Multiobjective Optimal Siting of Algal Biofuel Production with Municipal Wastewater Treatment in Watersheds with Nutrient Trading Markets

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Abstract: Using municipal wastewater effluent as a feedstock in algae cultivation is a promising approach for increasing the commercial viability of algal biofuel production. However, differences in site-specific characteristics at municipal wastewater treatment plants (WWTPs) could drive tradeoffs between maximizing the profitability of algae production and minimizing the cost of meeting water quality standards. A complicating factor is how water quality regulations are enforced, namely the potential presence of nutrient trading markets that would monetize removal of nutrients from wastewater effluent. This study develops an analytical framework for optimizing the siting of an algal biofuel production facility within a network of WWTPs. A combined life cycle assessment (LCA) and techno-economic analysis (TEA) model of an algal biofuel production facility is integrated with a simplified watershed model. An evolutionary algorithm is used to identify optimal sites for algal biofuel production and explore financial tradeoffs for algae biofuel producers and wastewater treatment plants. This analytical framework is then applied to a high-priority, impaired watershed in North Carolina, the Neuse River Basin. **DOI: 10.1061/(ASCE)WR.1943-5452.0001018.**

Introduction

Producing biofuels from microalgae offers a range of potential advantages over crop-based biofuels, including higher energy production per hectare and the ability to recover both water and nutrients used in cultivation, which collectively reduce net resource consumption and life cycle greenhouse gas emissions (Chisti 2007; Chowdhury et al. 2011; Quinn and Davis 2014). However, algal biofuel remains too costly to be competitive with fossil fuels (Davis et al. 2016). In order to improve the competitiveness of algal biofuel, its production can be paired with (and subsidized by) the coproduction of other high value products, including animal feed (Beal et al. 2015; Gerber et al. 2016; Kern et al. 2017), nutraceuticals (Stephens et al. 2010), and chemicals (Pittman et al. 2011). Algal biofuel production can also be integrated alongside other valuable industrial processes, including wastewater treatment (Pittman et al. 2011).

Using wastewater effluent as a feedstock in biomass cultivation would provide a low-cost source of nutrients (Lundquist et al. 2010; Woertz et al. 2009), while at the same time helping wastewater treatment plants (WWTPs) avoid capital and operations and maintenance (O&M) costs associated with conventional treatment (Clarens et al. 2010; USEPA 2015). However, there are major hurdles to effectively linking algal biofuel production with municipal wastewater treatment (Pittman et al. 2011), including those related to plant siting. Scant attention has been paid to the challenge of how to optimally place these facilities in networks of WWTPs, which vary individually with respect to effluent discharge volume and concentration, position within the watershed, as well as local land costs and land availability.

A key factor could be the specifics of how water quality is regulated in a given watershed. In impaired watersheds, states are required to establish a total maximum daily load (TMDL) specifying the amount of a pollutant [e.g., total nitrogen (TN)] that may be discharged to a water body. The TMDL is then allocated among contributing point-source and nonpoint source polluters. If regulations require WWTPs to independently adhere to discharge limits stipulated by a TMDL, there is no incentive for individual WWTPs to reduce effluent concentrations below the legal limit (via algae cultivation or otherwise). In many watersheds, however, it is permissible for groups of WWTPs to participate in nutrient cap and trade markets (Doyle et al. 2014; Willamette Partnership 2012). Take, for example, a hypothetical WWTP that currently releases 100 kg of TN per day. If this WWTP is required by new, more stringent water quality regulations to reduce its emissions to 90 kg TN per day, it could contract with (pay) a colocated algae producer to achieve this reduction. However, if the algae producer exceeds this treatment target and in fact reduces the WWTP's discharge to 50 kg per day, it would create 40 kg of surplus pollution reduction credits. These credits could then be sold by the algae producer to another WWTP in the basin seeking to avoid additional capital investment in denitrification technology. In this manner, water quality trading markets could allow the monetary value associated with algae-based water treatment to scale directly with biofuel production, regardless of location within a watershed. This additional flexibility

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may be valuable in optimizing the siting of algae production in watersheds.

A complicating factor, however, is that pollutant discharges from different WWTPs may contribute differently to the downstream TMDL, due to the natural attenuation of nitrogen in rivers over large spatial scales (Behrendt and Opitz 2000; Mulholland 2004; Williams et al. 2004). For example, a WWTP far upstream of a sensitive estuary may only contribute half a kilogram of TN to the TMDL for every one kilogram emitted in its waste stream, whereas emissions from a WWTP closer to the estuary may contribute on a one-for-one basis. Thus, if the objective is to minimize the cost of meeting a downstream TMDL, algae cultivation located at a WWTP closer to the estuary is more valuable, all other factors held constant. This raises the possibility that the objectives of algae producers and groups of WWTPs may in some cases be competing [i.e., siting algae cultivation in order to maximize financial success could result in suboptimal (higher) costs of meeting water quality standards].

Despite growing interest in the potential of colocated algal biofuel and WWTP facilities, very little consideration has been given to how this should be done in complex watershed systems. Joint management of water quality and biofuel production is a topic that has been given some treatment in the past (de Moraes et al. 2010; Ng et al. 2014); however, as a potential water treatment mechanism (as opposed to a source of pollution), algal biofuel poses a fundamentally different set of questions. This study developed an analytical framework for optimizing the siting of an algal biofuel production facility within a network of hydrologically connected surface water bodies and municipal WWTPs. The framework was then tested in a high-priority impaired watershed in North Carolina, the Neuse River Basin. This study demonstrates how watershed complexities can impact choices regarding the colocation of algal biofuel production with existing WWTPs, and offers a transferable framework for navigating these complexities in order to balance stakeholder objectives.

Methods

The analytical framework developed in this study is illustrated in Fig. 1. A simplified watershed model is developed that provides site-specific information about a network of WWTPs (all of which are candidate locations for algae production) and their respective contributions to a downstream TMDL. Key WWTP parameters considered are local topography, land use, and land cost data; the volume and concentration of WWTP effluent (i.e., the available supply of nutrients); and local transfer coefficients specifying the fraction of nutrients emitted from each WWTP that contribute to the downstream TDML. The watershed model is coupled with an existing life cycle assessment (LCA) and techno-economic analysis (TEA) model for a feed-and-fuel algal biofuel production facility. Together, these are used to formulate a multiobjective optimization problem with dual, somewhat competing objectives: (1) maximize annual financial performance of algal biofuel producers; and (2) minimize the basin-wide cost of meeting a downstream TMDL. A multiobjective evolutionary algorithm, NSGA-II, is then used to identify tradeoffs that emerge when siting algal biofuel production. Three progressively lower TMDLs and two different regulatory environments (with and without nutrient trading in place) are tested, for a total of six different scenarios. Resulting tradeoff frontiers are then subjected to sensitivity analysis in order to identify the major drivers of project performance and explore results under alternative watershed configurations.

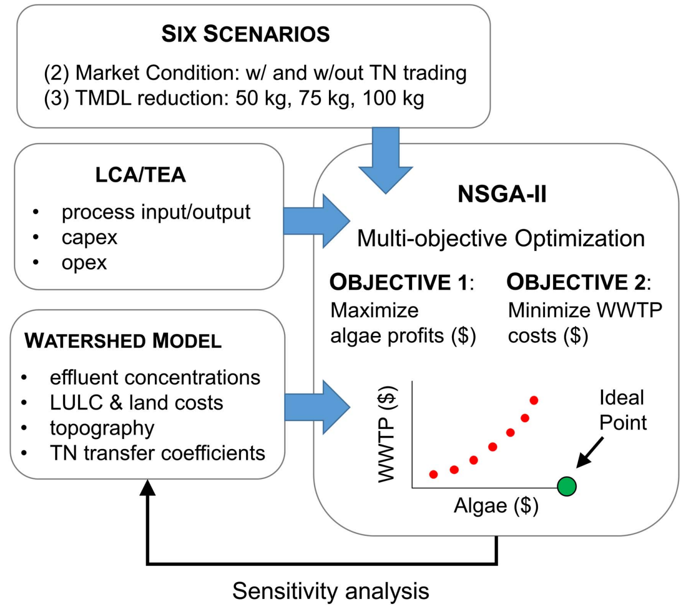

Fig. 1. Overall methodological approach taken in this study. A combined LCA/TEA and simplified watershed model is embedded within a multiobjective optimization. Tradeoffs between the two objectives are then subjected to uncertainty in watershed properties.

Watershed Model

The Neuse River Basin in North Carolina (Fig. 2) is chosen as a test bed for initial application of the analytical framework. Since the late 1990s, state and federal environmental regulations have aimed to reduce nitrogen loading in the Neuse River estuary. These include a TMDL specifying the amount of TN that may reach the downstream Neuse River estuary each year. This total waste load is allocated among more than 100 individual point source facilities and incorporated into each polluter's discharge permit (USEPA 2007). The primary point source polluters in the Neuse are a group of 19 major WWTPs, shown by shapes in Fig. 2, which all have effluent discharges of at least 3,785 kL (1 million gallons) per day.

A simplified watershed model of the Neuse River basin is developed that provides site-specific information about candidate WWTPs. The watershed model does not simulate watershed processes (e.g., streamflow) dynamically; rather, it offers a static, spatial representation of WWTP characteristics thought to be important in identifying the optimal location for algae production in the basin: permitted discharge, daily TN emissions, effluent concentration, and TN transfer coefficients, as well as local land costs and land availability for algae cultivation. This information is pulled together from a variety of academic and industry sources, as well as from a GIS analysis conducted for the Neuse River basin. The "Multiobjective Optimization" section describes how these site-specific watershed parameters plug-in to the formulation of the multiobjective optimization, including problem constraints and the two competing objective functions. The following three sections describe the different components of the watershed model.

Wastewater Treatment Plants

Table 1 lists the group of WWTPs in the Neuse River basin considered in this study, along with information regarding their permitted discharge and daily TN emissions, effluent concentration, and TN transfer coefficients. Effluent concentrations are calculated as permitted TN emissions divided by permitted discharge volume (note that actual concentrations reported by each WWTP vary

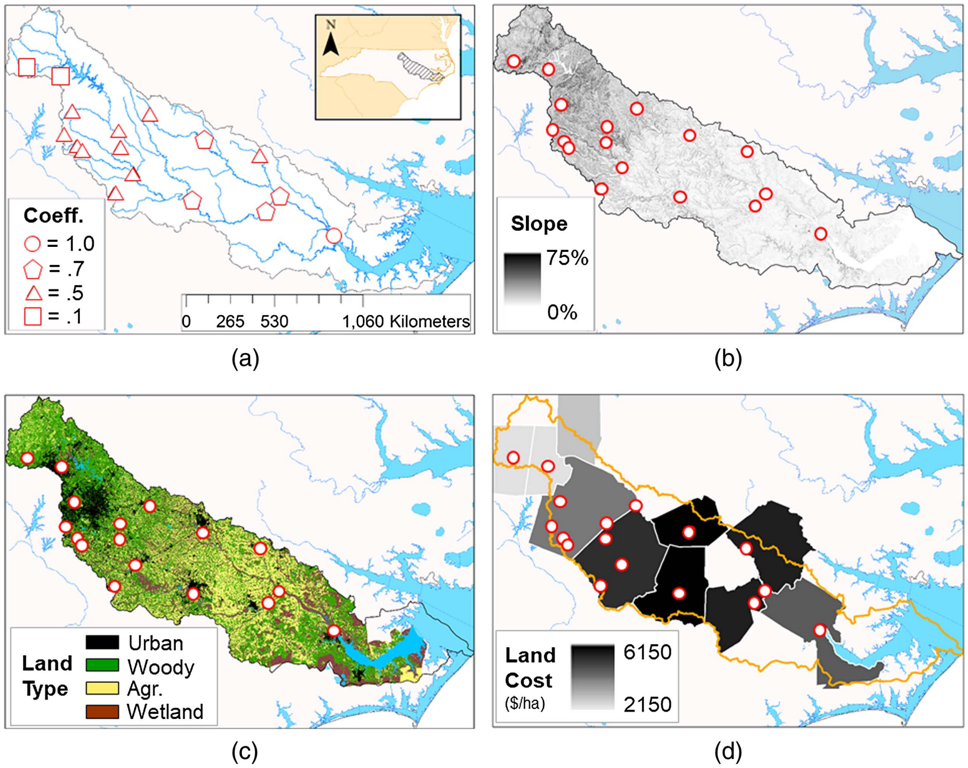

Fig. 2. Neuse River basin and the location of major WWTPs: (a) TN transfer coefficients for each WWTP; (b) basin slope; (c) land use–land cover classification; and (d) nonirrigated cropland prices.

Table 1. Parameters of major WWTPs in the Neuse River Basin

WWTP	Daily discharge (kL)	Daily TN emissions (kg)	Effluent concentration (mg/L)	Transfer coefficient	Land costs ($/ha)	Land availability (ha)	TN removal cost ($/kg)
New Bern	24,605	80	3.24	1	4,444	0	5.88
Contentnea	10,978	46	4.21	0.7	5,333	48	6.90
Goldsboro	66,623	248	3.72	0.7	6,148	99	5.37
Kinston Regional Water Reclamation Facility	45,046	157	3.49	0.7	5,407	43	5.51
Wilson	52,996	196	3.71	0.7	6,148	120	5.45
Apex	13,627	50	3.69	0.5	3,852	4	6.55
Benson	7,192	41	5.74	0.5	5,259	75	7.87
C. Johnston	51,103	89	1.74	0.5	5,259	47	0.00
Clayton	9,464	29	3.02	0.5	5,259	27	7.20
Farmville	13,249	53	3.97	0.5	5,333	86	6.59
Little Creek	8,328	33	3.98	0.5	3,852	64	7.49
Neuse River	283,906	854	3.01	0.5	3,852	51	5.14
North Cary	45,425	178	3.91	0.5	3,852	0	5.51
Smith Creek	22,712	88	3.87	0.5	3,852	57	5.95
South Cary	60,567	224	3.7	0.5	3,852	6	5.40
Terrible Creek	22,712	85	3.75	0.5	3,852	57	5.95
Hillsborough	11,356	63	5.51	0.1	2,148	36	6.84
North Durham	75,708	417	5.51	0.1	2,148	0	5.33
SGWASA	20,820	73	3.51	0.1	2,667	31	6.03

Note: Major WWTPs are defined as a plant with permitted discharge of at least 3,780 kL (1 million gallons) per day.

somewhat year to year and, in some cases, are lower than what is shown in Table 1). The transfer coefficients, which are estimated by the state of North Carolina for the purposes of administering the TMDL and overseeing potential trading of water quality credits, range from 0.10 to 1.00 and represent the percentage of TN emitted from a given WWTP that contributes to the downstream estuary's TMDL (McLawhorn 2016). WWTPs located nearer to/farther from the estuary have higher/lower values.

Note that each major WWTP considered currently uses some type of conventional biological nitrogen removal, yielding TN effluent concentrations between 1.5 and 6 mg/L. Thus algae biomass production colocated with WWTPs in the Neuse River basin would likely serve as a tertiary treatment, similar to the situation explored in Clarens et al. (2010). There is not currently a legal obligation to achieve further nutrient reduction from WWTPs in the Neuse River basin; aggregate TN emissions have fallen steadily since 1995 (even as wastewater discharge has increased by volume), and WWTPs are in attainment with regard to their collective contribution to the estuary's TMDL. However, nutrient pollution remains a critical issue for the Neuse River and many other rivers throughout the United States (American Rivers 2017; USEPA 2011), and continued population growth is likely to put pressure on WWTPs to further reduce effluent concentration. This could increase the market for algal biomass production as a form of advanced tertiary treatment.

GIS Analysis

The second piece of the watershed model is a GIS analysis of land availability (constrained by topography and land use–land cover) and land costs. Similarly to previous studies (Lundquist et al. 2010), we assume that algae cultivation is limited to geographical areas with slopes of less than 5%. To assess the suitability of WWTPs in the basin, county-level digital elevation maps are converted to slope maps in ESRI ArcMap [Fig. 2(b)]. Another geospatial parameter that similarly influences land availability is land use–land cover classification [Fig. 2(c)]. Due to the substantial greenhouse gas emissions associated with conversion of forest and grasslands to biofuel production (Fargione et al. 2008), only existing agricultural lands and marginal/abandoned lands are considered for algae production.

Circular buffers with radii of 1 km are created around each candidate WWTP, and a raster calculation based on slope and land use–land cover within these buffers is performed. For each WWTP in the basin, the total buffer area of existing agricultural and marginal/abandoned land with a slope of less than 5% is taken as the maximum amount of land available for algae cultivation. Table 1 shows resultant land availability for each WWTP considered.

A third geospatial parameter that is likely to drive algae plant economics is per hectare land costs, which vary on a county-by-county basis throughout the Neuse River basin. We estimate per-acre land costs using 2016 cash rents reported by the US Department of Agriculture's National Agricultural Statistical Service (US Department of Agriculture 2016). These estimates are shown in Table 1 and mapped in Fig. 2(d).

LCA/TEA Model

A combined engineering and economic representation of hypothetical colocated algae biofuel production at WWTPs in the Neuse River basin is modeled using an existing LCA/TEA model of a feed-and-fuel algal biofuel facility (Fig. 3). The model assumes that algae biomass is produced in open raceway ponds, with an algae areal productivity rate of 22 $\mathrm{g\,m^{-2}\,days^{-1}}$, 25% lipid content, and a hydraulic residence time in the growth ponds of 4 days, similar to Lundquist et al. (2010). Primary cultivation feedstock inputs include CO_2 and wastewater (nutrient-containing water). A number of previous studies have demonstrated the potential for algal assimilation of inorganic nitrogen to decrease TN concentrations in wastewater, although rates of removal can vary widely by algae species/waste stream. There is also a significant lack of knowledge regarding the nutrient removal capabilities of algae species best suited for biodiesel production (Cai et al. 2013; Cheah et al. 2016). Based on results reported in Cho et al. (2011), it is assumed that algae production reduces the TN concentration of wastewater by 1.25 mg/L-day in a 4-day batch treatment. Algae is then dewatered, lipids are extracted from the dewatered algae and then converted to biodiesel via transesterification, and lipid extracted algae is sold as feed meal.

Most process energetic requirements and emissions impacts in the model are taken directly from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model

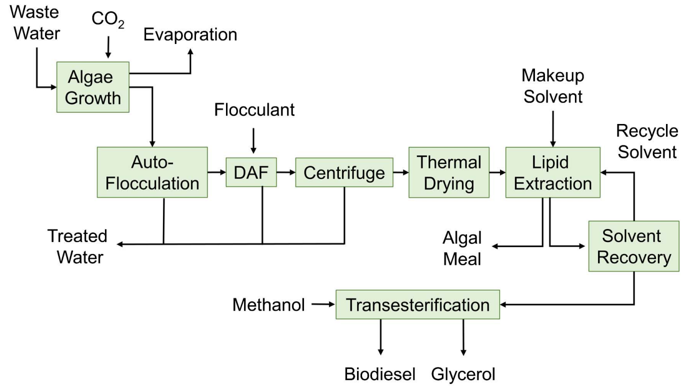

Fig. 3. Process diagram for fuel-and-feed algal biofuel facility represented in the LCA/TEA model. DAF = dissolved air flotation (a step in the algae dewatering process).

(Frank et al. 2011), while economic (cost, financing) information is taken from reports published by the National Renewable Energy Laboratory and others (Davis et al. 2014; Jones et al. 2014). The model has been validated against other LCA/TEA models of algal biofuel production; in particular, it yields similar life cycle impacts and cost estimates as harmonized models developed by several national labs (Quinn and Davis 2014). The model has been used in the past to assess the relative impacts of novel processing techniques and financing parameters (Hise et al. 2016) on algal biofuel costs, as well as the potential for using real options theory in designing algal biofuel facilities (Kern et al. 2017).

For a complete summary of all LCA/TEA model parameters and sources, as well as validation of the model's estimated cost and impact calculations, please see Hise et al. (2016).

A comprehensive Matlab-based version of the LCA/TEA model that contains options for alternative product pathways and plant designs (Kern 2018). However, for the purposes of this study, key process interactions and economic relationships from the Matlab model are translated to the R programming language and used to formulate a multiobjective optimization problem.

The LCA/TEA model represents the capital investment and physical operations of hypothetical algal biofuel facilities by first defining all process interactions and economic relationships on a per-unit basis (i.e., dry algae in kilograms). The inputs required, outputs produced, and relevant economic information (i.e., capital and operational costs, as well as revenues from the sale of biofuels, feed and—in the case of this study—TN sequestration) are then scaled by the total amount of algae produced. This facilitates subsequent formulation of the multiobjective optimization problem, with the scale of algae production at each WWTP serving as the single set of decision variables. See the "Multiobjective Optimization" section for further details about how relationships taken from the LCA/TEA model are incorporated into the problem's two objective functions (maximize profits for algae producers, minimize the cost of adhering to the TMDL) and its constraints.

Valuing Algal-Based Water Treatment

For an algal biofuel facility, there are two potential value streams associated with colocating near a WWTP: (1) reduced cost of nutrients; and (2) monetary payment by WWTPs for nutrient removal services. The former is easily determined by the supply of wastewater to the algae production facility and the market price of nitrogen fertilizer. A key remaining question is how to monetize algae-based water treatment.

Without a Nutrient Trading Market

A logical upper bound estimate on the value of algae-based water treatment is the cost of conventional nutrient mitigation technology (i.e., the WWTPs' avoided costs when algae-based treatment is implemented). Reported overnight capital costs (i.e., no consideration of financing) and operations and maintenance (O&M) costs associated with conventional nutrient mitigation technology are generally reported as a function of WWTP size and desired effluent concentration (Nutrient Reduction Technology Cost Task Force 2002; USEPA 2015). Cost information is publicly available for meeting three progressively lower TN concentrations: 8, 5, and 3 mg/L. Because denitrification technology is already in place at WWTPs in the Neuse River basin (all plants except two already have effluent concentrations below 5 mg/L), any further TN emissions reductions would necessitate technology capable of achieving 3 mg/L. However, it is not clear how much of the publically reported costs associated with 3 mg/L denitrification technology would apply to plants for which effluent concentrations are close to that target (some requisite infrastructure may already be in place). Because most plants in the Neuse River basin would only be marginally reducing effluent concentration, it is assumed here that WWTPs' avoided costs with algae-based water treatment are a fraction of the cost of using conventional technology to reduce effluent concentration to 3 mg/L from an original concentration of 8 mg/L (a 5-mg/L decrease), as follows:

$$Incremental\,Overnight\,Cost\,(\$) = \left(\frac{C_i - 3}{5}\right) \times [.229F_i + 627{,}190] \tag{1}$$

$$Incremental\,O\,\&\,M\,Cost\left(\frac{\$}{\text{year}}\right) = \left(\frac{C_i - 3}{5}\right) \times [.007F_i + 44{,}393] \tag{2}$$

where C_i = existing TN effluent concentration at plant i (mg/L): F_i = average treatment volume in liters per day at plant i. These avoided costs assume the use of deep bed denitrification filters, with O&M costs accounting for methanol, increased solids production and disposal, energy consumption, and labor (Nutrient Reduction Technology Cost Task Force 2002).

Overnight capital costs are converted to annualized capital costs using the same financing parameters (i.e., 4% interest rate, 30-year loan term) as the LCA/TEA model for algal biofuel production, yielding a \$/year capital avoided cost estimate of attaining 3 mg/L TN at each WWTP in the basin using algae. Capital and O&M costs can then be combined and converted to a \$/kg TN removal cost for each plant, determined as (1) the net present cost of the conventional treatment technology over 30 years, divided by (2) associated cumulative TN removal from the waste stream over 30 years. Estimated plant-specific TN removal costs are given in Table 1. Note that they decrease as a function of plant discharge, because discharge controls cumulative TN removal.

In the absence of a nutrient trading market, nutrient removal by algae is valued differently at each WWTP in the Neuse River basin, according to each plant's estimated \$/kg removal costs using conventional technology. Consider a situation in which all major WWTPs in the basin are individually required to reduce their effluent concentrations to 3 mg/L or below. The apex WWTP would be willing to pay an algal biofuels facility up to \$6.55/kg (its avoided treatment costs with algae in place) for every kg of TN removed. Note, however, that if water quality were regulated in this manner, the apex WWTP would be unwilling to pay for nutrient removal beyond a concentration of 3 mg/L. Without a nutrient trading market in place, a colocated algal biofuel facility might reduce effluent concentration below 3 mg/L, but payments from the WWTP would be capped at the level of investment needed to become in attainment.

Nutrient Trading Market

In theory, permissible nutrient trading among WWTPs would allow compensation for nutrient removal to scale more directly with algae cultivation, thus expanding siting possibilities. Water quality trading markets typically involve bilateral trading of credits among point source polluters (e.g., WWTPs). However, there is increasing participation nationally among third parties that bank (aggregate) credits through direct removal or offsets that can then be sold to polluters (US Department of Agriculture N. R. C. S 2018; USEPA 2018.) In this study, we assume that nutrient trading is not based on bilateral exchanges among individual WWTPs, but rather, a centralized cap and trade market; demand for TN removal is created by enactment of a lower TMDL. Then, each WWTP in the basin must purchase sufficient credits from the market (in this case, algal biofuel producers) to offset their own emissions, which results in a collective, basin-wide demand for algae-based TN removal.

Consider a situation in which the major WWTPs in the Neuse River basin are required to reduce their collective TMDL contribution from 1,450 to 1,282 kg/day TN, a level equivalent to each WWTP independently attaining an effluent concentration of 3 mg/L. In the presence of a nutrient trading market, if a third-party algal biofuel facility were capable of completely removing TN from the waste stream of the apex WWTP, all 50 kg/day of sequestered TN (not just the 9.35 kg/day required to achieve 3 mg/L) could be monetized. For the algal biofuel facility, this means that nutrient removal payments could come not only from the owner of the colocated WWTP, but from any plant in the basin with demand for TN removal. When a nutrient trading market is in place, it is assumed that every kg of TN removed via algae is paid for by WWTPs at a predetermined \$/kg market price, regardless of location in the basin. Note that this differs from a nonmarket scenario, in which the value of algae removal varies by location, and is tied to specific WWTPs' \$/kg avoided costs.

In order to determine the market price of TN removal, blocks of site-specific TN removal (i.e., a maximum amount in kilograms and an associated \$/kg avoided cost) are stacked in order of increasing cost, collectively forming a marginal cost curve for TN removal from major point source polluters. Then, for a given quantity of TN removal demanded, the market price is set equal to the most expensive \$/kg cost needed to achieve the basin's treatment target. Fig. 4 shows the estimated marginal cost curve for TN reduction in the basin, along with an estimate of the market price of TN removal at a hypothetical TMDL reduction of 150 kg TN. The size of each circle is scaled by plant discharge. Higher avoided costs are associated with smaller plants, because the costs of treatment are spread over fewer actual units of TN removed from the waste stream.

Multiobjective Optimization

Because the major WWTPs in the Neuse River basin are collectively in attainment with respect to their share of the TMDL for the downstream estuary, there is no requirement that WWTPs in the basin further reduce their nutrient emissions. Thus, for the purposes of this study, the TMDL must be artificially lowered to force investment in additional treatment. The WWTPs are currently permitted to discharge 3,004 kg/day TN (translating to 1,450 kg/day

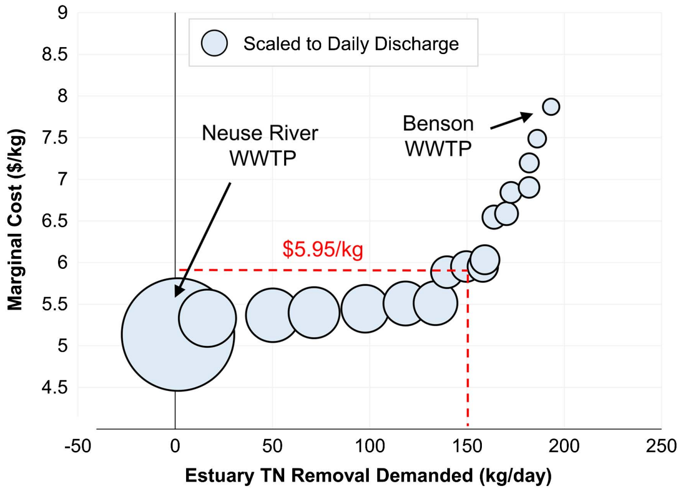

Fig. 4. Example determination of \$/kg TN removal price for hypothetical quantity demanded (TMDL reduction level) of 150 kg/day.

delivered to the estuary when accounting for transfer coefficients). In this study, three progressively lower TN emissions rules are enforced: 1,400, 1,375, and 1,350 kg/day, corresponding to TMDL reductions of 50, 75, and 100 kg/day, respectively. A second area of interest is how the absence/presence of nutrient trading markets in the Neuse River basin affects the optimal colocation of algal biofuel production. Thus, the amount of algal biofuel production sited at each individual WWTP is also evaluated with and without permissible nutrient credit trading, creating a total of six modeling scenarios.

An additional assumption, made in the interest studying potential future tradeoffs in algae siting, is that algae-based water treatment is the WWTPs' only viable option for meeting the more stringent TMDLs. Consideration of WWTPs' cost of conventional denitrification technology in the "Valuing Algal-Based Water Treatment" section is only included as a way to approximate the monetary value of algae-based TN removal, but implementation of conventional TN methods are not included as decision variables in the multiobjective optimization. This assumption likewise forces investment in algae production, regardless of whether algae producers and/or WWTPs find it optimal (or even profitable) to do so.

The question then becomes: what is the optimal location of algae production (nutrient removal) in the basin? The amount of algae produced at each WWTP in the basin directly influences two objectives: (1) maximizing annual financial performance of the algal biofuel facility; and (2) minimizing the cost of meeting the downstream TMDL. These objectives are likely to be somewhat competing; i.e., under certain circumstances, increasing profits for algal biofuel producers directly increases the cost of meeting the TMDL. This motivates the use of a multiple (as opposed to single) objective optimization approach that yields a set of alternatives that exhibit trade-offs among the competing objectives. Each alternative is said to be nondominated, meaning there exists no other solution for which all objective functions are improved (Branke et al. 2008). In the case of combinatorial multiobjective problems (i.e., ones that aim to find an optimal object composed of a larger, finite set of objects), performing an exhaustive search over the domain of each decision variable is not always feasible. The focus instead is on finding a smaller sample of solutions that are representative of the larger optimal set (Konak et al. 2006). A commonly used approach for efficiently finding this representative sample in multiobjective problems are evolutionary algorithms (Branke et al. 2008), which adopt principles of evolution (e.g., selection, mutation) while searching for and assessing multiple potential solutions at one time.

In this study, optimization is performed using a well-known multiobjective evolutionary algorithm called NSGA-II, which was developed in Deb et al. (2002) and has since been applied in a wide range of systems engineering applications. The NSGA-II algorithm can be implemented using the mco package in R libraries and the nsga2 function, which holds default values for the crossing probability (0.7), crossing distribution index (5), mutation probability (0.2), and mutation distribution index (10).

As noted previously, the primary process interactions and economic relationships in the core LCA/TEA model are written in terms of per-unit dry weight algae production, with total costs and benefits calculated by subsequent user-defined scaling. Likewise, sequestration of TN at each WWTP can also be quantified as a function of total dry algae production. As a result, both objective functions (maximizing annual profits for the algae producer, minimizing the annual cost of meeting the downstream TMDL) can be put in terms of a single set of decision variables ($\boldsymbol{A_i}$), which denotes the scale of annual algae cultivation at each WWTP

$Maximize\,Annual\,Algae\,Profits$ (\$):

$$\sum_{i=1}^{I}[BD \times BP + A_i \times FP + N_i \times NP_i - opex_i - capex_i] \quad (3)$$

where BD_i = the amount of biodiesel produced at plant i per year (L): BP = price of biodiesel (\$/L); A_i = algal biomass produced at plant i and sold as feed meal per year (kg); FP = price of feed meal (\$/kg); N_i = total nitrogen removed from plant i wastestream per year (kg); NP_i = price of nitrogen removal (\$/kg); $opex_i$ = annual operating expenses at biofuel plant i(\$); and $capex_i$ = annualized capital expenses at biofuel plant i(\$).

From the LCA/TEA model, A_i relates to the parameters BD_i, N_i, and $opex_i$ as follows:

$$BD_i = \frac{A_i}{X \times D} \quad (4)$$

$$N_i = \left(\frac{1}{1e^6}\right) \times C_i \times \left(\frac{1}{PC}\right) \times A_i \quad (5)$$

$$opex_i = 0.6123A_i - (.4725) \times N_i \quad (6)$$

where X = grams of algae required to produce one gram of biodiesel precursor: D = density of biodiesel fuel (kg/L); and PC = concentration of algae in pond at harvest (kg/L).

The variable $opex_i$ accounts for annual consumption of water, electricity, thermal energy, fertilizer, carbon dioxide, hexane, methanol, and chitosan. It also accounts for reduced consumption of nitrogen fertilizer due to use of WWTP effluent. The variable $capex_i$ represents annualized overnight capital costs, assuming a 30-year loan term. Overnight capital costs (covering a settling tank, dissolved air flotation with flocculation, a centrifuge, thermal drying, lipid extraction and transesterification) scale as follows:

$$O_i = A_i \times [(1.17) + (3.41e^{-5}) \times L_i] \quad (7)$$

$$capex_i = O_i/y \quad (8)$$

$$y = \frac{(1 - \frac{1}{(1+r)^t})}{r} \quad (9)$$

where Li = estimated cost of land around WWTP $i(\$/acre)$: y = annuity factor; r = cost of capital; and t = plant lifetime.

The second objective function, to minimize the annual cost of meeting the additional water treatment requirement, is written as follows:

$$Minimize\, Treatment\, Cost\colon \sum_{i=1}^{I} N_i \times NP_i \tag{10}$$

Note that if nutrient trading is permissible, NP_i is uniformly set equal to the market price of nitrogen removal (Fig. 4) for all plants; otherwise, it is equal to the \$/kg avoided cost estimated for each individual plant. Optimization of both objective functions is subject to several constraints. First, the amount of TN removed from the waste streams of WWTPs in the basin must allow the WWTPs to meet the new TMDLs for the downstream estuary. Thus

$$\sum_{i=1}^{I} N_i \times T_i \geq (1{,}450 - TMDL) \times 365 \tag{11}$$

where T_i = transfer coefficient of plant i.

It is also assumed that annual algae production at any given WWTP is limited by the available supply of nutrients in the waste stream. If a nutrient trading market is in place, this constraint can be stated as

$$A_i <= F_i \times PC \times 365 \tag{12}$$

If a nutrient trading market is not in place, this constraint is stated as

$$A_i \leq \frac{\min(C_i - 3, 0)}{C_i} \times F_i \times 365 \times PC \tag{13}$$

At the same time, the scale of algae production at each location must be within limits imposed by local availability of agricultural and marginal land with slope of less than 5%.

In order to solve the problem formulation stated previously using NSGA-II, the relevant engineering and economic relationships [Eqs. (4)–(13)] are first translated from the watershed and LCA/TEA models to R. Then, for each of the six modeling scenarios, the nsga2 function (population size: 500; number of generations: 50,000) is run to find a range of nondominated alternatives that vary in their ability to meet the two objectives.

Sensitivity Analysis

In order to understand how alternative watershed configurations might impact the optimal colocation of algal biofuel in the basin, as well as tradeoffs between algae profitability and the cost of meeting more stringent water quality standards, sensitivity analysis is performed. Although a number of sources of model uncertainty exist in the LCA/TEA model, previous analyses have explored these (Gerber et al. 2016). In this study, sensitivity analysis is used to explore the response of the optimization results to uncertainty in four key WWTP parameters: effluent concentration, transfer coefficients, land costs, and maximum algae production, the last of which is constrained by both land availability and the available supply of nutrients. For both market and nonmarket conditions, assuming a 50-kg TMDL reduction, 80 alternative watershed configurations are explored using 5,000 generations, each using NSGA-II. In 20 configurations, all parameters are held constant except effluent concentration, which is randomly reassigned (sampled without replacement); in another 20 configurations, all parameters are held constant except transfer coefficients, which are randomly reassigned, and so forth, for each of the four site parameters tested.

Results and Discussion

Before exploring the outcomes of the multiobjective optimization and sensitivity analysis, it is useful to understand how differences in site parameters, as well as the absence/presence of a nutrient trading market, influence the values of each objective function. Table 2 details the physical and financial outputs of hypothetical algae biofuel facilities located at each WWTP; these values are listed on a per-kilogram of algae (dry weight) basis, because the primary

Table 2. Per-unit (kg) algae physical and financial outputs for hypothetical biofuel facilities colocated with WWTPs in the Neuse River Basin

Facility	Feed (\$)	TN removal (kg)	Avoided fertilizer costs (\$)	TN removal revenues (\$)		Biodiesel		Capex (\$)	Opex (\$)	Profit (\$)	
				Market	No market	L	\$			Market	No market
New Bern	0.33	0.0065	0.0031	0.0357	0.0381	0.1987	0.2086	0.0712	0.6092	−0.1061	−0.1037
Contentnea	0.33	0.0084	0.0040	0.0464	0.0581	0.1987	0.2086	0.0719	0.6083	−0.0952	−0.0835
Goldsboro	0.33	0.0074	0.0035	0.0410	0.0399	0.1987	0.2086	0.0726	0.6088	−0.1017	−0.1028
Kinston Regional Water Reclamation Facility	0.33	0.0070	0.0033	0.0385	0.0385	0.1987	0.2086	0.0720	0.6090	−0.1039	−0.1039
Wilson	0.33	0.0074	0.0035	0.0409	0.0404	0.1987	0.2086	0.0726	0.6088	−0.1018	−0.1023
Apex	0.33	0.0074	0.0035	0.0407	0.0483	0.1987	0.2086	0.0707	0.6088	−0.1002	−0.0926
Benson	0.33	0.0100	0.0047	0.0551	0.0787	0.1987	0.2086	0.0719	0.6076	−0.0857	−0.0621
C. Johnston	0.33	0.0035	0.0016	0.0192	0.0000	0.1987	0.2086	0.0719	0.6107	−0.1247	−0.1439
Clayton	0.33	0.0060	0.0029	0.0333	0.0435	0.1987	0.2086	0.0719	0.6094	−0.1094	−0.0992
Farmville	0.33	0.0079	0.0038	0.0437	0.0523	0.1987	0.2086	0.0719	0.6085	−0.0981	−0.0895
Little Creek	0.33	0.0080	0.0038	0.0439	0.0596	0.1987	0.2086	0.0707	0.6085	−0.0968	−0.0810
Neuse River	0.33	0.0060	0.0028	0.0332	0.0309	0.1987	0.2086	0.0707	0.6095	−0.1084	−0.1106
North Cary	0.33	0.0078	0.0037	0.0431	0.0431	0.1987	0.2086	0.0707	0.6086	−0.0976	−0.0976
Smith Creek	0.33	0.0077	0.0037	0.0426	0.0461	0.1987	0.2086	0.0707	0.6086	−0.0981	−0.0947
South Cary	0.33	0.0074	0.0035	0.0408	0.0399	0.1987	0.2086	0.0707	0.6088	−0.1001	−0.1010
Terrible Creek	0.33	0.0075	0.0035	0.0413	0.0446	0.1987	0.2086	0.0707	0.6088	−0.0995	−0.0962
Hillsborough	0.33	0.0100	0.0047	0.0551	0.0684	0.1987	0.2086	0.0694	0.6076	−0.0832	−0.0699
North Durham	0.33	0.0100	0.0047	0.0551	0.0533	0.1987	0.2086	0.0694	0.6076	−0.0832	−0.0850
SGWASA	0.33	0.0070	0.0033	0.0007	0.0039	0.0042	0.1987	0.2086	0.0698	0.6090	−0.1363

Note: Assumes an algal meal price of \$0.33/kg; a nitrogen fertilizer price of \$.4725/kg; a price of biodiesel of \$1.05/L; and a TMDL reduction of 100 kg (TN removal price = \$5.51/kg). All results are shown on a per-year basis.

decision variables in the optimization are the scale of annual algae cultivation at each site (A_i). Results are shown with and without a nutrient trading market in place. They assume an algal meal price of \$0.33/kg, a nitrogen fertilizer price of \$0.4725/kg, and a biodiesel price of \$1.05/L, which are all equivalent to average historical prices (IndexMundi 2018; Jones 2016; US Department of Energy 2016.). A TMDL reduction of 100 kg/day is assumed for illustrative purposes, yielding a market price of TN removal of \$5.51/kg, where applicable.

Impact of Site-Specific Parameters

Among the key financial outputs tracked (revenues from selling algal meal, TN removal and selling biodiesel, as well as capital and operating expenses), Table 2 shows that only two (revenues from selling algal meal and biodiesel) are not affected by choice of WWTP. Per-unit TN removal from a WWTP's waste stream tracks directly with effluent concentration (algae removes more TN per unit algae at plants with higher C_i). Avoided fertilizer costs also vary with C_i across WWTPs, because it is assumed that all TN extracted is directly taken up by algae cultivation. As a result, operating expenses for the algae producer increase/decrease based on effluent concentration. Per-unit capital expenses also vary on a plant-by-plant basis, scaling directly with per hectare costs for non-irrigated cropland.

Impact of TN Market Condition

The absence/presence of a nutrient trading market impacts per-unit profits for algae producers, calculated as per-unit revenues (from the sale of algal meal, biodiesel, TN removal services) minus costs (capex and opex). If a market is in place, the theoretical price for TN removal is set by demand (i.e., the TMDL reduction required) (Fig. 4). This price is then applied uniformly to all TN removed by algae throughout the basin. Without a nutrient trading market in place, however, revenues from TN removal vary as a function of the \$/kg avoided costs at each WWTP, which range from \$5.14/kg (Neuse River) to \$7.87/kg (Benson).

Table 2 can be used to compare algae profitability at different locations in the Neuse River basin under both nonmarket and market conditions. A TN removal demand of 100 kg/day is assumed, yielding a TN removal price of \$5.51/kg under market conditions. At this level of TN removal demand, the presence of a trading market increases profitability of algae production located next to WWTPs with on-site treatment costs below \$5.51/kg, relative to a nonmarket scenario. At the same time, it decreases per-unit profitability for algae production located next to WWTPs with TN removal costs higher than \$5.51/kg.

Note that across both market conditions, per-unit profitability is negative at every plant, suggesting that investment in algae production is not financially viable under any condition. This was not an unexpected result—algal biofuel is known to not yet be commercially viable.

Although it is not reflected in Table 2, it is important to note that the presence/absence of a nutrient trading market also impacts the objective functions of both algae producers and WWTPs by increasing/decreasing the maximum amount of saleable TN removal at each WWTP. If a nutrient trading market is in place, maximum saleable TN is equal to all recoverable TN in a WWTP's waste stream; without a nutrient trading market in place; however, maximum saleable TN is set equal to the amount of TN that would be removed if conventional technology were used to achieve a target concentration of 3 mg/L. This assumption is based on the premise that, in the absence of permissible nutrient trading, there is no financial incentive for a WWTP to reduce its effluent concentration below the legally required amount.

Optimization Results

The NSGA-II algorithm is used to optimize algae cultivation at WWTPs in the basin according to two different objectives: (1) maximize annual profits for algae producers; and (2) minimize the cost of meeting a stricter TMDL, aggregated across all WWTPs. A single set of decision variables, the amount of algae produced at each WWTP (A_i), controls the value of each objective function. The optimization is performed for six scenarios: three different TMDL reductions (50, 75, and 100 kg); and two market conditions (with and without nutrient trading).

Table 3 summarizes financial outcomes for each scenario. Tradeoffs between the two objectives were found in every case, i.e., higher profits for algae producers are associated with a higher cost of meeting downstream water quality standards. Thus, results are reported in Table 3 in terms of the minimum and maximum objective function values discovered in the nondominated set. At greater TMDL reductions, greater levels of algae cultivation (TN removal) are required and WWTP costs increase. At the same time, because per-unit profitability of algae production is negative, algae producers' losses grow as a function of TMDL reduction.

Some differences in financial outcomes across the market and nonmarket scenarios are noticeable. For example, the presence of a nutrient trading market generally results in slightly lower WWTP costs. Although this is consistent with the theoretical impacts of water quality markets, given the relatively minor differences shown, some of this effect may be attributable to variable performance of the NSGA-II algorithm.

The presence of a nutrient trading market also increases algae profits (i.e., decreases losses), relative to a nonmarket scenario. This positive effect becomes more prominent as a function of TMDL reduction (i.e., improvement is much larger for a 100 kg reduction than it is for a 50 kg reduction). This suggests that the additional flexibility in siting algae production afforded by the

Table 3. Financial outcomes for algae producers and WWTPs under both market and nonmarket conditions, for each of the three TMDL reduction levels tested

		TMDL reduction (kg/day)					
		50		75		100	
Condition	Profits/costs	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Market	Algae profits (\$1000s/year)	−320.65	−305.3	−495.85	−479.16	−651.1	−633.14
	WWTP costs (\$1000s/year)	140	159.76	215.48	236.05	310.25	332.51
Nonmarket	Algae profits (\$1000s/year)	−359.88	−321.88	−544.31	−502.12	−792.27	−696.27
	WWTP costs (\$1000s/year)	140.82	169.36	213.09	239.57	312.65	366.53

Note: For nonmarket conditions a range of values is shown, which spans the estimated Pareto frontier.

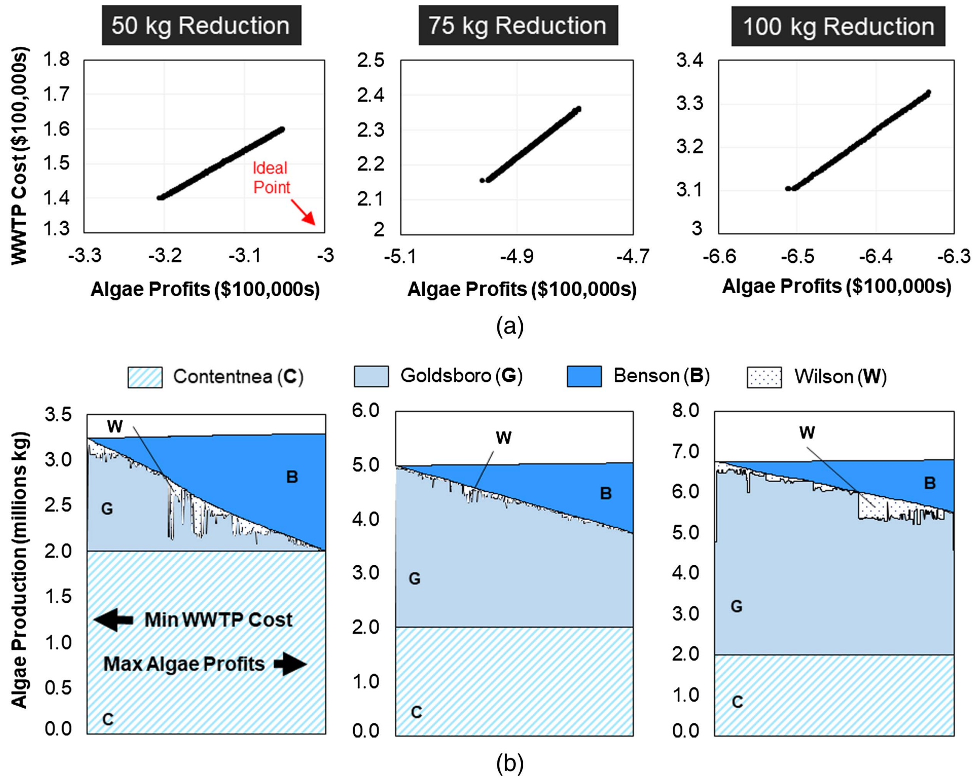

Fig. 5. Optimization results for the market scenarios (50, 75, and 100 kg TMDL reductions): (a) tradeoff frontiers between algae profitability and WWTP costs; and (b) amount of algae produced at each WWTP for every point along the tradeoff frontier. Algae profits are shown on a per-year basis.

presence of a market becomes more valuable as the scale of algae required production increases.

There is also considerable interest in understanding how tradeoffs between maximizing algae producers' profits and minimizing WWTP treatment costs manifest as differences in the optimal location of algae cultivation in the watershed. Fig. 5 shows optimization results for the three levels of TMDL reduction with a nutrient trading market in place. The panels in Fig. 5(a) show the nondominated set of solutions as a tradeoff frontier. Note that the ideal point would be a treatment cost of \$0 and positive algae profits (toward the bottom-right vertex). Across each of the three TMDL reduction levels, the tradeoff frontiers span a range of approximately \$20,000 per year for each objective function; this is effectively the difference between a best-case and worst-case scenario for each stakeholder group.

The panels in Fig. 5(b) show how the location of algae production at WWTPs in the basin changes as the tradeoff frontier is traversed. Colors/letters indicate production at a given WWTP. Algae production indicated at the left edge of the bottom panels maximize algae profits; production indicated at the right edge minimize WWTP costs; in between are production levels that achieve intermediate values of each objective.

Fig. 5 shows that under market conditions, the optimal placement of algae cultivation from the producer's standpoint is at the Contentnea and Benson WWTPs. These plants have high effluent concentrations, which increase the amount of nitrogen removed (fertilizer replaced, nutrient credits sold) per unit of algae. Optimal placement of algae cultivation from the WWTPs' standpoint is different; namely, production shifts away from the Benson WWTP to the Goldsboro WWTP. This shift is attributable to the Goldsboro WWTP having a higher transfer coefficient (0.7) than the Benson WWTP (0.5), which means that TN removed from the Goldsboro WWTP's waste stream counts more toward achieving the TMDL reduction. This in turn reduces the total amount of nitrogen removal (and by extension, algae cultivation) needed to meet the water quality standard.

Note that a higher TMDL reduction level increases the total amount of algae cultivation required, but it does not significantly affect the gradual shift in production from Benson WWTP to Goldsboro WWTP. In order to achieve progressively higher TMDL reductions, production at the Goldsboro WWTP is simply increased, an option that is only available due to the presence of a nutrient trading market.

Fig. 6 shows an analogous set of results for the three TMDL reduction scenarios without a nutrient trading market in place. The tradeoff frontiers shown in Fig. 6(a) are noticeably different than what are shown in Fig. 5; this is due to fewer nondominated solutions being identified over 50,000 generations of the NSGA-II algorithm. There are also differences apparent in the panels of Fig. 6(b). Namely, at each TMDL reduction level, a more diverse group of WWTPs is required to meet the treatment target, relative to scenarios in which a nutrient trading market is in place (Fig. 5). This is directly due to the assumption that, in the absence of a nutrient trading market, algae producers are not paid for any TN removal beyond that which is required to achieve an effluent concentration of 3 mg/L. As a consequence, production of algae occurs on a more limited scale at each individual WWTP. This is especially evident at high TMDL reduction levels (e.g., 100 kg), when a considerable amount of algae cultivation must be achieved using production distributed among 6–8 different WWTPs (whereas only 2–3 plants would be required with a market in place). Note that the left to right trend in allocation of algae cultivation across WWTPs shows a similar trend to that in Fig. 5, in which production shifts away from the plants with higher effluent

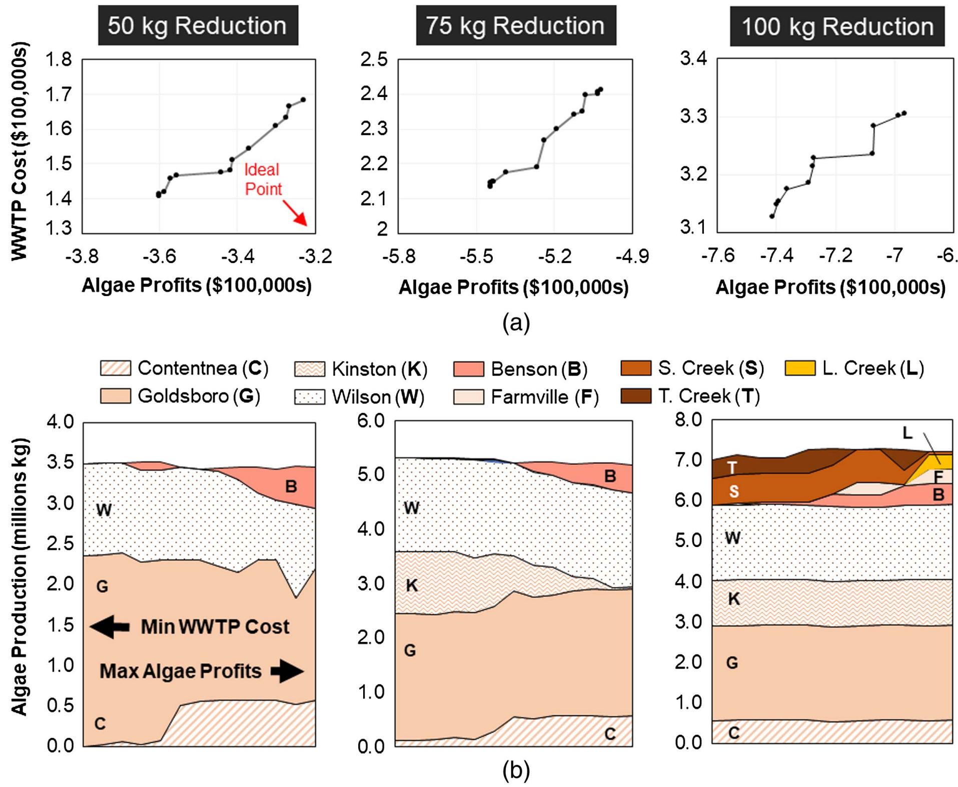

Fig. 6. Optimization results for the nonmarket scenarios (50, 75, and 100-kg TMDL reductions): (a) tradeoff frontiers between algae profitability and WWTP costs; and (b) amount of algae produced at each WWTP for every point along the tradeoff frontier. Algae profits are shown on a per-year basis.

concentrations (which helps maximize algae profits) to ones with higher transfer coefficients (which help minimize the cost of meeting the TMDL).

In both the market and nonmarket results, the impacts of site-to-site differences in land availability are also apparent. For example, in neither Fig. 5 nor Fig. 6 is any level of algae production indicated at the New Bern WWTP, despite the fact that this plant has a transfer coefficient of 1.0 (making algae production there extremely valuable from a water treatment standpoint). In the case of the New Bern WWTP, its location in a wooded coastal area precludes its consideration for algae cultivation. In other cases, e.g., North Durham WWTP and North Cary WWTP, a combination of local topography, wooded areas and urban development preclude any algae production due to a lack of viable land.

Sensitivity Analysis

Figs. 7 and 8 show the results of a sensitivity analysis designed to explore the impacts of uncertainty in the four main site parameters (effluent concentrations, transfer coefficients, land costs and maximum algae production) on objective function values. In each panel, the lighter circles represent nondominated solutions generated under alternative watershed configurations in which the specified WWTP parameter is randomly reassigned for each plant, with all others held constant. This information is plotted alongside the original trade-off frontier (black) for a TMDL reduction of 50 kg.

Fig. 7 shows results with a trading market in place. Both objective functions demonstrate sensitivity to alternative watershed configurations under a market scenario, but responses vary significantly by parameter. For example, randomly reassigning effluent concentrations is capable of increasing or decreasing algae profits, because effluent concentrations determine the amount of TN removed per unit of algae, but exploring uncertainty in effluent concentrations show very little ability to reduce WWTP costs, which (at least in the Neuse River basin) are currently more constrained by other factors. Likewise, reassigning land costs alters algae profits, but not WWTP costs. In a market environment, the primary controls on WWTP costs are transfer coefficients and the maximum amount of algae production possible at each plant, which is a function of both land and nutrient availability. Uncertainty in these parameters is shown to disproportionately reduce WWTP costs, suggesting that the actual configuration of the Neuse River basin would be constrained in its objective of minimizing the cost of meeting the downstream TMDL via algae based treatment. Note as well that alternative watershed configurations in which the transfer coefficients are different demonstrate improved algae profits as well, but altering maximum algae capacity at each plant has a limited ability to do so.

A similar pattern emerges in Fig. 8, which shows analogous results for a nonmarket scenario. Uncertainty in transfer coefficients and maximum algae capacity has an ability to significantly alter WWTP costs, whereas altered values of other parameters (effluent concentration and land costs) have no effect.

Note, however, that the responses of both objective functions to random reassignment of both transfer coefficients and maximum algae capacity are different from those under a market scenario (Fig. 7). In particular, altered values of both parameters demonstrate an equal ability to increase or decrease WWTP costs, and the responses are in general much stronger. This suggests that without a nutrient trading market in place, economic performance of a combined algal biofuel–WWTP project may depend more heavily on the specific watershed configuration. In some cases, nutrient trading markets in some cases appear to even provide a protective effect. At least with regard to uncertainty in maximum algae

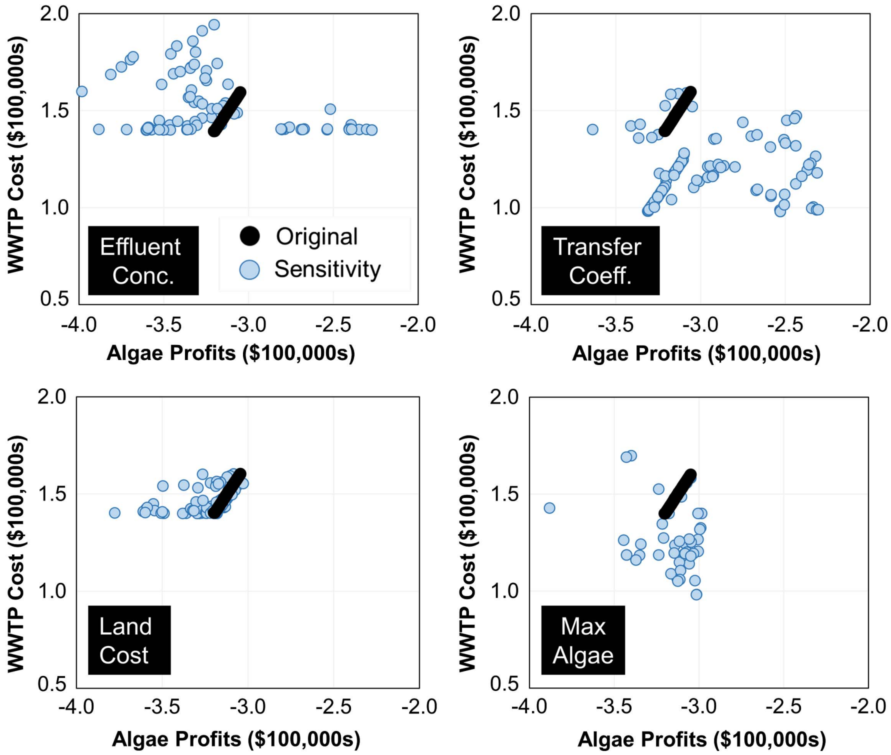

Fig. 7. Results of sensitivity analysis for the market scenario, assuming a TMDL reduction of 50 kg. Algae profits are shown on a per-year basis.

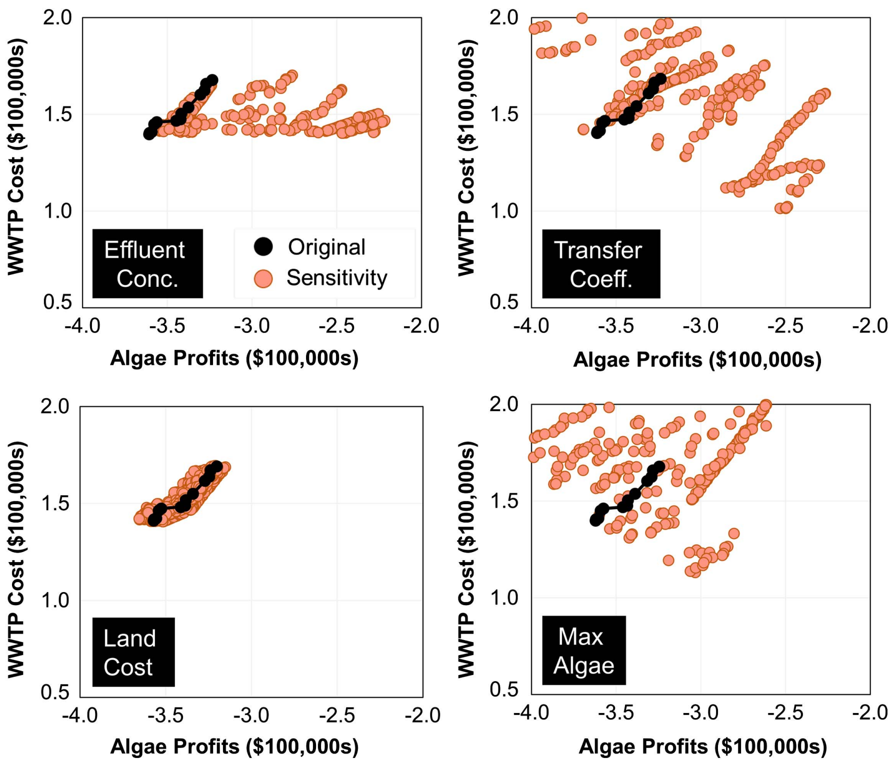

Fig. 8. Results of sensitivity analysis for nonmarket scenario, assuming a TMDL reduction of 50 kg TN. Algae profits are shown on a per-year basis.

cultivation and nutrient transfer coefficients, trading markets prevent less ideal outcomes in both objective functions, as evidenced by significantly fewer solutions found in the upper left quadrant of the relevant panels in Fig. 7. This finding is in line with a motivating hypothesis of this study, which is the idea that the presence of nutrient trading markets may improve financial outcomes for algae producers by increasing flexibility in siting algal biofuel projects within networks of WWTPs. However, a comparison across the market and nonmarket scenarios (Figs. 7 and 8) in terms of effluent concentration reveal the reverse effect, with the presence of markets showing greater potential for degradation in both objective functions. This suggests that the added flexibility afforded by nutrient trading markets may apply unevenly across site parameters.

Conclusion

This study develops and tests an analytical framework for optimizing the siting of algal biofuel production facilities within networks of municipal WWTPs, and evaluating the sensitivity of modeled outcomes to alternative watershed configurations. At the heart of this framework is a LCA/TEA model for an algal biofuel facility linked to a simplified watershed model, which characterizes WWTPs in terms of several key parameters, including effluent concentration, nutrient transfer coefficients, land costs and land availability. Site-specific differences in these parameters are shown to drive tradeoffs between two competing objectives: maximizing profits from producing algae, and minimizing the cost of meeting a required TMDL reduction for a downstream estuary. Results suggest that different WWTPs would be prioritized to optimize these two different objectives, but the worst-case scenario for either objective involves a modest penalty of roughly \$20,000 per year.

This study also examines the potential role of nutrient trading markets, which allow TN removal from algae to be monetized anywhere in the watershed. Results suggest that the presence of nutrient trading markets can be important for improving financial outcomes for both algae producers and WWTPs. There is also evidence that nutrient trading markets reduces the sensitivity of financial outcomes to uncertainty in WWTP parameters like TN transfer coefficients and maximum algae capacity.

Areas of future work in this area could include a more dynamically modeled representation of watershed processes and algal biofuel plant operations. The approach used in this study optimizes the objective functions on an expected value basis. However, it is possible to model the system at a higher (subannual) resolution, solving the multiobjective problem over ensembles of 30-year simulations of effluent discharge and concentration, as well as TN transfer coefficients, which are likely to depend on underlying hydrologic conditions. This would allow for the inclusion of additional objectives, namely probabilistic performance measures (e.g., financial risk) and regulatory adherence.

As the development of algae technologies continues (costs drop and potential applications broaden), understanding how these highly engineered systems interact with other sectors (water, agriculture, and electric power) in an industrial ecology context is becoming a more pressing need. This study simultaneously represents an advance in this area and provides a decision-oriented framework for navigating complexities involved in the synergistic pairing of algae production and wastewater treatment.

Data Availability Statement

The code used for solving both market and nonmarket scenarios is available online at https://github.com/romulus97/Biofuels/tree/master/NSGA2.

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References

American Rivers. 2017. "Neuse: River of peace." Accessed August 6, 2017. https://www.americanrivers.org/river/neuse-river/.

Beal, C., L. Gerber, D. Sills, M. Huntley, S. Machesky, M. Walsh, and C. Greene. 2015. "Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment." *Algal Res.* 10 (Jul): 266–279. https://doi.org/10.1016/j.algal.2015.04.017.

Behrendt, H., and D. Opitz. 2000. "Retention of nutrients in river systems: Dependence on specific runoff and hydraulic load." *Hydrobiologica* 410: 111–122. https://doi.org/10.1023/A:1003735225869.

Branke, J., K. Deb, K. Miettinen, and R. Slowinski. 2008. *Multiobjective optimization: Interactive and evolutionary approaches*. Edited by J. Branke, K. Deb, K. Miettinen, and R. Slowinski. Berlin: Springer.

Cai, T., S. Park, and Y. Li. 2013. "Nutrient recovery from wastewater streams by microalgae: Status and prospects." *Renewable Sustainable Energy Rev.* 19 (Mar): 360–369. https://doi.org/10.1016/j.rser.2012.11.030.

Cheah, W., T. Ling, P. Show, J. Juan, J. Chang, and D. Lee. 2016. "Cultivation in wastewaters for energy: A microalgae platform." *Appl. Energy* 179 (Oct): 609–625. https://doi.org/10.1016/j.apenergy.2016.07.015.

Chisti, Y. 2007. "Biodiesel from microalgae." *Biotechnol. Adv.* 25 (3): 294–306. https://doi.org/10.1016/j.biotechadv.2007.02.001.

Cho, S., T. T. Luong, D. Lee, Y.-K. Oh, and T. Lee. 2011. "Reuse of effluent water from a municipal wastewater treatment plant in microalgae cultivation for biofuel production." *Bioresour. Technol.* 102 (18): 8639–8645. https://doi.org/10.1016/j.biortech.2011.03.037.

Chowdhury, R., S. Viamajala, and R. Gerlach. 2011. "Reduction of environmental and energy footprint of microalgal biodiesel production through material and energy integration." *Bioresour. Technol.* 108 (Mar): 102–111. https://doi.org/10.1016/j.biortech.2011.12.099.

Clarens, A., E. Resurreccion, M. White, and L. Colosi. 2010. "Environmental life cycle comparison of algae to other bioenergy feedstocks." *Environ. Sci. Technol.* 44 (5): 1813–1819. https://doi.org/10.1021/es902838n.

Davis, R., C. Kinchin, J. Markham, E. Tan, L. Laurens, D. Sexton, and J. Lukas. 2014. *Process design and economics for the conversion of algal biomass to biofuels: Algal biomass fractionation to lipid and carbohydrate-derived fuel products*. Golden, CO: National Renewable Energy Laboratory.

Davis, R., J. Markham, C. Kinchin, N. Grundl, E. Tan, and D. Humbird. 2016. *Process design and economics for the production of algal biomass: Algal biomass production in open pond systems and processing through dewatering for downstream conversion*. Golden, CO: National Renewable Energy Laboratory.

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan. 2002. "A fast elitist multi-objective genetic algorithm: NSGA-II." *IEEE Trans. Evol. Comput.* 6 (2): 182–197. https://doi.org/10.1109/4235.996017.

de Moraes, M., X. Cai, C. Ringler, B. Albuquerque, S. da Rocha, and A. Amorim. 2010. "Joint water quantity-quality management in a biofuel production area—Integrated economic-hydrologic modeling analysis." *J. Water Resour. Plann. Manage.* 136 (4): 502–511. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000049.

Doyle, M., L. Patterson, Y. Chen, K. Schnier, and A. Yates. 2014. "Optimizing the scale of markets for water quality trading." *Water Resour. Res.* 50 (9): 7231–7244. https://doi.org/10.1002/2014WR015395.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. "Land clearing and the biofuel carbon debt." *Science* 319 (5867): 1235–1238.

Frank, E., J. Han, I. Palou-Rivera, A. Elgowainy, and M. Wang. 2011. *Life-cycle analysis of algal lipid fuels with the GREET model (RPRT)*. Lemont, IL: Argonne National Laboratory.

Gerber, L., J. Tester, C. Beal, M. Huntley, and D. Sills. 2016. "Target cultivation and financing parameters for sustainable production of fuel and feed from microalgae." *Environ. Sci. Technol.* 50 (7): 3333–3341. https://doi.org/10.1021/acs.est.5b05381.

Hise, A. M., G. W. Characklis, J. Kern, R. Gerlach, S. Viamajala, R. D. Gardner, and A. Vadlamani. 2016. "Evaluating the relative impacts of operational and financial factors on the competitiveness of an algal biofuel production facility." *Bioresour. Technol.* 220 (Nov): 271–281. https://doi.org/10.1016/j.biortech.2016.08.050.

IndexMundi. 2018. "Soybean meal." Accessed May 5, 2018. http://www.indexmundi.com/commodities/.

Jones, A. 2016. "Agricultural chemical companies: Crop and fertilizer price impact [ICOMM]." Accessed July 18, 2017. http://marketrealist.com/2016/06/chart-key-fertilizer-stocks/.

Jones, S., Y. Zhu, D. Anderson, D. Elliott, A. Schmidt, K. Albrecht, and C. Kinchin. 2014. *Process design and economics for conversion of algal biomass to hydrocarbons: Whole algae hydrothermal liquefaction and upgrading (RPRT)*. Richland, WA: Pacific Northwest National Laboratory.

Kern, J. 2018. "Biofuels." Accessed October 12, 2018. https://www.github.com/romulus97/Biofuels/core_model.

Kern, J. D., A. M. Hise, G. W. Characklis, R. Gerlach, S. Viamajala, and R. D. Gardner. 2017. "Using life cycle assessment and techno-economic analysis in a real options framework to inform the design of algal biofuel production facilities." *Bioresour. Technol.* 225 (Feb): 418–428. https://doi.org/10.1016/j.biortech.2016.11.116.

Konak, A., D. Coit, and A. Smith. 2006. "Multi-objective optimization using genetic algorithms: A tutorial." *Reliab. Eng. Syst. Saf.* 91 (9): 992–1007. https://doi.org/10.1016/j.ress.2005.11.018.

Lundquist, T., I. Woertz, N. Quinn, and J. Benemann. 2010. *A realistic technology and engineering assessment of algae biofuel production*. Berkeley, CA: Energy Biosciences Institute.

McLawhorn, D. 2016. "Neuse River Compliance Association 2016 annual report." Accessed July 18, 2017. https://lnba.net/system/files/2016NRCAAnnualReport33017.pdf.

Mulholland, P. J. 2004. "The importance of in-stream uptake for regulating stream concentrations and outputs of N and P from a forested watershed: Evidence from long-term chemistry records for Walker Branch Watershed." *Biogeochemistry* 70 (3): 403–426. https://doi.org/10.1007/s10533-004-0364-y.

Ng, T., J. Eheart, X. Cai, and J. Braden. 2014. "Agronomic and stream nitrate load responses to incentives for bioenergy crop cultivation and reductions of carbon emissions and fertilizer use." *J. Water Resour. Plann. Manage.* 140 (1): 112–120. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000320.

Nutrient Reduction Technology Cost Task Force. 2002. *Nutrient reduction technology cost estimations for point sources in the Chesapeake bay watershed*. Annapolis, MD: Chesapeake Bay Program.

Pittman, J., A. Dean, and O. Osundeko. 2011. "The potential of sustainable algal biofuel production using wastewater resources." *Bioresour. Technol.* 102 (1): 17–25. https://doi.org/10.1016/j.biortech.2010.06.035.

Quinn, J., and R. Davis. 2014. "The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling." *Bioresour. Technol.* 184 (May): 444–452. https://doi.org/10.1016/j.biortech.2014.10.075.

Stephens, E., I. Ross, Z. King, J. Mussgnug, O. Kruse, C. Posten, and B. Hankamer. 2010. "An economic and technical evaluation of microalgal biofuels." *Nat. Biotechnol.* 28 (2): 126–128. https://doi.org/10.1038/nbt0210-126.

US Department of Agriculture. 2016. USDA national agricultural statistics service surveys. Accessed August 22, 2017. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Cash_Rents_by_County/.

US Department of Agriculture, N. R. C. S. 2018. "Environmental feature markets: Stoking demand for nutrient credits in Virginia: Good news for farmers and for the Chesapeake Bay." Accessed May 1, 2018. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/emkts/?cid=nrcseprd354814.

US Department of Energy. 2016. "Alternative fuels data center." Accessed October 20, 2016. http://www.afdc.energy.gov/fuels/prices.html.

USEPA (US Environmental Protection Agency). 2007. "NPDES watershed-based permitting case studies: Neuse River watershed, North Carolina." Accessed July 18, 2017. https://www.epa.gov/sites/production/files/2015-09/documents/wq_casestudy_factsht11.pdf.

USEPA (US Environmental Protection Agency). 2011. "Waters assessed as impaired due to nutrient-related causes." Accessed August 10, 2017. https://www.epa.gov/nutrient-policy-data/waters-assessed-impaired-due-nutrient-related-causes.

USEPA (US Environmental Protection Agency). 2015. *A compilation of cost data associated with the impacts and control of nutrient pollution*. Washington, DC: USEPA.

USEPA (US Environmental Protection Agency). 2018. "Frequently asked questions about water quality trading." Accessed May 1, 2018. https://www.epa.gov/npdes/frequently-asked-questions-about-water-quality-trading.

Willamette Partnership. 2012. *In it together: A how-to reference for building point-nonpoint water quality trading programs (Part 1 of 3)*. Hillsboro, OR: Willamette Partnership.

Williams, M., C. Hopkinson, E. Rastetter, and J. Vallino. 2004. "N budgets and aquatic uptake in the Ipswich River basin, northeastern Massachusetts." *Water Resour. Res.* 40 (11): W11201. https://doi.org/10.1029/2004WR003172.

Woertz, I., A. Feffer, T. Lundquist, and Y. Nelson. 2009. "Algae grown on dairy and municipal wastewater for simultaneous nutrient removal and lipid production for biofuel feedstock." *J. Environ. Eng.* 135 (11): 1115–1122. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000129.