA Greenhouse Gas Reporting program), the fraction of total emissions, and total number of individual sites (NATCARB 2015; Middleton et al. 2014).

7.5 Approach and Assumptions

The overall approach to quantifying algae biomass supply is (1) developing engineering and cost estimates for co-location scenarios; (2) selecting priority land areas for co-location; (3) generating national, site-specific biophysically based production estimates; (4) developing spatially explicit transport pathways and incorporating available CO_2 supply, demand, and costs; and (5) generating estimates of minimum selling price as a function of supply. We also estimate the cost differential between co-location and a base case. The base case costs are primarily based on a process design case report for the production of algal biomass in open ponds (Davis et al. 2016). Both a current-technology productivity scenario (2014) and a future, high-productivity scenario are considered for algae strains *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water). For saline scenarios, both fully lined ponds and minimally lined ponds are considered (see fig. 7.1).

7.5.1 Engineering Design and Transport Cost Analysis

A major portion of the engineering analysis focused on the cost of transporting co-located resources to identify locations where it was cost-effective to transport waste CO_2. Cost-effective designs were created with specific pipe sizes, parallel piping, compressors, and power requirements. The transportation analysis feeds into the spatial analysis of potential co-location sites.

The transport of gaseous CO_2 is modeled as compressible gas flow, with major component costs in the transport pipeline and compression system. The major factor determining the system design and sizing is the gas flow rate required for the assumed productivity of algae, and this in turn is determined by the fraction of CO_2 in the flue gas stream. The pipe and compressor system are sized for 1.25 times the CO_2 needed to supply algae, to account for much of the summertime peaking. Under the future, high-productivity scenario, a larger system is engineered to meet the increased CO_2 demand, compared with the present productivity scenario. Strain type and seasonal variability of biomass production play a significant role in engineering design and are recognized to have a site-specific response. The engineering assumptions used herein provide a reasonable estimation considering varying growing conditions across the CONUS. We assume that (1) an aboveground pipeline carries the gas from the emission source to the algae production facility; (2) there is no separation of the CO_2 from the flue gas; and (3) the gas flow rate depends on the pipe diameter, pressure drop, and properties of the gas. The equation for the gas flow rate, as well as the assumed pipe configurations, is presented in appendix D.

Many assumptions go into the analysis that determines the engineering design for how to supply the required CO_2 to an algae production facility. The productivity of the algae is one significant variable. The mean annual biomass growth—13.2 g/m^2/day, as reported in ANL, NREL, and PNNL (2012)—is based on output from the BAT model for the Gulf Region as part of the DOE algae model harmonization study for open-pond production systems. It is used as a basis for the engineering design. This value corresponds closely with strain-specific mean annual values of 12.8 g/m^2/day for *Chlorella sorokiniana* and 13.8 g/m^2/day for *Nannochloropsis salina* in the Gulf Region, using common model harmonization sites. For purposes of gas transport engineering design, 1,000 acres of pond area (1,200 acres total with the required infrastructure) is used and is consistent with the DOE harmonization study. The resulting required gas flow rates from the coal-fired and natural gas–fired EGUs are higher than from the ethanol plants because of the lower CO_2 concentration in the former gas streams (table 7.4). Therefore, we assume a series of parallel pipelines from natural gas-fired EGUs and coal-fired EGUs. Electricity costs are estimated for powering transport (blower and pump) equipment.

Ethanol Plant Co-Location

The design of the ethanol plant co-location is defined by a 99% pure CO_2 stream, and systems are broken into two different system designs based on pipeline distance. A high-pressure system (>100 pounds per square inch gauge [psig]) is used for pipelines >10 miles, and a low-pressure system (20 psig) is used for pipelines ≤10 miles (fig. 7.5). For least-expensive system costing, the low-pressure (≤10 miles) and high-pressure (>10 miles) delivery systems were cost-competed. This cost-competition was trivial if

Table 7.4 | Volume Flow Rates for the Gas Transport Systems

CO_2 resource	CO_2 in gas stream (%)	Gas mass flow rate (max) for 1,000 acre, open-pond facility
Coal-fired EGU	14	7,700 scfm
Natural gas–fired EGU	5	22,000 scfm
Ethanol plant	99	1,100 scfm

scfm = standard cubic feet per minute.

all the cultivation sites being fed by a single ethanol CO_2 source were above or below the 10 mile threshold (defining a low- or high-pressure pipeline system). In many cases, however, a single CO_2 source is feeding an enterprise of cultivation sites that have pipeline distances ≤10 miles and >10 miles. In these cases, a "majority rules" approach is used; for example, if 12 cultivation sites have a cost preference for a high-pressure system and 3 cultivation sites have a cost preference for a low-pressure system, all cultivation sites are assigned to use a high-pressure system.

Coal EGU Co-Location

Coal EGU plants are assumed to have a 14% pure CO_2 stream. Under the current production scenario, the transport system is characterized by dual (parallel) low-pressure (20 psig) pipelines with blowers and in-line boosters as required by distance (to prevent pressure drops in the pipeline) (fig. 7.6). Under the future high-productivity scenario, the number of parallel pipelines increases to six. Since there is only one system, there was no requirement for cost-competing systems, as was the case with algae cultivation facilities receiving CO_2 from ethanol production.

Figure 7.5 | Ethanol-based CO_2 co-location using either a high-pressure or low-pressure system

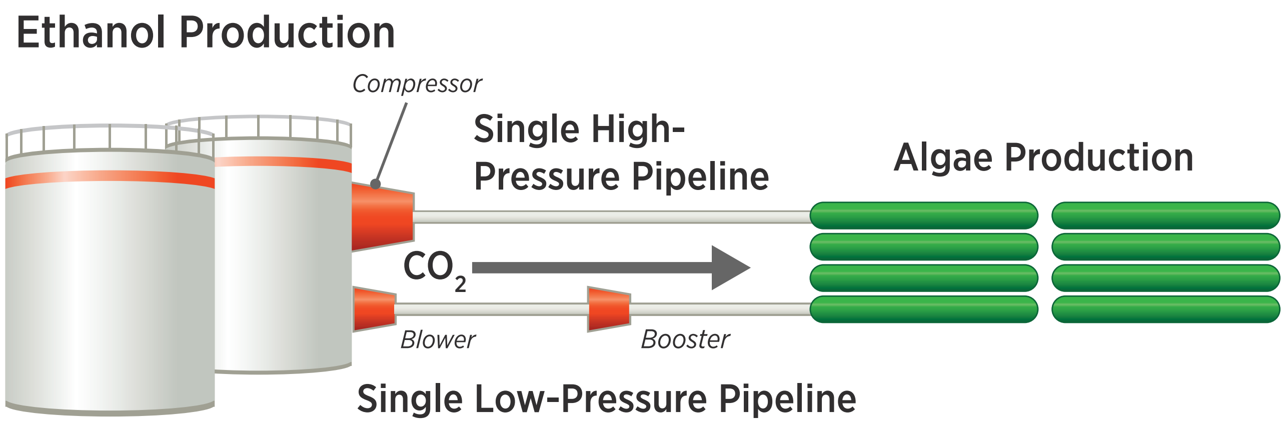
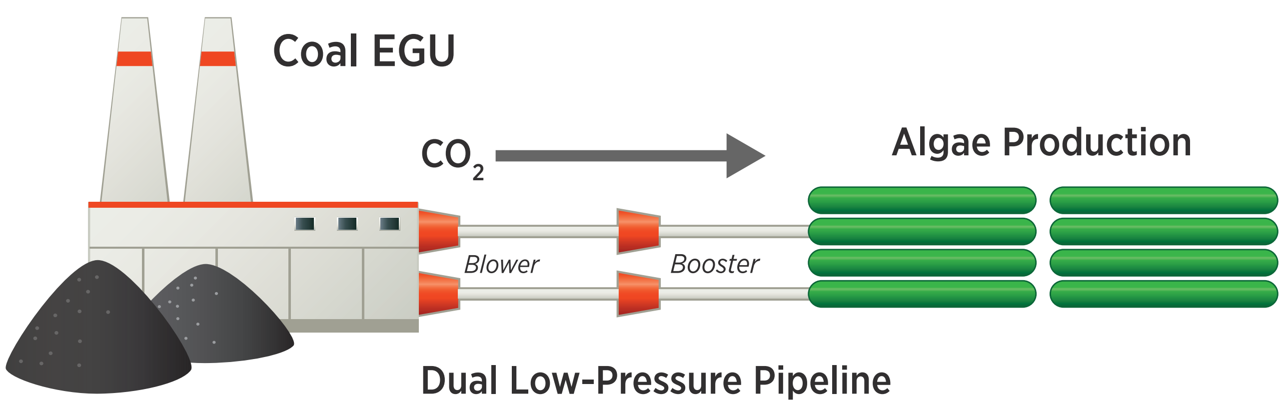


Figure 7.6 | Coal EGU-based CO_2 co-location using a dual low-pressure system with in-line boosters



Natural Gas EGU Co-Location

Natural gas–fired EGU plants are assumed to have a 5% pure CO_2 stream. Under the current-technology production scenario, the transport system is characterized by four low-pressure (20 psig) pipelines with blowers and in-line boosters as required by distance (to prevent pressure drops in the pipeline) (fig. 7.7). Under the future high-productivity scenario, the number of parallel pipelines increases to eight, as four additional pipelines were needed to minimize operational costs.

7.5.2 Biomass Assessment Tool

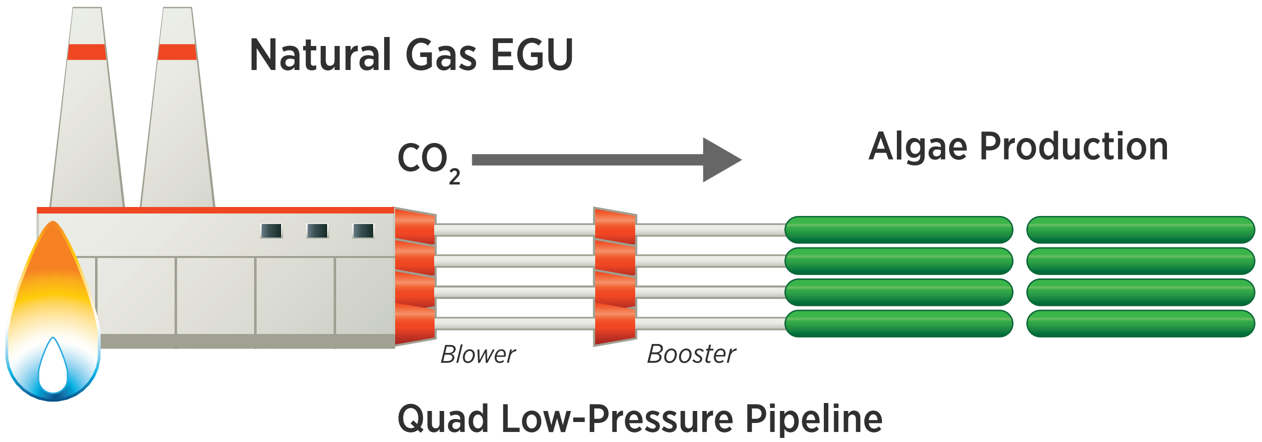
The BAT is an integrated model, analysis, and data management architecture that couples advanced spatial and numerical models to capture site-specific environmental conditions, production potential, resource requirements, and sustainability metrics for bioenergy feedstocks. The BAT operates at a high spatiotemporal resolution (e.g., 30–500 m depending on the dataset, hourly) within the CONUS. Various aspects of the BAT have been described and demonstrated in a number of published studies (Coleman et al. 2014; Venteris et al. 2012, 2013; Venteris, Skaggs et al. 2014b; ANL, NREL, and PNNL 2012; Wigmosta et al. 2011; Venteris, McBride et al. 2014; Venteris, Skaggs et al. 2014a; Venteris, Wigmosta et al. 2014).

The BAT integrates (1) a multi-scale land-suitability model; (2) an open-pond mass and energy balance pond model (Perkins and Richmond 2004) delivering hourly pond water temperature and evaporative water loss based on local weather data; (3) a biophysical growth model that incorporates pond temperature, optimal/sub-optimal temperature curves (appendix D), and photosynthetically active radiation to simulate strain-specific biomass growth and nutrient demand at an hourly time-step; (4) trade-off analysis routines to evaluate biomass production potential with available land, water, and nutrient resources; (5) water source and use intensity analysis for freshwater, seawater, and saline groundwater; (6) nutrient and CO_2 flue gas source, availability, and demand models; (7) least-cost transport models for water, nutrients, CO_2, and refinery access; (8) a partial techno-economic site scale-up model; (9) a land valuation/acquisition model; and (10) a surface leveling model that accounts for costs of site preparation.

7.5.3 Land Suitability

For the BAT (Wigmosta et al. 2011) land suitability analysis, we assume that each open-pond microalgae cultivation facility (unit farm, 1,200 acres) consists

Figure 7.7 | Natural gas EGU-based CO_2 co-location using a quad pipeline low-pressure system with in-line boosters

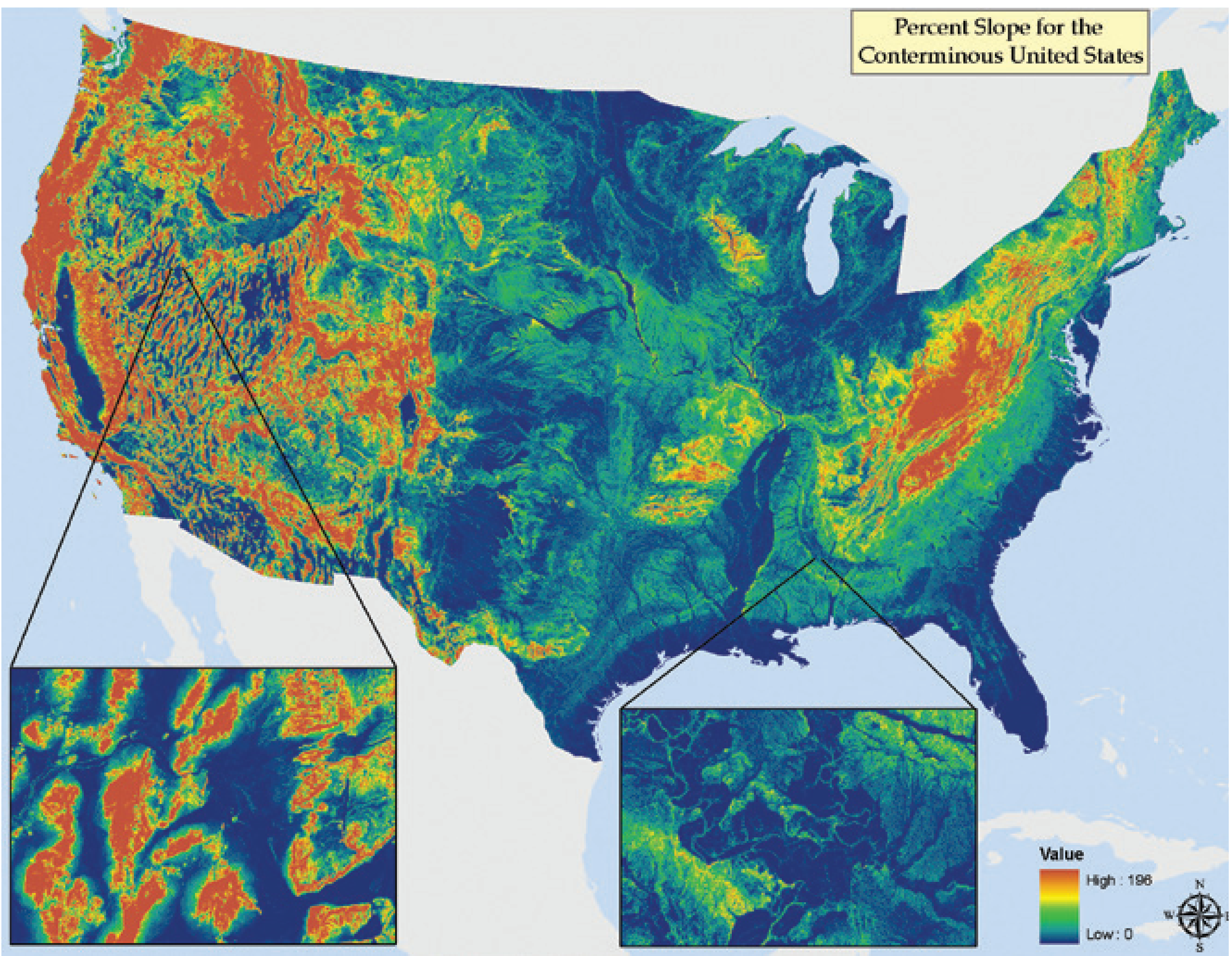


of one hundred 30 cm deep, 10-acre classic raceway style ponds (fig. 7.2) requiring 1,000 acres of land for ponds and another 200 acres for operational infrastructure. Additionally, the potential facilities and associated infrastructure are constrained by several topographic and land use/land cover criteria to determine potentially suitable lands.

The first major constraint is that suitable lands must be situated on relatively flat land, with a minimum 1,200 acre contiguous area and slopes of ≤1% (see figs. 7.8 and 7.9) to minimize initial site preparation/excavation and operational water pumping costs (Benemann et al. 1982; Maxwell, Folger, and Hogg 1985). Other pond designs that incorporate steeper slopes, terracing, and airlift pump systems are not considered in the current analysis (Beal et al. 2015; Huntley et al. 2015).

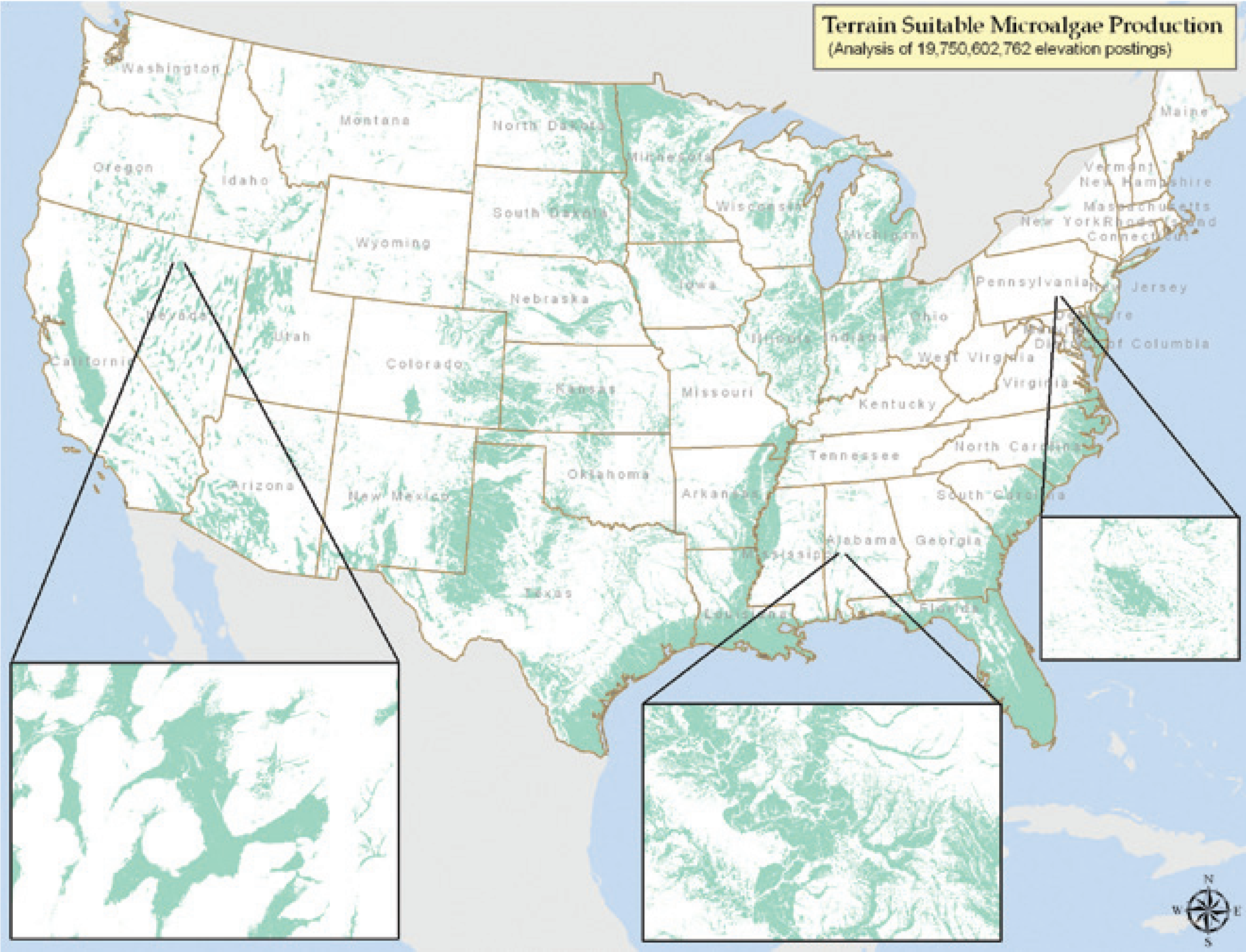
From the suitable slope areas, only non-agricultural, non-forested, undeveloped or low-density developed, non-sensitive, generally non-competitive land is considered for cultivation facilities. Specifically, this excludes open water, urban areas, airports, cultivated cropland and orchards (but not pastureland), forest/woodlands, federal and state protected areas such as national and state parks, wilderness areas, wildlife refuges, wetlands, riparian areas, and other areas that are deemed environmentally sensitive.

Figure 7.8 | A percent-of-slope analysis was conducted on 30 m USGS digital elevation models



Note: This high-resolution mosaicked dataset provides the basis for the ≤1% slope classification, the first level of land screening in the multi-criteria land suitability analysis.

Figure 7.9 | Reclassified slope data ranging from 0%–1% (green) provide the most terrain-optimal locations for open-pond development



Note: Keep in mind that the high-resolution analysis is not fully portrayed at the resolution and scale of this figure; thus, many suitable areas are not seen at the national scale. For example, see the insets of southeastern Pennsylvania and western Alabama.

7.5.4 CO_2 Co-Location Model

We used the database of stationary carbon sources obtained from the DOE National Energy Technology Laboratory's NATCARB v.1501 in addition to the database developed by Middleton et al. (2014), which captures the EPA Greenhouse Gas Reporting Program data. The Middleton et al. (2014) database considers only CO_2 point-sources with 25 kt/year of output, which represent 597 sources throughout the country. The remaining sources were supplemented with the NATCARB database. Plants that reported zero CO_2 production were assumed to be non-operating and were eliminated from the analysis. In addition, if a site was reported to already be providing CO_2 for another purpose (Middleton et al. 2014), it was not included in the analysis.

To assess the co-location potential of stationary CO_2 sources with algae cultivation—ethanol plant, coal EGU, and natural gas EGU sites are separated into their own GIS-based point datasets to enable independent analyses. For each of the unit farm data sets in the CONUS, the PNNL microalgae growth model (appendix D) was run for the selected strains, *Chlorella sorokiniana* (freshwater) and *Nannochloropsis* *salina* (saline water), to determine the 30-year average biomass production potential. The total annual carbon demand (Venteris, Skaggs et al. 2014b) for the produced biomass is calculated by Eq. (1):

$$D_{CO_2} = \frac{B * Wc_{Bio}}{E_{CO_2} * W_{CCO_2}} \quad (1)$$

where

D_{CO_2} = CO_2 demand (kg/year)

B = AFDW biomass (kg/year)

$W_{C_{Bio}}$ = Carbon fraction in biomass (0.55)

E_{CO_2} = CO_2 utilization efficiency (0.82)

W_{CCO_2} = Carbon fraction in CO_2 (0.273)

For the carbon demand, no CO_2 recycling is assumed (agnostic to the downstream processing pathway), 330 days of operation are considered, and CO_2 is used only during daylight hours. The daytime CO_2 use is consistent with several past studies: In Pate (2013), CO_2 is used based on 8 and 12 hours of daylight. In Beal et al. (2015), CO_2 delivery and use is a function of biomass productivity that is driven by the dominant controls of media temperature and available light. Lundquist et al. (2010) consider a balance of biomass productivity, CO_2 utilization efficiency, and pH constraints with a 10 hours/day delivery of CO_2. And Brune, Lundquist, and Benemann (2009) consider the ratio of sunlight hours to power plant operating hours (11–14 hours/day of sunlight vs. 18 hours/day for power plant), carbon storage in the pond, CO_2 transfer efficiency, pond outgassing rates, and pH limits. It is acknowledged that in colder regions, the number of days of operation will be lower, with productivities that may not justify operation; however, these low or zero productivities and associated CO_2 demands are reflected in total annual values.

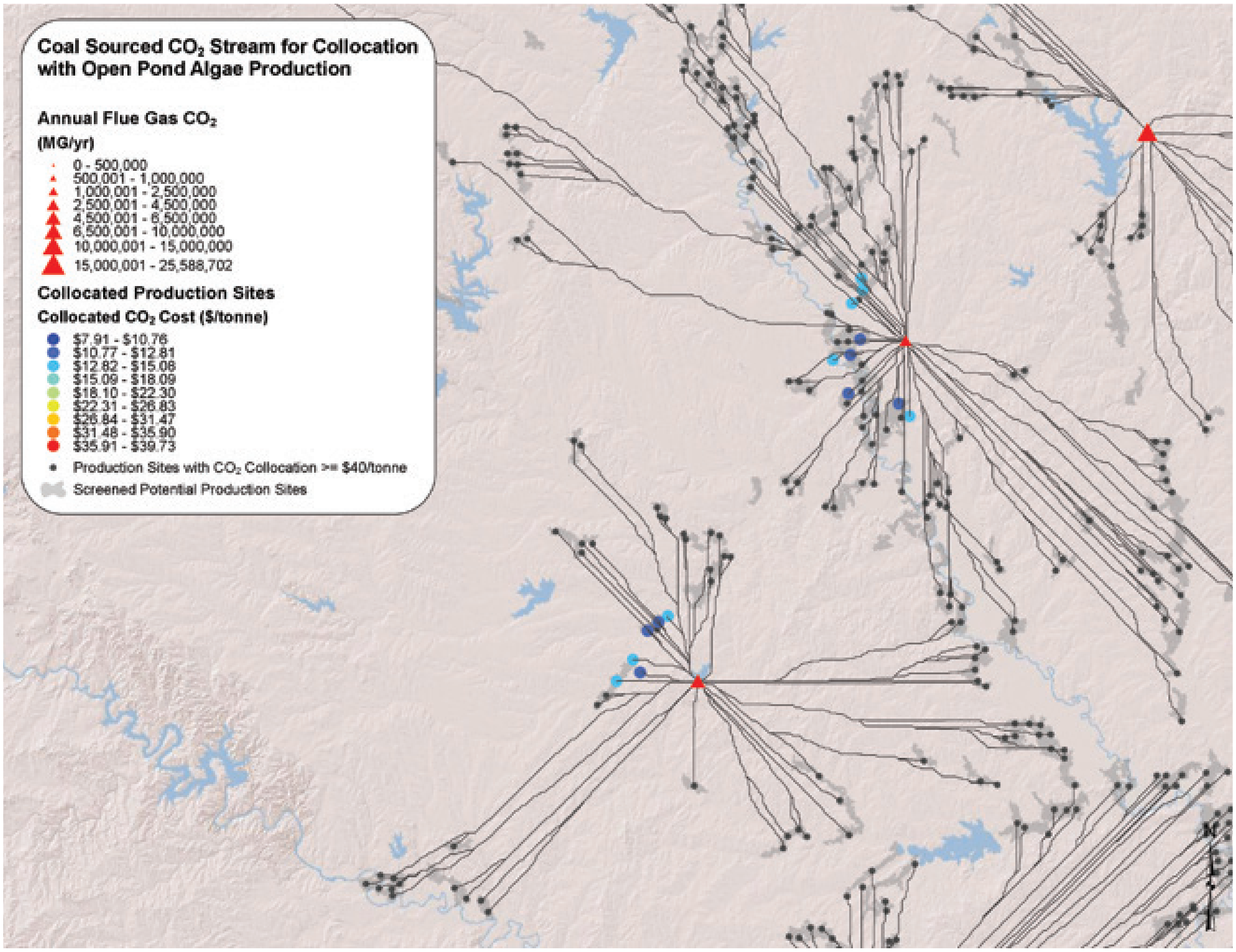
A GIS grid-based, cost-distance model is run to determine the least-cost pipeline routes from each CO_2 source to the unit farm. The flue-gas cost-distance model is based on an earlier work described in Venteris et al. (2013). The model will determine the closest distance between source and target and find the most cost-effective path while avoiding high-topography, sensitive, urban, and other unsuitable areas (see fig. 7.10).

Pipeline distances are determined along with capital costs (i.e., pipe length, material, sizing, compressor, blowers) and operational costs (i.e., transport energy) using estimates developed in section 7.4.1. The model supplies potential algal cultivation facilities with available CO_2 (as defined by the CO_2 demand) using the least expensive sources first (blend of the closest sites and total biomass production) and continues as long as it is technologically feasible. It is less expensive than commercial purchase at \$40 ton CO_2, and there is available supply. This is further illustrated in figure 7.11, in which an accounting takes place between site CO_2 demand and total available supply.

For a simplifying assumption in this analysis, we use 12 hours/day of daylight on average throughout the year for all CONUS sites. This value is based on the geographic center latitude of the CONUS, at 39.82°N (appendix D). For each flue gas source, we acknowledge operations are variable according to a cost-effective industrial process or, in the case of EGUs, as baseload, semi-baseload or peaking power capacity and demand require. For purposes of GHG emissions reporting, values are most typically provided as total tons per year; however, because algal photosynthesis is limited to daylight hours, CO_2 cannot be directly used 24 hours/day. We make the operational assumptions around flue gas availability and thus adjust total annual CO_2 output available for algal production as indicated below.

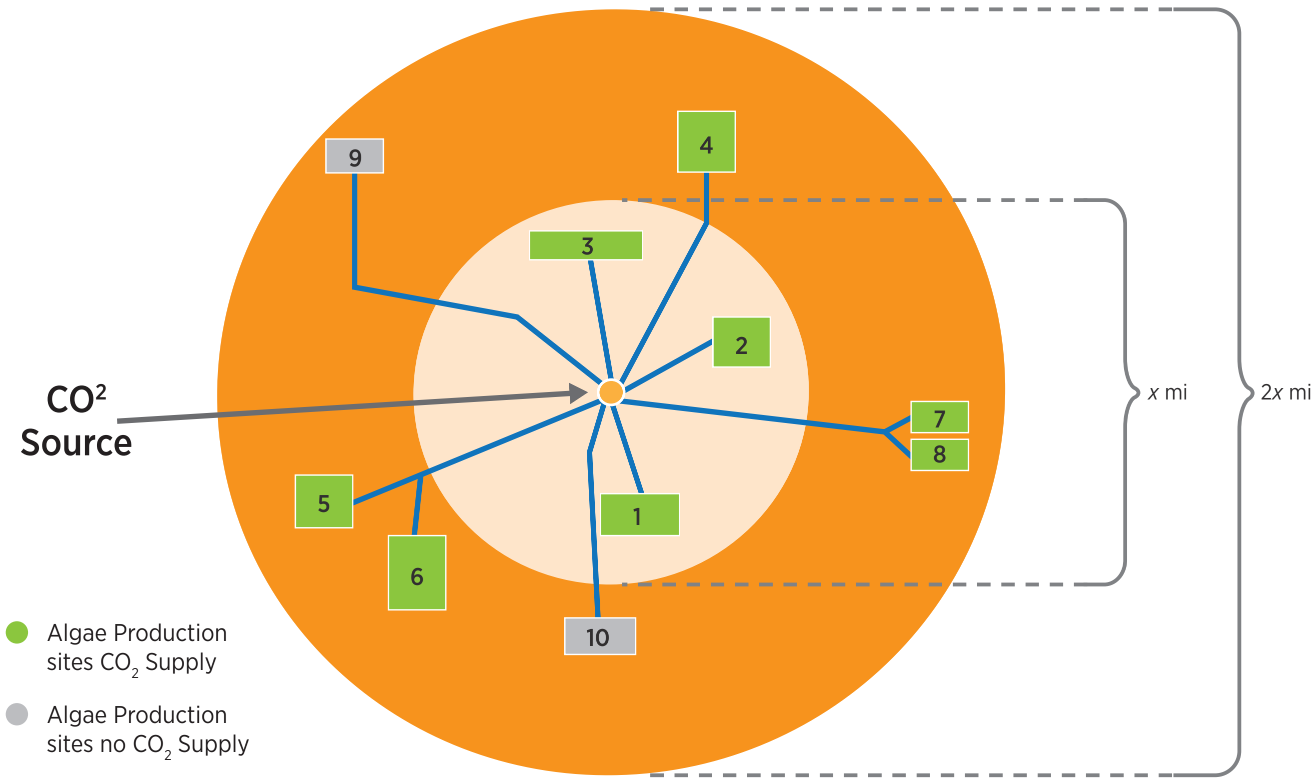
Ethanol plants are consistently operational 24 hours/day, 7 days/week and, assuming an annual average of 12 hours of daylight, can thus provide 50% of their total available CO_2 supply for algal production. EGUs are more complex and follow regional patterns that are temporally varying. In general, business weekdays between 7 a.m. and 10 p.m. are

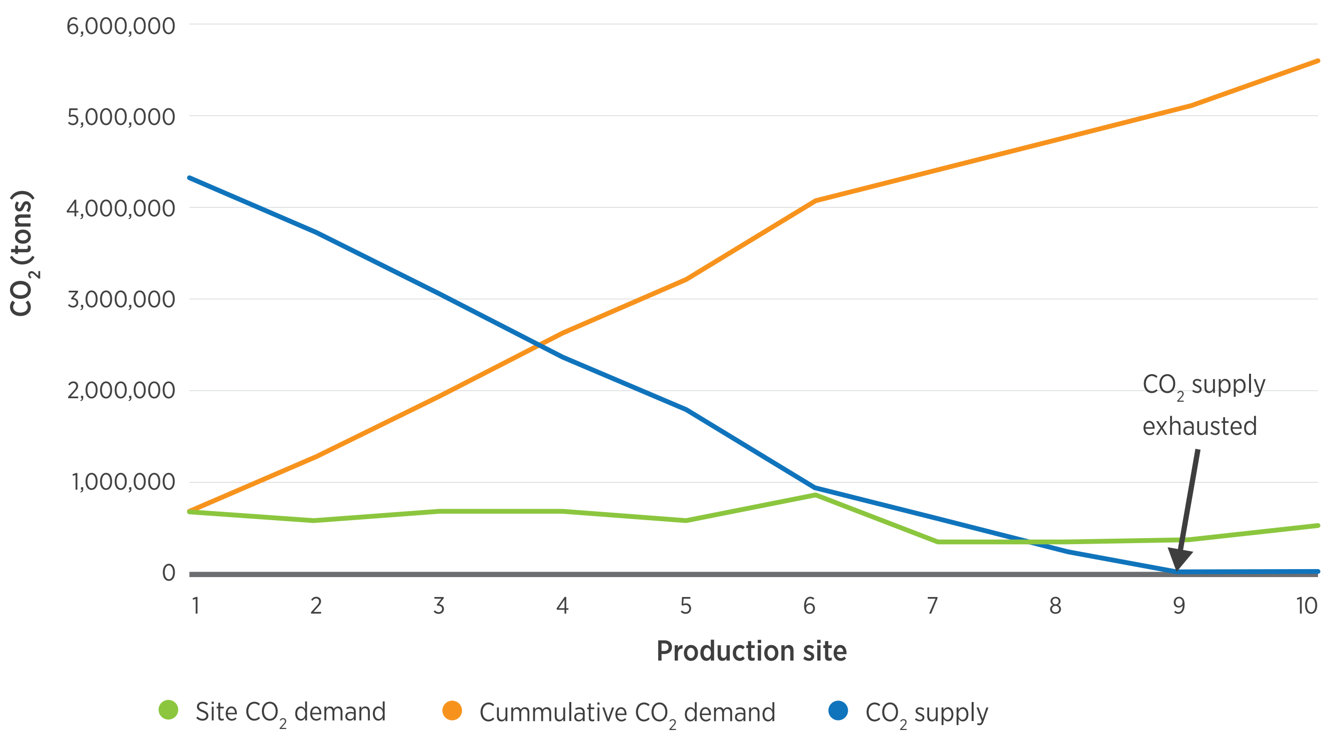
Figure 7.10 | Example results of the flue-gas cost-distance model that routes pipelines from source (stationary CO_2 source) to target (potential algae cultivation facility)



considered "on-peak" periods for power generation, whereas business days between 10 p.m. and 7 a.m. and all day on weekends are considered "off-peak." There are seasonal differences as well: summer and winter electricity demands are significantly higher than in spring and fall, when demand for cooling and heating, respectively, are not as great (fig. 7.12). In general, off-peak hours constitute 55% of the hours in a year, whereas on-peak hours represent 45%. In terms of actual power demand, on-peak hours make up 70% of the total power load and off-peak hours 30%. We assume a direct relationship between power generation and CO_2 output. Therefore, making adjustments considering the fraction of off-peak and on-peak hours with respect to CO_2 output, and factoring average daylight hours that overlap with off-peak and on-peak hours, we estimate that 30% of the total annual CO_2 emitted is available for algal production. Future detailed analysis could adjust available CO_2 values based on location, EGU function (i.e., base load, peaking power, load following), time of year, and fuel source. In addition, it is recognized that several technologies are available to continually capture, strip and store CO_2; these could be evaluated in future work.

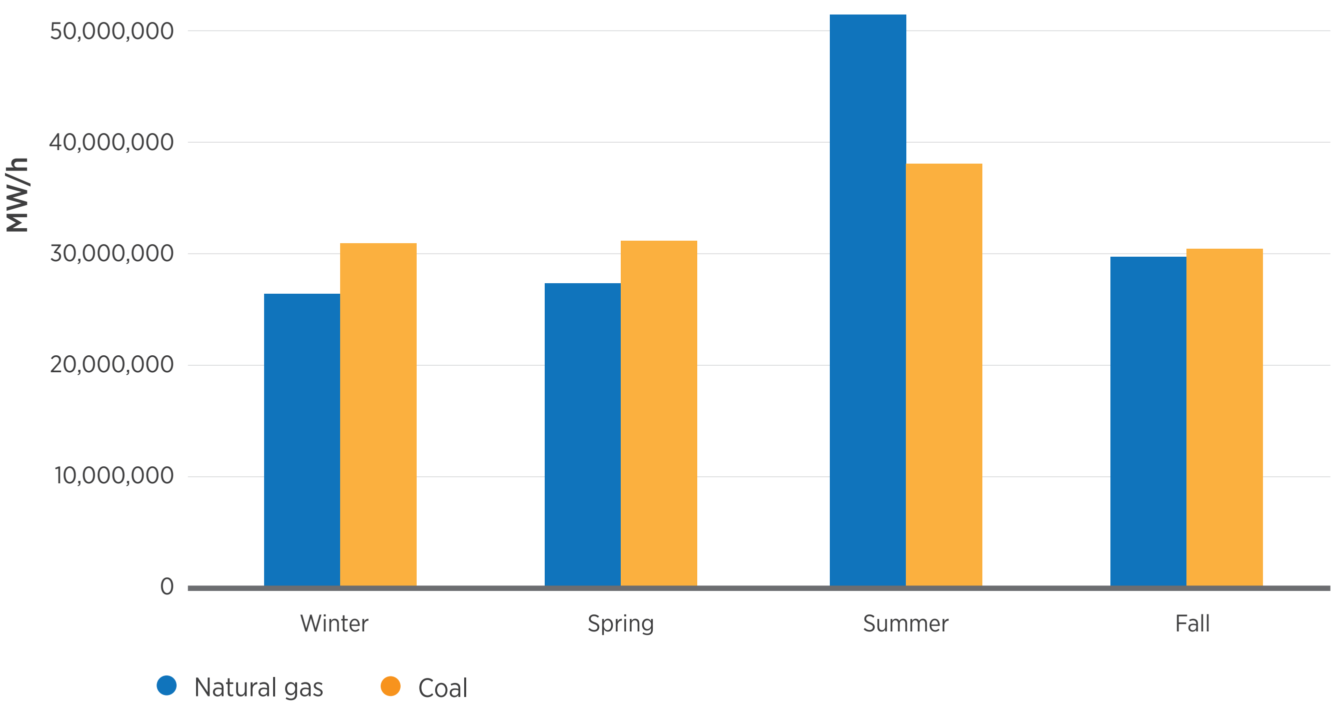
Figure 7.11 | Site prioritization of CO_2 delivery to algae cultivation sites





Source: Pacific Northwest National Laboratory.

Figure 7.12 | Example of fuel-specific seasonal power production in the Gulf Coast region; for more northern latitude locations, the winter demand would be higher to meet heating needs



7.5.5 Model Assumptions

The BAT model was run to capture the site-specific biomass production potential, associated CO_2 demand, and pipeline routes under a current technology scenario and a future productivity scenario for algae strains *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water). As with the DOE model harmonization study, a consumptive freshwater use constraint of no more than 5% of mean annual basin flow (cumulative for sites within a watershed) helped determine the number of sites allowed (ANL, NREL, and PNNL 2012). Because saline water resources are more plentiful, they were not constrained by required volume but rather by (1) locations where salinity ranges from 2 to 70 PSU[2] and (2) cultivation sites within 6.2 miles (10 km) proximal distance of acceptable salinity-range groundwater or seawater sources, to account partially for uncertainties in salinity ranges and provide economically viable water transport distances.

A common set of engineering assumptions were established for each CO_2 source and used for all sites in the CONUS based on average productivity values for the two strains and all sites (see section 7.5.1); however, growth rates, biomass production, and CO_2 demand were established as site-specific.

[2] Bartley et al. (2013) found that salinities of 22 PSU to 34 PSU provided the highest growth rates for *Nannochloropsis salina*; however, growth is possible between 8 PSU and 68 PSU. Abu-Rezq et al. (1999) found that ideal salinities for the same strain are between 20 PSU and 40 PSU. While the salinity range of 2 PSU to 70 PSU is broader than the ideal salinity target range for *Nannochloropsis salina*, it represents possible salinities that support growth of a wide range of other saline-based algae strains (Shen et al. 2015, Varshney et al. 2015, Kim, Lee, and Lee 2016). The wide salinity range also captures the uncertainties in the source data and geostatistical processing of saline water resources.

To develop the future production scenarios for *Chlorella sorokiniana*, a selection of the high-producing southeastern United States, Gulf Coast, and Florida sites were scaled from a mean annual productivity of 13.8 g/m^2•day to 25 g/m^2•day, resulting in an ~1.8x scale-up or a 55.2% improvement. This factor was used to scale all CONUS sites, which were then independently evaluated for co-location potential, including available CO_2 supply, required CO_2 demand, and capital expenditure and operating expenditure constraints. The *Nannochloropsis salina* strain performed at a mean annual productivity of 12.8 g/m^2•day, and all CONUS sites were scaled to a 51.2% improvement in productivity or a 1.95x scale-up. For the future high-productivity scenarios, the CO_2 supply is assumed to remain the same as current supply.

- Each co-location scenario is run independently and is not competed to determine the economic tradeoff space. The model operates under numerous other assumptions captured below. Open ponds are operated at a 30 cm depth at an hourly time-step for 30 years.
- The common set of supply engineering designs is established for each of the three categories of waste CO_2 sources based on 1,000 acre pond units (100 ten acre ponds) with a mean annual productivity of 1.25 x 13.2 g/m^2•day. Resulting gas flow rates used in this analysis are documented in table 7.4.
- Algal CO_2 uptake efficiencies are incorporated (not assuming 100% utilization) and are based on site-specific hourly growth model results (see Eq. [1]).
- If stationary waste-stream CO_2 sources are known to already be used for another purpose (e.g., carbon capture and storage, industrial gas supply, food industry, enhanced oil recovery), these sites are not included in this analysis.
- CO_2 is not assumed to be recycled (i.e., anaerobic digestion), thereby keeping this analysis agnostic to downstream processing pathways.
- The model for biomass production and CO_2 demand assumes 330 days of operation.
- CO_2 is used only during the daylight hours (average 12 hours assumed) when algae have active photosynthesis.
- Total CO_2 availability is constrained by the source operations and relationship to daylight hours. No specific considerations are made with regard to pH effects on the pond as result of CO_2 supply; the pH of the media is assumed to be constant where a balance of CO_2 supply is maintained according to biomass growth demand.
- Future high-productivity scenarios assume no change in the available CO_2 supply from the current scenario.
- Commercial CO_2 can be delivered at $40 per dry ton of CO_2; therefore, once this cost is exceeded for a unit farm, co-located CO_2 is no longer provided, even if there is available supply. (In Davis et al. (2016), this cost is $41 per dry ton in 2011 dollars.)
- Data from the NATCARB database provide total CO_2 emissions and do not distinguish between sites with multiple sources and purities of CO_2. We assume one source and purity as documented.
- Freshwater *Chlorella sorokiniana* strain model parameters are available in appendix D, table D.1.
- Saline *Nannochloropsis salina* strain model parameters are available in appendix D, table D.1.

7.5.6 Cost of Production: Economic Assumptions

Supply curves express price or cost per ton vs. cumulative supply of feedstock. The definition of a supply curve is described more fully in chapter 1. Costs of biomass are averaged at the county level. The minimum selling prices in this chapter assume a 10% internal rate of return.

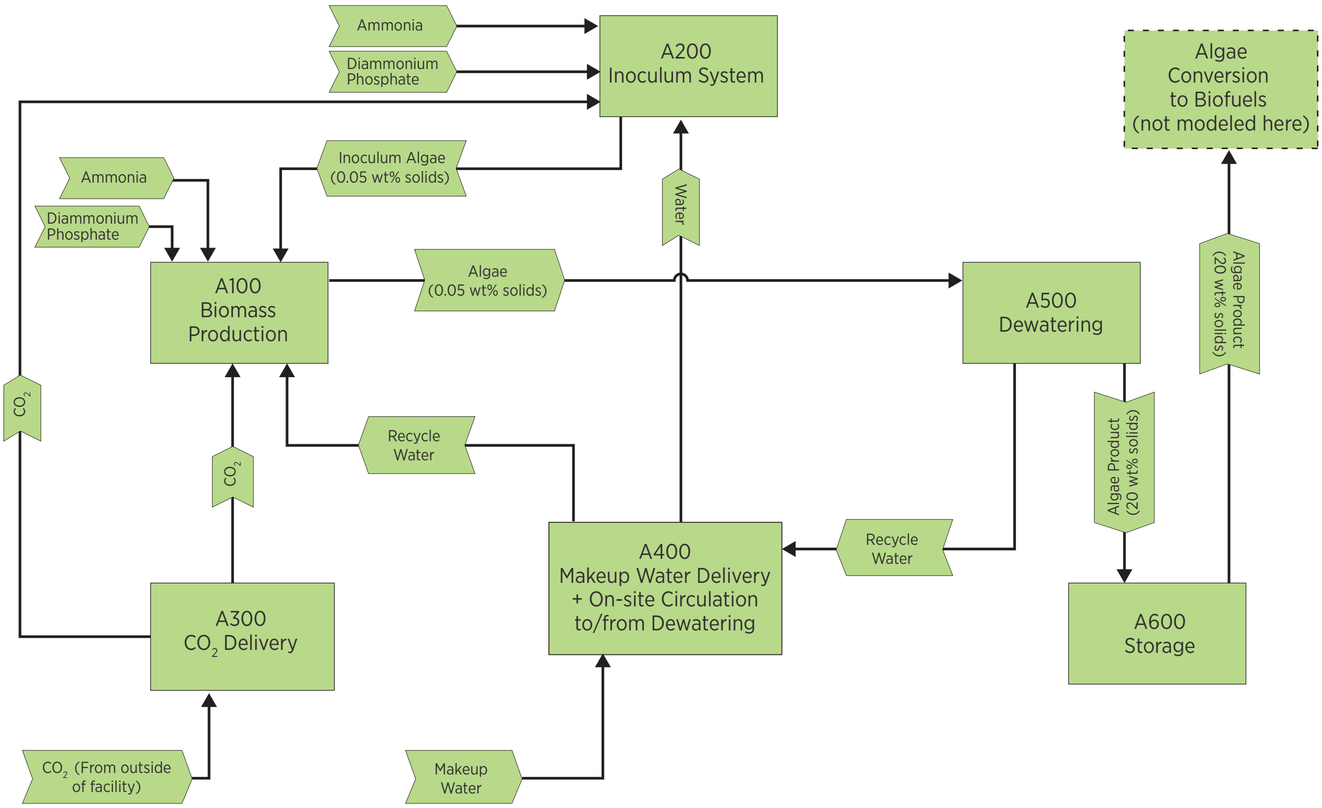
The basis for the cost assumptions for algae production is the NREL report *Process Design and Eco-*

nomics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion (Davis et al. 2016). That report describes minimum biomass selling prices of $452–$545 per dry ton AFDW[3] (an average $491 per dry ton) for facilities with 10 acre pond designs that are generally consistent with assumptions in the BAT model. The basic design is depicted in figure 7.13.

The major contributors to the minimum biomass selling price of $491 per dry ton AFDW in the Davis et al. (2016) base case are $278 per dry ton for cultivation costs other than nutrients, $112 per dry ton for nutrients including CO_2, and $101 for dewatering and other costs. Based on additional analyses of capital and operational expenses, NREL has determined that $491 in 2011 dollars is equivalent to $494 in 2014 dollars. These costs assume a freshwater open pond/raceway cultivation system that has average costs of four pond designs and, unlike the strains assumed in this analysis, they project productivities for *Scenedesmus acutus (LRB-AP 0401)*.

This chapter uses a biomass product endpoint of 20% solids by weight, consistent with the assumptions in Davis et al. (2016). They assume in-ground gravity settlers, followed by hollow fiber membranes and centrifugation to concentrate (dewater) the harvested biomass; yet, they note that the dewatering perfor-

Figure 7.13 | Simplified flow diagram of the algae production process assumed in cost estimates



Source: Modified from Davis et al. (2016) figure 3.

[3] Dry tons throughout the chapter are equivalent to AFDW.

Table 7.5 | Assumptions Contributing to Current and Future Estimates of Algae Biomass Costs and Production Potential That Are Derived From Davis et al. (2016)

Topic	Assumption in Davis et al. (2016)	Change needed for current case	Change needed for future case
Facility size, cultivation area	500 ten-acre cultivation ponds per facility	100 ten-acre cultivation ponds per facility; $102 per dry ton added based on economy of scale losses in Davis et al. (2016)	100 ten-acre cultivation ponds per facility; $102 per dry ton added based on economy-of-scale losses in Davis et al. (2016)
Algae strain	Mid-harvest, high-carbohydrate *Scenedesmus acutus*	Used BAT-modeled productivities for *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water); costs from base case in Davis et al. (2016 are adjusted upward by $3/ton for *Chlorella* and $35/ton for *Nannochloropsis*	BAT-modeled productivities used for *Chlorella sorokiniana* (freshwater) and *Nannochloropsis salina* (saline water); costs from base case in Davis et al. (2016) are adjusted upward by $3/ton for *Chlorella* and $35/ton for *Nannochloropsis*
Algal productivity	Cultivation productivity target of 25 g/m^2•day annual average across varying seasonal rates	Site-specific productivity for biomass growth and CO_2 demand modeled using BAT, whereas 13.2 g/m^2•day annual average is used for source-specific CO_2 transport engineering design; cost per dry ton adjusted based on productivity-price function from data in Davis et al. (2016)	Site-specific productivity for biomass growth and CO_2 demand modeled using scaled BAT results. Scaled using a factor of 1.8X for *Chlorella sorokiniana* and 1.95X for *Nannochloropsis salina* (25 g/m^2•d annual average for Gulf Region); source-specific CO_2 transport engineering design based on 25 g/m^2•day. Cost per dry ton adjusted regionally based on productivity-price function from data in Davis et al. (2016)
Freshwater	Minimal liners cover only 2%–25% of total pond area in four pond designs from which costs are derived	No change	No change
Saline water	No saline case; but costs are estimated for full liners at base case productivity	Estimated costs for both minimal liner and full liner cases used; $32 per dry ton added for blowdown waste disposal (Davis et al. 2016)	Estimated costs for both minimal liner and full liner cases used; $32 added per dry ton for blowdown waste disposal (Davis et al. 2016)

Table 7.5 *(continued)*

Topic	Assumption in Davis et al. (2016)	Change needed for current case	Change needed for future case
CO_2 delivery to facility gate	CO_2 costs estimated at $41/ton CO_2	CO_2 delivery costs estimated at $0/ton purchase price from waste stream, in addition to annualized capital expenses for infrastructure and operational costs for transport to facility gate, depending on transport distance and co-location scenario (i.e., CO_2 purity)	CO_2 delivery costs estimated at $0/ton purchase price from waste stream, in addition to annualized capital expenses for infrastructure and operational costs for transport to facility gate, depending on transport distance and co-location scenario (i.e., CO_2 purity)
Year dollars	2011 dollars	2014 dollars	2014 dollars

mance represents aspirational goals to meet cost targets. Like Davis et al. (2016), we assume that a nutrient recycle credit is applied to the downstream conversion process to reduce final fuel costs, rather than making an assumption about downstream nutrient recycles (based on a specific conversion pathway) to reduce biomass costs up front. We assume the same inoculum technology, water circulation pipelines, and product storage tanks as in Davis et al. (2016), and therefore, the same cost contributions to the total cost. And as in Davis et al. (2016), biomass is harvested and processed through three dewatering steps—gravity settling, hollow fiber membranes, and centrifugation—to concentrate the biomass from 0.5 g/L (0.05 wt % AFDW) to 200 g/L (20 wt %) in the product stream. Similarly, the same equity financing, depreciation, corporate tax, and working capital assumptions are used, as well as construction-time and start-up–time assumptions. Costs of conversion and refining of fuel are not included.

Some differences between the assumptions in this chapter and those in Davis et al. (2016) affect the cost per ton of algae biomass for the current or future cases. These differences are summarized in table 7.5. Some of the differences—for example, productivity estimates—relate to the different purposes of this chapter, one of which is to estimate current biomass potential, compared with that of the cultivation design case report, which is to describe "aspirational" targets in the future. For the current case, we assume lower site productivities than the target in Davis et al. (2016).

The economy of scale affects cost estimates. For example, dewatering equipment is more costly at the 1,000 acre pond scale than at the 5,000 acre pond scale assumed in Davis et al. (2016) (table 7.5). Also, pipeline circulation, storage, and labor and fixed operating costs are affected by the scale.

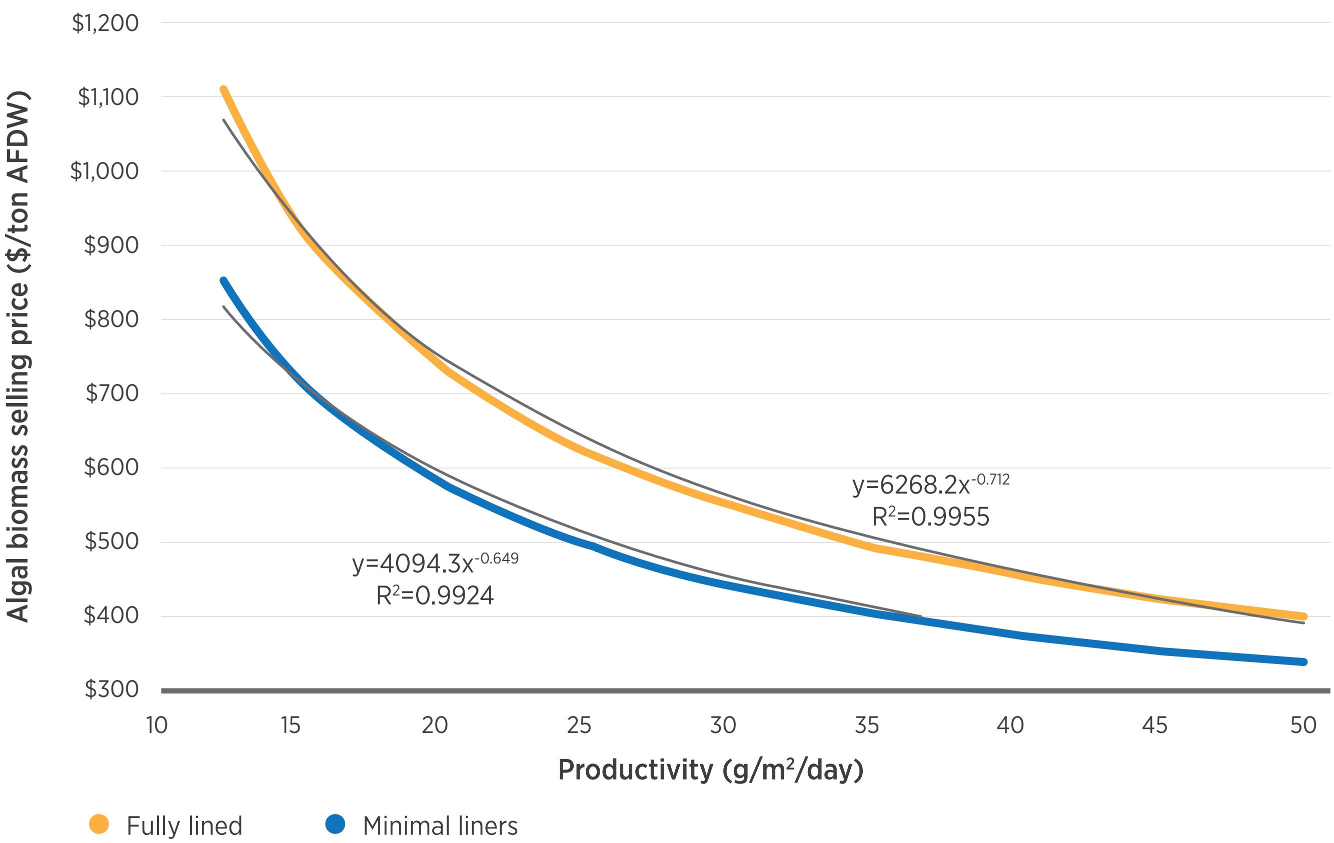
The use of saline water affects cost estimates. We consider a scenario that assumes that ponds must be lined if saline water is used. However, we recognize liners are not a requirement for every locale (see Open-Pond Production System in section 7.3.2), so we also consider a scenario wherein ponds are minimally lined, as with freshwater. Moreover, disposal costs cannot be assumed to be negligible for saline ponds and generally vary between those for injection wells and for ocean disposal. We make the more conservative assumption of the use of injection wells for all saline scenarios.

We estimate CO_2 costs in section 7.5.1 based on piping and compression needed for co-location scenarios. We replace the \$41/ton CO_2 cost for delivery to the facility gate from Davis et al. (2016) with values specific to co-location technology and distance.

An important assumption in Davis et al. (2016) is the "*n*th plant economics" stipulation, which assumes that a number of facilities using the same technology have been built and are operating, rather than assuming that a cultivation system or drying plant is the first of its kind. This avoids artificially inflating costs based on risk financing (which would require a higher than 10% initial rate of return), equipment over-design, process downtime, and so on. We use a 10% discount rate to be consistent with costs estimated in Davis et al. (2016). This rate is higher than the 6.5% that is assumed elsewhere in this report.

The association between minimum selling price per ton of biomass and productivity is generated based on figure 7.14. A power curve is used to fit the price-productivity data from Davis et al. (2016), with both minimal and full pond liners.

Figure 7.14 | Minimum biomass selling price per ton of biomass vs. productivity for the base case (minimally lined ponds) as presented in Davis et al. (2016) (blue) and with costs for fully lined ponds added as an option for Nannochloropsis salina (red). Model outputs are fit to power curves (thin black lines); the data are in 2011 dollars



Thus, the costs of biomass are estimated by the following equations, which adjust costs from the base case in Davis et al. (2016).

Freshwater: (2)

$$Y = (1+I)[(4094.3(X^{-0.649}) + E - B + C)] + FT \, .$$

Saline—minimally lined: (3)

$$Y = (1+I)[(4094.3(X^{-0.649}) + E - B + N + D)] + FT \, .$$

Saline—fully lined: (4)

$$Y = (1+I)[(6268.2(X^{-0.712}) + E - B + N + D)] + FT \, .$$

Where

C = cost per ton of biomass

I = inflation rate converting 2011 to 2014 dollars (1.006, cost index factor based on unpublished data from NREL and % allocation between capital and operating expenses)

X = average annual biomass productivity, $g/m^2 \bullet d$

E = economy-of-scale dollar loss for difference between 5,000 and 1,000 acres (102)

B = cost of CO_2 per ton of biomass in Davis et al. (2016) base case (91)

F = ton CO_2/ton biomass (2.2)[4]

T = cost per ton of co-located CO_2 in 2014 dollars

D = cost of blowdown disposal per ton of biomass for saline case in 2011 dollars (32)

C = additional cost for using *Chlorella* instead of *Scenedesmus* (3)

N = additional cost for using *Nannochloropsis* (with additional ash content and different nutrient content) instead of *Scenedesmus* (35)

7.6 Results

7.6.1 Cost-Effective Distance for Co-Location

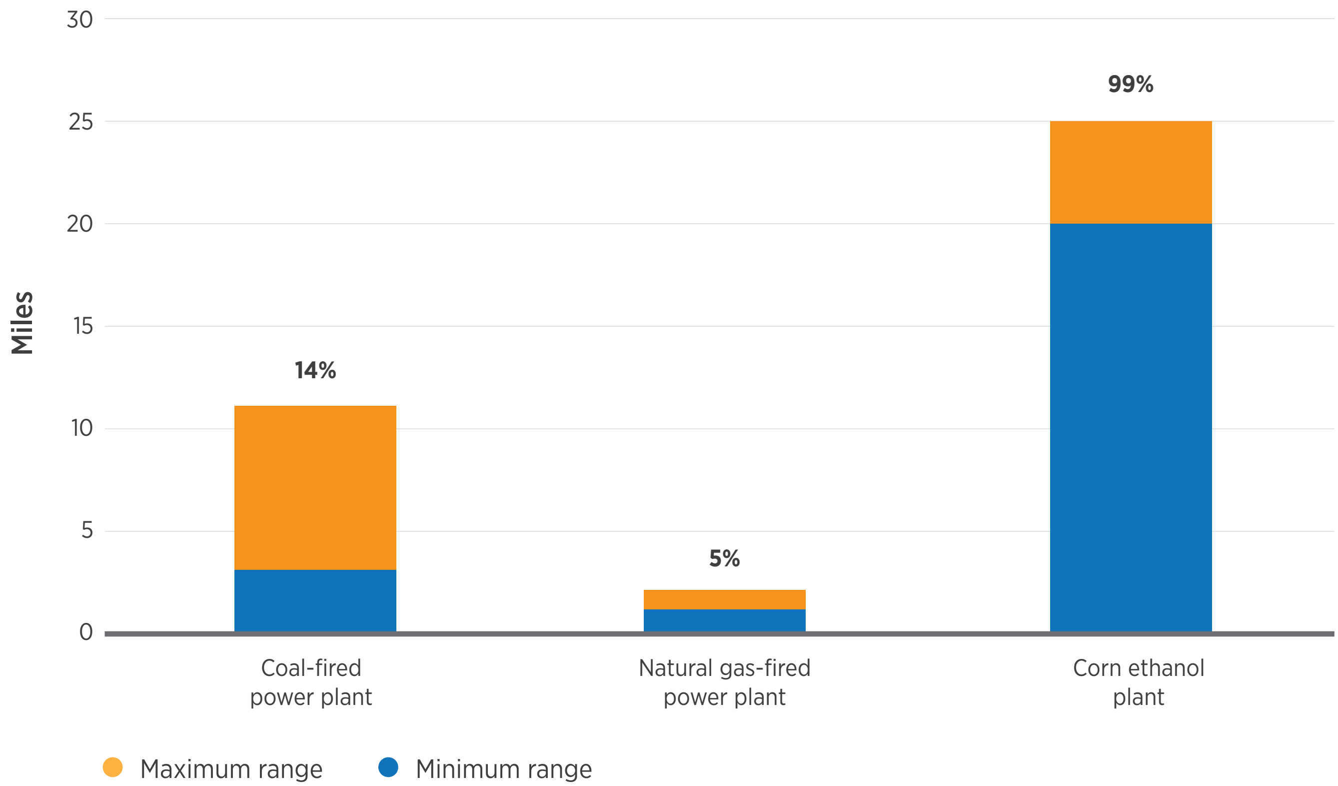
Table 7.6 presents results for cost-effective distance for co-location of CO_2 with algae cultivation. The range of costs includes system designs that minimize capital cost and system designs that minimize operating electricity for the compressors. Clearly, pure CO_2 can be transported cost-effectively for longer distances than EGU flue gases. Increasing the productivity in the future also increases the CO_2 requirements and the pipeline cost, reducing the cost-effective transport distance (relative to commercial CO_2) for all but the ethanol plant as a co-location source. The purity of CO_2 in the flue gas determines the cost-effective distance (fig. 7.15). The cost-effective distance for transporting flue gas from the natural-gas-fired EGU is the lowest.

Table 7.6 | Cost-Effective Distance for Co-Location of CO_2 with Algae Cultivations

CO_2 source	Cost-effective distance	
	Current productivity	Future productivity
Coal-fired EGU	3–11 miles	<5 miles
Natural gas-fired EGU	<1 mile	<0.5 miles
Ethanol plant	>20 miles	>20 miles

[4] Note that this value was used in Davis et al. (2016), so we use it here; but elsewhere in this analysis (i.e., in the BAT analysis), 2.45 is used.

Figure 7.15 | Cost-effective distance for CO_2 transport from co-located source to algae facility



More detailed results are included in appendix D. These costs and distances are incorporated in further analysis using the BAT to show potential savings for co-location in appropriate geographical locations.

7.6.2 Results of Land Suitability Analysis

This suitability analysis identified 74,606 unit farms throughout the CONUS (using assumptions defined in section 7.5.3), totaling approximately 139,886 mi2 (362,304 km2), that are potentially suitable for large-scale open-pond microalgae production (fig. 7.16). The suitable areas are ultimately represented by points that represent each unit farm within a suitable area polygon to enable model functions such as least-cost routing (fig. 7.17), to honor land-use restrictions. A subset of the total unit farm populations was selected based on the potential for co-location with key sources of waste CO_2 streams, as described in Section 7.3. Site selection criteria are identical to those identified in Wigmosta et al. (2011) and ANL, NREL, and PNNL (2012), with the exception that forested lands are also excluded.

7.6.3 Biophysically Based Production Estimates

This section provides BAT model analysis results for site-specific biomass production supported by CO_2-based co-location constrained by available supply and transport economics. In total, 12 scenarios are evaluated. Both current and future productivities are modeled for both *Chlorella sorokiniana* and *Nannochloropsis salina* with consideration of three CO_2 co-location options (i.e., ethanol, coal EGU, natural gas EGU) (scenarios shown in fig. 7.1). The site-specific results are ultimately aggregated to the county scale to estimate minimum selling prices at which the biomass can be obtained.

Figure 7.16 | The results of the BAT land characterization and suitability model resulted in 74,606 suitable “unit farms” (1,200 acres) totaling approximately 139,886 mi^2 (362,304 km^2)

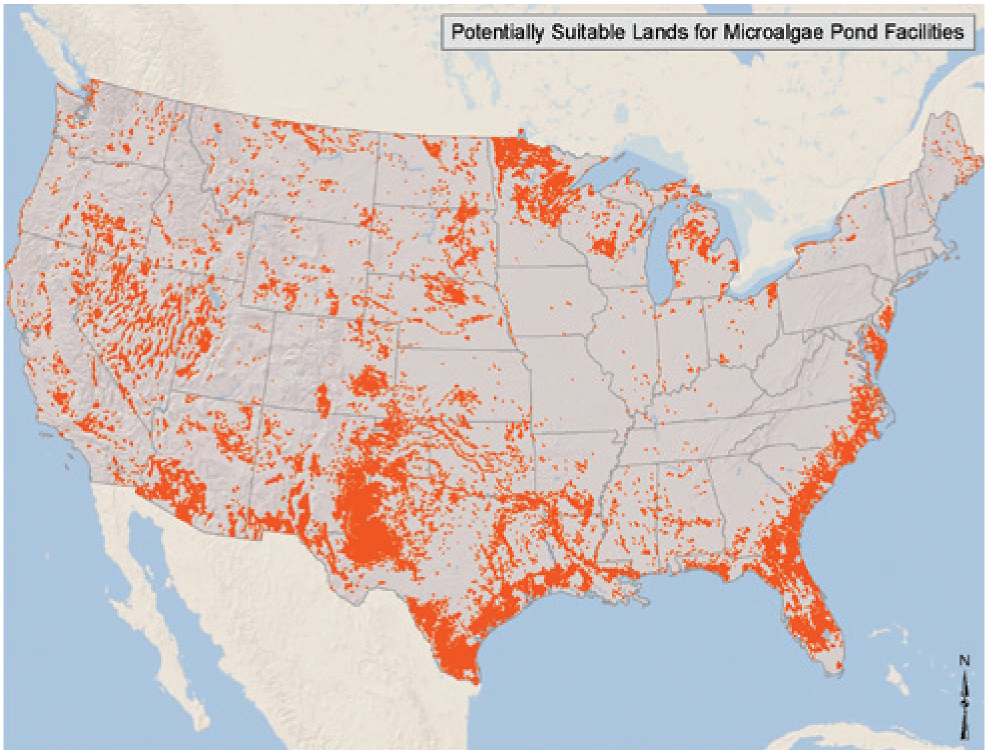
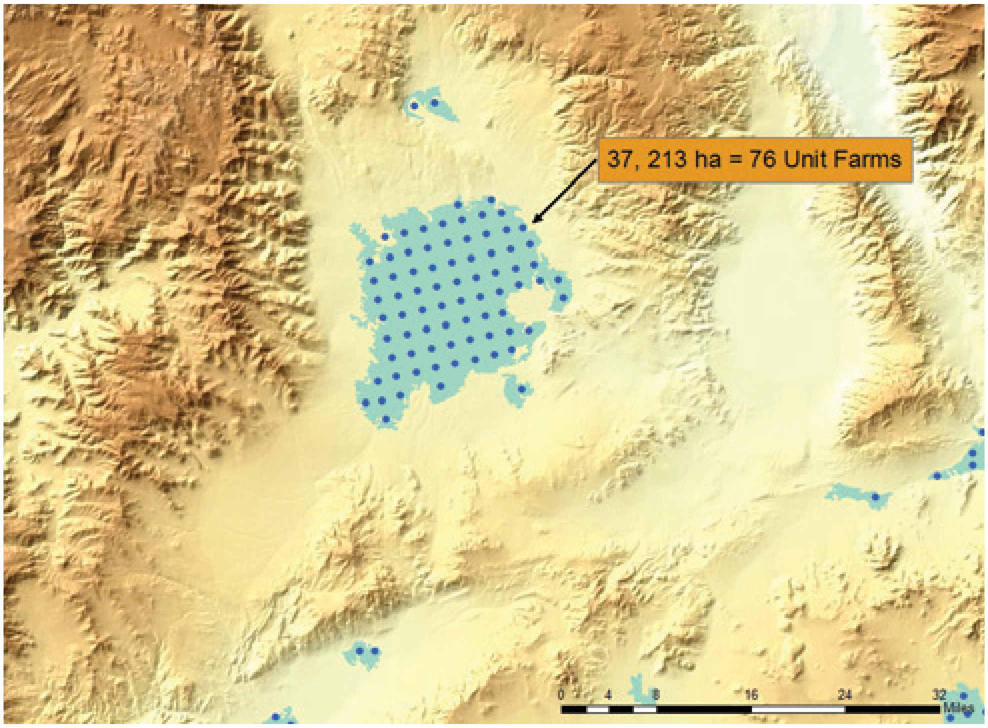


Figure 7.17 | Suitable land areas disaggregated to point-based “unit farms” representing 1,200 acres (1,000 acres of pond area) are used in the scenario modeling



The established scenarios in this chapter are designed to be independent; thus, the resulting biomass produced from *Chlorella sorokiniana* may not be added to the biomass produced from *Nannochloropsis salina*. In addition, results from one waste stream CO_2 type (i.e., ethanol, coal EGU, natural gas EGU) cannot be accurately combined with another. For example, across scenarios, a given production facility may have the opportunity to draw upon multiple sources of waste CO_2 or could grow either a freshwater-based or saline-water-based strain. Future efforts could evaluate economic and sustainability trade-offs between biomass production/strain type and co-located waste resources to identify the ideal combination for an enterprise of production facilities. Summary results of all scenario runs are presented in table 7.7. Additional results for each scenario can be found in appendix D.

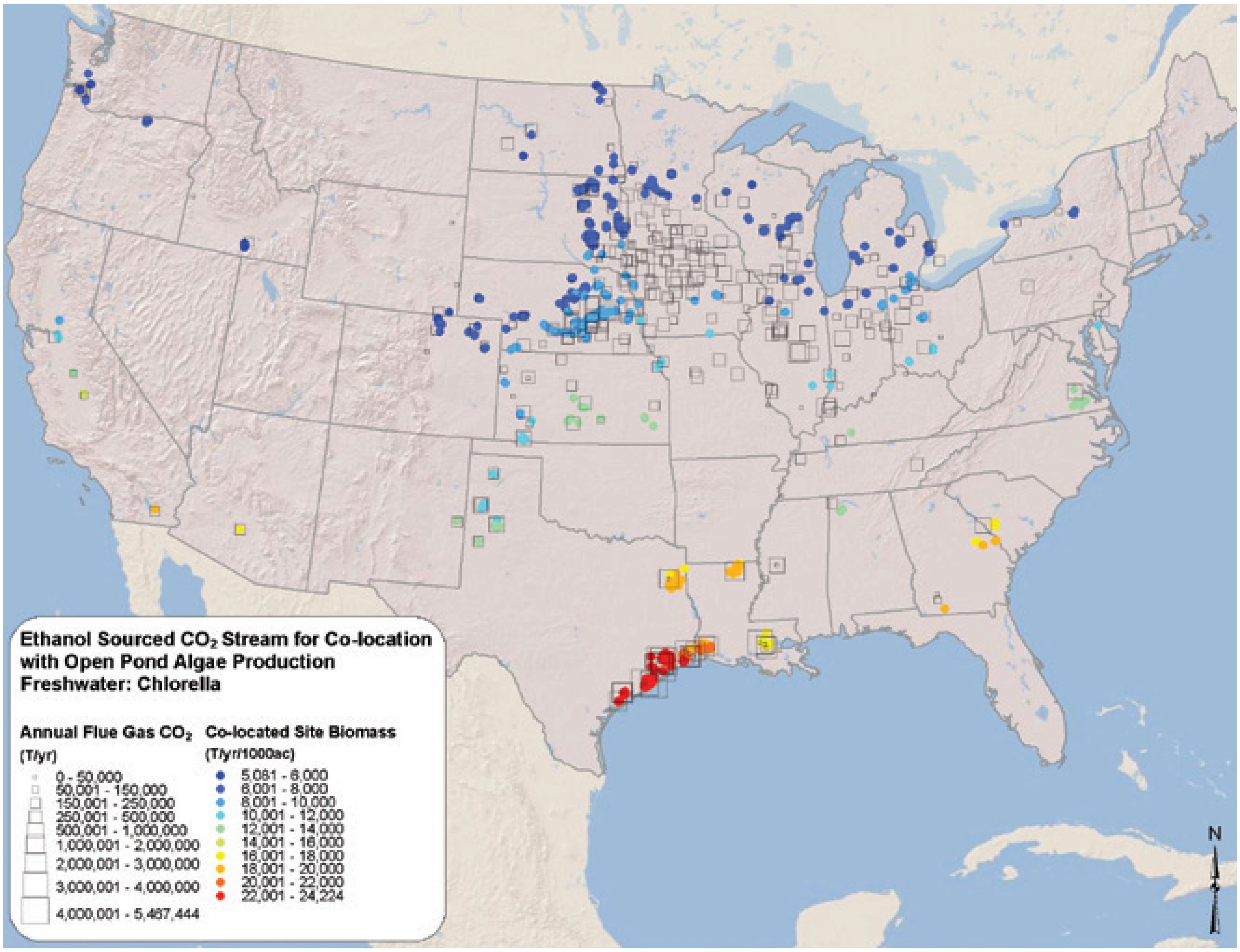
Table 7.7 | Summary Results for Potential Algae Biomass from CO_2 Co-Location with Ethanol Production, Coal EGUs, and Natural Gas EGUs Using *Chlorella sorokiniana* (freshwater) or *Nannochloropsis salina* (saline) Strains Under Current and Future Productivities

	Chlorella sorokiniana			*Nannochloropsis salina*		
	Ethanol production	Coal EGU	Natural gas EGU	Ethanol production	Coal EGU	Natural gas EGU
Current productivity						
Total annual biomass (million tons/year)	11.88	18.54	14.99	10.35	54.40	21.24
Total cultivation area (acres)	904,699	1,256,971	789,610	792,612	3,348,586	1,095,846
Total CO_2 used (million tons/year)	29.21	45.61	36.87	25.45	133.80	52.23
Percent of total CO_2 in CONUS used in co-located algae production	19.3%	1.7%	8.9%	16.8%	4.91%	12.6%
Average distance from CO_2 source to algae facility (miles)	15.2	6.2	4.8	16.0	8.9	6.7
Average cost of co-located CO_2 ($/ton)	$10.67	$19.48	$31.58	$10.92	$21.67	$34.43

Table 7.7 *(continued)*

	Chlorella sorokiniana			*Nannochloropsis salina*		
	Ethanol production	Coal EGU	Natural gas EGU	Ethanol production	Coal EGU	Natural gas EGU
Future productivity						
Total annual biomass (million tons/year)	13.11	10.03	--	11.35	12.35	--
Total cultivation area (acres)	508,393	257,199	--	435,336	299,231	--
Total CO_2 used (million tons/year)	32.24	24.66	--	27.91	30.38	--
Percent of total CO_2 in CONUS used in co-located algae production	21.3%	0.9%	--	18.5%	1.1%	--
Average distance from CO_2 source to algae facility (miles)	14.5	3.8	--	14.6	4.4	--
Average cost of co-located CO_2 ($/ton)	$7.79	$24.04	--	$8.01	$33.43	--

Figure 7.18 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Chlorella sorokiniana*; colored dots represent co-located biomass potential

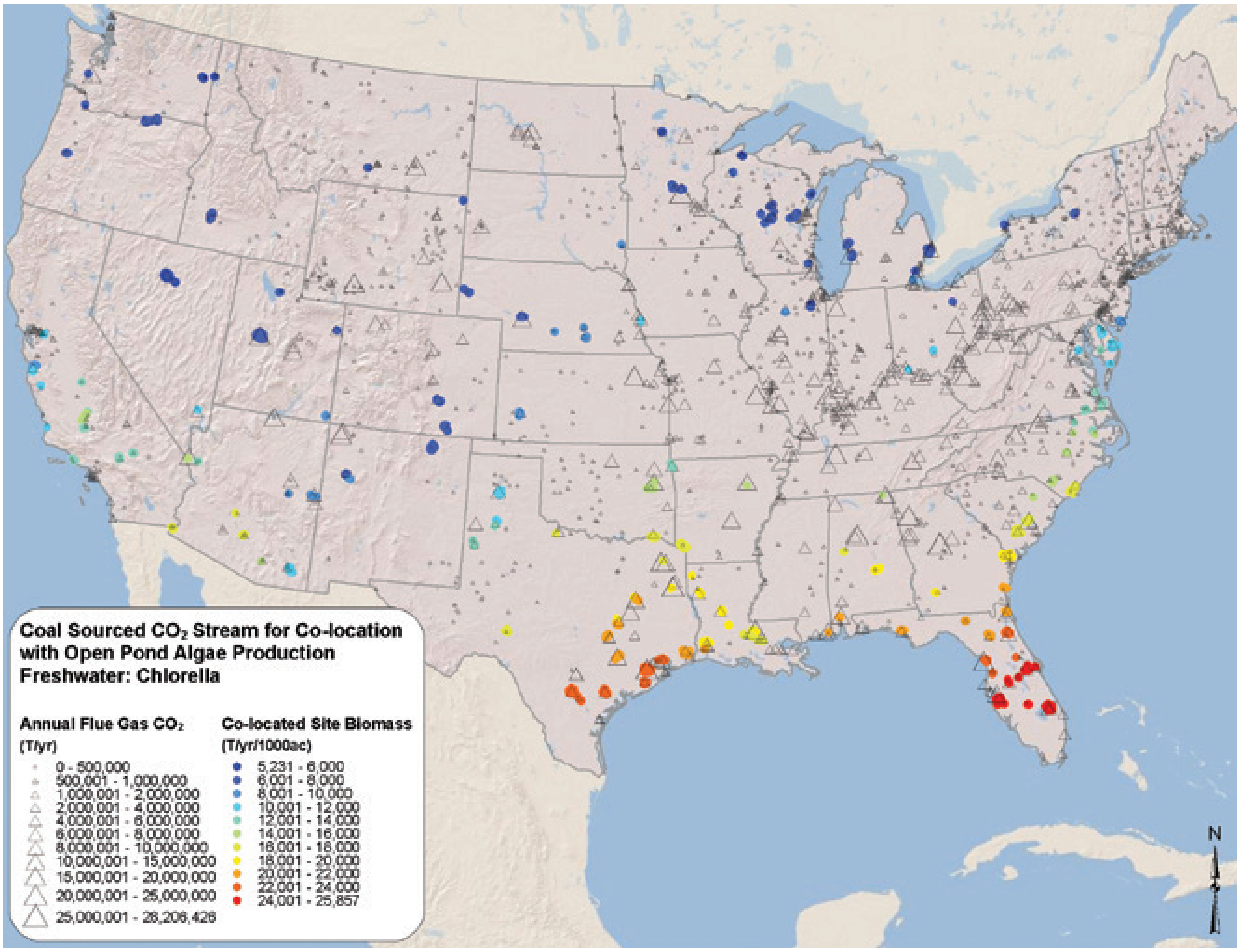


Ethanol Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Current Productivity

CO_2 from a total of 117 of 317 total ethanol production plants (37%) is available for cost-effective co-location with algae production sites under the current-productivity assumptions. A total of 904 unit farm sites make use of 29,209,615 tons/year or 19.3% of the total available CO_2 supply (fig. 7.18).

Collectively, these algae unit farms produce ~12 million tons/year of biomass with CO_2 delivery costs averaging \$10.67/ton of CO_2 (table 7.7). Additional details are available in table 7.E.1. The large majority of ethanol production sites are located in the upper Midwest, where meteorological conditions are not as favorable for algae production as in the southern CONUS. Under a closed-pond or PBR scenario, these northern locations would be more favorable than they are for open-pond algae production.

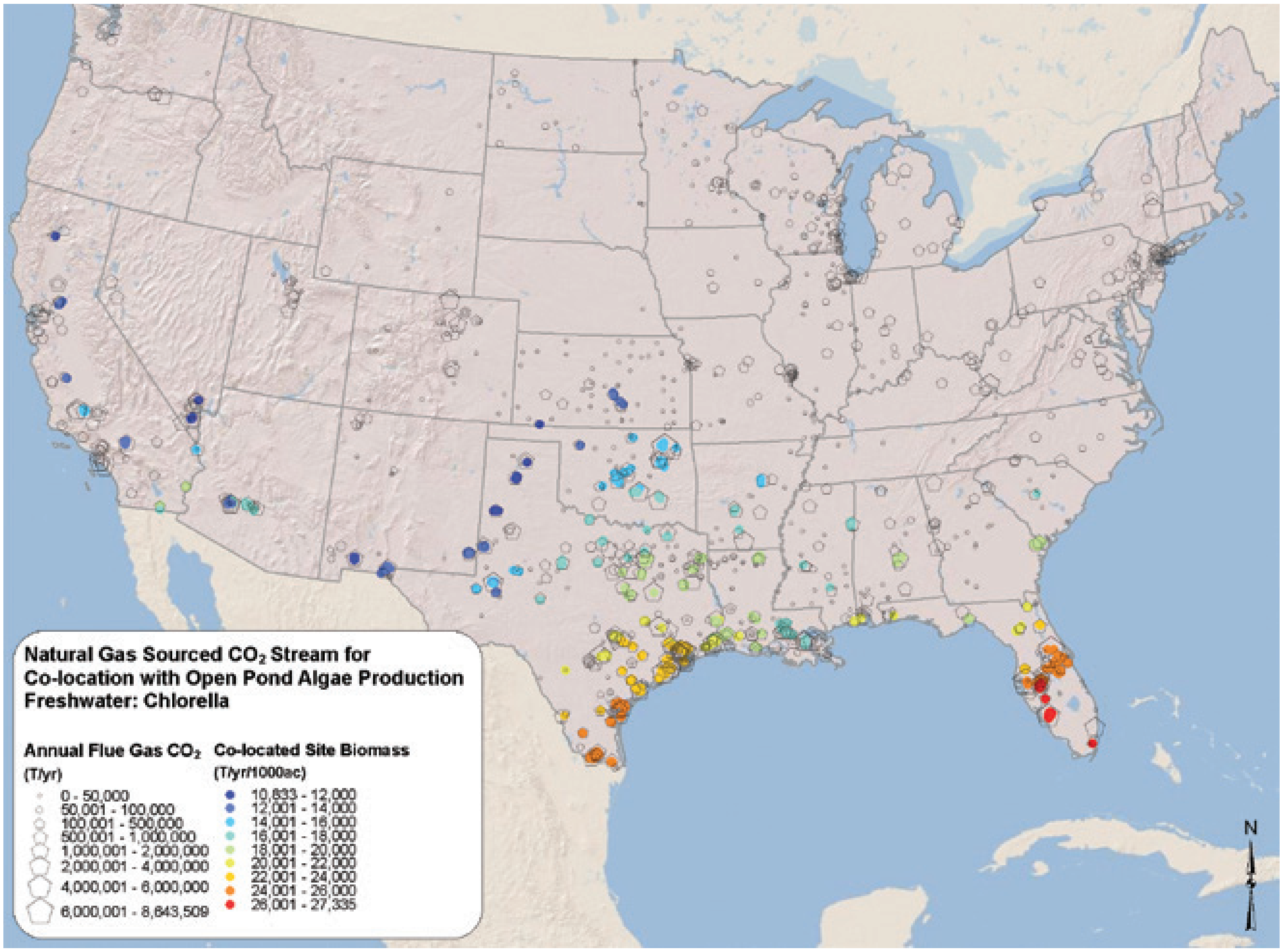
Figure 7.19 | CO_2 co-location opportunity for coal-fired EGUs and algae cultivation using freshwater strain *Chlorella sorokiniana*; colored dots represent co-located biomass potential



Coal EGU Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Current Productivity

CO_2 from a smaller fraction of coal EGUs than ethanol plants is available for cost-effective co-location—189 of 1,339 total power plants (14.1%), under the current assumptions, using only 1.7% (~46 million tons/year) of the total available CO_2 supply (table 7.7). The minimum unit of farm land footprint and general land suitability for algal cultivation facilities are not always well aligned. A total of 1,256 algae cultivation unit farms have potential for cost-effective co-location with the 189 coal EGUs, producing a total annual biomass yield of 18.54 million tons/year (fig. 7.19). Across all sites, CO_2 delivery costs an average \$19.48/ton of CO_2 with an average delivery distance of 6.2 miles (table 7.7). With the large number of coal EGUs in the CONUS, there is a good geographic distribution that can take advantage of more favorable meteorological conditions. The large majority of highly productive co-located plants are found in southeast Texas and Florida and along the eastern seaboard. Additional results are available in table 7.E.2.

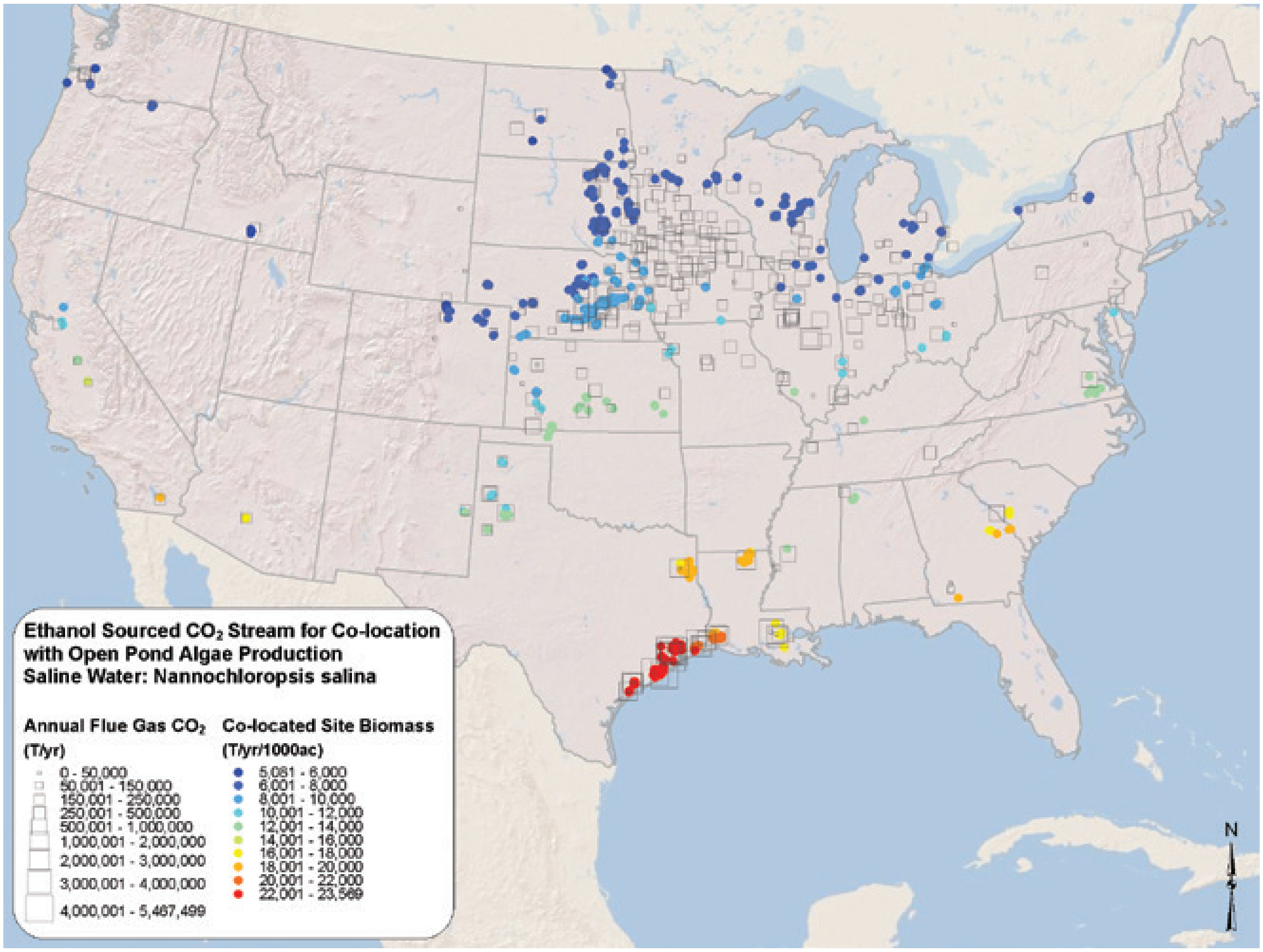
Figure 7.20 | CO_2 co-location opportunity for natural gas EGUs and algae cultivation with *Chlorella sorokiniana*; colored dots represent co-located biomass potential



Natural Gas EGU Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Current Productivity

CO_2 from a total of 176 of 1,132 (15.5%) total natural gas EGUs is available for cost-effective co-location under the current assumptions. This is a small fraction of the number of power plants; and, as with coal EGUs, the minimum unit of farm land footprint and general land suitability for algal cultivation facilities are not always well aligned. A total of 789 unit farm sites make use of ~37 million tons/year or 8.9% of the total available CO_2 supply (fig. 7.20). Collectively, these sites produce ~15 million tons/year of biomass with CO_2 delivery costs averaging $31.58/ton of CO_2 (table 7.7). As expected, as the CO_2 concentration in the flue gas decreases, the cost per ton of CO_2 increases, since much of the piping and energetics are involved primarily in transporting N_2, rather than CO_2. The average transport distance across all sites is 4.8 miles (table 7.7). Additional analysis results are available in table 7.E.3. The large majority of co-located natural gas EGUs are located in areas with favorable meteorological conditions (fig. 7.20), allowing for reasonable biomass production.

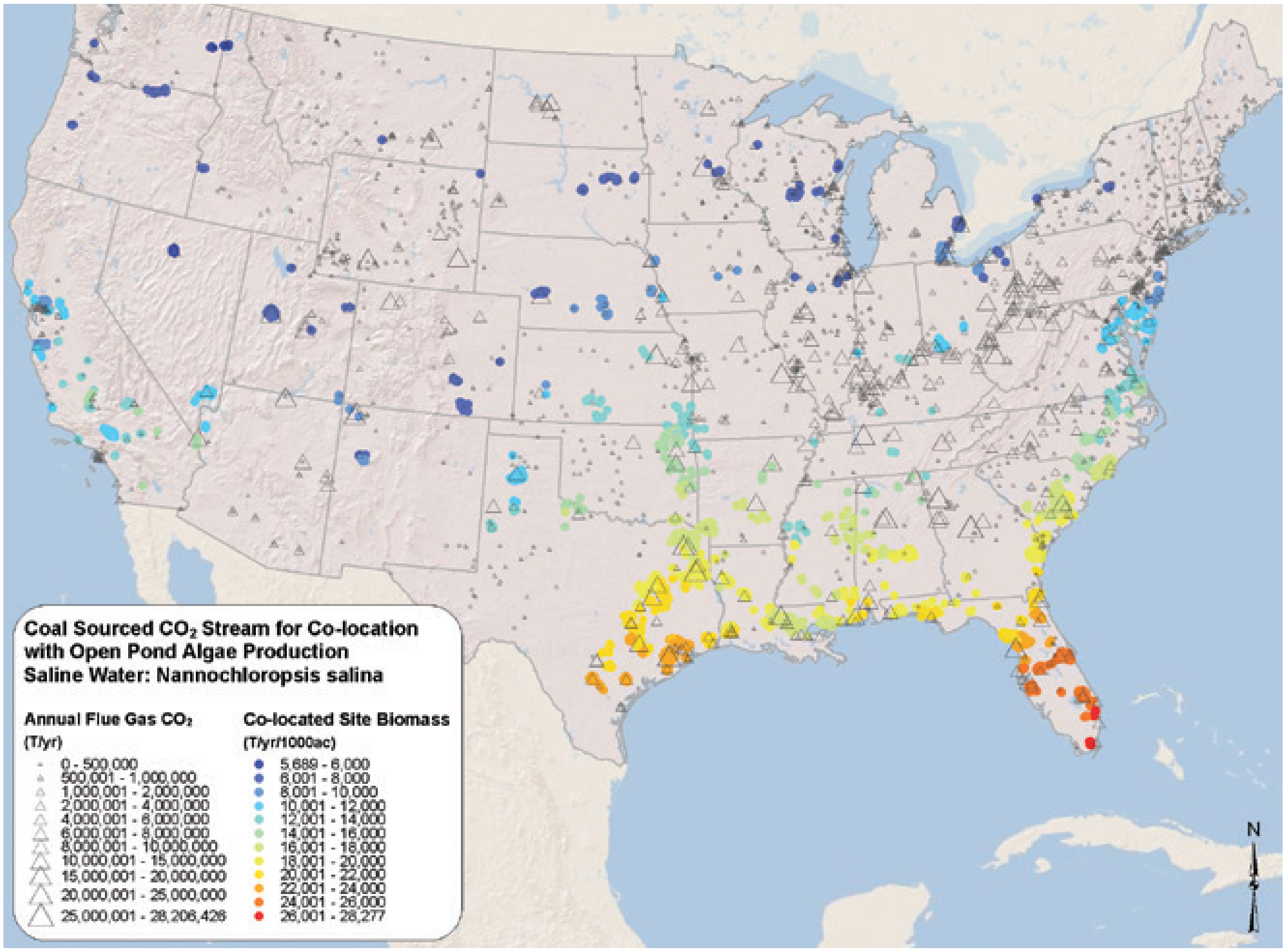
Figure 7.21 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Nannochloropsis salina*; colored dots represent co-located biomass potential



Ethanol Production Plant Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Current Productivity

CO_2 from a total of 134 of 317 ethanol production plants in the CONUS (42%) is available for cost-effective co-location with saline water sources under the current assumptions. A total of 792 unit farms make use of ~25 million tons/year or 16.81% of the total available CO_2 (fig. 7.21). Collectively, these sites produce ~10 million tons/year of biomass with CO_2 delivery costs averaging $10.92/ton of CO_2 (table 7.7). Additional details are available in table 7.E.4. The large majority of ethanol production sites are located in the upper Midwest where meteorological conditions are not as favorable for production as in the southern CONUS. However, the biomass is generated primarily in the southern United States, along the coast of Texas (fig. 7.21).

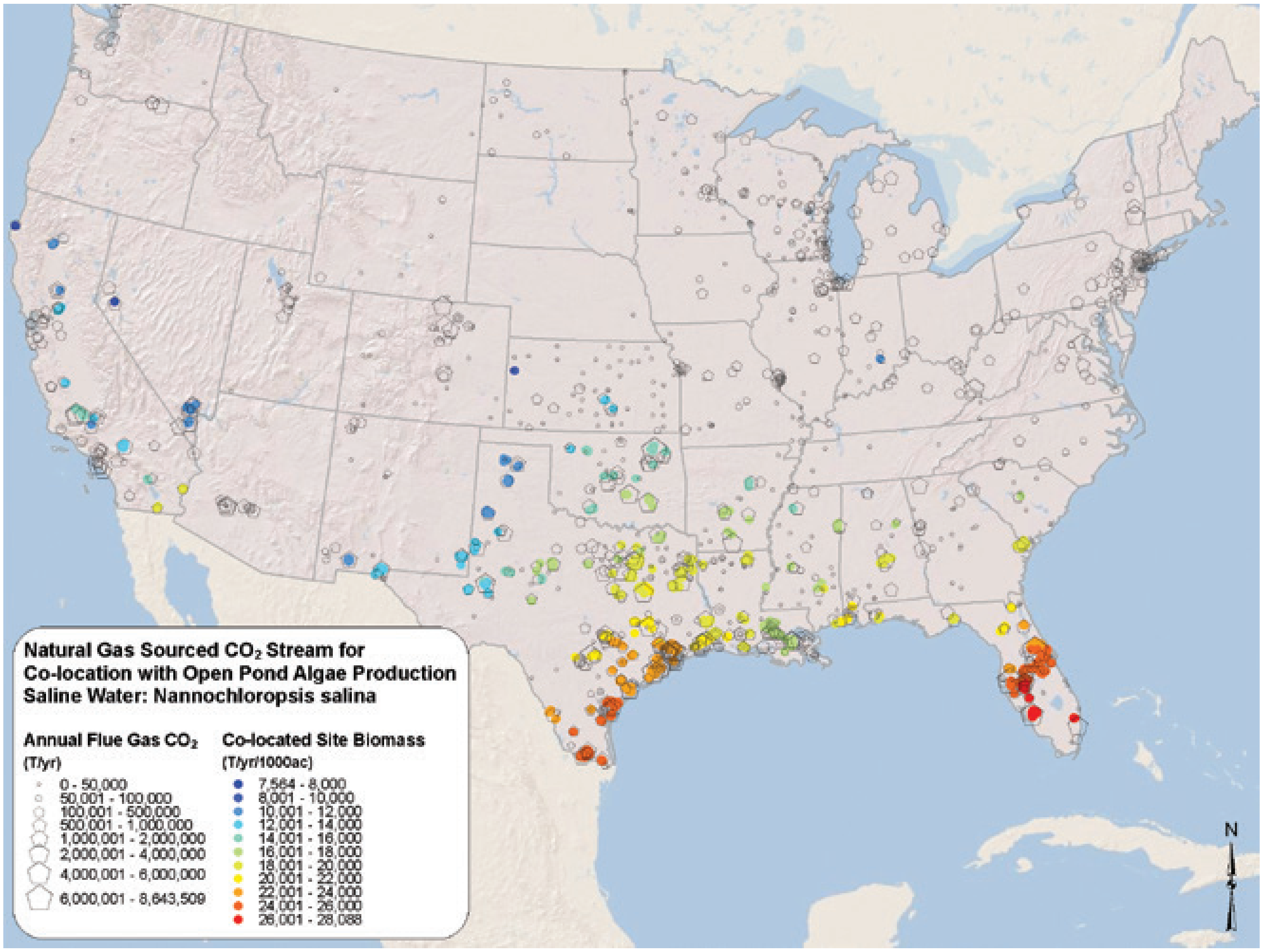
Figure 7.22 | CO_2 co-location opportunity for coal-fired EGUs and algae cultivation with *Nannochloropsis salina*; colored dots represent co-located biomass potential



Coal EGU Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Current Productivity

As with the other coal EGU scenarios, CO_2 from only a small fraction of coal EGU sites is available for cost-effective co-location; however, because of the larger saline water supply, an additional 57 sites (compared with the freshwater, current productivity scenario) are sourced for CO_2, bringing the total to 246 or 18.4% of the total number of EGUs in the CONUS. As a result of the increased number of sources near suitable land, under current assumptions, the total CO_2 supply used increases (compared with freshwater *Chlorella sorokiniana*) by approximately 88 million tons/year under the current assumptions for a total of ~134 million tons/year or 4.9% of the total available supply. The number of algae cultivation unit farms more than doubles (2.6x) with the addition of more coal EGU sources for a total of 3,346 co-located unit farms. These sites produce a total annual biomass of ~54 million tons/year, an increase of 35.8 million tons compared with the freshwater sites (fig. 7.22). Across all sites, CO_2 delivery costs average \$21.67/ton of CO_2 with an average delivery distance of 8.9 miles (table 7.7). Additional results are available in table 7.E.5.

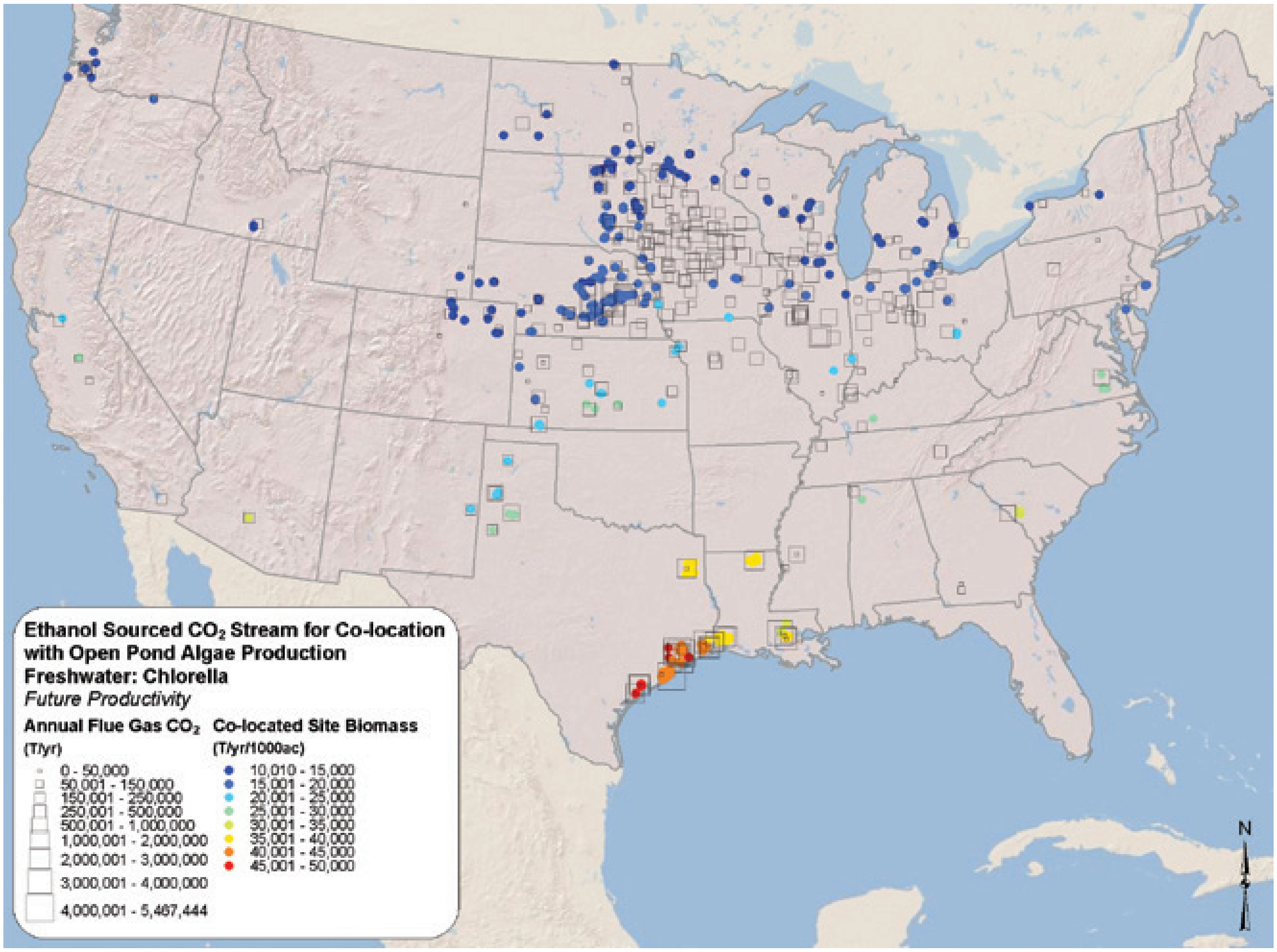
Figure 7.23 | CO_2 co-location opportunity for natural gas–fired EGUs and algae cultivation with *Nannochloropsis salina*; colored dots represent co-located biomass potential



Natural Gas EGU Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Current Productivity

Co-location of algae facilities with 151 out of 1,132 natural gas EGUs (13.3%) is established under the current assumptions. This is a small fraction of the total EGUs and CO_2 output available; and as with coal EGUs, the minimum unit of farm land footprint and general land suitability for algal cultivation facilities are not always well aligned. The 1,095 unit farm sites make use of ~52 million tons/year or 12.6% of the total available CO_2 supply (fig. 7.23). These unit farms produce a total of ~21 million tons/year of biomass with CO_2 delivery costs averaging $34.43/ton of CO_2 (table 7.7). The average transport distance between natural gas EGU and algae unit farm across all unit farms is 6.7 miles. Additional results are available in Table 7.E.6. As with other natural gas EGU scenarios, the large majority of co-located sites are in the southern United States and generally have favorable meteorological conditions (fig. 7.23) and relatively high yields.

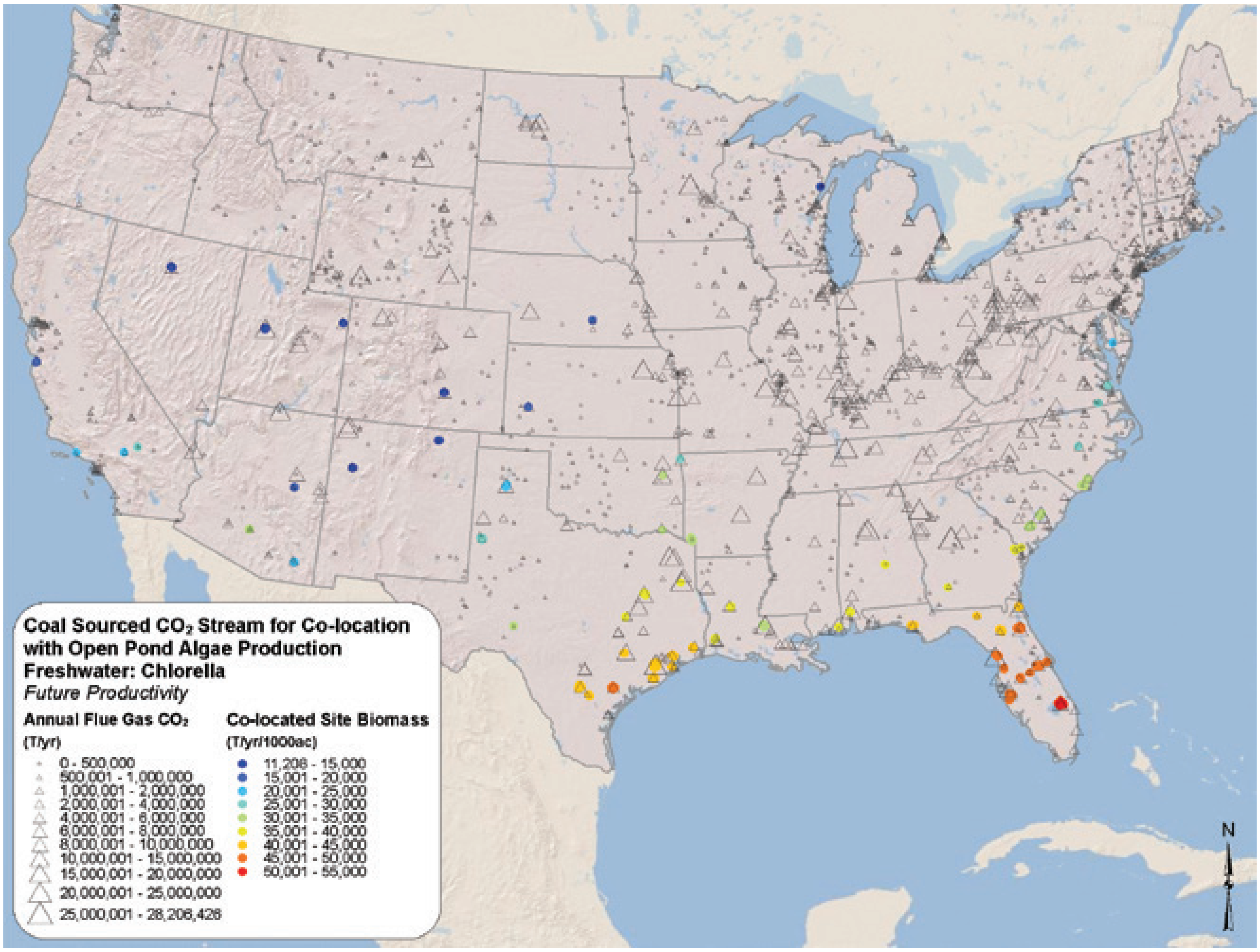
Figure 7.24 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Chlorella sorokiniana* under the future productivity scenario; colored dots represent co-located biomass potential



Ethanol Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Future Productivity

For *Chlorella sorokiniana* under the future high-productivity scenario, CO_2 from a total of 141 of 317 total ethanol production plants (44%) is available for cost-effective co-location under the future productivity assumptions. A projected 508 unit farms make use of ~32 million tons/year or 21.3% of the total available CO_2 supply (fig. 7.24). Collectively, these sites produce ~13 million tons/year of biomass with CO_2 delivery costs averaging \$7.79/ton of CO_2 (table 7.7). Additional details are available in table 7.E.7. Although the mean annual productivity doubles, the number of unit farms that could use a cost-effective CO_2 co-location supply to support the productivity shrinks by nearly 400. However, the overall produced-biomass productivity is higher by nearly 1.2 million tons, and CO_2 streams from additional 23 ethanol plants are used.

Figure 7.25 | CO_2 co-location opportunity for coal EGUs and algae cultivation with *Chlorella sorokiniana* under the future productivity scenario; colored dots represent co-located biomass potential



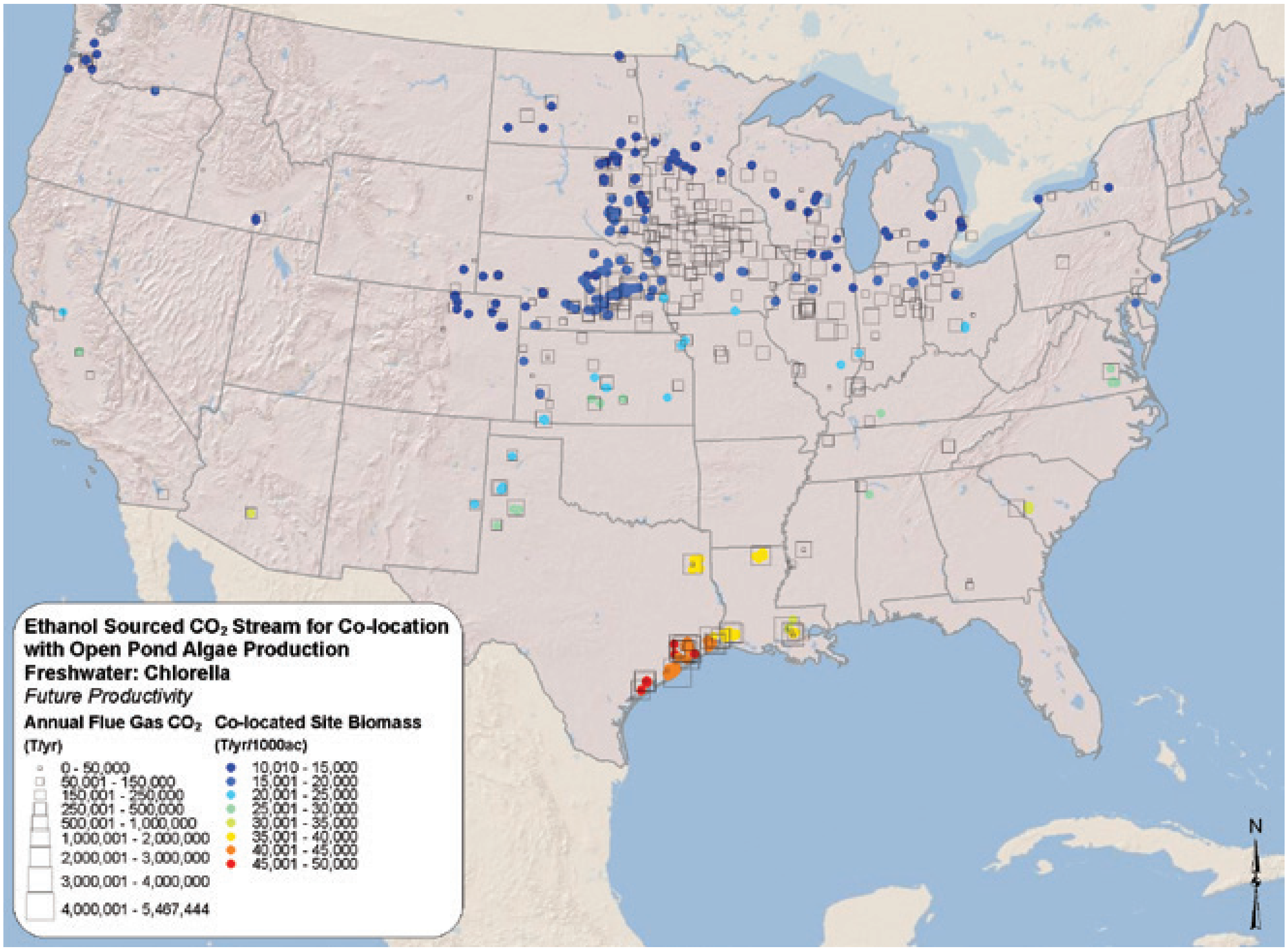
Coal EGU Co-Location—Freshwater Open-Pond Scenario (*Chlorella sorokiniana*): Future Productivity

Of the available coal EGU sites in the CONUS, a small total of 68 of 1,339 plants (5.1%) are co-located with algae production under the future productivity assumptions, using only 0.91% (~25 million tons/year) of the total available CO_2 supply. A projected 257 algae unit farms receive the co-located CO_2 supply, producing a total annual biomass of ~10 million tons/year (fig. 7.25). Across all sites, CO_2 delivery costs average \$24.04/ton of CO_2 with an average delivery distance of 3.8 miles (table 7.7). With the large number of coal EGUs in the CONUS, there is a good geographic distribution that can take advantage of more favorable meteorological conditions. The majority of co-located high-yield cultivation sites are found in the Gulf States. Additional results are available in table 7.E.8.

Natural Gas Production Plant Co-Location—Freshwater Open-Pond Scenario (*Chlorella sorokiniana*): Future Productivity

The operating expenditure costs of operating eight parallel pipelines for the low-CO_2-concentration flue gas from natural gas EGUs cannot economically compete with CO_2 at \$40/ton; therefore, no sites are selected.

Figure 7.26 | CO_2 co-location opportunity for ethanol production and algae cultivation with *Nannocloropsis salina* under the future productivity scenario; colored dots represent co-located biomass potential



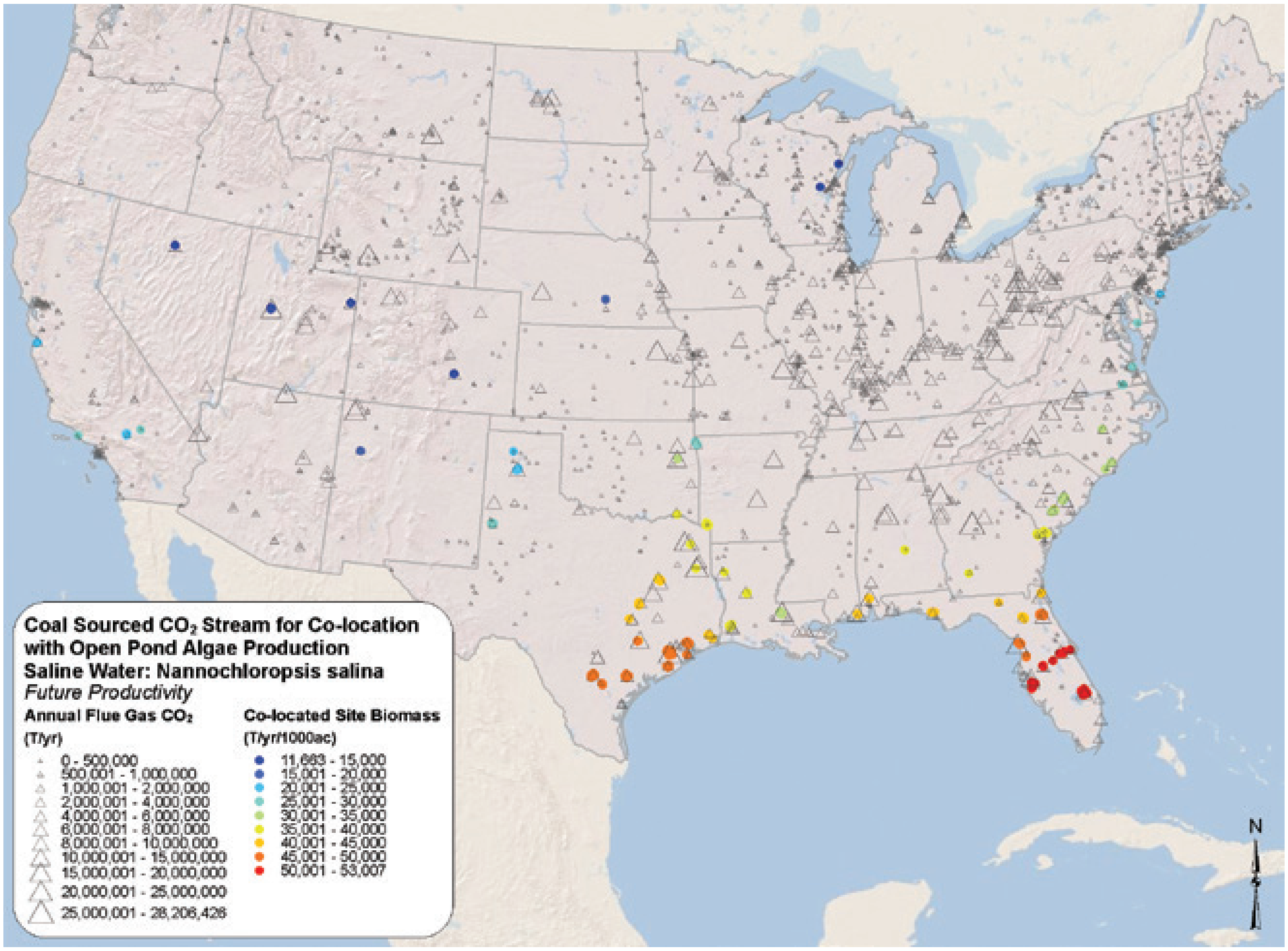
Ethanol Production Plant Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Future Productivity

Under the future high-productivity scenario using the *Nannochloropsis salina* strain, CO_2 from 127 of 317 (40.1%) of CONUS-based ethanol production plants is available for cost-effective co-location. A projected 435 unit farms use ~28 million tons/year or 18.45% of the total available CO_2 supply (fig. 7.26). Collectively, these cultivation sites produce ~11 million tons/year of biomass with CO_2 delivery costs averaging $8.01/ton of CO_2 (table 7.7). Additional details are available in table 7.E.9. The co-located unit farms are predominantly in the upper Midwest; however there is a strong presence of highly productive sites along the Texas Gulf Coast.

Coal EGU Co-Location—Saline Water Open-Pond Scenario (Nannochloropsis salina): Future Productivity

CO_2 from a small fraction of coal EGU sites is available for cost-effective co-location under the *Nannochloropsis salina* future productivity scenario, where CO_2 is used from only 70 of the 1,339 total coal EGUs (5.2%). Under the improved productivity assumptions, the selected algae production sites

Figure 7.27 | CO_2 co-location opportunity for coal EGUs and algae cultivation with *Nannochloropsis salina* under the future productivity scenario; colored dots represent co-located biomass potential



(unit farms) use 1.1% (~30 million tons/year) of the total CONUS-available CO_2 supply. A projected 299 algae unit farms produce a total annual biomass of ~12 million tons/year (fig. 7.27). Across all sites, CO_2 delivery costs average $33.43/ton of CO_2 with an average delivery distance of 4.35 miles (table 7.7). The cost is higher than for the same strain under the current productivity scenario as a result of the increased volumes of CO_2 being moved and consequent higher pipeline costs. The dominant majority of co-located coal EGU sites are located in the southeastern United States, where favorable productivities are observed. Additional results are available in table 7.E.10.

Natural Gas Production Plant Co-Location—Freshwater Open-Pond Scenario (Chlorella sorokiniana): Future Productivity

The operating expenditure costs of operating eight parallel pipelines for the low CO_2 concentration flue gas from natural gas EGUs could not economically compete with CO_2 available at $40/ton; therefore, no biomass is available from algae unit farms co-located with natural gas plants at high future productivities. This finding would not necessarily hold if CO_2 were stored at night or if natural gas plants were built in new locations.

7.6.4 Economic Availability: National Supply Curves

The unit farm location and BAT yield results, as well as co-location savings that are outputs of the BAT model, are used, along with the equations presented in section 7.5.6, to develop cost-biomass supply relationships at the county level. The variables include three co-location scenarios (coal EGUs, natural gas EGUs, and ethanol plants), freshwater and saline water, full liners and minimal liners for saline scenarios, and current and future productivities.

Table 7.8 shows the range of minimum selling prices per dry ton for co-located algae biomass potential. The lowest price per ton of biomass is for future productivity of *Chlorella sorokiniana* under the ethanol co-location scenario. The median of the minimum selling price for each scenario is much closer to the lowest minimum selling price of biomass than to the highest minimum selling price of biomass.

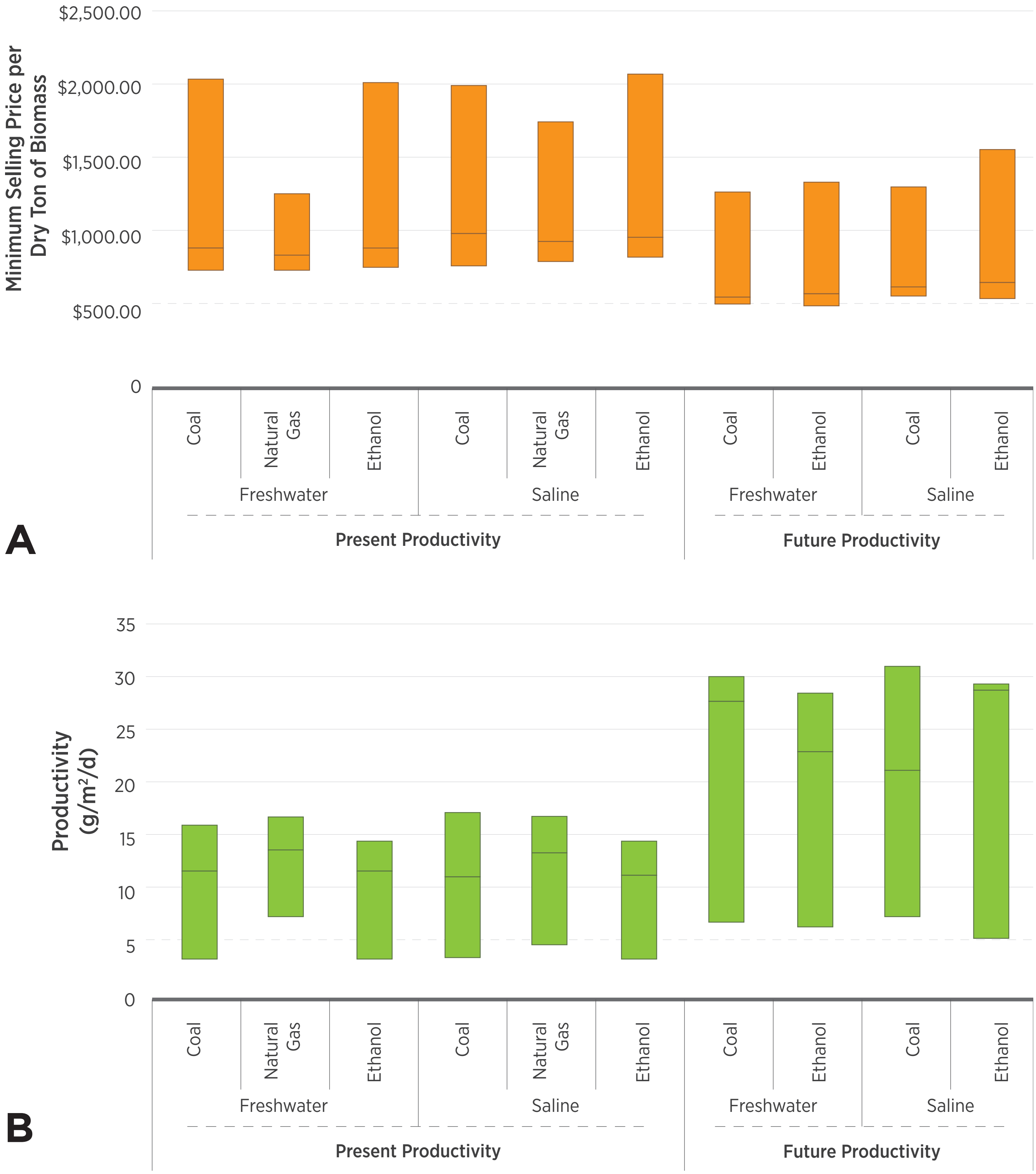
Figure 7.28*A* depicts the minimum selling prices at which biomass becomes available for the different scenarios. Clearly, biomass is available at lower prices in the future productivity scenarios. Figure 7.28*B* shows the productivities associated with the costs in figure 7.28*A*. Costs are lower at higher productivities. Productivities associated with minimum, maximum, and median costs per ton, as well as the Federal Information Processing Standard codes for the counties in which the productivities are observed, are presented in appendix D. On the following pages, we provide examples of price-supply curves for algal biomass.

Table 7.8 | Minimum Selling Prices of Algae Biomass Produced Using Co-Located CO_2 (\$/ton biomass) for *Chlorella sorokiniana* (example freshwater strain) and *Nannochloropsis salina* (example saline strain)

Scenario (time)	Scenario (culture medium)	Source of CO_2	Minimum	Median[a]	Maximum
Present productivity	Freshwater	Coal	$ 719	$ 881	$ 2,030
		Natural gas	$ 724	$ 829	$ 1,243
		Ethanol	$ 753	$ 871	$ 2,010
	Saline (minimally lined)	Coal	$ 755	$ 977	$ 1,987
		Natural gas	$ 791	$ 913	$ 1,741
		Ethanol	$ 817	$ 949	$ 2,078
	Saline (fully lined)	Coal	$ 936	$ 1,248	$ 2,745
		Natural gas	$ 977	$ 1,148	$ 2,334
		Ethanol	$ 1,032	$ 1,218	$ 2,889
Future productivity	Freshwater	Coal	$ 498	$ 541	$ 1,258
		Ethanol	$ 490	$ 564	$ 1,327
	Saline (minimally lined)	Coal	$ 550	$ 599	$ 1,294
		Ethanol	$ 540	$ 632	$ 1,546
	Saline (fully lined)	Coal	$ 653	$ 709	$ 1,698
		Ethanol	$ 649	$ 764	$ 2,074

[a]The median is the minimum selling price below which half of the biomass would be available.

Figure 7.28 | Minimum, maximum, and median (bottom, top, and middle of bars) of minimum selling prices of algae biomass (*A*) and associated algae productivities (*B*) for algae production facilities co-located with EGUs or ethanol plants. The distribution of productivities is based on the geographic distribution of CO_2 co-location facilities.



Note: The example species modeled for freshwater media is *Chlorella sorokiniana* and for saline water is *Nannochloropsis salina*. The median minimum selling price is the price at which half of the potential biomass is available across the United States.

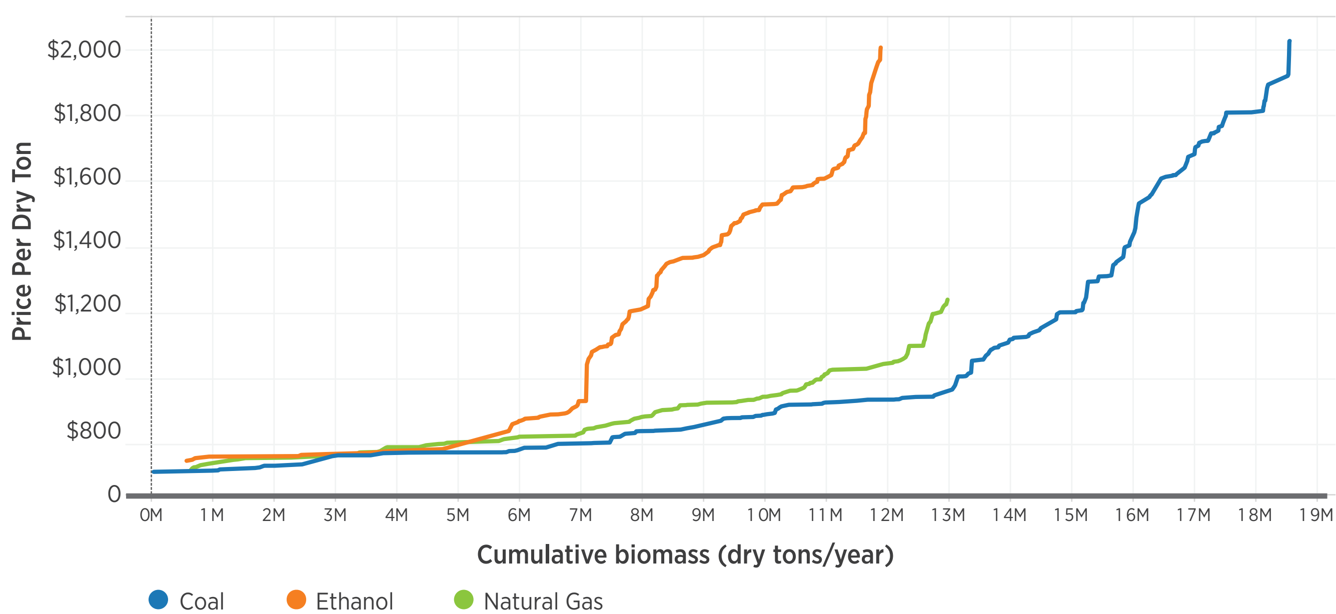
Current Chlorella sorokiniana (Freshwater) Algal Biomass Potential with CO_2 Co-Location

The projected available biomass of *Chlorella sorokiniana* at different minimum selling prices in the United States, assuming current productivities, is depicted in figure 7.29. The data represent algae production facilities co-located with coal EGUs, natural gas EGUs, and ethanol plants. Because simulations of each co-location scenario are run independently, the cumulative biomass supplies will have some uncertainty, as there may be some overlap in locations supplied by each type of CO_2 source.

Figure 7.30*A* depicts the projection of total potential tons of algae biomass by county from freshwater algae production systems in the United States under the current-productivity scenario using the example of coal EGUs as CO_2 sources. Coal EGU-fed production is not distributed randomly across the United States, but rather is clustered along coastlines and waterways and in some southwestern counties. Figure 7.30B depicts the related biomass supply curve of minimum selling price vs. dry tons of algae. The least expensive biomass for *Chlorella* production at present productivities uses CO_2 from the flue gas of coal-fired EGUs (table 7.8).

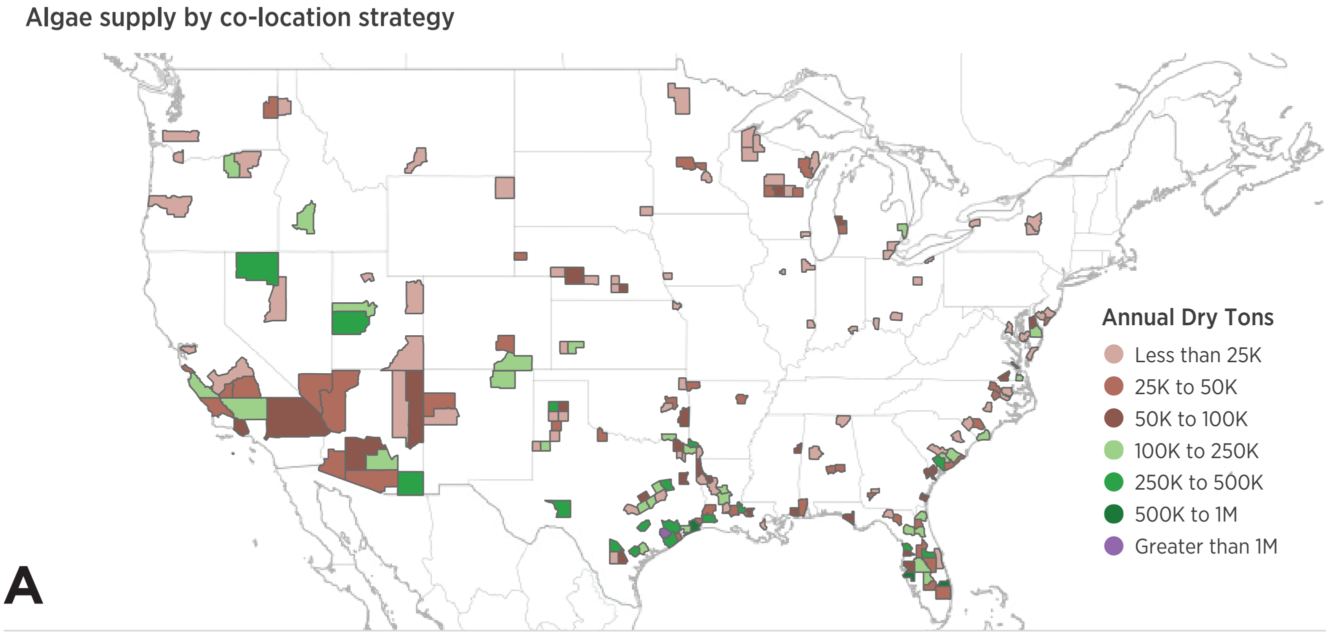
Figure 7.30 and an interactive visualization depict the national distribution of algae unit farms supplied by natural gas EGUs and ethanol production plants, analogous to the coal example. The interactive visualization shows variables for biomass and price results, as well as spatially explicit information. The data project significant geographic diversity for *Chlorella sorokiniana* biomass co-location potentials in the United States. Counties in Florida, Texas, and southern Arizona are among those with the highest biomass productivity rates, which are due to potentially available production sites, CO_2 co-location in the Midwest, especially the western part of the Midwest, is from ethanol plant co-location. Algae biomass potential in the western states is dominantly from co-location with coal-fired EGUs.

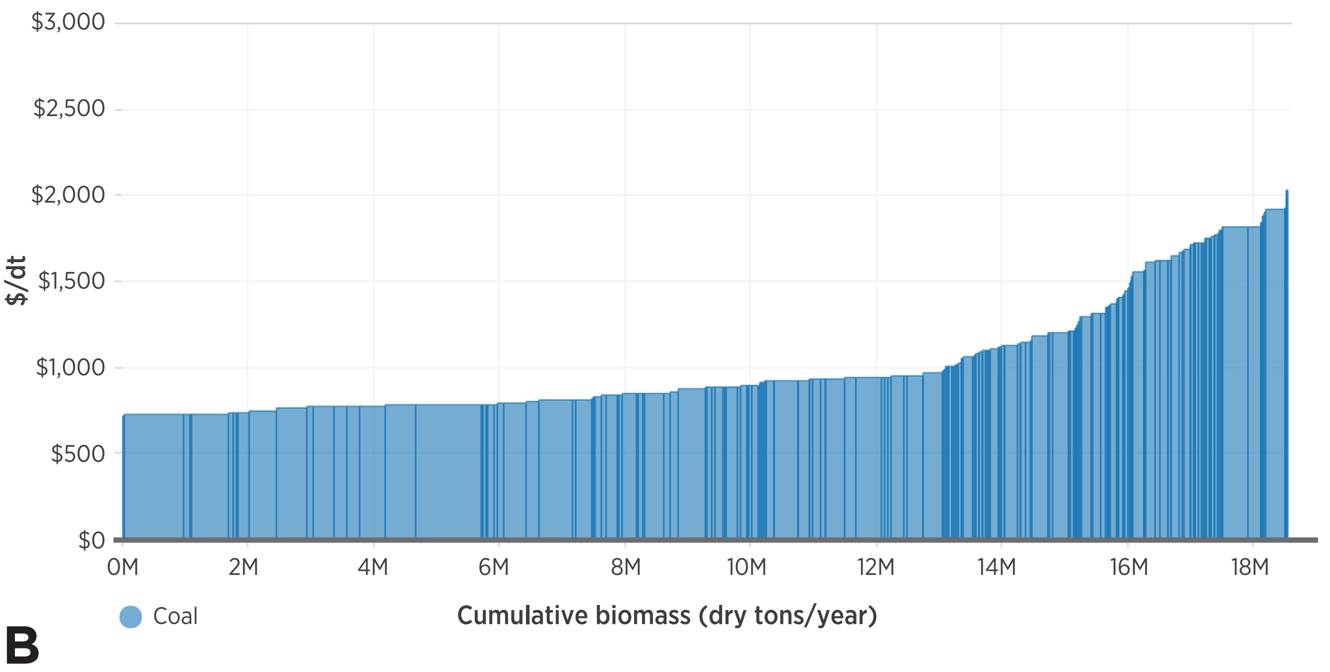
Figure 7.29 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Chlorella sorokiniana* at present productivities[5]



[5] Interactive visualization: https://bioenergykdf.net/billionton2016/7/3/tableau

Figure 7.30 | Potential biomass supply under coal co-location scenario at current productivity levels using *Chlorella sorokiniana*. *A*, Geographic distribution of potential algae supply. *B*, Supply curve of marginal price ($/AFDW ton) vs. million AFDW tons *(B)*.[6]





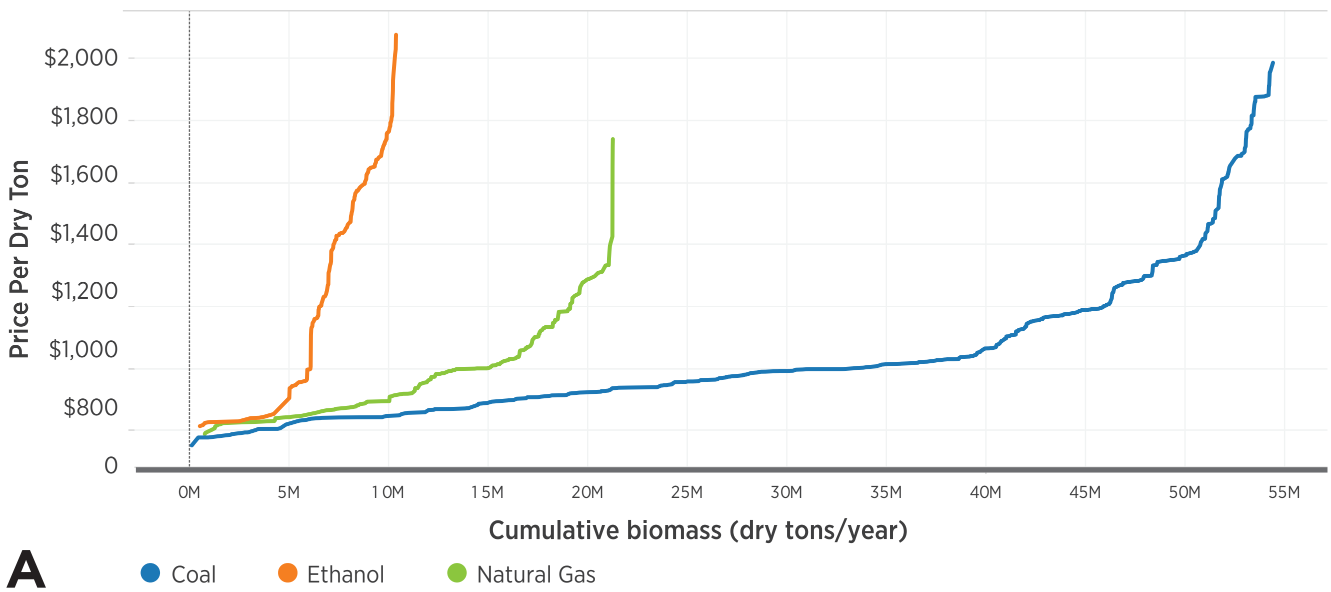
[6] Interactive visualization: https://bioenergykdf.net/billionton2016/7/1/tableau

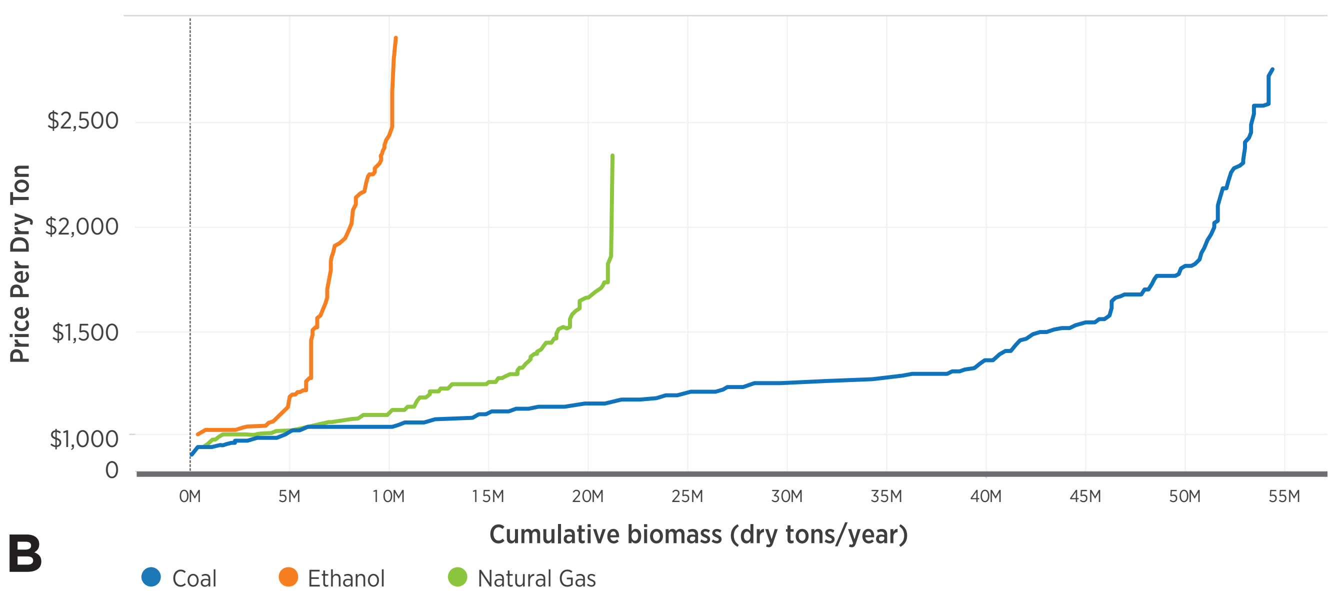
Biomass co-located with ethanol plants becomes available at close to $800 per AFDW ton (fig. 7.29). Ethanol plants are dominantly located in the cooler climates of the upper Midwest; therefore, annual biomass productivity in an open-pond system is lower than in the warmer Gulf region.

Current Nannochloropsis salina (Saline Water) Algal Biomass Potential with CO_2 Co-Location

The projected available biomass of *Nannochloropsis salina* at different minimum selling prices in the United States is depicted in figure 7.31. The data

Figure 7.31 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Nannochloropsis salina* at present productivities for *(A)* minimally lined ponds and *(B)* fully lined ponds.[7]





[7] Interactive visualization: https://bioenergykdf.net/billionton2016/7/3/tableau

represent algal biomass at facilities co-located with natural gas EGUs, coal-fired EGUs, and ethanol plants. Biomass for minimally lined ponds is presented in figure 7.31*A* and for fully lined ponds in figure 7.31*B*. The greatest amount of biomass, nationally, is available using coal EGUs as a CO_2 source; the least is available from ethanol plant sources. For current productivities, the full liner adds more than $200/ton of algae biomass.

Figure 7.32*A* depicts total potential tons of algae biomass by U.S. county produced from *Nannochloropsis salina* (saline media); the example of natural gas EGUs as the source of CO_2 with minimal pond liners is shown. Natural-gas–fed production is centered in the south-central United States, with additional production in California and Florida. Figure 7.32*B* depicts a biomass supply curve of minimum selling price based on CO_2 co-location with natural gas EGUs vs. AFDW tons of algae biomass.

Future *Chlorella sorokiniana* (Freshwater) Algal Biomass Freshwater Potential with CO_2 Co-Location

The projected available biomass of *Chlorella sorokiniana* at different minimum selling prices in the United States, assuming future productivities, is depicted in figure 7.33. The data represent algal biomass at facilities co-located with coal EGUs and ethanol plants. The biomass does not reflect any co-location with natural gas, because the power required to transport sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40 commercial purchase price. When productivity is increased in the future, the lowest costs are substantially lower than under current productivity levels, a cost savings of more than $200 per ton (table 7.8).

The geographic distribution of production, as well as the curve of minimum selling price vs. biomass supply for *Chlorella sorokiniana* in the example scenario of co-location with ethanol plants, is shown in figure 7.34. Biomass becomes available at the lowest price when ethanol plants are the source of CO_2 (fig. 7.34). About 5 million tons of biomass is available at $500/ton. While much of the production is in the upper Midwest, the least expensive production is on the coast of Texas. Ethanol plants as CO_2 sources are associated with the least expensive biomass in all future productivity scenarios.

Future *Nannochloropsis salina* (Saline Water) Algal Biomass Freshwater Potential with CO_2 Co-Location

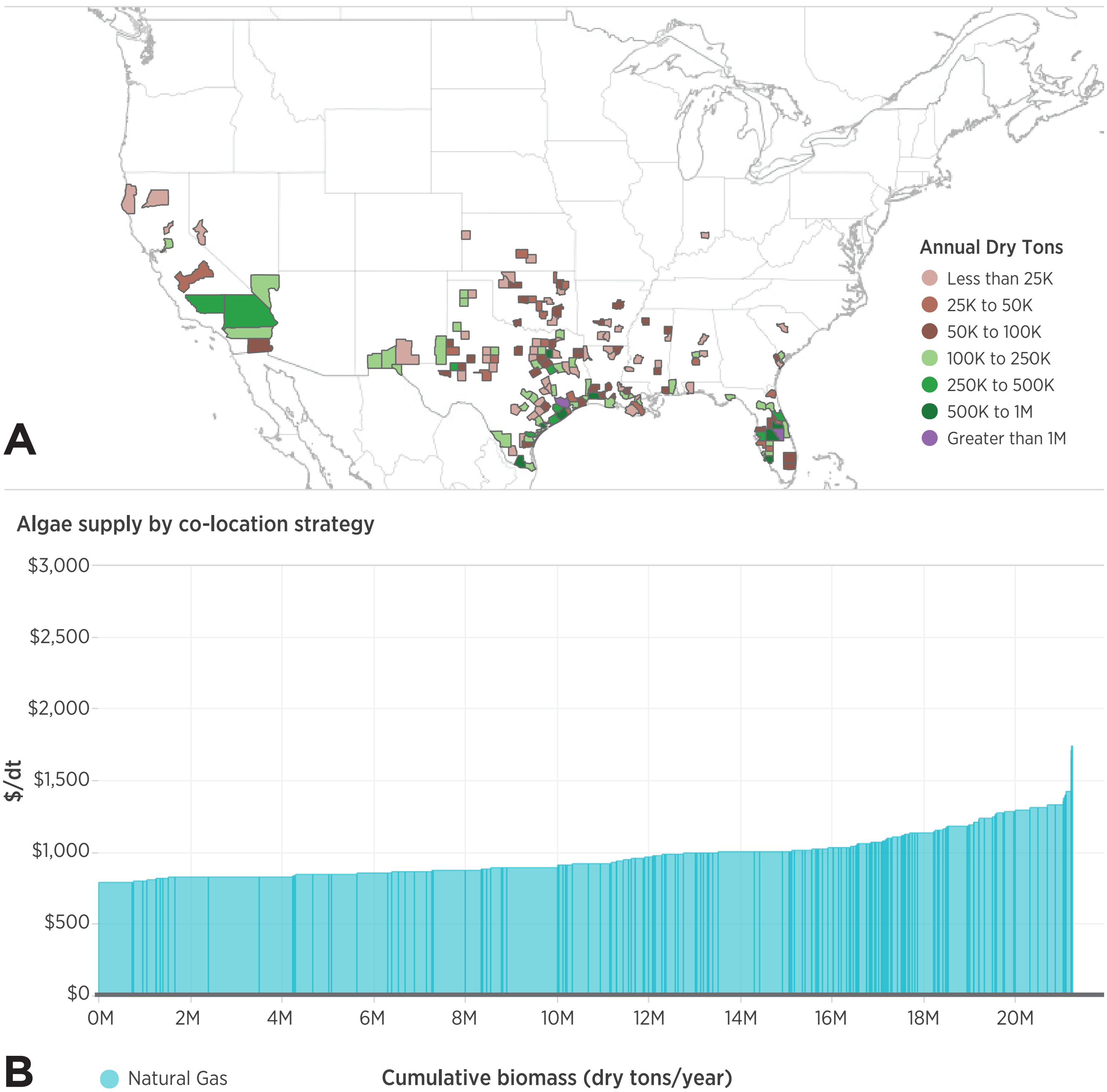
The projected available biomass of *Nannochloropsis salina* at different minimum selling prices in the United States, assuming future productivities, is depicted in figure 7.35. The data represent algal biomass at facilities co-located with coal EGUs and ethanol plants. More biomass is available at the national scale when CO_2 is obtained from coal EGUs than from ethanol plants. As with the future freshwater scenario, the biomass does not reflect any co-location with natural gas. At future productivities, the liner is less expensive than at current productivities, with the highest-productivity site having liner costs at close to $100 per ton of biomass.

Cost Savings

One of the goals of this chapter is to determine the potential cost savings associated with co-location with CO_2. Cost savings are show in table 7.9. For the present and future productivities, the highest cost savings are projected for ethanol plants as a CO_2 source. However, total costs of biomass associated with ethanol plant CO_2 sources are generally highest for the present-productivity scenarios.

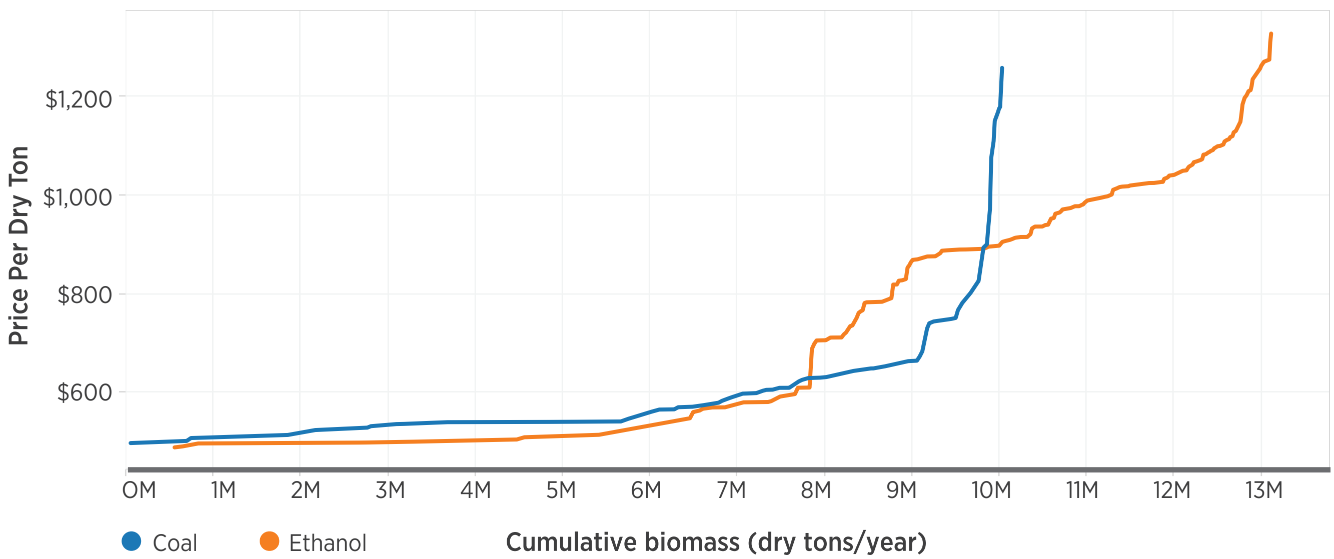
Additional types of cost savings in the scenarios considered in this chapter are projected if (1) higher productivities, such as those assumed for the future, are attained; (2) a freshwater strain is used instead of a saline strain, because of the increased disposal costs, throughput costs (increased ash content), and difference in nutrient requirements of the latter; or (3) minimal rather than full liners are selected.

Figure 7.32 | Potential biomass supply under natural gas EGU co-location scenario at current productivity levels using saline media. *A*, Geographic distribution of potential algal biomass supply. *B*, Supply curve of marginal price ($/AFDW ton) by supply (million AFDW tons), including costs for minimal pond liners only.[8]



[8] Interactive visualization: https://bioenergykdf.net/billionton2016/7/1/tableau

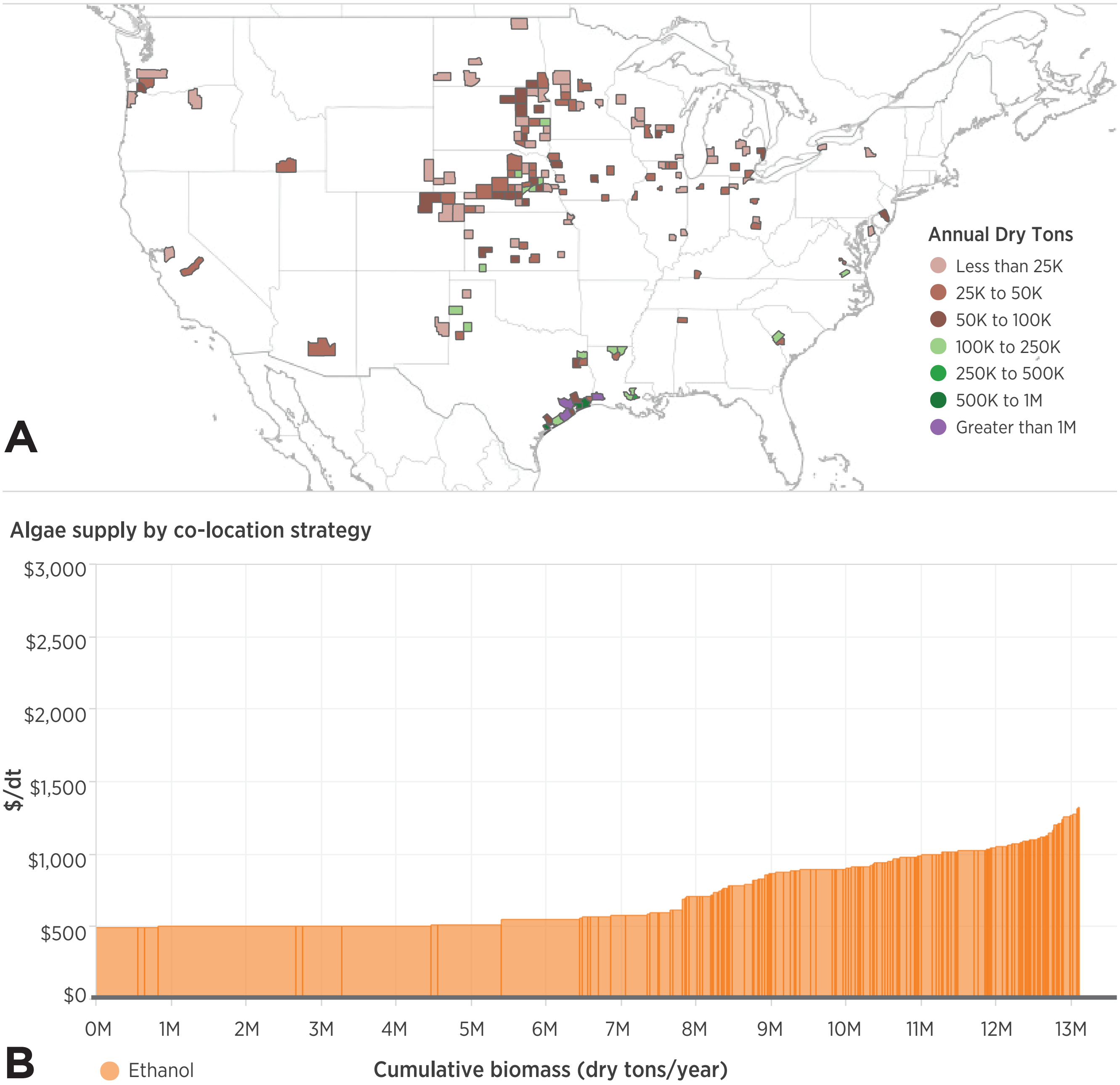
Figure 7.33 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Chlorella sorokiniana* at future productivities[9]



Note: The biomass does not reflect any co-location with natural gas, because the power required to move sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40/ton commercial purchase price.

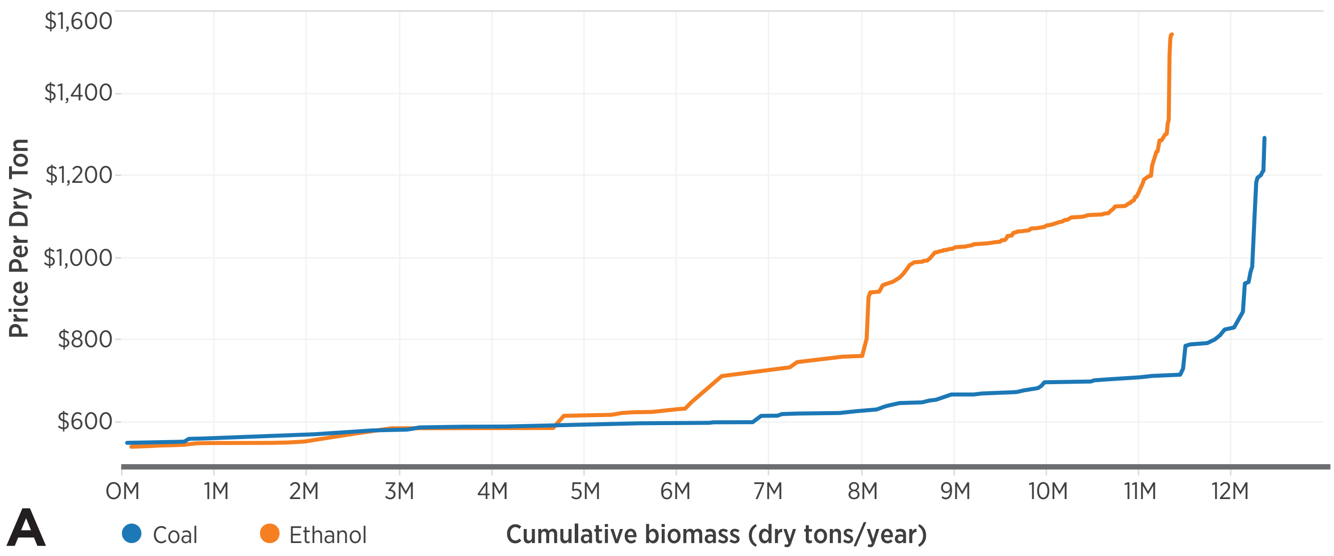
[9] Interactive visualization: https://bioenergykdf.net/billionton2016/7/3/tableau

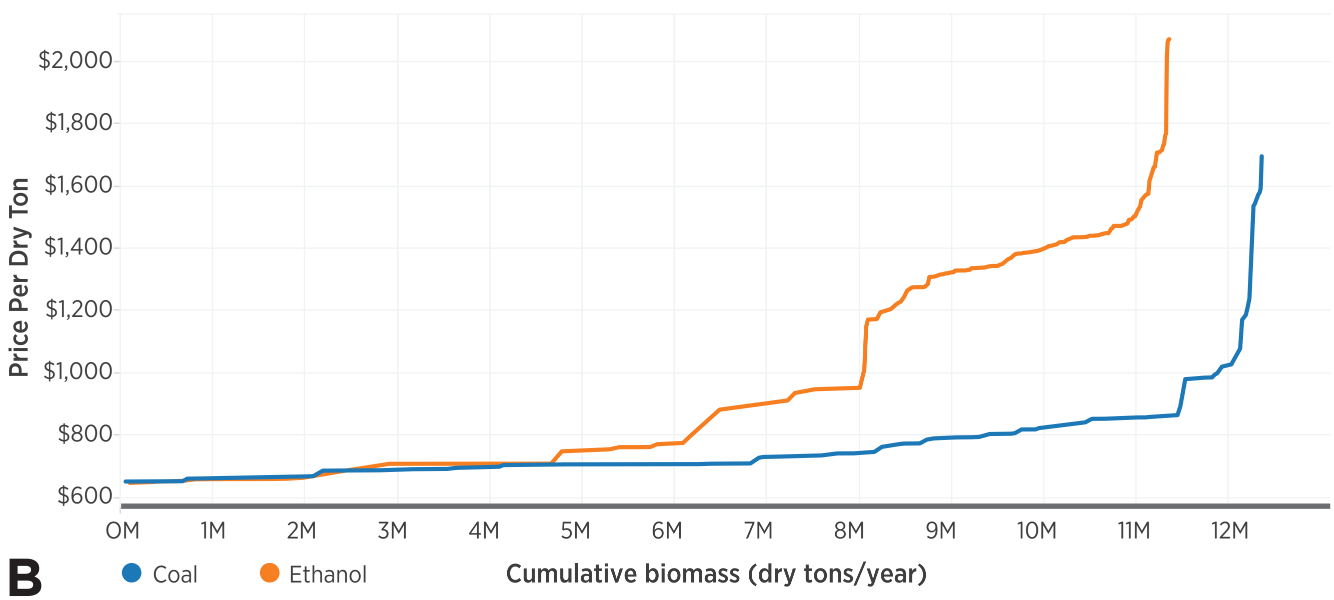
Figure 7.34 | Potential biomass supply under ethanol plant co-location scenario at future productivity levels using *Chlorella sorokiniana* in freshwater media. *A*, Geographic distribution of potential algae supply. *B*, Curve of marginal minimum selling price ($/AFDW ton) vs, supply (million AFDW tons)[10]



[10] Interactive visualization: https://bioenergykdf.net/billionton2016/7/1/tableau

Figure 7.35 | Minimum selling price per dry ton vs. cumulative total biomass for each co-location strategy using *Nannochloropsis salina* at future productivities for *(A)* minimally lined ponds and *(B)* fully lines ponds.[11]





Note: The biomass does not reflect any co-location with natural gas, because the power required to move sufficient CO_2 for the high-productivity scenario brought the cost of CO_2 above the $40/ton commercial purchase price.

[11] Interactive visualization: https://bioenergykdf.net/billionton2016/7/3/tableau

Table 7.9 | CO_2 Co-Location Cost Savings in Open-Pond Algae Production Systems with *Chlorella sorokiniana* (example freshwater strain) or *Nannochloropsis salina* (example saline strain)

Scenario (time)	Scenario (water medium)	Source of CO_2	Mean cost (\$/ton CO_2)	Mean cost savings (\$/ton biomass)
Present and future productivities	NA	Purchase (assumption)	41.00	NA
Present productivities	Freshwater	Ethanol	10.67	69.66
		Coal	19.48	52.04
		Natural gas	31.58	27.84
	Saline	Ethanol	10.92	69.16
		Coal	21.67	47.66
		Natural gas	34.43	22.14
Future productivities	Freshwater	Ethanol	7.79	75.42
		Coal	24.04	42.92
	Saline	Ethanol	8.01	74.98
		Coal	33.43	24.14

7.7 Discussion

This section discusses the implications, caveats and limitations, and uncertainties of the presented results. It also discusses briefly how coproducts and future policies could affect the production costs and prices of algal biomass and presents plans for future resource analysis.

It is important to reiterate that the chapter provides an estimate of biomass potential at given minimum selling prices. The market for algae-based biofuel is still developing, and the conversion of biomass to biofuel remains an active area of research that is often carried out by the same companies that are cultivating the biomass. This is a different model from the terrestrial feedstock model, in which typically the companies that handle conversion are distinct from the producing farms.

Although there is algae biomass potential, biomass for use in the algal biofuel pathways discussed here is not yet economically sustainable. Co-location of facilities with a CO_2 source can provide significant cost savings; but other advances, such as increases in productivity, are necessary for an economically viable industry.

7.7.1 Implications of Results

The potential biomass estimated from the three CO_2 co-location scenarios could complement the potential terrestrial biomass resources. For the present-productivity scenarios, annual algae biomass is estimated at up to 46 million tons from *Chlorella sorokiniana* (freshwater)[12] or up to 86 million tons from *Nannochloropsis salina* (saline water)[13] from co-location with the three selected CO_2 sources.

Under higher-productivity rates that are anticipated in the future, up to 23 million tons per year could be cost-effectively produced from *Chlorella sorokiniana* or up to 24 million tons annually from *Nannochloropsis salina* from co-location with the three CO_2 sources. The lower future biomass totals are largely due to the increased cost of moving larger quantities of CO_2, which often exceeds the $40/ton purchase price of CO_2 under the implemented technology assumptions. If CO_2 capture and delivery technology becomes cheaper, then the number of sites where potential algae production is co-located with the CO_2 sources considered in this report could be expanded. Even if the benefit of co-location with some CO_2 sources is reduced in the future, that does not imply that the total algae biomass potential would be reduced in the future. Clearly, increasing productivity would decrease the overall cost and price of biomass.

Lands on which terrestrial biomass is produced are not excluded from the potential land base for algae production, so there could be some overlap between the lands used for production of potential terrestrial biomass in chapter 4 and those used for potential algae production in this chapter. However, a previous analysis determined that there would be little competition between algae and terrestrial biomass for specific pastureland sites (Langholtz et al. 2016). Therefore, we assume that the addition of potential algal biomass to potential terrestrial biomass in this report should not lead to a large error in the total, beyond that associated with the uncertain productivities in the future and other uncertainties described below.

The combination of production systems (secretion and other PBR systems described below) and co-location options not quantified in this study (including other CO_2 co-location sources and waste nutrient co-location; see section 7.7.5), as well as the potential for capturing and storing CO_2 24 hours/day, 7 days/week, could represent substantial additional production potential and cost reductions. Of course, the use of commercial CO_2, including in combination with co-located CO_2, could also significantly increase the total national production potential. Moreover, the land suitability criteria used here (e.g., slope) do not necessarily apply to PBRs or terraced open-pond systems. Algae could be grown in offshore membrane enclosures as well (NASA 2012). Additional algae biomass potential could come from innovative cultivation management practices; these include algal crop rotation, in which strains are used to maximize productivity based on seasonal meteorological conditions; polyculture, in which multiple strains are combined to increase productivity and decrease susceptibility to pathogens and predators; and/or thermal management of media, in which, for example, heat is conserved overnight (Waller et al. 2012) or co-located waste heat is used to maintain ideal growing temperatures. As noted earlier, biomass for heterotrophic fuel production is not considered.

Even with the benefit of co-location for CO_2, algal biomass has higher production costs than terrestrial feedstocks. Under current productivities, algae estimated costs reported here range from $719 to almost $3,000 per dry ton, compared with terrestrial feedstocks largely available at farmgate and roadside prices ranging from $30 to $60 per dry ton, as

[12] "Up to" is used because the co-location scenarios were independent and not competed, so there may be some overlap in productivity from these three scenarios.

[13] These biomass values should not be added because some of the biomass potential estimated for *Chlorella sorokiniana* occurs on the same lands as that estimated for *Nannochloropsis salina*.

reported in chapters 3 and 4. This is not surprising, given the early development state of algae production technologies, as well as the need to handle a large amount of water and to build an engineered pond. The cost of algal biofuel is very sensitive to the cost of algal biomass (cultivation and dewatering) (Davis et al. 2016).

However, it is important to note that the harvested algae at the end of this analysis are more "finished" than the terrestrial biomass. That is, algae producers are economically closer to a finished fuel product than are terrestrial biomass producers. Davis et al. (2016) estimate that at a $430 per dry ton minimum biomass selling price for either the algal lipid extraction or hydrothermal liquefaction conversion pathway, the lowest fuel cost would be $4.35 to 4.49/gasoline gallon equivalent. (The fuel price would be higher at the minimum biomass selling prices estimated in this chapter, with lower productivity assumptions in the present scenarios; smaller facility sizes; and, in some of the saline cases, full pond liners.)

The cost of transporting CO_2 is an important determinant of the cost of biomass. And the purity of the CO_2 being transported is a major factor affecting the feasible transport distance: with a higher-purity CO_2 stream, energy is not being spent to transport unnecessary gases (i.e., N_2). Thus, different sources of CO_2 are associated with different transport distances, resulting in different costs (and minimum selling prices) of biomass production.

The cost-effective transport distances for CO_2 are greatest for ethanol plants. But the lowest-cost biomass potential is from coal EGU co-location scenarios, rather than ethanol plant scenarios, despite the higher costs of moving the impure flue gas. The main reason is that ethanol plants tend to be located in cool locations, rather than on the Gulf Coast or in Florida, where production facilities have the highest productivities. In other words, the gains in productivity for warmer locations outweigh the CO_2 cost savings differential from the higher-purity CO_2 from ethanol plants, given the dramatic cost dependencies on productivity (particularly at lower productivity values). If PBRs or even covered ponds were considered, more biomass would be available at lower prices from cultivation facilities co-located with EGUs or ethanol plants.

Although EGUs would appear to be ideal sources of CO_2 for algae because they are ubiquitous, and because minimizing, eliminating, or using their GHG emissions is desirable, the dilute gas stream increases the infrastructure required for transport and use. On the other hand, the CO_2 stream from ethanol plants (considered here), as well as from cement plants, ammonia plants, and steam methane reformers (producing hydrogen), is pure enough that it can simply be captured and transported. However, many pure CO_2 waste streams may already be supplying industry as a commercial product (Middleton et al. 2014).

For future productivities, the minimum selling price is as low as $489 per dry ton for *Chlorella sorokiniana* biomass produced in freshwater media using CO_2 from an ethanol plant. The cost savings for increasing the productivity substantially is much higher than the cost savings for co-location with the CO_2 sources considered in this chapter. Davis et al. (2016) estimate that if productivity could be increased from an annual average of 25 to 35 g/m^2•day, then the minimum biomass selling price would decrease by $90 per dry ton. Productivity has an even greater effect on price at lower productivities, with a reduction from 25 to 15 g/m^2•day, giving a penalty of $220/ton of biomass (Davis et al. 2016). Cost would be very sensitive to changes in the low productivities observed in the upper Midwest. When productivity is low, the efficiency of pond usage (i.e., capital) is poor.

It is notable that at the future productivities assumed here, under our technology assumptions, there is no cost savings for algae co-located with natural gas. The power requirements to pipe sufficient CO_2 to meet higher biomass productivities are very costly with respect to energy. This might not be the case if an alternative technology were used, in which flue gas stream is captured 24/7, CO_2 is stripped, and purified gas is transported as a gas or even absorbed in water and then transported. The transport of super-critical CO_2 is more efficient than transport of CO_2 as gas; but in general, compressing CO_2 to a super-critical state is expensive (from an energy and cost perspective). Supercritical, high-pressure transport of purified CO_2 via flue gas carbon capture would allow for decoupling the algae farm from the CO_2 source, thereby allowing for longer transportation distances and considerably higher potential for national-scale biomass production than do estimates constrained to co-location scenarios.

As expected, biomass of *Nannochloropsis salina* from the saline production systems is not as economically viable as *Chlorella sorokiniana* biomass produced in freshwater culture. The high cost of algal biomass from the saline scenarios with liners shows the importance of technology development in that area. Costs of blowdown waste disposal could be reduced as well, and some may already be lower than the assumptions in this analysis. There will always be extra costs for handling higher-ash saline cultures. Incorporating the externality costs and benefits of using saline water in place of freshwater could influence these results and is a research gap.

Economies of scale are also important. In line with Davis et al. (2016), we assume 10-acre ponds, yet cultivation ponds specific to biofuel production that are greater than 2–3 acres are not common today. If smaller ponds were assumed, economies of scale would be reduced.

The current results suggest that DOE's targets of modeling a sustainable supply of 1 million tonnes

Text Box 7.2 | Photobioreactors and Secretion of Fuel Products

PBRs are closed production systems that allow regulation of the culture environment, including light, temperature, water supply, pH, and biomass density. PBRs are found in a wide variety of engineered configurations and may be constructed as tubes, cylinders, helical tubes, or flat plates. Most systems use pelagic cyanobacteria (water columns) that secrete ethanol or hydrocarbons, whereas others grow microalgae as a biofilm (Schnurr, Espie, and Allen 2014). At both commercial and research sites, it is common to have a hybrid system of PBRs and open ponds, in which the bioreactors are used as nurseries to cultivate pure stocks of algae to a given concentration (0.5–1.0 g/L), after which they are used to inoculate the open ponds.

Arizona State University Algae Testbed Public-Private Partnership flat-panel photobioreactor

PBRs have many advantages in that they are generally less prone to biological invasions such as by pathogens, lose very little water to evaporation (if cooling water is not required), maintain higher temperatures than open ponds during cold seasons, and can potentially use industrial waste heat. Less frequent harvesting than for pond/raceway systems is required if ethanol or hydrocarbons are secreted by cyanobacteria. Conducting conversion in the cultivation system could reduce fuel costs.

However, PBRs may present operational challenges associated with overheating and fouling. PBRs require significant capital investment and have yet to be demonstrated for large-scale energy production.

(1.1 million tons) of AFDW cultivated algal biomass by 2017 and of modeling a sustainable supply of 20 million tonnes (22 million tons) of AFDW cultivated algal biomass by 2022 should be achievable. Definitions of "sustainable" will be discussed in Volume 2 of this report, which is focused on the sustainability implications of the potential biomass results.

As Davis et al. (2016) note, some major ways to decrease the costs of algal pond systems, moving into the future, would be to increase productivity, to use large ponds and overall facility and farm sizes to maximize economies of scale, and to avoid fully lined ponds. The decreased costs in the future scenario reiterate the importance of productivity in determining costs. Alternatively, considering smaller farms may result in more potential sites and broader co-location potential and thereby lead to greater overall biomass potential.

7.7.2 Applicability, Limitations, and Uncertainties

Various algae production technologies and designs have different capital and operating costs (Abodeely et al. 2014; Davis, Aden, and Pienkos 2011; Venteris, Skaggs et al. 2014b) and may benefit in varying degrees from different co-location strategies. Depending on the extent of the supply chain considered, related production options include algal strain(s) used, cultivation technology, harvest and dewatering technology, fuel upgrading process, and system water and nutrient recycling options.

One important assumption is the use of open-pond/raceway systems rather than PBRs or hybrid PBR-open-pond systems (Beal et al. 2015). The results of this analysis are not relevant to PBRs. PBRs would have a distinct advantage, compared with open pond/raceway systems, if facilities were co-located with CO_2 in cooler climates, because temperature could be controlled and waste heat from co-located facilities could potentially be used (see text box 7.2).

Regional issues will also affect costs. In the current analysis, both capital expenditure (piping and blowers) and operating expenditure (energy requirements) costs will be impacted by the distance from the CO_2 source and the purity of the CO_2. Pipe size is optimized accordingly to fit the spatial relationship between site and CO_2 source.

The most important regionally sensitive variable is actual biomass productivity, which is simulated here, and which will affect the projected biomass and significance of CO_2 savings. Cultivation productivity is the strongest cost driver, especially below an annual average productivity of 25 $g/m^2 \cdot day$ (Davis et al. 2016).

Many caveats and limitations apply to the curves of minimum selling price versus potential biomass supply. They are most applicable to the modeled cultivation systems assumed in the BAT model and in Davis et al. (2016), including inoculum technologies. The biomass yield results are most applicable to species assumed in the production model: a *Chlorella sorokiniana* strain for freshwater media and *Nannochloropsis salina* for saline media. The base case costs that were taken from Davis et al. (2016) assume the use of *Scenedesmus acutus (LRB-AP 0401)*, a freshwater strain, to determine nutrient and CO_2 requirements; so adjustments to the other strains introduce some uncertainty into the supply curves.

Results are applicable to co-location conditions assumed here. Sources include ethanol plants, coal-fired EGUs, and natural gas EGUs. Costs of transporting dilute CO_2 restrict the number of potential co-located unit farms, but these costs could change with new technologies in the future. The assumption that CO_2 is not stored at night is a major assumption affecting results. Some algae companies are storing CO_2 at night, which could decrease CO_2 transport system costs and increase potential biomass production, compared with the assumptions in this chapter.

Many uncertainties in the assumptions in this chapter potentially affect the accuracy of results:

- **Productivity.** Although the BAT biomass productivity model has been validated against numerous observation data sets, values simulated by the BAT model have a degree of uncertainty; and we have not optimized the strain choice for regional and/or seasonal productivity. It is possible to improve upon less favorable thermal growth conditions with particular open-pond designs (e.g., ARID Pond) (Khawam et al. 2014, Waller et al. 2012). Many additional factors could affect productivity. For example, crash frequency is not considered in productivity estimates. Also, if flue gas is used, contaminants could cause productivity to increase or decrease (Napan et al. 2015). Future productivities assumed in these analyses are already found in open-pond systems at some highly suitable locations, but scientific advances are needed to achieve this value in other locations. The year that future productivity levels assumed in this chapter will be achieved is uncertain.
- **Facility size.** Whereas Davis et al. (2016) assume 5,000 acre cultivation facilities, we assume 1,000 acre cultivation facilities, with an additional 200 acres of infrastructure, for both current and future cases. In doing so, some economies of scale (for dewatering equipment, circulation pipelines, storage and labor/fixed operating costs) are reduced (compared with Davis's estimates at the 5,000 acre scale) and are approximately quantified, resulting in an approximate increase of $102 per ton (Davis et al. 2016), adjusted for 2014 dollars. Moreover, this decrease in economies of scale could add significant costs to conversion pathways, considering final dollar-per-gallon fuel costs. However, there would be an advantage in the biophysical potential of decreasing the minimum facility size so that more lands with co-location potential could be included in the BAT-based resource analysis, particularly with respect to coal EGUs, where the total CO_2 utilization is limited under this analysis.
- **Pond liner.** As in Davis et al. (2016), we assume that liners are not needed for freshwater ponds, except for portions of the ponds/raceways that are vulnerable to erosion. Freshwater ponds are assumed to self-seal in all soils, although in reality, sandy soils are less likely to seal than clay soils. Venteris, McBride, et al. (2014) identify some locations where natural soil conditions would minimize water losses and water quality concerns below freshwater ponds. Ongoing research is investigating soil and substrate requirements for sealing. The assumption that only saline cultivation systems may require liners may not be conservative, as some soils may not seal, and current environmental regulations may require liners for permitting. Also, carbon sources may be needed for microbial sealing, which would add costs. Moreover, pond liners might need to be replaced within the 30 year facility lifetime.
- **Capital and operating costs.** Capital costs for the current case are taken from Davis et al. (2016) and adjusted to 2014 dollars. Uncertainties in these values could be large. Some of the costs, especially savings at scale, are uncertain. Also, the costs of distributing dilute CO_2–containing flue gas from coal-fired EGUs or natural gas EGUs would be higher than the base case of purified/concentrated CO_2 in Davis et al. (2016). Moreover, capital and operating costs for the future scenario are not altered from present costs. Therefore, future costs are highly uncertain; and some costs could be reduced and others increased, depending on the future year. Fertilizer costs in the future are uncertain.
- **Water availability.** A key assumption is that biomass production is not constrained by local water policies, but rather is constrained consistently across the nation to use only 5% of available

mean annual surface water flow within an HUC-6 (hydrologic unit code–6) scale watershed (ANL, NREL, and PNNL 2012). That is a questionable assumption, given competition over freshwater and restrictions on new development in some parts of the country. Accounting for the externality costs of freshwater use would reduce its economic competitiveness over saline water.

- **Water sources.** The use of seawater instead of saline groundwater would alter costs of supply and disposal; however, these costs would be site-dependent with respect to ocean access and water transport distances.
- **Nutrient sources.** If wastewater is used, nutrients would be cheaper than the costs used in this analysis, with potential for wastewater credits; but costs for piping to the production site would have to be added. Lundquist et al. (2010) suggest that operating expenses may be 10% lower if waste treatment is used as a source of nutrients.
- **Pipeline size.** CO_2 pipelines are sized based on average annual productivity values for all sites, with a 1.25 multiplier for peak periods and an assumption that CO_2 is used only during the daytime. For lower-productivity sites, smaller pipelines with slightly lower costs could be used, compared with the costs estimated in our analysis. Pipelines may be under-sized in the summer months and over-sized in the winter months. Higher production (and thus CO_2 demand) will occur during the warmer, longer-light summer months. A site- or region-specific engineering design based on biomass production and CO_2 supply can provide a better estimation of biomass potential. Pipeline costs may be lower than those assumed here if pipelines are connected between adjacent unit farms, becoming smaller as they feed fewer unit farms. Technologies are available (e.g., bicarbonate absorption stack) to capture and store waste CO_2 24/7 in a water medium and then transport the water instead of the gas, but this approach is not considered here because the costs are unknown. Reducing the sizing of the piping required could lead to lower costs and more production locations.
- **Flue gas-related costs.** CO_2 purification costs for flue gas are not included. Also, the cost of distributing CO_2 through on-site pipelines to individual ponds could be higher for flue gas than for ethanol, whereas we use the same estimate for all CO_2 sources. Relevant research and development supported by DOE's Office of Fossil Energy is directed towards reducing the cost of CO_2 capture. Future improvements in carbon capture could influence future opportunities for siting algae.
- **Competition for CO_2.** Competition for CO_2 is possible from enhanced oil recovery in regions with oil fields. Although CO_2 is often obtained from natural underground "domes" of CO_2, it can also be obtained from EGUs and industrial plants and compressed and transported by pipeline to oil fields. In those regions, CO_2 costs might be higher than those assumed here, although we eliminate source plants from our analysis that have a known competitive use of CO_2. Competition for CO_2 is also possible from medical or food production industries. However, these uses should not require a large portion of the available CO_2 and should not affect pricing substantially.
- **Productivity-cost relationship.** Because uncertainties may be highest at low productivities, the highest costs in the supply curves may be the most uncertain. Regional costs would vary somewhat, with the most extreme case (Hawaii) presented as a scaling factor in Beal et al. (2015).
- **Waste disposal costs.** As in Davis et al. (2016), the analysis assumes that costs for blowdown brine disposal would add about $32 per dry ton to the cost of biomass production using saline water, but this value is a conservative estimate

from deep-well injection, highly variable and uncertain. The cost would depend on local geology. The net seasonal water evaporation rates across the country could differ from those assumed in Davis et al. (2016) and used to generate this cost. The actual waste disposal cost could be much lower for regions located in close proximity to a coast or where waste could be reinjected in the well. For strains with a lower range of salinity tolerance, the blowdown fraction would need to be adjusted. As in Davis et al. (2016), we acknowledge that blowdown streams removed from the primary dewatering clarified recycle line could contain low salt levels, but we do not include these costs.

- **Power.** We use power costs from Davis et al. (2016) in both the current and future cases. Actual power costs will vary by region; for example, Beal et al. (2015) note that the energy to supply water to the production site varies regionally. Costs of power in the future are even more uncertain. It is possible that renewables would provide less costly power in the coming decades. Beal et al. (2015) consider the use of wind power in techno-economic assessments of algae and find a per-kilowatt-hour cost savings in Hawaii but not in Texas. Moreover, Lundquist et al. (2010) note that wastewater credits can reduce electricity costs. Energy return on investment and potential economic ramifications are not investigated here.
- **Future conditions.** As in other chapters, the future scenario assumes that land use/land cover categories (agriculture, urban, and forest area) do not change in the future. Algae production is excluded from agricultural, forest, and high-density developed land. The assumed biomass potential could be quite different if the areas of these land use/land cover classes change. Moreover, many coal-fired EGUs are expected to shut down in the future. Estimated facility retirement dates are not included in this analysis.
- **Financial assumptions.** The internal rate of return and discount rate of 10% is adopted from Davis et al. (2016). This is higher than the discount rate (6.5%) assumed in analyses of terrestrial feedstocks. However, it is lower than the cost of capital that might be required for risk financing. Therefore, this rate constitutes a large source of uncertainty in the analysis. Moreover, in the techno-economic analyses for several complete algal biofuel supply chains in Beal et al. (2015), the minimum biocrude price is highly sensitive to the discount rate, as well as the interest rate, loan term, and tax rates.
- **CO_2 policies.** Cap-and-trade programs are in effect in California and in the northeastern United States that could decrease CO_2 costs. The U.S. Clean Power Plan[14] could also affect future CO_2 costs, at least from EGUs. It is unclear whether various CO_2 producers are likely to give or sell CO_2 to algae production facilities. It is also unclear who will bear the cost for integration. At present, only EGUs are included in the Clean Power Plan.

7.7.3 Logistical Considerations

Nutrient recycling can reduce costs. When the full algae-to-biofuels process is considered, CO_2 can be generated for recycling by combusting the methane produced in anaerobic digestion. We assume that any nutrient recycling credit would be applied on the downstream conversion process to reduce final fuel or product costs (Davis et al. 2016) because previous DOE design case reports on conversion processes assume that recycling would reduce fuel costs rather than biomass costs (Davis et al. 2014, Jones et al.

[14] At the time of publication, the Clean Power Plan was in judicial review.

2014) and because the specific degree of recycle potential is dependent on a particular conversion technology pathway. Davis et al. (2016) estimate a credit of $14/ton for 90% nitrogen recycling if it is credited to biomass costs. Heat from CO_2-containing gases transported short distances might be used to aid in drying algae. A portion of the CO_2 may also be used to increase the shelf life of wet algae in storage (Isenberg 1979, Floros and Newsome 2010).

7.7.4 Importance of Coproducts to Economics

Coproducts are increasingly understood to be important to the economics of algal biofuels and the viability of the algal biofuel industry. Numerous coproducts are possible if the lipid fractionation pathway is used. If hydrothermal liquefaction is used, algal biomass could be co-processed with less expensive feedstocks such as terrestrial biomass or waste grease (Jones et al. 2014).

Table 7.10 | Microalgae Products and Prices

Product	Substitutes	Price	Unit[a]
Biodiesel	Diesel	$2.27	USD/gal
Bio-ethanol	Gasoline	$3.96	USD/gal
Bio-methane (fuel)	Liquified petroleum gas	$1.92	USD/gal
Jet fuel (bio-jet)	Jet fuel	$2.49	USD/gal
Electricity	Fossil energy	$0.13–$0.21	USD/kWh
Bio-methane (electricity)	Natural gas	$0.05–$0.06	USD/kWh
Biofertilizers	Synthetic fertilizers	$0.25–$0.63	USD/kg
Biostimulants	Growth promoters	$37.50–$312.50	USD/kg
Biopesticides	Synthetic pesticides	$5.00	USD/acre
Bioplastics	Fossil based plastics	$1.75	USD/kg
Food	Proteins, carbohydrates, oils	$50.00	USD/kg
Beta-carotene	Synthetic/natural	$275.00–$2,750.00	USD/kg
Omega-3 polyunsaturated fatty acids	Fish	$50.00	USD/g
Aquaculture	Fishmeal/fish oil	$68.75–$625.00	USD/kg
Livestock feed	Soybean meal	$300.00	USD/Mg
Feed additives	Botanicals, antibiotics	$20.00	USD/kg

Source: Data from Van der Voort, Vulsteke, and de Visser (2015).

[a]Original prices in Euro are converted to U.S. dollars (USD) using a conversion factor of 1.25.

Example prices of fuel products and potential co-products are shown in table 7.10. The price of animal feed has a strong influence on techno-economic analyses for algal biofuel production (Beal et al. 2015)). According to one source, about 30% of the world's algae-produced biomass is sold as animal feed (Lum, Kim, and Lei 2013). While the portion of biomass used for animal feed has regulatory toxicant limits, and feed used for poultry has protein limits (Spolaore et al. 2006), animal feed coproducts can be produced with biomass from the algal biofuel supply chain.

7.7.5 Summary and Future Resource Analysis Research

The potential biomass estimated from the three CO_2 co-location scenarios could complement the substantial terrestrial biomass resources. For the present-productivity scenarios, annual algae biomass is estimated at up to 46 million tons from *Chlorella sorokiniana* (freshwater) or up to 86 million tons from *Nannochloropsis salina* (saline water) based on co-location with the three selected CO_2 sources (table 7.11). Under the technology assumptions used here, the co-location benefit is lower at future, higher productivities because of an increased cost of transporting the CO_2. As expected, higher productivities lead to lower overall minimum selling prices of algae biomass. Costs of biomass grown in saline media are somewhat higher than those of biomass grown in freshwater media, and full liners add substantial costs. Under both high and low productivity scenarios, prices are substantially higher than those at which terrestrial biomass is potentially available, but less processing is required to convert algae biomass to biofuel.

The combination of production systems and co-location options not quantified in this study could represent substantial additional production potential and

Table 7.11 | Summary of Biomass Potential from Co-Location (million tons/year) with CO_2 in Open Ponds Using *Chlorella sorokiniana* (example freshwater strain) or *Nannochloropsis salina* (example saline strain)

Scenario	Ethanol plant	Coal EGU	Natural gas EGU	Total[a]	Range of minimum prices per dry ton[b]
Present productivities, freshwater media	**12**	19	15	<46	$719–$2,030
Present productivities, saline media	**10**	54	21	<86	$755–$2,889
Future productivities, freshwater media	**13**	10	0	<23	$490–$1,327
Future productivities, saline media	**11**	12	0	<24	$540–$2,074

Co-located algae biomass potential with CO_2 sourced from natural gas plants is reduced to 0 at future productivities because of the increased cost of moving larger quantities of impure CO_2, which makes purchasing CO_2 more economically efficient. However, future research and development should reduce the costs of capturing and transporting CO_2 from flue gas.

[a]Totals are uncertain because analyses of different co-location sources were run independently; therefore, some production facilities that are close to multiple CO_2 sources may be double-counted.

[b]For *Nannochloropsis salina*, the range of minimum selling prices includes both minimally lined ponds and lined ponds. For *Chlorella sorokiniana*, the range of minimum selling prices includes only minimally lined ponds.

cost reductions. Of course, the use of commercial CO_2, including in combination with use of co-located CO_2, could also significantly increase the total national production potential.

Future research could consider the effects on production costs of additional production technologies and scales of production, as well as additional co-location scenarios and specific technologies (such as technologies for nighttime storage of CO_2). Some of these may decrease minimum selling prices and increase the projected biomass production further. Tradeoffs in productivity and ultimate costs between freshwater and saline conditions and algal strains will be examined.

A research priority is to include PBRs and hybrid systems in future analyses as soon as peer-reviewed cost data, including capital and operating expenses, are available and there is consensus on an appropriate design on which to focus. The costs of CO_2 delivery from EGUs and ethanol plants to PBRs with higher annual productivity have already been estimated, but results are not reported here because baseline capital and operating costs of PBRs are not well established. Ongoing research is estimating these costs.

Potential resource co-location scenarios include the use of CO_2 from cement plants, hydrogen production, ammonia fertilizer facilities, refineries, sugar mills, and other point-source production facilities. Some algae companies are already planning to co-locate facilities with cement plants. Future analysis will more specifically capture daily site CO_2 usage based on modeled daily/hourly CO_2 output and hours of potential CO_2 utilization by algal production facility.

As CO_2 purification technologies improve, they should become less expensive, expanding the number of economically efficient co-located algae production sites. Moreover, as utilities and other industries have increasing incentives for CO_2 utilization, it may become possible to decouple the CO_2 source spatially from the site of algae production. This would expand the range of sites available for algal biofuel production, (including remote sites), increase the algae biomass potential nationally, and decrease GHG emissions. Furthermore, some facilities could be co-located with flue-gas-derived CO_2 and use supplemental commercial CO_2 where needed.

Waste heat is another potential focus of co-location. Ethanol plants and EGUs, as well as other industrial plants, produce waste heat, which must be managed by some type of cooling system. Often the thermal management of waste heat, especially for an EGU, involves cooling water, sometimes from a nearby open source but often provided by a closed loop with cooling towers. The use of waste heat could reduce the need for thermal management by the source facility and lead to enhanced productivity for algal biomass facilities in the cold seasons, especially for PBRs. Because the co-location distance limits for CO_2 are lower for EGUs, using waste heat from these plants could be even more useful for reducing costs and determining feasible locations for co-location than using waste heat from ethanol plants. Also, heat from the EGU can be used in the downstream drying process. This concept has not yet been evaluated.

Aquatic nutrient loading, as well as fertilizer costs, can be reduced by sourcing nutrients from effluent streams of municipal waste treatment plants or confined animal-feeding operations. Future research could investigate the economic benefits of these co-location examples as well.

The implications of these results for environmental sustainability (i.e., water quantity and quality, soil quality, air quality, biodiversity, GHG emissions, and productivity) are discussed in *BT16* Volume 2. The discussion of sustainability of the production of algal biomass will be qualitative, as few data are available related to the sustainability of large-scale production of algae for fuel.

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