Coupling Greenhouse Gas Credits with Biofuel Production Cost in Determining Conversion Plant Size

Jianbang Gan and C.T. Smith

Biofuel plant size is one of the key variables in biofuel supply chain analysis as it plays a pivotal role in controlling the efficacy of both feedstock supply and feedstock-to-biofuel conversion. The unit production cost and greenhouse gas (GHG) balance of biofuels vary with plant size. We develop an analytical framework for integrating biofuel production costs and GHG balance derived from life-cycle analysis into supply chain optimization, followed by its application to ethanol production using forest biomass in the southern United States. We derive formulas for determining the optimal biofuel plant size and the corresponding feedstock supply radius based on the minimization of biofuel production costs less GHG benefits. Our results indicate that though biofuel plant size and feedstock supply radius should be augmented by considering GHG benefits, the GHG price will have a more significant impact on net biofuel production costs than on conversion plant size or feedstock supply radius. With a rise in the GHG price the net biofuel production cost tends to increase while the directions of change in plant size and feedstock supply radius are uncertain, depending upon the costs and GHG emissions of biomass transport and feedstock-to-fuel conversion. Combining GHG offset values with biofuel production costs enables us to more holistically examine the biofuel supply chain.

1 Introduction

Our renewed interest in biofuels has been in large part due to their potential for displacing greenhouse gas (GHG) emissions from burning fossil fuels. Although this potential has been widely discussed, methods for incorporating it into decision-making in biofuel development and deployment have not been well developed. Further, carbon balance varies considerably across different types of biofuels and different production processes and systems (Kennedy 2007). For instance, cellulosic ethanol produced from sustainable feedstock sources generally can offset more CO_2 emissions than corn or grain ethanol because the former requires less input to produce. The boundaries of analyses/systems also matter. When land use change and transnational carbon leakage are accounted for, ethanol produced from corn, corn stover, and herbaceous biomass may generate net GHG emissions rather than offsets (Seachinger et al. 2008). Hence, decisions on biofuel development and deployment should be based on sound analyses of its entire value chain, including the values of GHG emission offsets among other benefits and costs.

Biofuel conversion plant size is a pivotal factor in the biofuel supply chain. On the one hand, the choice of plant size directly influences feedstock-to-biofuel conversion costs as suggested by the economies of scale. On the other hand, plant size determines feedstock transport distance and ultimately feedstock hauling costs. Thus, there exists an optimal plant size and a corresponding feedstock supply radius that minimizes the total biofuel production cost (Gan and Smith 2009). This is also true for GHG emission offset on a unit biofuel basis. Too large or too small a plant will increase GHG emissions from one unit of biofuel produced.

With these in mind, we develop an analytical framework for determining the optimal biofuel plant size, optimal feedstock supply radius, and minimum net biofuel production costs. Our approach incorporates feedstock production, feedstock-to-biofuel conversion, and life-cycle GHG balance. It minimizes biofuel production costs (including the costs of biomass and biomass-to-biofuel conversion) (Gan and Smith 2009) less GHG offset values from the entire biofuel life cycle (from well to wheel) (Wang et al. 2007). Its application is illustrated using the case of producing ethanol from forest biomass in the U.S. This approach is unique by integrating biofuel supply chain optimization with GHG offsets derived from life-cycle analysis. As such, our results provide useful guidance for more prudent and comprehensive decision-making in biofuel development and deployment.

2 Theoretic Framework

Building on our previous work (Gan and Smith 2009), we attempt to couple net GHG emissions with cost minimization in decision analysis. Per-unit biofuel production costs vary with plant size, which also defines feedstock supply radius. As plant size increases, biomass transport distance rises, leading to higher per-unit biomass transport costs (Cameron et al. 2007, Gan 2007). On the other hand, per-unit costs of converting feedstock to bioenergy decrease as plant size increases due to the economies of scale (Jenkins 1997, Kumar et al. 2003, Gallagher et al. 2005). The cost-minimizing plant size (S^*) and corresponding feedstock supply radius (R^*) can be determined via minimizing total per-unit biofuel production costs (Gan and Smith 2009). Namely see Eq. 1, where *HC* is the biomass hauling cost; *CC* is the feedstock-to-energy conversion cost; *FC* is all other costs such as the costs of growing, harvesting/gathering, processing, loading/unloading, and storing biomass feedstock, which for simplicity are assumed to be independent of conversion plant size [1]; *S* is the scale of the conversion plant; ϕ is the proportion of the land where biomass is grown assuming a circular area; *M* is the spatial distribution density of biomass (bdt ha^{-1});

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[1] This assumption is justifiable because these costs are relatively insensitive to production scale compared with the costs of biomass hauling and feedstock-to-energy conversion though some of them may not be completely independent of conversion plant scale (Jenkins 1997). It can also be relaxed, if needed, by incorporating other scale-dependent costs into Eq. 1.

Equations 1–5

Eq. 1

$$Min_{S} \; TC = HC(S) + CC(S) + FC = 3.52 \, c_h \tau (1+\lambda) \sqrt{\frac{n\theta S}{M\varphi\varepsilon^3\eta^3}} + CC_o \left(\frac{S}{S_o}\right)^{\alpha-1} + FC$$

Eq. 2

$$S^* = \left[1.76 \frac{c_h \tau (1+\lambda)}{(1-\alpha) CC_o S_o^{1-\alpha}} \sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}} \right]^{\frac{2}{2\alpha-3}}$$

Eq. 3

$$R^* = 5.28 \left[1.76 \frac{c_h \tau (1+\lambda)}{(1-\alpha) CC_o \varepsilon^\alpha \eta^\alpha} \left(\frac{M\varphi}{n\theta S_o}\right)^{1-\alpha} \right]^{\frac{1}{2\alpha-3}}$$

Eq. 4

$$TC^* = \frac{3-2\alpha}{1-\alpha} \left\{ \frac{\left[1.76 c_h \tau (1+\lambda) \sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}} \right]^{2(\alpha-1)}}{(1-\alpha) CC_o} \right\}^{\frac{1}{2\alpha-3}} + FC$$

Eq. 5

$$NCO = a - bBTW_1 - e_o \left(\frac{S}{S_o}\right)^{a-1}$$

λ is the moisture content of biomass transported; τ is the tortuosity factor (ratio of actual distance traveled to sight distance) that reflects the existing road network; $1/n$ is the fraction of a circular biomass-producing area that can be harvested due to geographic and other constraints; θ is the conversion plant factor (operation rate); ε is the energy content of biomass (energy unit bdt^{-1}) [2]; η is the efficiency of the conversion plant (the ratio of energy output in terms of the final product to energy input in terms of feedstock); c_h is the cost per unit of biomass transportation work ($\$ \, t^{-1} \, km^{-1}$); CC_o is the cost per unit of bioenergy converted from biomass at a base scale (S_o) of the conversion plant; and α is the conversion plant scale factor (usually ranging from 0.6 to 0.9).

The solution [3] to Eq. 1 is Eq. 2.

Correspondingly, the cost-minimizing feedstock supply radius (km) is shown in Eq. 3 and the minimum possible production cost ($\$$ per unit of biofuel) is given in Eq. 4.

Now let us consider the net GHG balance (offset) of a specific biofuel in its life cycle. The net GHG balance depends upon the biofuel production process/system and conversion plant scale. Obviously, for a given production system, GHG offset diminishes as biomass transport distance increases to support a larger plant (assuming that fossil fuels are used in transporting feedstock). On the other hand, a larger plant tends to be more efficient than a smaller one in terms of offsetting GHG emissions because of improved efficiency in energy conversion among other things. Hence, we assume that the net GHG (CO_2 equivalent) offset (NCO) of the biofuel can be measured by using Eq. 5,

where BTW_1 is the biomass transport work required to produce one unit of biofuel; e_o is the GHG emissions from the conversion plant for producing one unit of biofuel at the base scale S_o; a and b are positive coefficients with a representing the maximum GHG offset per unit of biofuel and b the GHG emissions from transporting the feedstock required to produce one unit of biofuel

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[2] The energy unit here should be the same unit as used for plant scale (S). Otherwise, a unit conversion is needed for the equation to be valid.

[3] Details about the derivation of optimal plant size, optimal feedstock supply radius, and minimum production cost can be found in (Gan and Smith 2009).

Equations 6–9

Eq. 6 $BTW = 3.0838 \times 10^4\, \tau(1+\lambda)\sqrt{\dfrac{n\theta^3 S^3}{M\varphi\varepsilon^3\eta^3}}$ (t km)

Eq. 7 $BTW_1 = \dfrac{BTW}{365\,(days) \times 24\,(hours)\,\theta S} = 3.52\,\tau(1+\lambda)\sqrt{\dfrac{n\theta S}{M\varphi\varepsilon^3\eta^3}}$ (t km per energy unit)

Eq. 8 $NCO = a - 3.52\,b\tau(1+\lambda)\sqrt{\dfrac{n\theta S}{M\varphi\varepsilon^3\eta^3}} - e_o\left(\dfrac{S}{S_o}\right)^{\alpha-1}$

Eq. 9

$$\underset{S}{Min}\quad TC_c = HC(S) + CC(S) + FC - P_c NCO$$

$$= 3.52\,c_h\tau(1+\lambda)\sqrt{\frac{n\theta S}{M\varphi\varepsilon^3\eta^3}} + CC_o\left(\frac{S}{S_o}\right)^{\alpha-1} + FC - P_c\left[a - 3.52b\tau(1+\lambda)\sqrt{\frac{n\theta S}{M\varphi\varepsilon^3\eta^3}} - e_o\left(\frac{S}{S_o}\right)^{\alpha-1}\right]$$

$$= 3.52\tau(1+\lambda)\sqrt{\frac{n\theta S}{M\varphi\varepsilon^3\eta^3}}\left(c_h + bP_c\right) + (CC_o + e_o P_c)\left(\frac{S}{S_o}\right)^{\alpha-1} + FC - aP_c$$

one km; and all other symbols are the same as described earlier.

According to Gan and Smith (2009), the total transportation work of feedstock required for the plant size of S is given in Eq. 6.

Thus, the biomass transport work required for producing one unit of biofuel is presented in Eq. 7.

Substituting Eq. 7 into Eq. 5 yields the Eq. 8.

Now we can couple the value of GHG offset with biofuel production cost. The net total biofuel production cost after accounting for the GHG offset value is given in Eq. 9, where P_c is the price of GHG offset. Solving this problem will derive the optimal biofuel plant size.

3 Analytical Results

3.1 Optimal Plant Size, Optimal Feedstock Supply Radius, and Production Cost

The first-order necessary condition for the minimization problem of Eq. 9 is given in Eq. 10.

Solving for S, we derive the optimal biofuel plant size as is presented in Eq. 11.

Based on Gan and Smith (2009), the relationship between feedstock supply radius and biofuel plant size is presented in Eq. 12.

Substituting Eq. 11 into Eq. 12 (see Appendix A) and into Eq. 9 (see Appendix B) respectively gives rise to optimal feedstock supply radius (R_c^*) presented in Eq. 13 and minimum net biofuel production cost (TC_c^*) when GHG benefits/costs are valued as given in Eq. 14.

3.2 Sensitivity Analysis

Sensitivity analysis is performed to measure both directions and magnitude of the impacts of changes in factor values on the optimal biofuel plant size, optimal feedstock supply radius, and

Equations 10–14

Eq. 10
$$\frac{dTC_c}{dS} = 1.76\tau(1+\lambda)\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3 S}}\left(c_h + bP_c\right) + (\alpha - 1)(CC_o + e_o P_c)\frac{S^{\alpha-2}}{S_o^{\alpha-1}} \equiv 0$$

Eq. 11
$$S_c^* = \left[\frac{1.76\tau(1+\lambda)\left(c_h + bP_c\right)}{(1-\alpha)(CC_o + e_o P_c)S_o^{1-\alpha}}\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}}\right]^{\frac{2}{2\alpha-3}}$$

Eq. 12
$$R = 5.28\sqrt{\frac{n\theta S}{M\varphi\varepsilon\eta}} \quad (km)$$

Eq. 13
$$R_c^* = 5.28\left[\frac{1.76\tau(1+\lambda)\left(c_h + bP_c\right)}{(1-\alpha)(CC_o + e_o P_c)\varepsilon^\alpha\eta^\alpha}\left(\frac{M\varphi}{n\theta S_o}\right)^{1-\alpha}\right]^{\frac{1}{2\alpha-3}}$$

Eq. 14
$$TC_c^* = \frac{3-2\alpha}{1-\alpha}\left\{\frac{1.76\left[\tau(1+\lambda)(c_h + bP_c)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}\right]^{2(\alpha-1)}}{(1-\alpha)(CC_o + e_o P_c)}\right\}^{\frac{1}{2\alpha-3}} - aP_c + FC$$

net production cost (total production costs less GHG offset value). Taking partial derivatives of Eqs. 2, 3, and 4 for the case without considering GHG offset values and Eqs. 11, 13, and 14 for the case with consideration for GHG offset values reveals the direction of impact of each factor on the optimal plant size, feedstock supply radius, and net production cost, respectively. Yet the magnitude of changes is difficult to be inspected in this way for some variables due to nonlinear functions involved. Thus, we use elasticity, percentage change in plant size, supply radius, or net production costs due to a 1% change in the value of a specific factor, to measure sensitivity. The elasticity is computed by taking the logarithms of the above equations and then their partial derivatives with respect to a specific variable.

3.2.1 Plant Size

By inspection, Eq. 11 reveals that for $0 < \alpha < 1$ the optimal biofuel plant size increases with a decrease in c_h, b, τ, λ, n, and θ or an increase in ε, η, CC_o, e_o, M, and ϕ. This suggests that a larger conversion plant is more cost-effective with a fall in feedstock transportation cost, GHG emissions

resulting from transporting feedstock, tortuosity factor, moisture content of feedstock transported, fragmentation of the lands where feedstock is grown, and conversion plant operation rate or a rise in feedstock energy content, GHG efficiency and cost of converting feedstock to fuel, feedstock spatial distribution density, and concentration of the lands used to grow feedstock. The effect of the GHG price on the optimal plant size depends upon the sign of $c_h e_o - bCC_o$ (Appendix C, (a)). If $c_h e_o > bCC_o$, an increase in the GHG price will lead to a bigger plant. A rise in the GHG price will have no (a negative) impact on the optimal plant size if $c_h e_o = (<) bCC_o$. And, the optimal plant size increases as scale factor rises, which is not easy to see directly from the equation but will be demonstrated by simulation later.

The sensitivity of the optimal plant size to a change in a variable/factor is shown in Table 3. The results confirm the direction of change in plant size due to changes in the values of c_h, τ, λ, n, θ, ε, η, CC_o, M, and ϕ as discussed above. Besides, the elasticities reveal the magnitude of the impacts. The optimal plant size is much more sensitive to a change in feedstock energy content and feedstock-to-energy conversion efficiency than a change in any other factor.

3.2.2 Feedstock Supply Radius

According to Eq. 13 (by inspection), for $0 < \alpha < 1$ the optimal feedstock supply radius increases with a decrease in c_h, b, τ, λ, M, and ϕ or an increase in CC_o, e_o, n, θ, ε, and η. Namely, feedstock supply radius should be extended with (i) a decline in feedstock transportation cost, GHG emissions resulting from shipping unitary biomass transport work, tortuosity factor, feedstock moisture content, feedstock spatial distribution density, and proportion of the land where feedstock is grown or (ii) a rise in the cost and energy efficiency of converting feedstock to biofuel, GHG emissions from converting biomass to produce one unit of biofuel, fragmentation of feedstock lands, conversion plant operation rate, and feedstock energy content. Similarly, the direction of the effect of the GHG price on the optimal feedstock supply radius is determined by the sign of $c_h e_o - bCC_o$ (Appendix C, (b)). The optimal feedstock supply radius is positively related to the GHG price if $c_h e_o - bCC_o > 0$; they are negatively related if $c_h e_o - bCC_o < 0$; they are unrelated if $c_h e_o - bCC_o = 0$.

The sensitivity of the optimal feedstock supply radius varies with the scale factor of the conversion plant. Of all the factors, feedstock supply radius is most responsive to changes in feedstock transportation cost, biofuel conversion cost, cost of GHG emissions from feedstock transportation and biofuel conversion, tortuosity factor, and feedstock moisture content.

3.2.3 Production Costs

Inspection of Eq. 14 suggests that, for $0 < \alpha < 1$ biofuel production cost decreases with a decrease in c_h, b, τ, λ, CC_o, e_o, n, and θ or an increase in M, ϕ, ε, and η. This implies that the net biofuel production cost [4] can be reduced with (i) a

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[4] The costs here represent only the scale-dependent costs per unit of biofuel actually produced. They do not include scale-independent costs and costs associated with the lost utilization of the plant capacity. If the capacity loss is accounted for, the impact of plant operation rate on biofuel production cost might be different.

decrease in feedstock transportation cost, GHG emissions from transporting feedstock and converting feedstock to biofuel, tortuosity factor, feedstock moisture content, feedstock-to-energy conversion cost, fragmentation of feedstock lands, and conversion plant operation rate or (ii) an increase in feedstock spatial distribution density, feedstock energy content, and efficiency of converting feedstock to biofuel. The GHG price will have a negative impact on net biofuel production cost if $(c_h e_o - bCC_o) \geq 0$; the impact becomes uncertain if $(c_h e_o - bCC_o) < 0$.

Similarly, the sensitivity of net biofuel production cost to changes in different factors depends upon the scale factor of the conversion plant (Table 3). When $1 > \alpha > 0.67$, the sum of the cost of converting feedstock to biofuel and the cost of GHG emissions from the conversion process has the greatest impact on net biofuel production cost, followed by feedstock energy content and energy conversion efficiency and then by tortuosity factor and feedstock moisture content, whereas feedstock spatial distribution density and feedstock land fragmentation have the least impact. Hence, reducing the costs of feedstock-to-energy conversion and GHG emissions from the conversion process and improving feedstock energy content and energy conversion efficiency will be most effective in terms of reducing the overall net biofuel production cost.

The impact of conversion plant scale factor on biofuel production cost is more complex. On the one hand, the cost decreases at an increasing rate with an increase in scale factor, suggesting that a rise in conversion plant scale factor can dramatically reduce biofuel production cost. On the other hand, as scale factor increases the rate of change in costs (slope of the cost curve) declines for all factors except for feedstock-to-energy conversion cost and the associated GHG value. This implies the impact of other factors on biofuel production costs will diminish as scale factor goes up.

Further, by inspecting Eq. 14 or taking its partial derivative with respect to P_c or GHG emission/offset parameters we learn that a rise in GHG emissions from both feedstock transport and energy conversion or a fall in the GHG price or the maximum GHG offset per unit of biofuel will increase the net biofuel production cost.

Table 1. Energy efficiency and carbon balance of biofuels, gasoline, and diesel.

Fuel type	Well-to-pump		Well-to-wheel GHG (CO_2 equivalent) emissions				
	Energy efficiency (%)	Fossil fuel use ($MJ\ MJ^{-1}$) fuel available at pumps)	Feedstock (including GHG uptake by feedstock regrowth and land use change within the U.S.) ($g\ MJ^{-1}$)	Fuel conversion ($g\ MJ^{-1}$)	Vehicle operation ($g\ MJ^{-1}$)	Total ($g\ MJ^{-1}$)	% change in net GHGs vs. gasoline
Forest residues	52.1	0.235	–41	9	72	41	–55
Woody biomass	45.8	0.061	–57	9	72	25	–73
Corn	46.0	0.627	–31	36	72	78	–15
Corn stover	52.7	0.145	–46	9	72	36	–61
Herbaceous biomass	51.0	0.135	–41	9	72	40	–56
Sugar cane	50.2	0.180	–35	9	72	47	–49
Diesel	84.9	0.175	5	9	67	81	–12
Gasoline	81.1	0.214	4	14	74	92	0

Notes: The results were derived based on GREET (Wang et al. 2007) simulations.

Table 2. The values of coefficients used in simulations.

Coefficient	Description	Value
ϕ	Proportion of the land where biomass is grown	0.30
λ	Moisture content of biomass (wet base)	0.45
M	Spatial distribution density of annually available biomass (based on the total area used to grow biomass)	$0.50\ bdt\ ha^{-1}$
$1/n$	Fraction of a circle where biomass can be harvested	1/4
τ	Tortuosity factor of the road system	1.50
θ	Conversion plant factor (operation rate)	0.90
ε	Energy content of biomass	$19\ GJ\ bdt^{-1}$
η	Efficiency of converting feedstock to biofuel	$285\ L\ bdt^{-1}$
c_h	Cost per unit of biomass transportation work	$\$0.20\ t^{-1}\ km^{-1}$
S_o	Base scale of the conversion plant	$50\times10^6\ L$
CC_o	Per unit feedstock-to-energy conversion cost at the base scale of the conversion plant	$\$0.35\ L^{-1}$
α	Conversion plant scale factor	0.6~0.9
b	GHG emissions (CO_2 equivalent) from transporting the amount of biomass needed to produce one liter of ethanol for one km	1.41 g
e_o	GHG emissions (CO_2 equivalent) from converting biomass to produce one liter of ethanol	191 g
P_c	CO_2 price	$\$25\ t^{-1}$

3.3 Effect of GHG Offset Values

Because in general $c_h \gg bP_c$ and $CC_o \gg e_oP_c$, considering GHG offsets will not dramatically alter the optimal biofuel plant size and optimal feedstock supply radius. Yet, net biofuel production cost will decline when GHG offset values are accounted for. Such cost reductions will also be partially offset because accounting for GHG values will tend to increase conversion plant size

and consequently feedstock supply radius.

The elasticity for all factors except c_h and CC_o does not change whether GHG values are incorporated or not. The absolute value of the elasticity for both c_h and CC_o decreases after GHG benefits/costs are included (Table 3).

The coefficient a (the maximum GHG offset per unit of biofuel as expressed in Eq. 5) does not affect the optimal conversion plant size or optimal feedstock supply radius. Obviously, how

Table 3. Sensitivity of the optimal conversion plant size, optimal feedstock supply radius, and minimum bioenergy production cost to changes in factor values with and without considering carbon offset value.

Factor	Percentage change in the optimal plant size for a 1% change in the factor value in column 1	Percentage change in the optimal feedstock supply radius for a 1% change in the factor value in column 1	Percentage change in the minimum net variable production cost for a 1% change in the factor value in column 1
c_h	$2/(2\alpha-3) < 0\ (\downarrow)$	$1/(2\alpha-3) < 0\ (\downarrow)$	$2(\alpha-1)/(2\alpha-3) > 0\ (\downarrow)$
$\tau,\ (1+\lambda)$	$2/(2\alpha-3) < 0\ (0)$	$1/(2\alpha-3) < 0\ (0)$	$2(\alpha-1)/(2\alpha-3) > 0\ (0)$
CC_o	$-2/(2\alpha-3) > 0\ (\downarrow)$	$-1/(2\alpha-3) > 0\ (\downarrow)$	$-1/(2\alpha-3) > 0\ (\downarrow)$
$n,\ \theta$	$1/(2\alpha-3) < 0\ (0)$	$(\alpha-1)/(2\alpha-3) > 0\ (0)$	$(\alpha-1)/(2\alpha-3) > 0\ (0)$
$M,\ \phi$	$-1/(2\alpha-3) > 0\ (0)$	$(1-\alpha)/(2\alpha-3) < 0\ (0)$	$(1-\alpha)/(2\alpha-3) < 0\ (0)$
$\varepsilon,\ \eta$	$-3/(2\alpha-3) > 0\ (0)$	$-\alpha/(2\alpha-3) > 0\ (0)$	$3(1-\alpha)/(2\alpha-3) < 0\ (0)$

Notes: The meaning of the variables/factors is described in Table 2.
The elasticity shown in the table is based on the case without considering the value of carbon offsets (Gan and Smith 2009). The arrows inside parentheses indicate the direction of change in the absolute value of the elasticity when carbon offset is valued. Zero (0) means no change.

the biofuel will be used will have no influence on the selection of conversion plant size. Considering GHG offset values, however, can significantly impact the production cost and thus profitability of a biofuel, depending upon CO_2 prices and the net GHG offset that can be materialized by the biofuel.

4 Simulation Results: Bioethanol

We use forest biomass for ethanol production in the U.S. to illustrate the applicability of our theoretical approach and to verify the analytical results described earlier. The coefficient values used in our simulations are presented in Table 2, which presumably reflect current technology and marketing conditions in the U.S. The results for this example consist of two major components. One contains the life-cycle energy efficiency and GHG balance of forest biofuels with comparisons to ethanol produced from other non-forest feedstocks. These results are derived from simulations of the GREET (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) model. GREET is a transportation analysis tool that is capable of performing full fuel cycle analyses of energy efficiency and environmental consequences of vehicle technologies and fuels (Wang et al. 2007). These simulation results will then be used along with other data to simulate the

optimal conversion plant scale, optimal feedstock supply radius, and net biofuel variable production cost (the total variable production cost less GHG credits) [5].

The life-cycle analysis results are shown in Table 1. Ethanol produced from forest biomass fares well with that produced from non-forest biomass in terms of both energy efficiency and GHG offset. Woody biomass from energy plantations shows a dominant advantage over other types of biomass feedstocks in fossil fuel use and GHG offset. Among different forest biomass, forest residues are more energy efficient but less carbon efficient than woody biomass from energy plantations. This is mainly because energy plantations are assumed to be established on marginal agricultural lands, and the resultant land use change enhances the GHG offset capacity of woody biomass for energy production. Using forest residues for biofuel production does not have such a carbon advantage, yet is among the most energy-efficient.

Incorporating GHG benefits into consideration or an increase in CO_2 prices will lead to expansions of conversion plant size and feedstock supply radius, but reductions in net biofuel variable production costs. The effects of changes in

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[5] For simplicity and without loss of generality, FC was set to zero in simulations. As such, the simulation results reflect net variable production costs not the total production cost as in the analytical results.
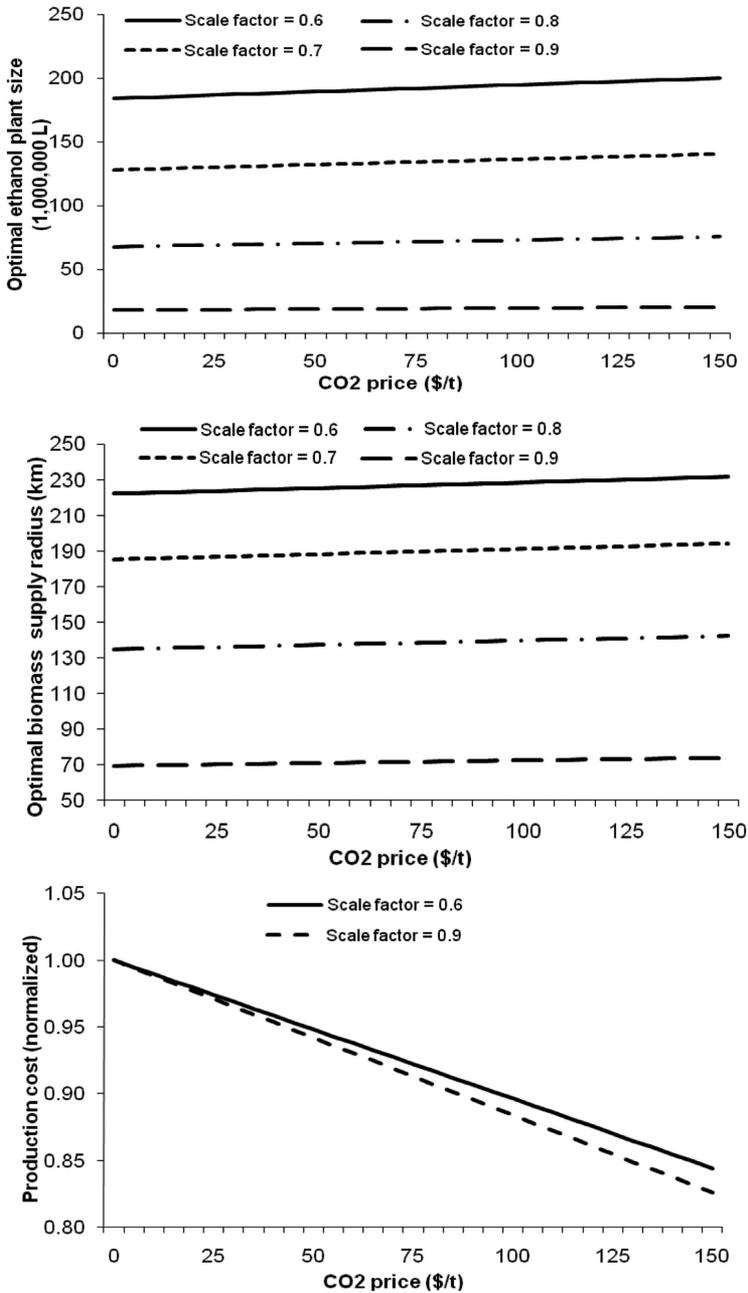
Fig. 1. Impact of CO_2 price on the optimal plant size, biomass supply radius, and net biofuel variable production cost.

CO_2 prices on the optimal plant size and biomass supply radius are very moderate and smaller than that on net biofuel variable production costs (Fig. 1). Changes in GHG emissions from transporting feedstock (b) or converting feedstock (e_o) to produce one unit of biofuel have very small impacts on the optimal plant size, biomass supply radius, and production costs. An increase

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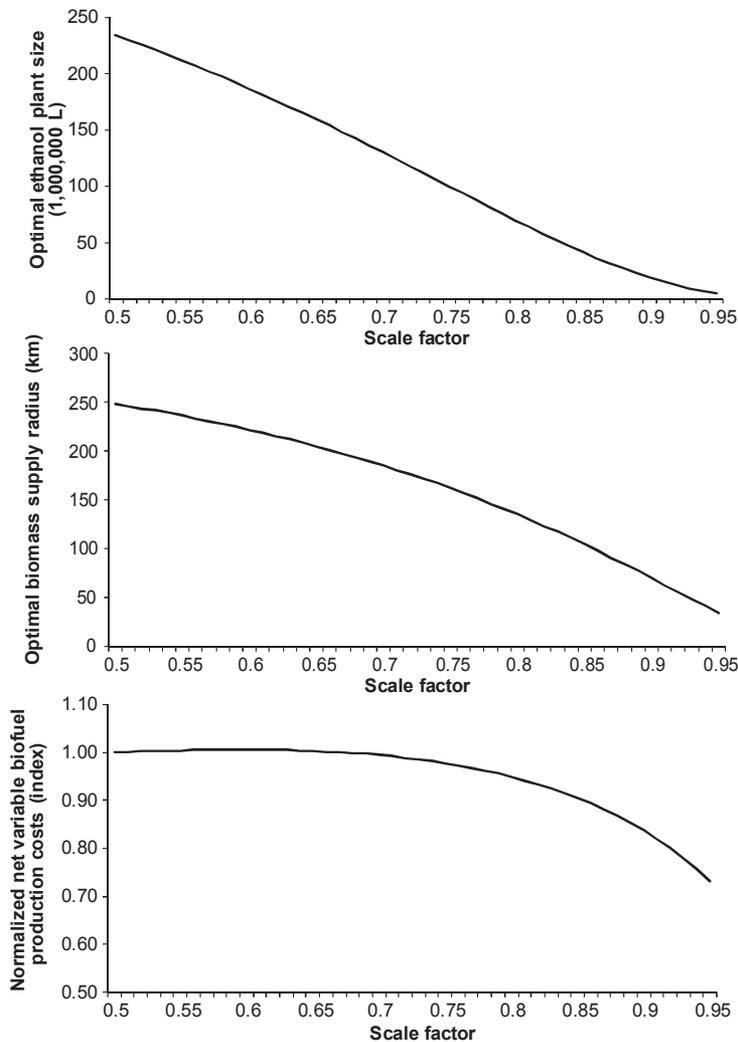
Fig. 2. Impact of biofuel plant scale factor on the optimal plant size, biomass supply radius, and net biofuel variable production cost.

in b or a decrease in e_o will make a smaller plant or feedstock supply radius more cost-effective. Net biofuel variable production costs will go up with a rise in both b and e_o. These simulation results can be used to empirically guide decision making in forest biofuel development, including the selection of conversion plant scale and feedstock supply radii and estimation of bioenergy production cost under different scenarios.

Because the impacts of scale factor cannot be so obviously determined based on the inspection

of Eqs. 11, 13, and 14, we simulate its effects on the optimal plant size, optimal feedstock supply radius, and net variable production costs. The simulation results are shown in Fig. 2.

Finally, in our example we do not include transnational carbon leakage associated with land use change across countries. When such a leakage is considered, bioethanol might generate additional GHG emissions rather than offset existing emissions from burning fossil fuels (Seachinger et al. 2008). If this is the case, the value of the

coefficient a will become smaller or even negative. This will not affect the selection of the optimal conversion plant size and optimal feedstock supply radius, but net biofuel variable production costs will increase, making biofuels less favorable economically and environmentally (particularly in terms of GHG benefits). Additionally, accounting for transnational carbon leakage may provide a relative advantage to forest biomass, especially forest residues because their production does not involve transnational land use shifts.

5 Conclusions

We attempt to incorporate GHG benefits/costs as well as biofuel production costs into the determination of the optimal feedstock supply radius, optimal conversion plant scale, and net biofuel production cost. By minimizing the total cost of feedstock production and feedstock-to-energy conversion less the value of GHG offset during the biofuel life cycle, we develop a generic framework for determining the optimal biofuel plant scale and optimal feedstock supply radius, which in turn lead to the derivation of the minimum possible net biofuel production cost. Based on the analytical results, the relationships between the optimal plant scale, optimal feedstock supply radius, or biofuel production cost and various factors are further illustrated for the cases of producing ethanol from forest biomass. The results with and without considering GHG offset values are also compared.

Our major findings and their implications for biofuel development and deployment are:

– For a biofuel that generates a positive GHG offset, its plant size and feedstock supply radius should be augmented when its GHG offset potential is accounted for.
– A decrease in GHG emissions resulting from doing unitary biomass transport work or an increase in GHG emissions from converting biomass to biofuels at the base scale will increase the optimal biofuel plant size, and correspondingly the optimal feedstock transport distance, though the impacts are generally modest.
– The effect of the GHG price on the optimal bio-

fuel plant scale and feedstock transport distance is ambiguous, depending upon the sign of $c_h e_o - bCC_o$.
– An increase in GHG emissions from both feedstock transport and energy conversion or a decrease in the GHG price will increase the net biofuel production cost (total production cost less GHG offset values). The cost is more responsive to a change in the GHG price than in conversion plant size and feedstock supply radius.
– The optimal biofuel plant size, feedstock transport radius, biofuel production cost will become less responsive to feedstock transportation cost and feedstock-to-biofuel conversion cost with accounting for GHG offset than without accounting for GHG displacement.

These findings have significant implications for biofuel development and deployment particularly given the uncertainty in GHG markets and valuation. It is clear that accounting for GHG offset values will enhance the cost competitiveness of biofuels. Because the costs of feedstock supply and biofuel conversion outweigh GHG offset values in defining biofuel plant size, uncertainty about GHG market development will have a limited impact on decision-making about plant size. In other words, GHG offset is not a critical determinant of biofuel plant size though accounting for GHG offset values can significantly influence the profitability of biofuel production. Furthermore, when GHG offsets are valued the selection of plant size will become a less critical issue in designing a biofuel supply chain because of the reduced sensitivity of biofuel plant scale to changes in feedstock and conversion costs.

Due to the difficulty in assigning monetary values of energy balance, we do not incorporate it into our cost function, Eq. 8. Yet, if we assume that energy balance is positively related to GHG offset, similar results can be derived. If this assumption is held, Eq. 8 with some minor modification (multiplying the last term, P_cNCO, by a constant) can represent total net production cost with consideration of both GHG offset and energy balance. Thus, the results for this broader case will be similar to those described above.

This study can be expanded by including other benefits and/or costs associated with biofuel production and consumption. For instance,

intersectoral and interregional impacts of biofuel production and consumption could be incorporated. It will entail more integrative analyses and modeling approaches. Additionally, applications of our approach can be extended to various types of biofuels produced from many biomass sources. Such analyses would enable us to compare economic and environmental consequences of different biofuels from a boarder and more comprehensive perspective, leading to better decisions.

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Appendix A

Substituting Eq. 11 into Eq. 12 leads to the optimal feedstock supply radius:

$$
\begin{aligned}
R_c^* &= 5.28 \sqrt{\frac{n\theta}{M\varphi\varepsilon\eta}} \left[\frac{1.76\tau(1+\lambda)\left(c_h + bP_c\right)}{(1-\alpha)(CC_o + e_o P_c)S_o^{1-\alpha}} \sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}} \right]^{\frac{1}{2\alpha-3}} \\
&= 5.28 \left[\frac{1.76\tau(1+\lambda)\left(c_h + bP_c\right)}{(1-\alpha)(CC_o + e_o P_c)\varepsilon^\alpha\eta^\alpha} \left(\frac{M\varphi}{n\theta S_o} \right)^{1-\alpha} \right]^{\frac{1}{2\alpha-3}} \quad (\text{km})
\end{aligned}
$$

Appendix B

Substituting Eq. 10 into Eq. 8 gives rise to

$$TC_c^* = 3.52\tau(1+\lambda)(c_h+bP_c)\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}}\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)}{(1-\alpha)(CC_o+e_oP_c)S_o^{1-\alpha}}\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}}\right]^{\frac{1}{2\alpha-3}}$$

$$+(CC_o+e_oP_c)\left(\frac{1}{S_o}\right)^{\alpha-1}\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)}{(1-\alpha)(CC_o+e_oP_c)S_o^{1-\alpha}}\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}}\right]^{\frac{2(\alpha-1)}{2\alpha-3}}+FC-aP_c$$

$$=2\left\{\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}}{(1-\alpha)(CC_o+e_oP_c)}\right]^{2(\alpha-1)}\right\}^{\frac{1}{2\alpha-3}}$$

$$+\left\{\frac{\left[1.76\tau(1+\lambda)\left(c_h+bP_c\right)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}\right]^{2(\alpha-1)}}{(1-\alpha)^{2(\alpha-1)}(CC_o+e_oP_c)}\right\}^{\frac{1}{2\alpha-3}}-aP_c+FC$$

$$=(2+\frac{1}{1-\alpha})\left\{\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}}{(1-\alpha)(CC_o+e_oP_c)}\right]^{2(\alpha-1)}\right\}^{\frac{1}{2\alpha-3}}-aP_c+FC$$

$$=\frac{3-2\alpha}{1-\alpha}\left\{\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}}{(1-\alpha)(CC_o+e_oP_c)}\right]^{2(\alpha-1)}\right\}^{\frac{1}{2\alpha-3}}-aP_c+FC$$

This derives Eq. 14, the minimum net production cost per unit biofuel.

Appendix C

(a) Impact of the CO_2 price on the optimal conversion plant size

Taking the partial derivative of Eq. 11 with respect to Pc, we have

$$\frac{\partial S_c^*}{\partial P_c} = \frac{2}{2\alpha-3}\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)}{(1-\alpha)(CC_o+e_oP_c)S_o^{1-\alpha}}\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}}\right]^{\frac{5-2\alpha}{2\alpha-3}}\frac{1.76\tau(1+\lambda)}{(1-\alpha)S_o^{1-\alpha}}\sqrt{\frac{n\theta}{M\varphi\varepsilon^3\eta^3}}\frac{bCC_o-c_he_o}{\left(CC_o+e_oP_c\right)^2}$$

Given $0<\alpha<1$,

$$\frac{\partial S_c^*}{\partial P_c} \begin{array}{c}>\\=\\<\end{array} 0 \quad if \quad c_he_o-bCC_o \begin{array}{c}>\\=\\<\end{array} 0.$$

Thus, the direction of the impact of CO_2 price change on the optimal biofuel conversion plant size depends upon the sign of $(c_he_o - bCC_o)$.

(b) Impact of the CO_2 price on the optimal conversion plant size

Taking the partial derivative of Eq. 13 with respect to Pc, we derive

$$\frac{\partial R_c^*}{\partial P_c} = 5.28\frac{1}{2\alpha-1}\left[\frac{1.76\tau(1+\lambda)\left(c_h+bP_c\right)}{(1-\alpha)(CC_o+e_oP_c)\varepsilon^\alpha\eta^\alpha}\left(\frac{M\varphi}{n\theta S_o}\right)^{1-\alpha}\right]^{\frac{4-2\alpha}{2\alpha-3}}\frac{1.76\tau(1+\lambda)}{(1-\alpha)\varepsilon^\alpha\eta^\alpha}\left(\frac{M\varphi}{n\theta S_o}\right)^{1-\alpha}\frac{bCC_o-c_he_o}{(CC_o+e_oP_c)^2}$$

For $0<\alpha<1$,

$$\frac{\partial R_c^*}{\partial P_c} \begin{array}{c}>\\=\\<\end{array} 0 \quad if \quad c_he_o-bCC_o \begin{array}{c}>\\=\\<\end{array} 0.$$

Hence, the direction of the impact of a change in the CO_2 price on the optimal biomass feedstock supply radius relies on the sign of $(c_he_o - bCC_o)$.

(c) Impact of the CO_2 price on net biofuel production costs

Taking the partial derivative of Eq. 14 with respect to Pc gives rise to

$$\frac{\partial TC_c^*}{\partial P_c} = \frac{1}{\alpha-1}\left\{\left[\frac{\left[1.76\tau(1+\lambda)\left(c_h+bP_c\right)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}\right]^{2(\alpha-1)}}{(1-\alpha)(CC_o+e_oP_c)}\right]^{\frac{4}{2\alpha-3}}\frac{\left[1.76\tau(1+\lambda)\sqrt{\frac{n\theta S_o}{M\varphi\varepsilon^3\eta^3}}\right]^{2(\alpha-1)}}{(1-\alpha)}\frac{bCC_o-c_he_o}{(CC_o+e_oP_c)^2}-a\right\}$$

Therefore, given $0<\alpha<1$, $\dfrac{\partial TC_c^*}{\partial P_c}<0$ if $(c_he_o-bCC_o)\geq0$; $\dfrac{\partial TC_c^*}{\partial P_c}$ is ambiguous if $(c_he_o-bCC_o)<0$.