Supporting Information for:

"Life cycle assessment of biochar systems:
Estimating the energetic, economic and climate change potential"

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This SI document includes text, tables, and figures with detail on the process data for the inventory analysis of the LCA; background on the economic assessment; some further discussion on the LCA results; and the sensitivity analysis.

Process data

Crop residues. For this assessment, the energy and greenhouse gas emissions are from Kim, Dale, and Jenkins (1) for corn stover collection in Fulton County, IL. The corn stover LCA from (1) uses the system expansion approach for determining the impacts of stover production separate from corn grain production in seven counties in the US Corn Belt. The stover is collected with a second-pass harvest, which provides a more conservative estimate of energy use and emissions, as single-pass harvest (2) technologies are not yet available. The stover removal rate is 50% of the above ground biomass to meet erosion tolerances (1). A 50% collection rate may not be appropriate for all regions, but it is assumed that it will keep erosion within tolerable limits. The effect of corn stover removal on soil organic carbon (SOC) levels is also a concern for soil health. This analysis assumes that the biochar is returned to the soil (containing approximately one-third of the C from the removed stover), allowing for a more sustainable soil C balance. A corn stover to grain ratio of 1:1 was assumed, and an average corn yield for Fulton County, IL of 8.15 dry t ha^{-1} yr^{-1} (which is a four-year average yield value from 2000-2003) (1). At a 50% removal rate, 0.25 ha field area is required to supply 1 t dry stover. Weather and field conditions can influence corn stover harvest times (3, 4). For this analysis, both late and early stover harvests are considered, with moisture contents of 15% and 30%, respectively (5).

The energy and emissions from agrochemicals, field operations, and field emissions associated with corn stover harvesting are shown in Table S1. This process data includes nutrient replacement from those lost in the stover removal and effects of stover removal on soil nitrogen-related emissions and CO_2 emissions from decreased SOC accumulation.

Although our analysis uses a stover removal rate of 50%, other LCA studies have modeled stover removal rates at 62% (2), at 40% for fields under continuous corn production for typical tilling practices (mulch till), and at 70% of the stover for no-till practices (6). The field emissions for corn stover harvesting include the effects of residue removal on SOC levels and nitrogen-related emissions (N_2O, NO_x, NO_3^-). The SOC and nitrogen-related emissions are dependent on soil properties, climate, and agricultural management practices, and thus vary with site. Removing stover decreases SOC as compared to removing corn grain alone because less residue is left on the field to add to the SOC levels, resulting in emissions of 31.8 kg CO_2e t^{-1} dry stover removed. Removing stover also decreases N_2O, NO_x, and NO_3^- emissions because less residual biomass is available to convert to nitrogen-related emissions (1).

Bioenergy crops. Due to the complexity of economic, technological, political, regulatory, environmental, and historical forces, the life cycle emissions model (LEM) estimates rather than formally models changes in land use. However, LEM does assume energy crops will bring new land into production, as agricultural land is not fixed and increased yields alone cannot make up the total crop production (7). LEM assumes the following categories of land-use displacement for grass energy crop production: 55% temperate grass, 19% low intensity (increasing productivity on existing cropland), 10% generic agriculture, 5% desert, 5% wetland, 3% boreal forest, and 3% temperate forest. The cultivation-related emissions from LEM are dominated by the changes in soil C, as the energy crops are assumed to mainly displace grasslands, which have higher soil C than managed energy croplands.

As mentioned in the main article, the switchgrass B scenario uses the results from a comprehensive worldwide agricultural model for land-use change from Searchinger et al (8), which takes into consideration the effects of cropland diversion from annual crops to perennial grass energy crops in the US (direct land-use change), and land conversion in other countries from forest and pasture to cropland to replace the crops lost to bioenergy crops in the US (indirect land-use change). (See the supporting online material of (8) for the detailed process description.) The total land-use emissions are +939.4 kg CO_2e and the total sequestered C in soil is -53.4 kg CO_2e t^{-1} dry switchgrass, resulting in net emissions of +886.0 kg CO_2e.

There is an obvious, large difference in net CO_2e emissions (+406.8 vs. +886.0 kg CO_2e t^{-1} dry switchgrass) between the switchgrass A and B scenarios. The differences between the models arise from a number of factors: LEM does not utilize a formal partial-equilibrium model for agricultural change as does Searchinger et al; LEM assumes that crop yields abroad will equal those in the US; LEM does not account for the loss of annual sequestration on converted forest; and LEM uses a discount rate for emissions accounting of 30 years, while Searchinger et al calculate the net impact over a 30 year period (8). Recent research on biofuels from Kim et al (9) has argued that the Searchinger et al assessment is inaccurate in assigning the entirety of the emissions burden from indirect land-use change to domestic industries (i.e. biofuels production). Kim et al state that the GHG emissions from indirect land-use change are dependent on a multitude of assumptions, such as social and environmental behaviors, crop management methods, and time frames (9). Accounting methods for indirect land-use change impacts for energy crop production are currently insufficient and are a work-in-progress among the LCA, economic, and geography communities (10). Despite the controversy on the allocation of indirect land-use change emissions in the biofuels industry, the two scenarios for this analysis were chosen so that a range of possibilities could be taken into consideration at the early stage of estimating the potential life-cycle impacts of biochar production from energy crops. This method is a first approach to considering a range of outcomes, similar to the "intensification" and "deforestation" scenarios reported in (11).

The energy and agricultural inputs for switchgrass establishment and collection (Table S1) for both the switchgrass A and B scenarios are from LEM (7). The LEM model allocates the inputs over the expected 10 year life of the switchgrass rotation and an estimated crop yield of 12 dry t ha^{-1} yr^{-1}. The agricultural inputs each have GHG emissions associated with them and are accounted for in the LCA.

Yard waste collection. The yard waste is a mixture of leaves, brush, and grass clippings, where the relative fraction of each (67, 25, and 8 wt. %, respectively) is estimated from typical yard waste collections in Suffolk County, NY (12).

TABLE S1. Feedstock production and collection inventory data, per dry tonne

Corn stover	Data from Kim, Dale, Jenkins 2009, for Fulton County, IL	
	Energy (MJ)	GHG emissions (kg CO_2e)
Agrochemicals	600	35
Field operations	300	28
Field emissions		5
Switchgrass A & B inputs	Data from LEM model	
	Energy (MJ)	
Diesel	258	
Gasoline	39.9	
Electricity	19.8	
	Quantity (kg)	
N fertilizer	10.1	
P_2O_5 fertilizer	0.39	
K_2O fertilizer	0.36	
Lime	18.2	
Pesticides	0.045	
Seeds	0.045	
Swithgrass A GHGs	Data from LEM model	
Emissions		GHGs (kg CO_2e)
N_2O related to fertilizer input (synthetic plus manure)		82.47
N_2O related to biological N fixation, use of crop residue		1.74
N_2O from cultivation, independent of fertilizer use		2.96
NO_x emissions related to the use of synthetic fertilizer or animal manure		5.99
CO_2 emissions from on-site soil, due to cultivation		301.86
CO_2 emissions from on-site biomass, due to cultivation		34.00
CO_2 equivalent GHG emissions from residue burning		0.19

Reductions	GHGs (kg CO_2e)
CO_2 sequestered due to fertilization of off-site ecosystems by nitrogen fertilizer leached from field of application	-13.13
CH_4 and CO_2 soil emissions related to synthetic fertilizer and animal manure, and CH_4 emissions independent of fertilizer use	-9.60
	Net GHG = +406.48 kg CO_2e

Swithgrass B GHGs Data from Searchinger et al model	
Emissions	GHGs (kg CO_2e)
CO_2e emissions related to land-use change (Assumes 446.15 MT CO_2e emitted per ha of corn land diverted to produce cellulosic biomass, and optimum yields of 18 MT ha^{-1} are achievable)	939.43
Reductions	GHGs (kg CO_2e)
CO_2e sequestered from crop uptake (Assumes 1 MT CO_2e ha^{-1} yr^{-1} is sequestered, as modeled by GREET)	-53.46
	Net GHG = +885.97 kg CO_2e

Feedstock transport to the pyrolysis facility. The collected yard waste, stover, and switchgrass are transported to the pyrolysis facility in a heavy duty diesel truck with no backhaul. The truck is assumed to make a return trip loaded with the finished biochar product and is accounted for in the biochar application process. The distance transported is variable, however, a baseline of 15 km is used for comparisons based on the requirements for a pyrolysis plant processing 10 t hr^{-1} (13). The average transport distance of 15 km is calculated by McCarl et al (*13*) from the amount of feedstock required to fuel the plant (including 5% losses in transport and storage) and the crop yield based on an assumed corn density of 20% in mid-western US states.

Biomass pre-processing. The feedstock is transported and stored at the pyrolysis facility where it is pre-processed and pyrolyzed. For pre-processing, the biomass is reduced in size by shredding and dried to a final moisture content of 5% (wet basis). The biomass size reduction energy is from a recent study of knife mill size reduction of lengthy straw/stalk biomass such as switchgrass, wheat straw, and corn stover (*14*). Under optimal operating conditions, reducing the feedstock to 25.4 mm consumes 27.2, 37.9, and 31.9 MJ t^{-1}, respectively. The biomass size reduction process of this LCA assumes an average diesel fuel consumption of 32.3 MJ t^{-1} biomass. The feedstock is dried in a large rotary dryer with a fuel efficiency of 3.48 MJ kg^{-1} of water evaporated (*15*). The amount of water removed by the dryer is dependent on the feedstock's moisture content upon arrival at the facility. The moisture contents of the different feedstocks are given in Table S2. The manufacture and disposal of the shredding and drying equipment are incorporated as part of the pyrolysis plant construction and dismantling.

Slow pyrolysis: Biochar and syngas production. There are some companies in various stages of having small to large-scale, biochar slow-pyrolysis units in production, but detailed process data directly from facilities are not available at this time as the units are still under development and data are often kept confidential. It is evident that slow pyrolysis for biochar production is a technology in development with many operating parameters yet to be optimized for consistent performance. However, there has been significant laboratory research of pyrolysis of organic materials, with a thorough review on charcoal production and slow pyrolysis from Antal and Grønli (*16*). Based on these factors, the process data for the slow pyrolysis module is taken from multiple sources: peer-reviewed publications, industry best-estimates, and personal communication based on laboratory experiments. A range of values for the pyrolysis process data is included in the sensitivity analysis.

For our generalized model of a large-scale slow pyrolysis facility, the feedstock is pyrolyzed in continuous operation in a swept drum kiln at 450°C. The kiln is an externally heated, horizontal cylindrical shell (*17*). The biomass is continuously fed and moved through the drum with paddles, allowing the biomass to reside in the drum for several minutes as it moves through the vessel. Air does not enter the drum, except in the gaps between biomass particles. The residence time of the pyrolysis vapors is long enough that most of it is cracked to non-condensable gases in the pyrolysis drum, but some amount of tar remains with the gas (*17*). Some of this gas is available to heat the kiln by burning in a firebox below the kiln (*17*). The pyrolysis kiln efficiency is assumed to be 50%, and 90% of this heat can be recovered from the kiln and used for drying feedstock. The syngas produced during pyrolysis is in the temperature range of 550 – 750°C, and the main gaseous species are CO, H_2, and CH_4 (*18*) along with a small fraction of higher molecular weight hydrocarbons. The syngas leaves the kiln and flows into the thermal oxidizer where air at ambient temperature is introduced to combust the syngas. The gases and tars are combusted in the thermal oxidizer, producing a gas stream in the temperature range of 1000 – 1100°C (*18*), where the high temperature achieves clean combustion. In this system, it is assumed that all CO, CH_4, and hydrocarbons are combusted and the only emissions are CO_2 and H_2O. A heat exchanger coupled to an air ducting system have an assumed efficiency of 75% (*18*) for transferring the heat from the combusted gases to heating applications on-site (such as heating greenhouses or hen houses, or for drying biomass). We acknowledge that in these assumptions the heat is restricted to on-site use and demand may be seasonal. However, future work will consider the feasibility of on-site energy demand for large-scale pyrolysis systems, where the process details are subject to the needs of the end user, site location, and feedstock availability.

TABLE S2. Feedstock properties, pyrolysis process yields, and biochar properties for various biomass sources

Property	Late stover	Early stover	Switchgrass	Yard waste
Moisture content, wet basis	15%	30%	12%	45%
Ash content (wt.% DM)	5.6[b]	5.6[b]	4.6[c]	4.5[a]
C content of feedstock (wt.% DM)	45[d]	45[d]	48[e]	47[d]
Lower heating value (MJ t^{-1} DM)	16000	16000	17000	18000
Yield of biochar (wt. %)	29.60[f]	29.60[f]	28.80[g]	29.63[f]
C content of biochar (wt.%)	67.68[h]	67.68[h]	63.09[e]	65.89[f]
Stable portion of total C in biochar		80%[i]		
Improved fertilizer use efficiency (for N, P, K)		7.2%[j]		
Reduced soil N_2O emissions from applied N fertilizer		50%[k]		

DM = dry matter
[a] (*19*); [b] (*20*); [c] (*21*); [d] (*22*); [e] (*23*); [f] unpublished data; [g] (*16*); [h] (*24*); [i] (*25*); [j] (*26*); [k] (*27, 28*)

Field application of biochar. The biochar is transported from the pyrolysis facility to the farm by a heavy duty diesel truck. The trip is assumed to be the backhaul from the biomass delivery for all feedstocks considered. The distance transported is the same as that from the farm to the facility, where 15 km is used as the baseline for comparisons. The biochar is applied to a corn field at a rate of 5 t C ha^{-1} (*29*). The maximum amount of biochar that can be applied to field crops has not yet been determined experimentally; however application rates as high as 50 t C ha^{-1} have shown crop yield improvements (*30*). In fact, most plant species and soil conditions have not shown growth reductions even at applications of 140 t C ha^{-1}, demonstrating the ability to continue adding biochar to soils for an extended period of time. The field application of the biochar is assumed to be similar to other soil amendment applications. The energy consumption related to biochar application equipment was taken from (*31*), where the diesel fuel consumption of the tractor for biochar application is 506 MJ ha^{-1} and the embodied energy in manufacturing, transportation, and repair of machinery is 60 MJ ha^{-1}.

Improved fertilizer use efficiency. In a study on N retention and plant uptake on highly weathered soils, it was found that the total N recovery in soil, crop residues, and grains was significantly higher for biochar amended soils (18.1%) as compared to only N mineral-fertilized soils (10.9%) (*26*). The difference of 7.2% between total N recovery in soils fertilized with biochar and the control is used as the baseline scenario for improved N, P, and K fertilizer use efficiency. The total amount of fertilizer avoided was calculated assuming average N, P_2O_5, and K_2O application rates for corn of 154, 65, and 94 kg ha^{-1}, respectively (*32*).

Soil N_2O emissions. Currently it is estimated that 1.325% of the N in the N fertilizer for corn is converted into N_2O emissions (*33*). Biochar reportedly reduces N_2O soil emissions that result from N fertilizer application (*27, 28, 34*). A laboratory study in Japan (*27*) found that soils amended with 10 wt.% of the soil as biochar suppressed 89% of N_2O emissions. Meanwhile, laboratory incubation experiments (*28*) showed that soils amended with biochar from poultry litter emitted approximately 40 – 80% less N_2O than the control. However, this same study found that yard waste biochar produced at a lower temperature increased N_2O emissions by 100%. These results indicate that not all biochars will reduce N_2O emissions equally (*28*). For this analysis, the baseline scenario assumes that the biochar processing is done under conditions such that soil N_2O emissions from N fertilizer applications are reduced by 50%. Therefore, for every tonne of biochar applied, 0.394 kg of N_2O emissions to the air will be avoided. The sensitivity analysis also looks at the effect of varying soil N_2O emissions.

Pyrolysis plant construction and decommissioning. The energy and emissions associated with the construction of the pyrolysis facility have been estimated from the production and assembly of the construction materials. The amounts of materials required (listed in Table S3) were approximated similar to the method used in LCA studies of a biomass gasification combined-cycle system and of a natural gas combined-cycle power generation system (*35, 36*). For the pyrolysis facility, a plant throughput of 10 t hr^{-1} was used to approximate the plant size and materials required, assuming the biomass will require storage on-site. The energy and emissions from the decommissioning of the plant are estimated from the dismantling of three different power plants (*37*), and includes the disassembly, transport (100 km), recycling and disposal of the construction materials. The contribution of the plant construction and decommissioning to the 1 t of biomass management functional unit is calculated from the fraction of the total number of tonnes of biomass processed for a plant lifetime of 20 years operating at 80% of full capacity.

TABLE S3. Inventory data for agrochemicals and construction materials

Agrochemicals	Data from GREET 1.8b	
	Energy (MJ kg^{-1})	GHG emissions (kg CO_2e kg^{-1})
N fertilizer	48	3.0
K_2O fertilizer	9	1.0
P_2O_5 fertilizer	14	0.7
$CaCO_3$ (lime)	8	0.6
Pesticides/Herbicides	332	25.2
Plant construction	Data from Mann (1997) and Spath (2000)	
	Adapted for 10 tonne/hour plant capacity	
	Quantity (kg)	
Concrete	1759482	
Steel	558540	
Iron	7344	
Aluminum	3672	

Construction materials. The energy and emissions for the steel, iron, and aluminum were taken from the Greenhouse gases, regulated emissions, and energy use in transportation

(GREET) 2.7 model (*38*). The GREET 2.7 version is for vehicle-cycle analysis and includes energy use and emissions for materials in the automobile industry. For steel, an average mix of 30% virgin and 70% recycled was used, and for aluminum an average mix of cast aluminum of 41% virgin and 59% recycled was used. Cast iron was used for the iron. The energy and emissions associated with the concrete production were taken from the BEES 4.0 database (Building for Environmental and Economic Sustainability) (*39*). The concrete used was assumed to be a 100% Portland Cement concrete (no cement substitute), and the concrete constituents are 12% Portland Cement, 42% coarse aggregates, 28% fine aggregates, and 8% water. The GREET and BEES materials data include transportation up to the point of the material production. The methodology for estimating transport distances and modes by the Standard Classification of Transported Goods (SCTG) codes using the US Commodity Flow Survey (*40*) described in (*41*) was used to approximate the transport of construction materials to the pyrolysis facility site.

Electricity, fuels, agrochemicals. The GREET 1.8b (*33*) model was used for compiling the upstream energy and air emissions for electricity generation and fossil fuel production and combustion. The unit process data for each was extracted prior to the final software results, and includes energy use and emissions associated with mining, refining, transportation, and distribution. The GREET 1.8b model was also used for fuel combustion in the following: medium-heavy duty diesel truck (class 6), heavy-heavy duty diesel truck (class 8), diesel rail, diesel farm tractor, gasoline tractor, diesel stationary reciprocating engine, residual fuel oil barge, natural gas small utility boiler, and coal IGCC plant. The avoided fossil fuel modeled in this analysis is on-site natural gas combusted in a large utility boiler for the baseline scenario, and the sensitivity analysis also compares a coal IGCC plant and a diesel stationary reciprocating engine.

The N, P_2O_5, K_2O fertilizers, lime, pesticides, and herbicides data are also from the GREET 1.8b model (Table S3), and the seed production data is from (*42*). The agrochemical transportation distance and mode was estimated from (*40*) as described in (*41*).

Composting. The avoided composting process from which the yard waste is diverted is assumed to be a centralized composting facility. Only the avoided compost production is included, while the use of compost is outside the system boundaries for this analysis. The energy and greenhouse gas emissions associated with composting are adapted from the EPA report (*43*). The compost piles are turned (211.6 MJ diesel and 14.71 kg CO_2e per tonne material), and the yield of finished compost product is 0.476 tonne compost per wet tonne input material.

The EPA report (*43*) calculates the amount of C stored by the formation of very stable C compounds (humus), rather than released to the atmosphere by decay. The report concludes that the upper bound on C storage from composting in the form of humus formation is more than 166 kg CO_2e per wet tonne of organic material (immediately after compost application), and the lower bound is approximately 100 kg CO_2e per wet tonne after 100 years. To estimate the C storage from humus formation for this analysis, the average of the upper and lower bounds at time equals 100 years was selected, at 123 kg CO_2e per wet tonne organic matter. Finally, the report acknowledges that the C storage rate declines with time after the initial compost application. The EPA uses a mean residence time for passive C of 400 years to designate the rate at which passive C is degraded to CO_2 and released into the atmosphere. The EPA report also states that 0.02 MTCE is stored in the soil because adding compost restores soil organic C to higher levels. However, the “C restoration” is not exclusive to “passive” C, which is defined as very stable and remains in the soil for thousands of years. Therefore, only the passive C (123 kg

CO_2e per wet tonne), and not the C restoration, is counted towards a long-term C storage mechanism in this analysis.

Despite the claims of some reports that good management of compost piles results in negligible to zero CH_4 or N_2O emissions (*43, 44*), multiple studies have found that even well managed (turning, aeration, proper moisture content) compost piles emit measurable amounts of CH_4 and N_2O (*45-48*). The CH_4 is formed by microorganisms when the biomass is stored in anaerobic conditions. The N_2O is formed during the decomposition of biomass through denitrification and nitrification processes. From studies of yard waste compost (grass clippings, green leaves, and brush), it was estimated that 0.030 kg and 2.79 kg of N_2O and CH_4 are emitted, respectively, per tonne of dry organic material (*45*), assuming a moisture content of 45% (wb).

Economic analysis. The net profit of the biochar production system based on the functional unit of one dry tonne of biomass is calculated from:

$$\pi = BC + E + Tip + Av - F - Trans - O - C - A - LS \qquad (1)$$

Where π is the profit associated with 1 dry tonne, BC is the value derived from the biochar, E is the value of the energy created in the process, Tip is the value obtained from any tipping or disposal fees received for the feedstock, Av is the avoided cost of composting (for yard waste only), F is the cost of producing or collecting the feedstock, $Trans$ is the transportation cost for both the feedstock and the biochar product, C is the capital cost associated with processing a unit of the feedstock, O is the operating cost incurred for processing a unit of feedstock, A is the cost of applying the biochar to the field, and LS is the lost sales (for yard waste compost only).

Biochar value. The three components of the economic value of biochar are: (i) the value of the P and K nutrient content contained in the biochar, (ii) the improved fertilizer use efficiency, and (iii) the value of GHG reductions provided by the life cycle of the biochar. Specifically, the value of biochar (*BC*) is given by the equation:

$$BC = p_P qc_P + p_K qc_K + \alpha\delta(p_P qBase_P + p_K qBase_K + p_N qBase_N) + p_{GHG} q_{GHG} \qquad (2)$$

Where the value of biochar (*BC*) is defined by the price of phosphorus (p_P), the quantity of phosphorus in the char (qc_P), the price of potassium (p_K), the quantity of potassium in the char (qc_K), a conversion factor (α) of 0.14 ha t^{-1} biochar assuming a 67.68 wt % C content of biochar applied at 5 t C ha^{-1}, the difference in fertilizer uptake efficiency between soil amended with biochar and soil without char (δ), the quantities of phosphorus and potassium fertilizers applied to the soils under base circumstances ($qBase_P$), ($qBase_K$), ($qBase_N$), the price of N fertilizer (p_N), the price of GHG emission reductions (p_{GHG}), and the quantity of GHG reductions associated with the biochar (q_{GHG}).

For (i), it is assumed all of the P and K that is in the biomass remains in the biochar and is available to the plants (*24*). The P and K content will vary based on the feedstock, and the amounts are from (*49*), (*19*), and (*24*) for stover, yard waste, and switchgrass, respectively. For stover, yard waste, and switchgrass biochar, the calculated P and K values are \$75.10, \$37.54, and \$37.36 t^{-1} biochar, or \$18.39, \$10.01, and \$9.68 t^{-1} dry feedstock for fertilizer prices of \$1.98 kg^{-1} P_2O_5 and \$1.02 kg^{-1} K_2O (*50*). For component (ii), the improved fertilizer use efficiency (δ) is assumed to be 7.2% (*26*), and the *qBase* values (assuming average fertilizer application rates for corn) are 154.4, 64.9, and 94.0 kg ha^{-1} for N, P_2O_5, and K_2O, respectively (*32*). This adds \$4.11 t^{-1} biochar or \$1.22 t^{-1} feedstock (with the P and K prices above, and N fertilizer price of \$1.27 kg^{-1} N (*50*)). In valuing the GHG offsets, there are two approaches one can use: either to value only the stable C in the biochar, or to value the total life-cycle GHG emission reductions in biochar production. By including the life-cycle GHG reductions, more value is added to the biochar, primarily from the avoided fossil fuels production and combustion. For this analysis, we use the life-cycle GHG emissions reductions to calculate the C offset. The other variable is in the value per tonne CO_2 sequestered. Low and high values of \$20 and \$80 t^{-1} CO_2e are used, based on the IPCC recommendations (*51*).

Energy value. The energy created by the pyrolysis system also has value. It is important to note that the amount of energy required to convert the feedstock to biochar will be subtracted in the operating expenses. In other words, the energy generated is used to reduce the energy purchases that are included in the operating costs. The value of the excess syngas energy of the process is dependent on which type of fuel it is replacing. For this comparison we consider the replacement of natural gas. The average natural gas price for all sectors (January of 2009) is \$10.27 per 1000 cubic feet (*52*), or 0.95 cents MJ^{-1}. The value of the syngas energy per dry tonne of late stover, switchgrass and yard waste are \$42.81, \$55.05 and \$35.20, respectively.

Tipping. Depending on the source of the yard waste, its collection can actually be a source of revenue when there is an associate tipping fee for the waste management. For example, the tipping fee for yard waste collection in Suffolk County (Long Island), NY has a range of +\$60-77 t^{-1} wet material (*53*). A quick survey of yard waste collection operations reveals tipping fees of \$27-81 t^{-1} wet material collected. In this analysis, a conservative estimate of the revenue from the yard waste tipping fee of +\$27 per wet tonne is used. In the case of stover and switchgrass no tipping fees are included. We acknowledge that tipping fees can change quickly. For example, if the disposed material has value, the price that people pay to dispose of the material will be reduced and with enough competition those taking the material will have to pay for its true value. This is also true of any feedstock that is under consideration. However, it is beyond the scope of the current analysis to forecast market creation and purchase prices and how fast the competition for this resource will evolve.

Avoided costs and sales. The avoided cost of composting is another, smaller revenue, at +\$10.81 t^{-1} DM for the yard waste scenario (*54*). However, the lost revenue from compost sales is another consideration and is estimated at -\$56.03 t^{-1} DM (*55*).

Feedstock production. The feedstock production cost (F) for stover is calculated from:

$$F = H + N + P \qquad (3)$$

Where H is the cost of harvesting, N is the cost to replace nutrients lost in harvesting the stover (that otherwise would not be lost in corn harvest alone) and P is the farmer payment. The total cost of corn stover collection is estimated at \$43.46 t^{-1} dry matter (DM), which includes the harvesting at \$13.99 (*56*), the nutrient replacement at \$19.47, calculated from nutrients removed in stover (*49*) and fertilizer prices (*50*), and a farmer payment of \$10.00 (13). The switchgrass production and harvesting cost is \$36.89 per tonne, from a detailed study by Graham et al (*57*) of energy crop production costs.

Transportation. The total cost of transportation per functional unit is the sum of the feedstock and biochar transportation costs:

$$Trans = Trans(F) + Trans(BC) \qquad (4)$$

Where *Trans(F)* is the cost of transporting the feedstock 15 km to the facility (\$5.30 t^{-1}) from:

$$Trans(F) = 4.1 + 0.08 * D \qquad (5)$$

And D is the distance (km), \$4.10 is the load and unload charge per tonne, and \$0.08 is the shipping cost per tonne-km (13). The yard waste does not have a cost to transport, as it is assumed there is a payment for transport included in the tipping fee. The cost of transporting the biochar, *Trans(BC)*, is calculated from the same equation as the feedstock transport.

Application. The cost of applying the biochar to the field includes the implement cost, fuel, and labor, at \$10.80 per acre, or at 5 t C ha^{-1}, \$3.62 t^{-1} biochar (*58*).

Pretreatment operations and capital. The pretreatment module at the pyrolysis facility includes the feedstock reception, drying, size reduction, storage, and feeding. The cost of operations and capital for the feedstock pretreatment (summarized in Table S4) are from the McCarl et al (13) economic analysis for a fast pyrolysis system with a 10 t DM hr^{-1} feedstock throughput. The operating cost is \$334,000 (2007 USD) per year, or \$4.77 per tonne feedstock (assuming the plant operates at 80% capacity). The capital cost for the pretreatment equipment from the same study is \$3.6 M. The equivalent annual capital cost of the pretreatment equipment was calculated based upon a 20 year lifetime and a 5% discount rate according to (6).

$$Annual\_capital = \frac{Total\_capital}{\frac{1}{r} - \frac{1}{r(1+r)^n}} \qquad (6)$$

The annual capital cost of the pretreatment equipment is \$288,873, and the annual capital cost per tonne of feedstock is \$4.12.

Pyrolysis operations and capital. We have compared the costs associated with the pyrolysis capital and operations from three sources: (i) the economic analysis from McCarl et al (13) for a fast pyrolysis system, (ii) a techno-economic assessment from Bridgwater et al (*59*) for fast pyrolysis systems, and (iii) a price estimate from Coaltec Energy for a slow-pyrolysis/gasification system (*18*). The results of this comparison are in Table S4.

From McCarl et al, the operating costs are calculated to be \$26.81 t^{-1} dry feedstock, while the capital costs are \$10.6 M. For a lifetime of 20 years and 5% discount rate, the annual capital costs are \$850,571, and the cost per tonne dry feedstock is \$12.14.

The Bridgwater et al study is calculated in Euros for the year 2000. For these estimates, we convert the 2000 Euro to 2000 USD using the 2000 exchange rate of 0.9231 (*60*), and then use a price inflator of 1.189 for fixed investment (*61*) to convert 2000 USD to 2007 USD (to be comparable to the McCarl et al study). From Bridgwater et al, the operating costs per tonne dry feedstock are calculated to be \$21.23 (2007 USD). For the capital, this study formulates an equation to model the total pyrolysis plant cost (*TPC*) as a function of feedstock throughput:

$$TPC \text{ (2000 kEuros)} = 40.8 * (Q_{h,pret,dry} * 1000)^{0.6194} \quad (7)$$

Where $Q_{h,pret,dry}$ is the mass flow rate of prepared wood feed into the reactor in oven dry tonnes. Using eq. (7), and converting to 2007 USD, the *TPC* is \$13,450,993. For a lifetime of 20 years and 5% discount rate, the annual capital costs are \$1,079,342, and the cost per tonne dry feedstock is \$15.40.

The price estimate from Coaltec is for the capital cost only – therefore in comparing the three, we use the operating cost of \$26.81 t^{-1} dry feedstock from McCarl. The capital cost estimate from Coaltec is \$8,930,377 (2007 USD). For a lifetime of 20 years and 5% discount rate, the annual capital costs are \$716,597, and the cost per tonne dry feedstock is \$10.23.

TABLE S4. Pyrolysis facility cost comparison

Costs (2007 USD)	McCarl et al	Bridgwater et al	Coaltec
Pretreatment			
Operating ($ t^{-1} DM)	$4.77	$4.77	$4.77
Capital ($ t^{-1} DM)	$4.12	$4.12	$4.12
Pyrolysis			
Operating ($ t^{-1} DM)	$26.81	$21.23	$26.81
Capital ($ t^{-1} DM)	$12.14	$15.40	$10.23
Iron			
Total Operating ($ t^{-1} DM)	$31.58	$25.02	$31.58
Total Capital ($ t^{-1} DM)	$16.26	$19.52	$14.35
Total ($ t^{-1} DM)	$47.84	$44.54	$45.93

It is encouraging to see from Table S4 that the pyrolysis facility cost comparison amongst the three sources yields comparable results (within a $4 range per tonne dry feedstock). For our analysis we have used the study from McCarl et al, as it is the highest of the three providing the most conservative estimate of the pyrolysis facility costs. It is also important to note that if the plant were designed to clean the syngas for applications in engines with purity requirements, the costs of the gas cleanup equipment can be significant (*59*).

Net profit. The costs, revenues and net profit as defined by eq. (1) for the late stover, switchgrass A and B, and yard waste scenarios are summarized in Table S5.

TABLE S5. Costs and revenues per dry tonne of feedstock. Each feedstock has a low and high revenue scenario, representing \$20 and \$80 per tonne CO_2e sequestered, respectively

	Late stover		Switchgrass A		Switchgrass B		Yard waste	
	Low	high	Low	High	low	High	low	high
Biochar								
P & K content	18.39		9.68		9.68		10.01	
Improved fertilizer use	1.22		1.18		1.18		1.22	
C value	17.28	69.12	8.84	35.36	-0.72	-2.88	17.70	70.80
Energy	42.81		55.05		55.05		35.20	
Tipping fee	NA		NA		NA		49.09	
Avoided compost cost	NA		NA		NA		10.98	
Lost compost revenue	NA		NA		NA		-56.03	
Feedstock	-43.46		-36.89		-36.89		NA	
Transport								
Biomass	-6.24		-6.02		-6.02		NA	
Biochar	-1.57		-1.53		-1.53		-1.57	
Biochar application	-1.07		-1.04		-1.04		-1.07	
Pyrolysis								
Operating	-31.58		-31.58		-31.58		-31.58	
Capital	-16.26		-16.26		-16.26		-16.26	
Net value (\$)	**-17.07**	**34.77**	**-18.57**	**7.95**	**-30.29**	**-28.13**	**15.87**	**68.97**

Impact Assessment. The biogenic CO_2 emissions are accounted for in the C balance of each biomass-to-biochar system as illustrated in Figure S1 for late stover. The CO_2 emissions from the biomass pyrolysis and combustion of the syngas are balanced by the biomass uptake of CO_2 from the atmosphere, and the only biomass C that has a global warming impact is the stable C sequestered in the biochar. Therefore, the only biogenic CO_2 included in the impact assessment and contribution analysis for each feedstock are those due to the stable C in the biochar.

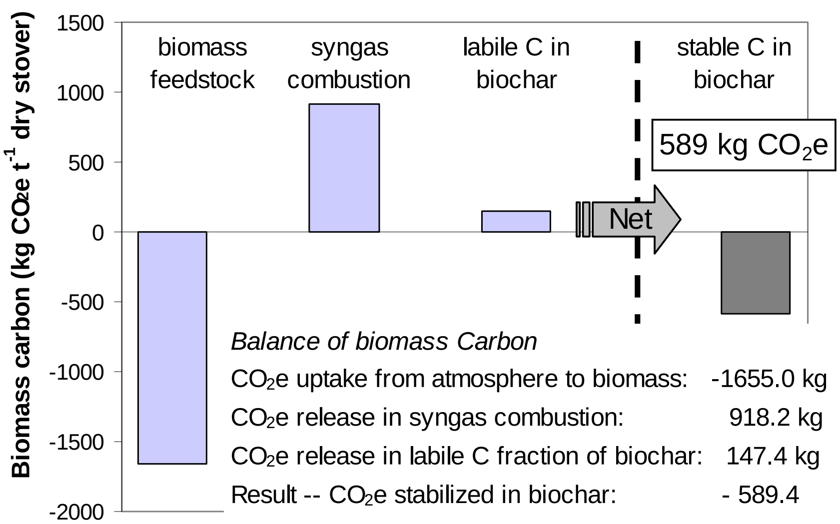

FIGURE S1. Biomass C balance for a biochar system with bioenergy production using the example of the late stover feedstock.

Table S6 provides a summary of the energy, climate change, and economic impacts of the biochar systems.

TABLE S6. Impact assessment results for late stover, early stover, switchgrass A and B, and yard waste feedstock for pyrolysis with biochar returned to soil

Energy	Late stover	Early stover	Switchgrass A	Switchgrass B	Yard waste
Net energy (MJ t^{-1} DM)	4116	3044	4899	4899	4043
Fossil fuels (MJ t^{-1} DM)	-750	-1007	-893	-893	424
Excess syngas energy (MJ t^{-1} DM)	4859	4002	5787	5787	3507
Climate change					
Net GHG (kg CO_2e t^{-1} DM)	-864	-793	-442	36	-885
GHG emissions (kg CO_2e t^{-1} DM)	81	98	517	1028	19
GHG reductions (kg CO_2e t^{-1} DM)	-945	-890	-959	-992	-904
Economics					
Net cost (high) (\$$t^{-1}$ DM)	35	11	11	-26	69
Net cost (low) (\$$t^{-1}$ DM)	-17	-17	-16	-27	16

Continuing the discussion in the main article, we also compare the energy yields of our LCA to other published literature. In terms of energy yield (defined as the net output divided by the total inputs), the Gaunt and Lehmann analysis (*62*) found a net energy yield of 6.9 and 5.3 MJ MJ^{-1} for corn stover and switchgrass, respectively. Our LCA found the net energy yield to be less than those, at 2.8 and 3.1 MJ MJ^{-1} for stover and switchgrass, respectively. Since the syngas heat energy output of our system (37% of the feedstock energy) is higher than the cleaned syngas energy output in their report (38% of the feedstock energy), it is evident that there are differences in the calculation methods. These could arise from the higher energy inputs associated with the feedstock production and processing included in our LCA, and possibly different lower heating values of the feedstock used in the energy yield calculations.

Our LCA results for potential GHG emission reductions and bioenergy production fall on the lower end of the calculations for both of these detailed GHG accounting analyses of biochar

(*62, 63*), likely due to our comprehensive life cycle assessment methodology and utilizing more conservative estimates for biochar's soil amendment properties.

Economics. We have also considered the case where there is no value assigned to CO_2 offsets. The results in Table S7 demonstrate that without C offsets, none of the feedstocks are economically viable at this stage. Yard waste is the closest, with less than \$2 t^{-1} DM to break even. Another scenario is if only the stable C in the biochar receives C offset value, instead of the life cycle emissions reductions. From the results in Table S7 it is evident that the yard waste is again the most economically viable of all feedstocks (\$44 t^{-1} DM for the high revenue scenario), but it is lower than when the life cycle C offsets are valued (\$69 t^{-1} DM, see Table S6). Late stover is also less viable when only the stable C is valued as compared to the life cycle emissions (\$13 vs. \$35 for the high revenue scenario). However, switchgrass A and B become more profitable when only the stable C is valued, as the CO_2e from the biochar is greater than the net CO_2e reductions (or net positive emissions for switchgrass B).

TABLE S7. Net profits under scenarios varying C offset values (\$ t^{-1} DM).

	Late stover	Switchgrass A	Switchgrass B	Yard waste
No C value	-34.35	-27.41	-27.41	-1.83
Value stable C in biochar only				
High revenue scenario	12.77	16.77	16.77	43.91
Low revenue scenario	-22.57	7.95	7.95	9.59

Sensitivity Analysis. Sensitivity analyses were conducted for the late stover system on the feedstock and biochar transportation distance, stover collection energy and GHG emissions, avoided fossil fuels, soil N_2O emissions, syngas energy yield, biochar yield, stable C content of the biochar, and fertilizer use efficiency. The data with the most uncertainty are the soil N_2O emissions and syngas energy yield, followed by the stable C, char yield and stover collection inputs. The manuscript includes the analysis of the transportation distance, and the remaining analyses are summarized in the discussion below and in Table S8.

The syngas energy yield was varied by comparing lower and upper bounds of 50% and 150% of the baseline and found a change in the net energy by ±63%, where both were still net energy positive, at +1509 MJ and +6722 MJ, respectively. Unfortunately, publications with process data for slow pyrolysis with syngas energy capture and heat production is severely limited at this time, and further research and reporting is required in order to improve these data.

The avoided fossil fuel production and combustion processes (due to syngas production and combustion) were varied from the baseline (natural gas combusted in a large utility boiler) to coal in an integrated gasification combined cycle (IGCC) and diesel combusted in a stationary reciprocating engine. When the avoided fossil fuel process is changed from the baseline to coal IGCC, 24% more GHG emissions are avoided. For diesel combusted in a stationary reciprocating engine, 10% more GHG are avoided. Meanwhile, the net energy only changes by +6% and -6% from the baseline for diesel and coal, respectively.

The sensitivity analysis considers the cases where there are no changes in soil N_2O emissions with biochar application and where there is an 80% decrease in N_2O emissions. As the contribution analysis indicates, the soil N_2O emissions have only a small impact on the net GHG emissions. Varying the decrease in soil N_2O emissions from 0% (i.e. biochar has no effect on soil N_2O emissions) to 80% reduced N_2O emissions, the net GHG emissions change only 4% at most.

For the stable C sensitivity analysis, the portion of stable C in the biochar is varied from 0 wt.% to 90 wt.%, with a baseline of 80 wt.%. If we assume only 50% of the C in the biochar is stable, then the net GHG emissions increase by 26% from -864 to -643 kg CO_2e, still resulting in C sequestration and net negative GHG emissions. For 0% stable C, the net GHG are -275 kg

CO_2e, resulting from the avoided fossil fuels. When 90% of the C in the biochar is stable, 9% more GHG are sequestered.

The biochar yield was varied from 12 wt.% to 35 wt.% of the dry feedstock, based on values for biochar yields from fast pyrolysis and carbonization, respectively (*64*). Varying the biochar yield from 12 to 35 wt. %, causes the net GHG emissions change by -13% and 1%, respectively.

The stover collection energy was varied from 723 to 833 MJ t^{-1} collected and GHG emissions from -33 to 76 kg CO_2e t^{-1} collected, where this range of values is found for seven counties in the US Corn Belt (1). The net energy is relatively insensitive to the range of stover collection energies, with changes by only 1-2%. Varying the GHG emissions from stover collection results in either 12% more or 3% less GHG reductions.

The sensitivity analysis overall reveals that the net energy is most sensitive to the syngas energy yield. However, even a conservative estimate at 50% of the baseline value results in a net energy positive system, with +1509 MJ per tonne. The net GHG emissions are most sensitive to the avoided fossil fuel combustion process and the stable C content of the biochar. Regardless, all of the late stover scenarios result in net GHG reductions, generally within the -650 to -900 kg CO_2e range.

TABLE S8. Sensitivity analysis of stover collection energy and emissions, biochar yield, stable C, soil N_2O emissions, syngas energy yield, avoided fossil fuels, and transportation for the late stover system

Stover collection energy sensitivity				
Energy per tonne collected (MJ)	723	765 (baseline)	833	
Net energy (MJ)	4165	4116	4036	
% change	1%	0%	-2%	
Stover collection emissions sensitivity				
Emissions per tonne collected (kg CO_2e)	-33	58 (baseline)	76	
Net CO_2e (kg)	-970	-864	-843	
% change	12%	0%	-2%	
Char yield sensitivity				
Char yield input	12 wt %	28.8 wt % (baseline)	35 wt %	
Net CO_2e (kg)	-756	-864	-875	
% change	-13%	0%	1%	
Stable C sensitivity				
Stable C content of biochar	0%	50%	80% (baseline)	90%
Net CO_2e (kg)	-275	-643	-864	-938
% change	-68%	-26%	0%	9%
Soil N_2O sensitivity				
Decrease in soil N_2O emissions	0%	50% (baseline)	80%	
Net CO_2e (kg)	-828	-864	-885	
% change	-4%	0%	2%	
Syngas energy sensitivity				
Energy yield input	50% of baseline	(baseline)	150% of baseline	
Net energy (MJ)	1509	4116	6722	
% change	-63%	0%	63%	
Net CO_2e (kg)	-703	-864	-1025	
% change	-19%	0%	19%	

Avoided fossil fuels sensitivity

Fuel combustion process	natural gas large utility boiler (baseline)	diesel stationary reciprocating engine	coal IGCC
Net energy (MJ)	4116	4377	3860
% change	0%	6%	-6%
Net CO_2e (kg)	-864	-947	-1070
% change	0%	10%	24%

Distance sensitivity

Distance (km)	0	15 (baseline)	30	100	200	500	1000
Net energy (MJ)	4165	4116	4066	3835	3505	2514	863
% change	1%	0%	-1%	-7%	-15%	-39%	-79%
Net CO_2e (kg)	-868	-864	-860	-844	-819	-747	-626
% change	0%	0%	0%	-2%	-5%	-14%	-28%

Comments

The LCA conducted in this paper is used as a tool to estimate the potential impacts of biochar systems. We acknowledge that there are still gaps in the process data, as is expected for emerging technologies. Specifically, we have not included water consumption; electricity and energy consumption of the ancillary pyrolysis plant operations (beyond the pre-processing and pyrolysis processes, such as building requirements, lighting, heating, etc); and soil structure and fertility improvements. All of these would likely influence the overall energy, GHG emissions, and economic balance of the biochar system. As more data becomes available, it is our goal to incorporate it and improve the Biochar energy, greenhouse gases, and economic (BEGGE) LCA and make it publicly available.

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