Supporting Information:

Supply Cost and Life-Cycle Greenhouse Gas Footprint of Dry and Ensiled Biomass Sorghum for Biofuel Production

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S1. Modeling Overview

We propose two potential supply chain options to deliver bioenergy sorghum to the biorefinery: (i) direct supply from the field to the biorefinery; and (ii) biomass is first transported to the preprocessing facility (storage depot) in the forms of chopped biomass, modules, and bales, pellets are produced at the depot, and then pellets are delivered to the biorefinery. The first route is applicable for near-term biorefineries or if biorefineries are located within the resource-rich area, where the biorefinery can directly contact the farmers to collect the required feedstock. The second route is applicable if the biorefinery is located outside the resource-rich area.

We developed the overall feedstock supply model considering previous supply chain models for biomass sorghum[1–3] and other notable commercial-scale cellulosic biomass feedstock supply models including the Integrated Biomass Supply Analysis and Logistics (IBSAL) model[4] developed by Oak Ridge National Laboratory (ORNL), and the Uniform-Format Solid Feedstock Supply System[5] developed by Idaho National Laboratory (INL). Our model captures the variabilities associated with different input parameters and provides the probabilistic cost and GHG emissions associated with each stage of the entire supply chain. The different stages of the biomass supply chain are presented in Figure 1. The detailed discussion of the different components/stages of the biomass supply chain are available in the previous studies, [1–5] the following sections discuss the modeling process, major data sources, and assumptions made in this study.

S1.1 Bioenergy Sorghum Production

While the production cost of corn is not considered as a part of the corn stover feedstock cost or allocated entirely for corn grain,[4,5] this should be a part of the biomass sorghum supply chain as it is cultivated entirely for biomass production. We considered an average production cost instead of specifying a specific location. Table S1 summarizes data inputs used to determine the biomass sorghum production cost. Previous studies[2,6–8] provide the detailed cost analysis. However, the labor rate and fuel price for biomass production/-establishment are updated in this study, which are consistent with biomass harvesting operations (Tables S3 and S7).

Table S1. Input parameters used to determine biomass sorghum production cost

Parameter	Unit	μ	a	b	σ	Probability distribution
Biorefinery size (assumed)	t/day	2000.0	-	-	-	None
Harvest rate[3,7–14]	t/ha	17.9	5.2	27.6	5.4	Lognormal
Land utilization for sorghum farming[ω]	%	5.0	2.0	10.0	-	Triangular
Establishment cost (except nutrient, herbicides, land rent, labor, and fuel) [6–8]	$/ha	186.2	179.7	192.6	-	Uniform
Establishment fuel-diesel[6–8]	L/ha	59.2	41.7	94.1	-	Uniform
Establishment labor[6–8]	h/ha	3.7	0.8	7.2	-	Triangular
Land rent[15]	$/ha	136.0	32.0	340.0	-	Triangular

Note: **t** = metric ton; ***μ*** = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation

[ω]Percentage of the total area (including land, water bodies, and others) around the biorefinery.

Fertilizer application is a part of the production cost and could have substantial impact on both feedstock supply cost and GHG emissions. Therefore, the impacts of fertilizers on biomass feedstock supply cost and GHG emissions are assessed separately. We only consider the primary nutrient replenishment cost including nitrogen, potassium, and phosphorus, which is the major part of the biomass production cost.[2] Table S1 summarizes the baseline and the range of the primary nutrients and their prices. Nitrogen fertilizer is modeled as a combination of ammonia, urea, and ammonium nitrate, using ratios consistent with GREET. While biomass sorghum has tolerance to disease and insects, herbicides, such as 2,4-D, atrazine, metolachlor, and bromoxynil, could be used for forage sorghum.[8,16] We consider atrazine[6,8] for analysis in this study and its application rate is summarized in Table S1. The tolerance to insect is may be due to the toxic substance (toxic to corn rootworm larvae) is produced in the sorghum roots.[16] Therefore, biomass sorghum can be grown without application of soil insecticides. For instance, chemical controls are not recommended for forage sorghum in Pennsylvania.[17]

Other costs associated with the biomass sorghum production could be considered as incentives to growers and opportunity costs (dependent on the demand of biomass sorghum for animal feedstock, and feedstock for bioproduct or power generation). Biorefineries may or may not pay this incentive to the farmers and the opportunity cost, particularly for bioenergy sorghum, is still unclear to date; therefore, these are excluded in this study.

Table S2. Primary nutrients and chemical inputs for biomass sorghum and their prices

Parameter	Unit	μ	a	b	σ	Probability distribution
Nitrogen[3,12,18–20]	kg/ha	121.24	48.00	217.00	51.88	Triangular
N_2O emissions[21]	g/kg-N	11.5	10.7	12.8	-	Triangular
Phosphorus[3,18,19]	kg/ha	23.89	9.30	67.25	16.74	Triangular
Potassium[3,18,19]	kg/ha	168.09	20.00	293.66	100.53	Triangular
Price of nitrogen[22–26]	$/kg	1.06	0.60	1.40	0.34	Triangular
Price of phosphorus[22–26]	$/kg	1.01	0.82	1.20	0.15	Triangular
Price of potassium[22–26]	$/kg	1.09	0.91	1.26	0.14	Triangular
Herbicides[6,8,27]	kg/ha	3.13	1.79	5.60	-	Triangular
Herbicides[6–8,27]	$/ha	62.12	24.46	111.20	-	Triangular

Note: ***μ*** = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation

S1.2 Field Operations

We consider a harvesting window of 31.5 days/year[28] and working hours are assumed to be 16 hours/day for the baseline analysis (Table 1). Biomass sorghum is a thick-stemmed crop which contains moisture of 40-70 wt% (reported as fraction of wet weight)[29,30] at the time of harvest. Two potential harvesting options for this high moisture feedstock are a direct cut system (such as chopped biomass) and a wilting system (such as mowing or windrowing, field drying, and module building or baling).[1,31] The field drying could reduce moisture content from more than 75% to 40-50% after a few hours to 2 days[1] depending on the relative humidity of the biomass growing regions. After the field drying, chopping and the subsequent module building is the easiest option instead of the direct baling due to the remaining moisture and hard stem; however, the baling technologies are being improved for biomass sorghum. Therefore, we considered all these different promising field operations for analysis in this study.

S1.2.1 Chopped Biomass or Direct Cut System

In this scenario, we consider self-propelled forage harvester to harvest biomass sorghum. The forage harvester directly chopped biomass into small pieces where the size of the chopped biomass is controlled by changing the knife configurations of the forage harvester. Following this, we consider two potential field operations, i.e., with or without infield transportation. For the first option, the chopped biomass is blown into a wagon, which is pulled by the forage harvester. Once filled, the chopped biomass is dumped into another wagon, which is pulled by a tractor. The tractor is driven to the field-edge where chopped biomass is dumped into a truck. And then, the fully loaded truck is transported either directly to the biorefinery (Figure 1) or to the storage depot (Figure 1). Each of these dumping processes (loading or unloading time of wagon) takes about 1 to 2.5 minutes or less.[1] The bulk density of the chopped biomass is generally in the range of 60-125 kg/m^3.[31–33] The estimated average bulk density of dry chopped biomass of 87.5 kg/m^3 is used for the baseline analysis.[31–33] We consider the capacity of the wagon of 31.2 m^3 and the maximum payload of 5.67 t (wet).[34] This capacity requires 4 loads of the wagon to meet the federal weight limit of a truck of 22.7 t.[1] Another potential route is that the chopped biomass could be directly blown into a truck in the field and then transported either directly to the biorefinery (Figure 1) or to the storage depot (Figure 1). Although advanced self-propelled forage harvester with active fill control is available that can reduce losses of biomass during harvesting, we consider the total harvesting losses for the direct cut system in the range of 2 to 10% (Table 1).[31,34]

The direct loading of the chopped biomass into a truck is an attractive option as it eliminates the cost and emissions associated with infield transportation, loading, and unloading operations. However, the direct loading in the field may not be always convenient depending on the field conditions (i.e., wet field and space availability for the large truck) and soil compaction[35] issues. Nonetheless, discussion with members of the National Sorghum Producers reveals that the direct loading option is the most commonly preferred biomass sorghum harvesting option at present. Therefore, this option is selected a primary scenario for chopped biomass although we also present results with the infield transportation option. Table S2 summarizes all the required input data for these two potential field operations of the direct cut system.

Table S3. Operating data and purchasing price for forage harvester and infield transportation system

Parameter	Unit	μ	a	b	σ	Probability distribution
Forage harvester						
Productivity[1,31,34]	t/h	31.67	26.33	49.22	10.45	Triangular
Field efficiency[1,31,36]	%	76.43	60.00	90.00	9.88	Triangular
Fuel consumption[1]	L/h	61.61	28.62	104.15	26.85	Triangular
Labor rate[37]	$/h	19.36	12.62	29.81	6.82	Triangular
Wagon unloading time[1,31]	h	0.03	0.02	0.05	0.02	Triangular
Purchasing price[1,31,38–40]	$/unit	230,570	179,334	259,725	30,710	Triangular
Repair and maintenance[1,31,36]	%	7.36	5.57	10.14	-	Triangular
Service life[1,31,36]	yr	4.50	4.00	5.00	-	Constant
Salvage value[1,31,36]	%	18.60	15.00	25.00	-	Constant
Material loss[31,34]	%	6.00	2.00	10.00	-	Triangular
Infield transportation						Triangular
Bulk density of silage[31–33]	kg/m^3	87.50	60.00	125.00	27.23	Triangular
Infield transportation distance[1,4]	km	0.8	0.2	1.6	0.20	Triangular
Tractor speed[1,31]	km/h	11.3	4.8	16.1	-	Triangular
Wagon loading/unloading time[1,31]	h	0.03	0.02	0.05	0.02	Triangular
Tractor and wagon price[1,31]	$	37,877	37,104	38,650	1,093	Triangular
Tractor fuel consumption[1]	L/h	9.12	7.56	11.34	1.97	Triangular
Tractor and wagon maintenance[1]	%	7.36	5.57	10.14	-	Triangular
Tractor service life[1,31,36]	yr	6.00	5.00	8.00	-	Constant
Tractor salvage value[1,31,36]	%	12.30	5.00	24.00	-	Constant
Infield winding factor[4]	-	1.20	-	-	-	Constant

Note: μ = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation; **t** = metric ton

S1.2.2 Module Building System

Although biochemical/biological conversion of biomass requires process water, the transportation of water in the form of moisture is an unrecoverable cost. It is usually preferred to transport biomass feedstock at lowest moisture and highest bulk density as possible to reduce the feedstock transportation cost. The low moisture content of the feedstock is also preferred to reduce the dry matter loss and to preserve the quality of biomass during storage.[5] Biomass modules are one of the potential options to achieve these requirements. The module is a large rectangular bale and densified form of the chopped biomass. The module system composed of following field operations (Figure 1): (i) mowing or windrowing; (ii) infield drying; (iii) chopping; (iv) module building; and (v) module hauling or module collection at the field edge.

Mowing or windrowing operation includes cutting of the standing biomass sorghum. This operation is similar to corn stover or energy crops as discussed in the previous study.[5] following this, biomass is left in the field for drying. This could be few hours to 14 days depending on the moisture content of biomass at the time of harvest and the local climate.[1,31] We assumed the moisture content of biomass after the field drying of 40% to reduce the dry-down time. This moisture can be achieved after around two days of the field drying.[1] Windrow turner is used once in three days to turn the biomass for effective drying. Table S3 summarizes the operating data and purchasing price for windrower and windrow turner.

Table S4. Operating data and purchasing price for windrower and windrow turner

Parameter	Unit	μ	a	b	σ	Probability distribution
Windrower						
Productivity[1,5,31]	t/h	32.39	19.63	54.14	13.38	Triangular
Field efficiency[1,5,31]	%	75.00	50.00	90.00	12.91	Triangular
Fuel consumption[1,5,31]	L/h	25.06	18.90	34.10	6.87	Triangular
Labor rate[37]	$/h	19.36	12.62	29.81	6.82	Triangular
Purchasing price[1,5,31]	$/unit	48,691	23,000	83,096	23,234	Triangular
Repair and maintenance[1,31]	%	27.50	7.50	48.00	20.25	Triangular
Service life[1,31]	yr	4.50	4.00	5.00	0.71	Constant
Salvage value[1,31]	%	19.72	15.00	25.00	4.12	Constant
Windrow turner/raking						
Productivity[1,31]	t/h	64.78	2.64	108.27	26.76	Triangular
Field efficiency[1,31]	%	75.00	50.00	90.00	12.91	Triangular
Fuel consumption[1,31]	L/h	9.12	7.56	11.34	1.97	Triangular
Labor rate[37]	$/h	19.36	12.62	29.81	6.82	Triangular
Purchasing price per unit[1,31]	$	37,876	37,103	38,649	1,093	Triangular
Repair and maintenance[1,31]	%	7.36	5.57	10.14	2.00	Triangular
Service life[1,31]	yr	6.25	5.00	7.50	1.77	Constant
Salvage value[1,31]	%	12.30	5.00	24.00	8.19	Constant

Note: $\boldsymbol{\mu}$ = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation; t = metric ton

After the 2 days of field drying, a forage harvester is used for chopping. The chopped biomass is blown in the wagon, which is towed by the forage harvester. This operation is similar to the chopped biomass harvesting operating as discussed earlier. Therefore, we used the same sizes of forage chopper and wagon for this operation (Table S2). When the wagon is filled, the biomass is dumped into the module builder, which is pulled by a tractor and moved parallel to the forage harvester. The module builder compressed the biomass into a constrained package. At the same time, the forage harvester continuously blows the chopped biomass in the wagon towed by itself. The required number of module builders for each forage harvester is estimated considering their productivity and time required for loading (for the chopped biomass), unloading (for the module), and preparation (for plastic wrap) operations (Tables S2 and S4). The typical dimensions of a cotton module are 9.8 m long, 2.4 m wide, and 2.4 m high.[31] The targeted bulk density of a biomass module is 240.3 kg (dry)/m^3.[31] While a commercial module builder for biomass is yet to be built, the maximum length of a biomass module should be less than the length of 14.6 m (48 ft) of a common semitrailer. However, it is hard to achieve the required limits of both weight and dimensions of a tractor-semitrailer with a single large module due to variability present in biomass moisture and bulk density. Therefore, we propose a typical module of 4.92 m long, 2.4 m wide and 2.4 m high (in this case, the maximum length of a module should be less than 7.3 m). Two modules with the proposed dimensions, targeted bulk density, and assumed moisture content after field drying of 40% result in the mass of a wet module of 22.7 t (equal to the federal weight limit of a truck). Current commercial forage harvester/chopper has the built-in moisture sensor, which is useful to adjust the length of a module. Therefore, a future commercial module builder should be flexible to allow for module length adjustment, if required.

Once the predefined weight of a module of 11.35 t (wet) is reached (this requires two full loads of the wagon consider in this study), the package will be closed to create an anaerobic environment, the module will be dropped in the field, and next one will be started. The anaerobic environment or airtight packaging (similar to the ensiling) can prevent the degradation of the quality of biomass during storage. Finally, the module hauler collects the module at the field edge or loading point at the field where the modules are loaded in a tractor-semitrailer and transported either to the storage depot or to the biorefinery. The detailed operating conditions for module builder and hauler are summarized in SI-Table S4.

Table S5. Operating data and purchasing price for module builder and module hauler

Parameter	Unit	μ	a	b	σ	Probability distribution
Module builder						
Productivity[1]	t/h	29.65	21.27	39.25	6.30	Triangular
Field efficiency[1]	%	76.43	60.00	90.00	9.88	Triangular
Fuel consumption[1,31]	L/h	64.55	30.08	94.00	27.08	Triangular
Labor rate[37]	$/h	19.36	12.62	29.81	6.82	Triangular
Purchasing price[31]	$/unit	450,000	350,000	550,000	39,727	Triangular
Repair and maintenance[1,31]	%	7.36	5.57	10.14	2.00	Triangular
Service life[1,31]	yr	6.25	5.00	7.50	1.77	Constant
Salvage value[1,31]	%	12.30	5.00	24.00	8.19	Constant
Plastic wrap[1,31]	$/m^2	0.34	0.10	0.61	0.26	Triangular
Module unloading time[1,31]	h	0.04	0.01	0.07	0.03	Triangular
Preparation time[1,31]	h	0.01	0.003	0.02	0.007	Triangular
Bulk density of module[31]	kg/m^3	240.30	192.20	288.40	48.10	Triangular
Module hauler						
Maximum weight[1]	t/trip	15.96	7.98	23.94	7.98	Triangular
Transport efficiency[1]	%	85.00	75.00	95.00	8.16	Triangular
Fuel consumption[1,31]	L/h	67.89	30.08	91.09	27.39	Triangular
Labor rate[37]	$/h	19.36	12.62	29.81	6.82	Triangular
Purchasing price[31]	$/unit	375,000	250,000	500,000	125,000	Triangular
Repair and maintenance[1,31]	%	7.36	5.57	10.14	2.00	Triangular
Service life[1,31]	yr	8	5.00	10	-	Constant
Salvage value[1,31]	%	12.30	5.00	24.00	8.19	Constant
Speed[1,31]	km/h	10.73	4.80	16.10	5.67	Triangular
Loading time[31]	h	0.03	0.02	0.05	0.02	Triangular
Unloading time[31]	h	0.03	0.02	0.05	0.02	Triangular
One-way transportation distance[1,4]	km	0.80	0.20	1.60	0.20	Triangular

Note: ***μ*** = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation; **t** = metric ton

S1.2.3 Baling system

Biomass harvesting in the form of a rectangular or round bale is a common field operation for the most of the agricultural residues and energy crops, including corn stover, Miscanthus, and switchgrass.[5,41] However, the baling is very challenging for biomass sorghum due to the high moisture content in the range of 40-70% at the time of harvest.[29,30] Therefore, infield drying is required for biomass sorghum to achieve the acceptable moisture content of around 20%.[5] The baling system includes the following field operations: (i) windrowing and conditioning; (ii) infield drying; (iii) baling; and (iv) stacking or collection of bales at the field edge. We consider a single-pass conditioning and windrowing operation that takes standing biomass sorghum directly to a windrow. After cutting the standing biomass, it passes through the conditioning rollers. The conditioning rollers crush and/or split the biomass sorghum stem. This is a very important process for biomass sorghum because it reduces the stiffness of the biomass, accelerates the field drying, and facilitates to produce the uniform and compact bales. For instance, a prior study[42] reported that a good conditioning with the "V" impeller, chisel impeller and fluted roll conditioner, the thin-layer drying time could be as low as 43.2, 32.2, and 12.5 hours, respectively. These drying hours were 30.2, 47.8, and 79.7% reduction relative to the unconditioned material. Although the field drying is different from the thin-layer drying, a good conditioning is key for reducing the dry-down time in the field.[42] Researchers in at Oklahoma State University have released educational videos indicating that the dry-down time in the field could be as low as 5 days to reach moisture content of about 20%. Another study[31] reported the field drying time of 10-14 days achieving moisture content of 20 to 50%; however, they have not evaluated the impact of biomass conditioning in the field drying. Khanchi et al.[43] found moisture content in sorghum bales in the range of 8.5 to 13.6% (wb) with an average value of 10.1% (wb) after 21 days of field drying at Chickasha, Oklahoma. These prior studies show dry down time in the field is highly uncertain and largely dependent on the biomass conditioning and the local climate. Based on these prior studies, we assume dry-down time of 10 days for the field drying. We also consider windrow turners to turn around the biomass, which is operated once in every three days.[44] This dry-down duration and the windrow turning operation are expected to reduce the moisture content of biomass from the baseline value at the time of harvest of 59.69% to an acceptable value of 20%. To capture the impacts of variabilities associated with the dry-down time, we further conducted sensitivity and uncertainty analyses considering 5 to 21 days of the dry-down time. Operating data and purchasing cost used for windrower and windrow turner are summarized in Table S3. Other operations, including baling and stacking, are consistent with previous studies.[1,5,45] We consider the rectangular bale (2.42 m long, 1.17 m wide, and 0.98 m high) with the bulk density of 168.45 ± 26.13 kg/m^3.[42] Table S5 summarizes the operating data and purchasing price of baler and stacker.

Table S6. Operating data and purchasing price of baler and stacker

Parameter	Unit	μ	a	b	σ	Probability distribution
Baler[1,5,45]						
Productivity	t/h	25.91	20.00	43.31	10.70	Triangular
Field efficiency	%	66.29	35.00	90.00	19.36	Triangular
Fuel consumption	L/h	33.50	18.90	53.00	12.84	Triangular
Labor rate	$/h	20.11	12.62	29.81	7.18	Triangular
Consumable: string	m/bale	38.00	38.00	38.00	-	Constant
Cost of consumable string	$/m	0.02	0.02	0.02	0.00	Constant
Purchasing price	$/unit	109,531	87,700	135,000	17,986	Triangular
Repair and maintenance	%	20.00	5.00	35.00	21.21	Triangular
Service life	year	6.00	5.00	7.00	1.41	Constant
Salvage value	%	22.50	20.00	25.00	3.54	Constant
Stacker[1,5,45]						
Productivity	bales/h	65.00	50.00	80.00	10.64	Triangular
Field efficiency	%	87.00	70.00	97.00	10.20	Triangular
Fuel consumption	L/h	21.17	8.47	37.90	12.00	Triangular
Labor rate	$/h	20.11	12.62	29.81	7.18	Triangular
Purchasing price	$/unit	79,967	70,000	90,000	10,000	Triangular
Repair and maintenance	%	26.17	3.33	49.00	32.29	Triangular
Service life	year	5.00	5.00	5.00	-	Constant
Salvage value	%	10.00	5.00	15.00	7.07	Constant

Note: μ = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation; **t** = metric ton

S1.3 Transportation of chopped biomass, module, and bale

The harvested biomass in the form of chopped biomass, module and bales are transported either directly to the biorefinery or to the storage depot. This transportation operation includes loading at the field edge, transportation via truck, and unloading at the biorefinery/or storage depot. As the part of the field operations of the chopped biomass and module include loading into the truck, therefore, the loading operation at the field is excluded for these two forms of biomass feedstock. However, all the loading, transportation, and unloading operations associated with the feedstock transportation are included to transport bales, which are consistent with previous studies.[5,45] Briefly, a squeeze bale loader is used to load and unload the bales. A group of people conducts these loading and unloading operations. For each group, two squeeze bale loaders (one at each end) and 4 trucks[46] are assigned. Each truck can carry up to 36 bales/trip due to the size limit. The same truck can transport as much as 2 modules per trip. We consider a box truck with a capacity of 133.8 m^3 to transport chopped biomass[1] where the maximum payload is assumed to be 22.7 t. Table S6 summarizes the operating data associated with feedstock transportation. The detailed methods for estimation of resources and cost for feedstock transportation are available elsewhere.[45,47,48]

Table S7. Operating data associated with the feedstock transportation operation

Parameter	Unit	μ	A	b	σ	Probability distribution
Truck						
Purchasing price[1,49]	$/unit	140,000	130,000	150,000	-	Triangular
Labor cost[37]	$/h	20.83	12.94	30.36	6.95	Triangular
Fuel consumption[45]	L/km	0.43	0.35	0.50	0.06	Triangular
Diesel price[50]	$/L	0.88	0.61	1.05	0.18	Lognormal
Loader for bale						
Purchasing price[1]	$/unit	30,000	20,000	40,000	-	Triangular
Labor cost[37]	$/h	19.36	12.62	29.81	6.82	Triangular
Fuel consumption[45]	L/h	20.80	17.00	24.60	5.70	Triangular
Loading time[45]	h	0.63	0.33	0.95	0.31	Triangular
Unloading time[Φ45]	h	0.49	0.17	1.49	0.58	Triangular
Storage or biorefinery transport for chopped biomass, module, and bale						
Working days[28]	days/yr	31.54	15.00	75.00	14.59	Triangular
Working hours [λ]	h/day	16.00	8.00	24.00	8.00	Triangular
Biorefinery transport for pellets						
Working days[45]	days/yr	330	300	360	-	Triangular
Working hours[45]	h/day	16	12	20	-	Triangular

Note: $\boldsymbol{\mu}$ = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation

[Φ]The same unloading (includes unloading and waiting time) time is considered for the chopped biomass, module, and pellets

[λ]*Assumed based on the current harvesting practices of biomass sorghum.*

S1.4 Feedstock storage

Different storage methods for the chopped biomass, module, and bale are used at the storage depot and the biorefinery. The chopped biomass is ensiled in a bunker silo, which is covered by the tarp.[36] This ensiling process creates an anaerobic environment, which prevents degradation of the quality of biomass.[31] Module, which is packed in the airtight package, and bale (contains <20% moisture) are stored in open space under the tarp. Gravels are laid in the floor to protect bales and module from moisture seepage from ground. Detailed methods to estimate the storage cost is provided in the previous studies.[5,36,45]

S1.5 Pellet production and transportation

Pelletization is a promising form of feedstock for both biochemical and thermochemical conversions of biomass because of several benefits, including can be directly fed into the reactor without size reduction, easy for long-term storage, transportation and handling, low chance of biological degradation.[41] Pellets can be fully utilized the truck carrying capacity and reduce the transportation cost when compared to loose biomass, module and bale due to its high bulk density of 700 kg/m^3.[33] Therefore, we considered the preprocessing of the chopped biomass, module, and bale into the pellet at the storage depot. The process model for the pellet production process and assumptions are consistent with previous studies.[41,51] Briefly, this includes feedstock handling and primary milling (primary milling is only required for module and bale), drying, secondary milling, conditioning and pellet production, and steam generation units. The primary milling breaks the module and reduces particle size of bale to about 7.62 cm.[41] While modeling assumptions for the primary hammer mill are consistent with the previous study,[41] we increased throughput of the hammer mill by 2 fold and energy consumption is reduced by half for module as the module (i.e., the compact form of chopped biomass) can be processed faster than the bale. The chopped biomass is typically in the range of 0.95-1.9 cm,[52] therefore, we consider a secondary milling after drying to achieve the proper particle size for the pellet of 0.635cm.[41] We considered rotary steam dryer for drying operation. We assume 2% dry matter loss during the overall pelletizing process.[41] In additional to this, 90% of the initial organic acids present in silage are assumed to be lost during the drying process. The initial organic acids in silage, although varies over the storage period, are assumed to be, on average, 8 wt%. This assumption is required to be validated with large-scale experimental analysis. Our model at present does not considered recovery of waste organic acids at this point; however, if large fractions of acids are presented in biomass silage, acids recovery could be beneficial. The cost and carbon credits from the recovered acids reduce the overall pellet production cost and GHG emissions for the silage-based system. The required process steam for drying and conditioning is generated by using natural gas. The waste heat from the returned process steam is recovered to reduce the boiler energy (natural gas) consumption. We also considered solar drying[41] as an alternative drying process for the optimal future case scenario.

Pellets are stored at the storage depot and delivered to the biorefineries based on their requirement. Box truck is used to deliver the pellets to the biorefinery. The pneumatic conveyor is used to load pellets at the storage depot, which is unloaded at the biorefinery using a truck dumper. We considered the allowable payload capacity of 22.7 t[1] per trip as the truck carrying capacity can be fully utilized with pellets due to its high bulk density of 700 kg/m^3.[33] Table S6 summarizes the input data considered to estimate labor, fuel, and transportation resources required to deliver pellets to the biorefinery. Figure S1 shows the resulting cost and carbon footprint of pellets production system at the depot.

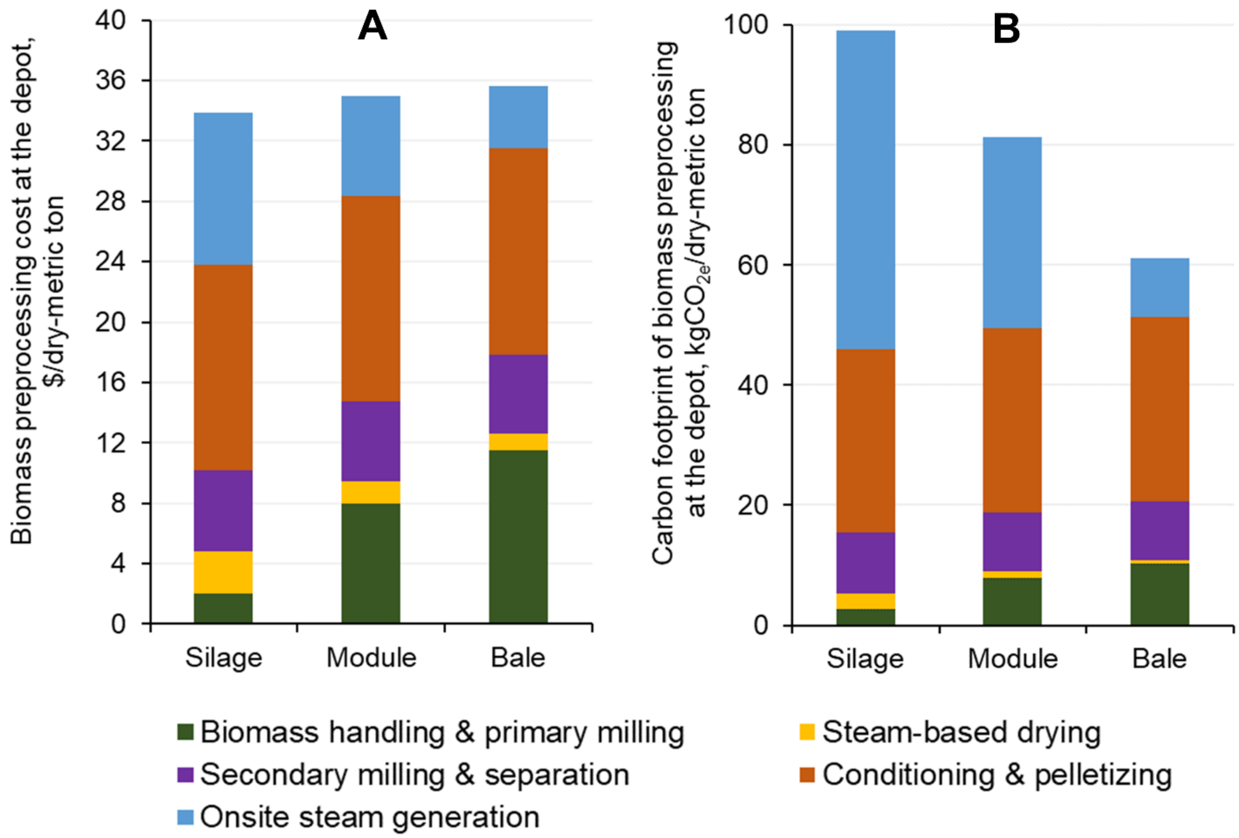


Figure S1. Biomass preprocessing cost (A) and carbon footprint (B) at the depot. The large carbon footprint for onsite steam generation is due to the use of natural gas as an energy source to the boiler. This carbon footprint can be reduced by using renewable energy sources such as hog fuel or switching to solar drying. The solar drying[41] is considered for the optimal future case scenario.

S1.6 Feedstock handling and preprocessing at the biorefinery

While the chopped biomass and pellet can directly feed into the pretreatment reactor (considering the biochemical conversion process), module and bale require preprocessing at the biorefinery before delivered to the reactor throat. Regardless of the forms of biomass feedstock, the feedstock-handling system is required at the biorefinery. The feedstock handling system developed in this study is consistent with the NREL 2011 ethanol report,[53] which includes truck scale, truck dumper, truck dumper hopper, short-term storage, belt scale, and conveyors. Additionally, a shredder is used to achieve the particle size of bales of as much as 38 mm(1.5 in.)[54] to be consistent with the particle size of the chopped ensiled biomass and modules. Purchase cost, energy consumption, and throughput of the bale shredder were consistent with previous NREL report.[54] Modules are assumed to be broken apart with a combination of impact and shearing actions as it is a new system. The expected module-braking machine is not available at present. Therefore, energy consumption of such machine is assumed to be 5 kWh/metric ton (half of the bale shredder), throughput is increased from 28 to 40 metric ton/h (same as the stover shredder), and the purchase cost is assumed to be the same as the bale shredder[54] of $302,000

(2000$). Figure S2 shows the resulting cost and carbon footprint of biomass handling and/or preprocessing stage at the biorefinery.

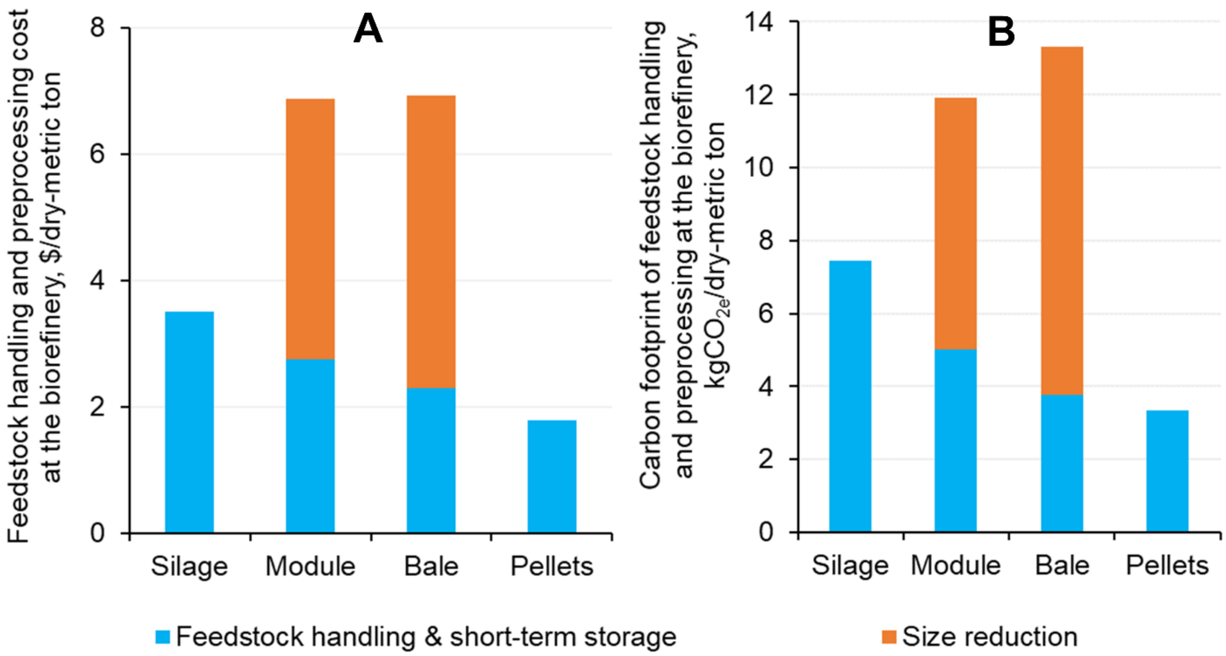


Figure S2. Biomass handling and/or preprocessing cost (A) and carbon footprint (B) at the biorefinery. Relatively large handling and short-term storage cost and carbon footprint for silage at the biorefinery is due to its high moisture content of (59.69%) as the biorefinery is assumed to process 2000 bone-dry-metric ton of biomass sorghum per day regardless of biomass feedstock forms considered in this study.

S2. Techno-economic analysis and Lifecycle assessment

We determine the cost of each stage of the supply chain considering capital investment, ownership costs (including depreciation, interest, taxes, insurance, and housing), and operating costs (including repair and maintenance, fuel, lubrication, labor, and consumable materials, such as string, tarp, and plastic wrap). The sum of the cost of each stage of the entire supply chain results in the overall feedstock supply cost. Detailed method to estimate these different cost components are discussed in previous studies.[4,5,36] In addition to the feedstock supply cost, lifecycle GHG emissions is determined for each stage of the entire supply chain. The required materials and energy (i.e., fuel and electricity) estimated from the feedstock supply model and their corresponding GHG emissions factors are used to quantify the GHG emissions of each stage. This analysis is based on a hybrid process-based/input-output approach, which is discussed in the previous study.[55] The emissions factors were gathered from widely used LCA databases.[56–58]

We further considered GHG emissions from land use change.[59,60] The net GHG emissions from land use change is taken from the best-available literature, and includes net emissions associated with the loss of top soil carbon and existing vegetation when land is converted for sorghum cultivation,[61] carbon sequestration from accumulation of below-ground biomass,[59] and the emissions associated with indirect land use change.[62] The soil carbon sequestration potential of biomass sorghum reported in the DOE Billion-Ton study is striking in that it is larger than other bioenergy crops, including perennial grasses.[59] However, the soil organic carbon gain with biomass sorghum farming in cropland/pasture land presented in the DOE Billion-Ton study[58] is based on only a limited number of counties and there are not many supporting studies in the scientific literature, therefore, the soil carbon sequestration potential of biomass sorghum requires further analysis. We accounted the variability present in the data inputs (-0.04 to -0.8 tCO_{2e}/ha/year[21]) and presented the resulted uncertainty with error bars (Figures S31-S36).

S3. Sensitivity and uncertainty analysis

We considered the minimum and maximum values of all the input parameters gathered from published literature (Table 1 and SI-Tables S1-S6) to determine their influences on the overall feedstock supply cost and GHG emissions. However, we only provided the results of the most influential input parameters. In addition to the single point sensitivity analysis, we determine uncertainty associated with the overall feedstock supply cost and GHG emissions by modeling the variabilities present in each input parameter with the standard probability distributions, including uniform, normal, triangular, and lognormal (Table 1 and SI-Tables S1-S6). The process of defining the probability distribution is consistent with the authors' recent study.[63] We further determine the impact of each stage of the supply chain to the overall uncertainty associated with the cost and emissions. The simulations were run for 10,000 trials.

S4. Sensitivity on the biomass feedstock supply cost

a. Direct supply of chopped ensiled biomass to the biorefinery

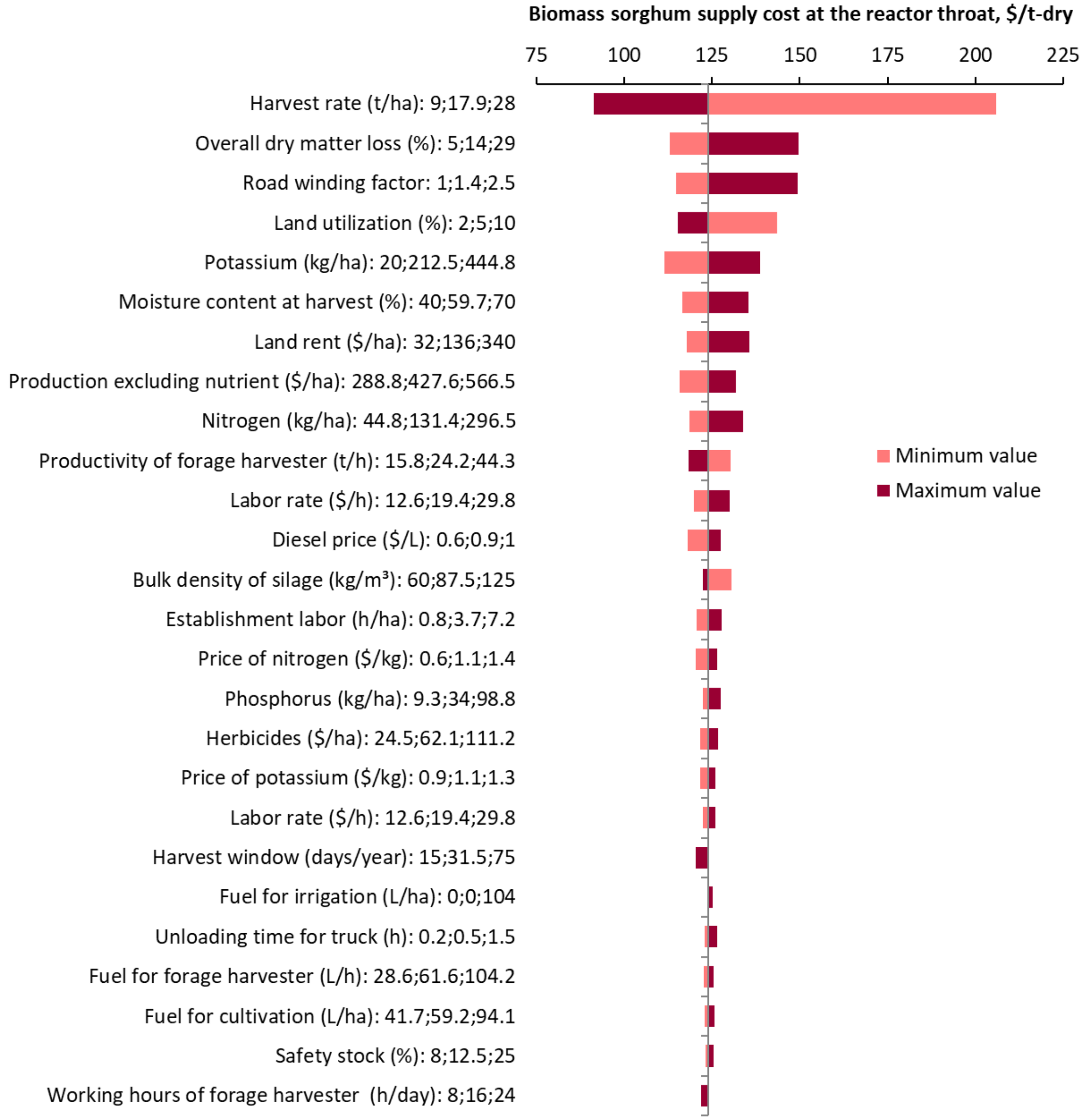


Figure S3. Sensitivity to the biomass feedstock supply cost for the chopped ensiled biomass supply system without preprocessing depot. **t** = metric ton.

b. Chopped ensiled biomass and pellet system

Figure S4. Sensitivity to the biomass feedstock supply cost for the chopped ensiled biomass supply system with preprocessing depot. **t** = metric ton.

c. Direct transportation of module to the biorefinery

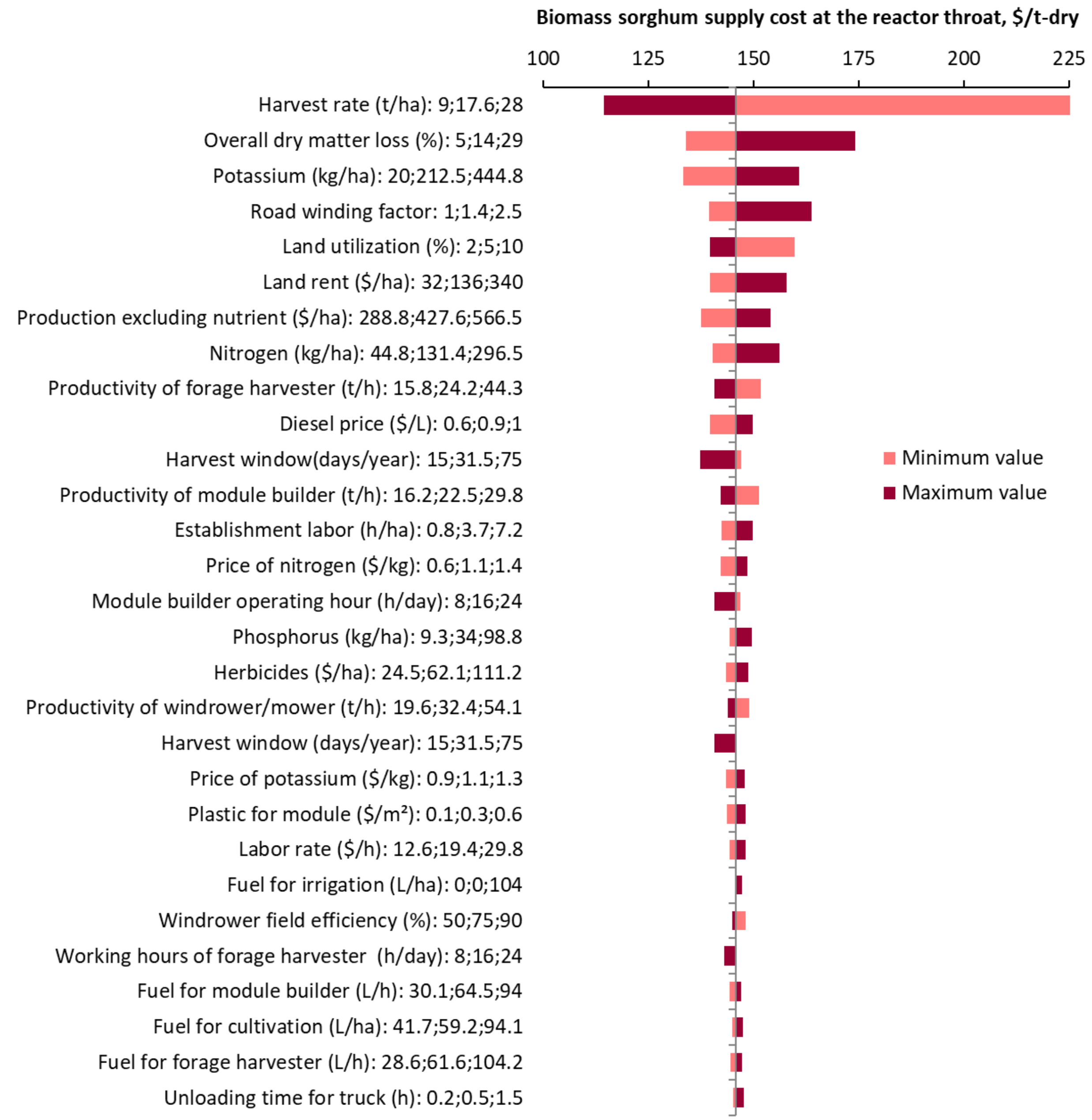


Figure S5. Sensitivity to the biomass feedstock supply cost for the biomass module supply system without preprocessing depot. **t** = metric ton.

d. Module and pellet system

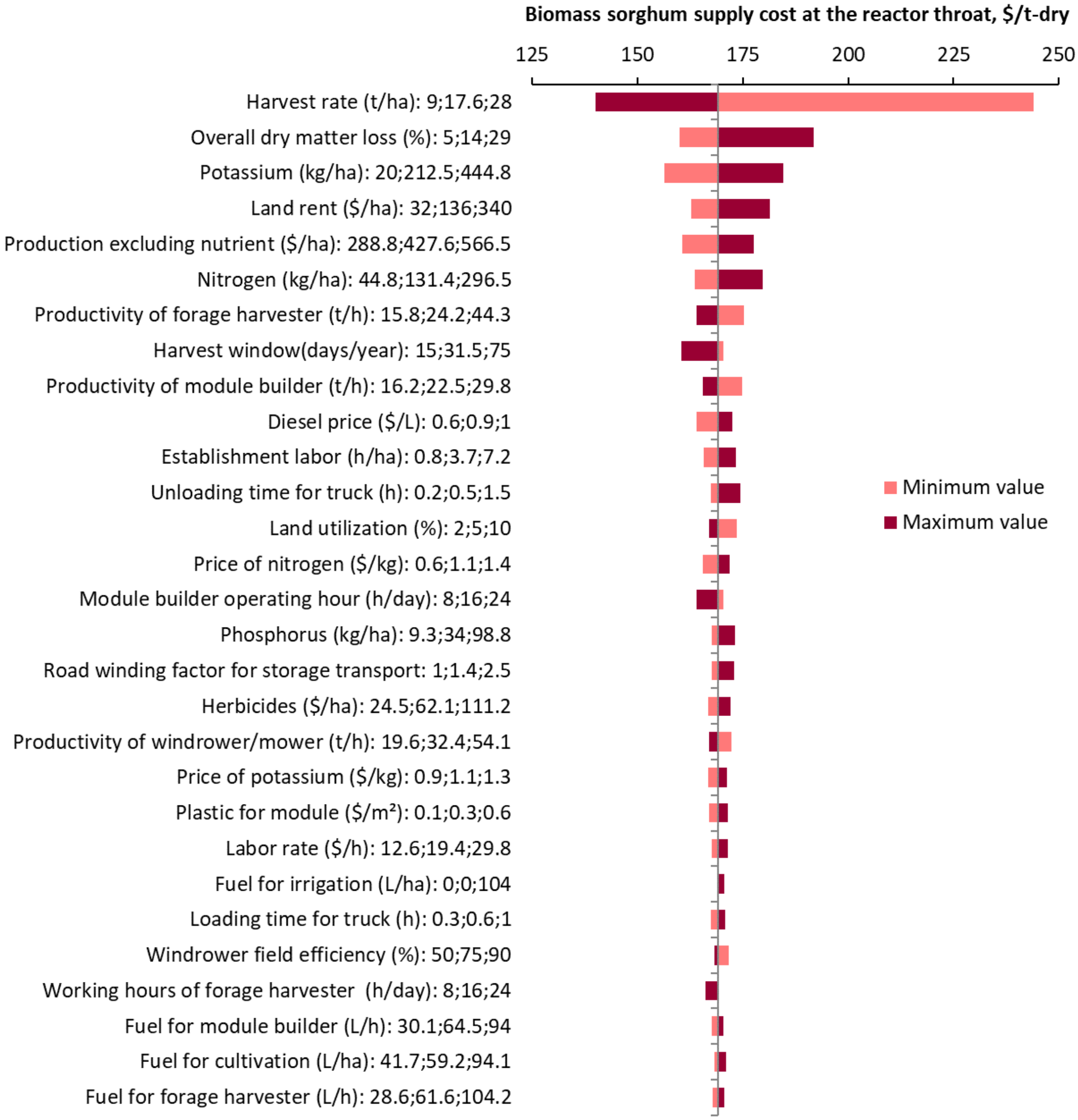


Figure S6. Sensitivity to the biomass feedstock supply cost for the biomass module supply system with preprocessing depot. **t** = metric ton.

e. Direct transportation of bale to the biorefinery

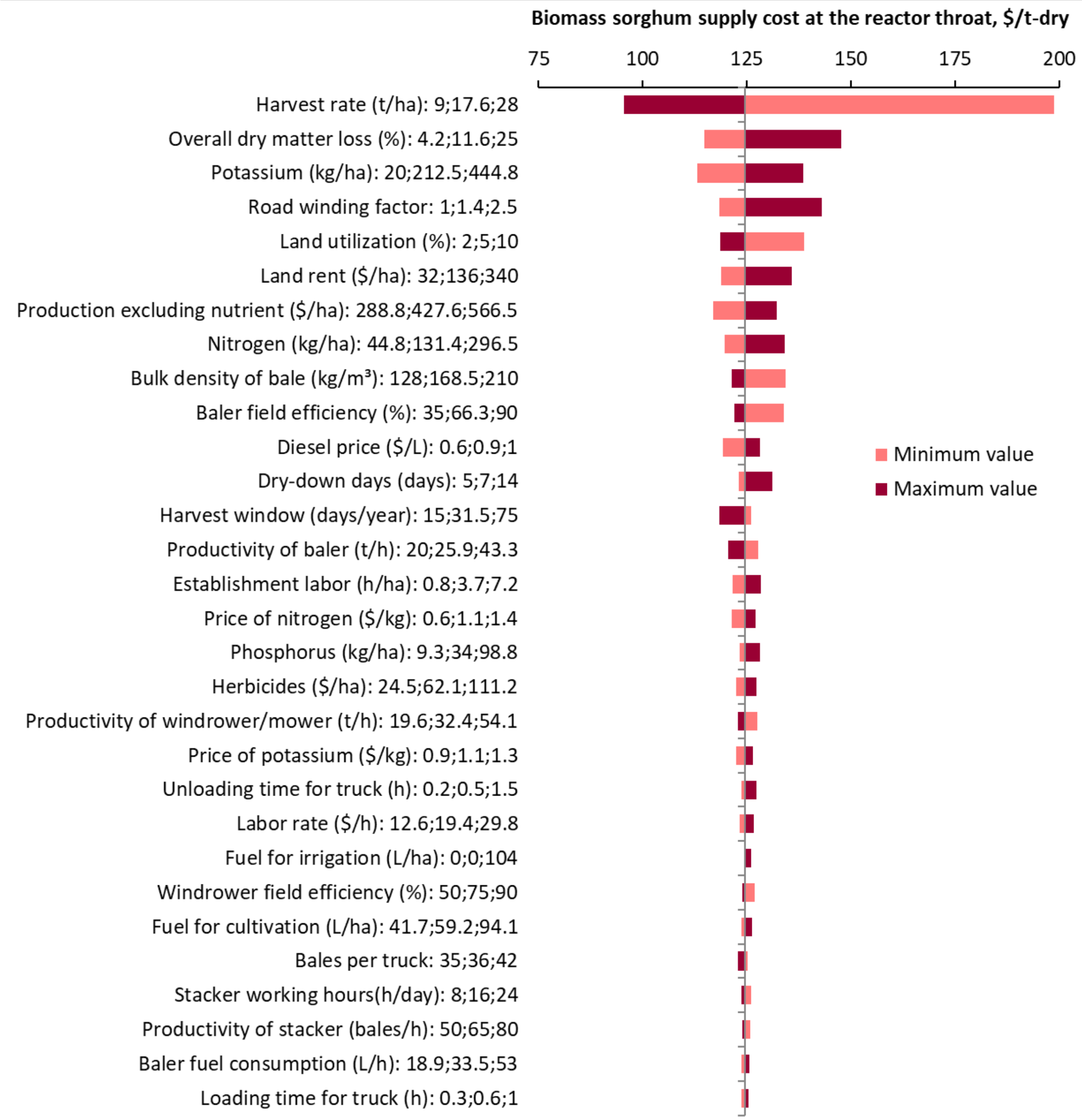


Figure S7. Sensitivity to the biomass feedstock supply cost for the biomass bale supply system without preprocessing depot. **t** = metric ton.

e. Bale and pellet system

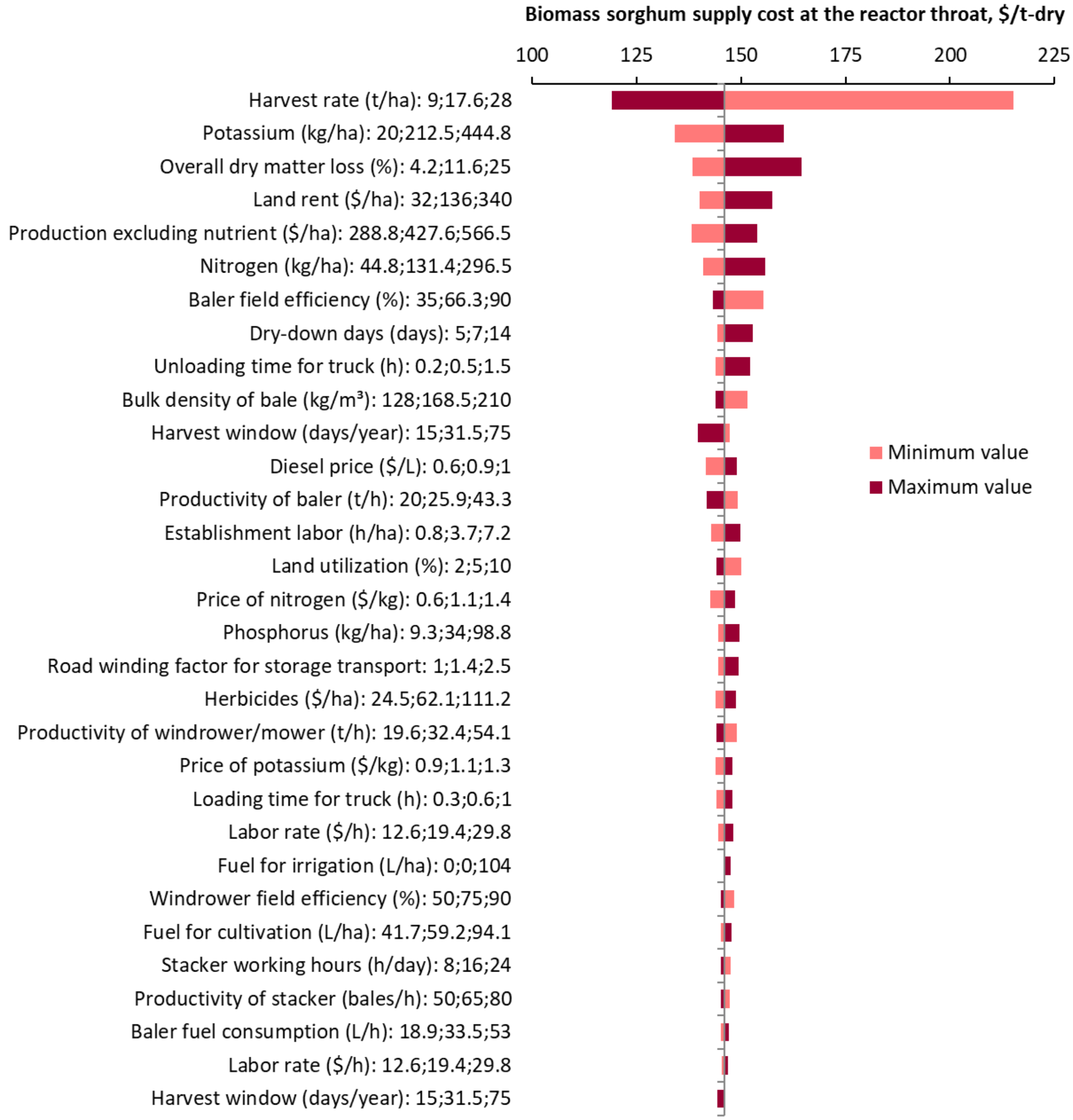


Figure S8. Sensitivity to the biomass feedstock supply cost for the biomass bale supply system with preprocessing depot. **t** = metric ton.

S5. Uncertainties associated with biomass sorghum feedstock supply cost

a. Direct transportation of chopped ensiled biomass to the biorefinery

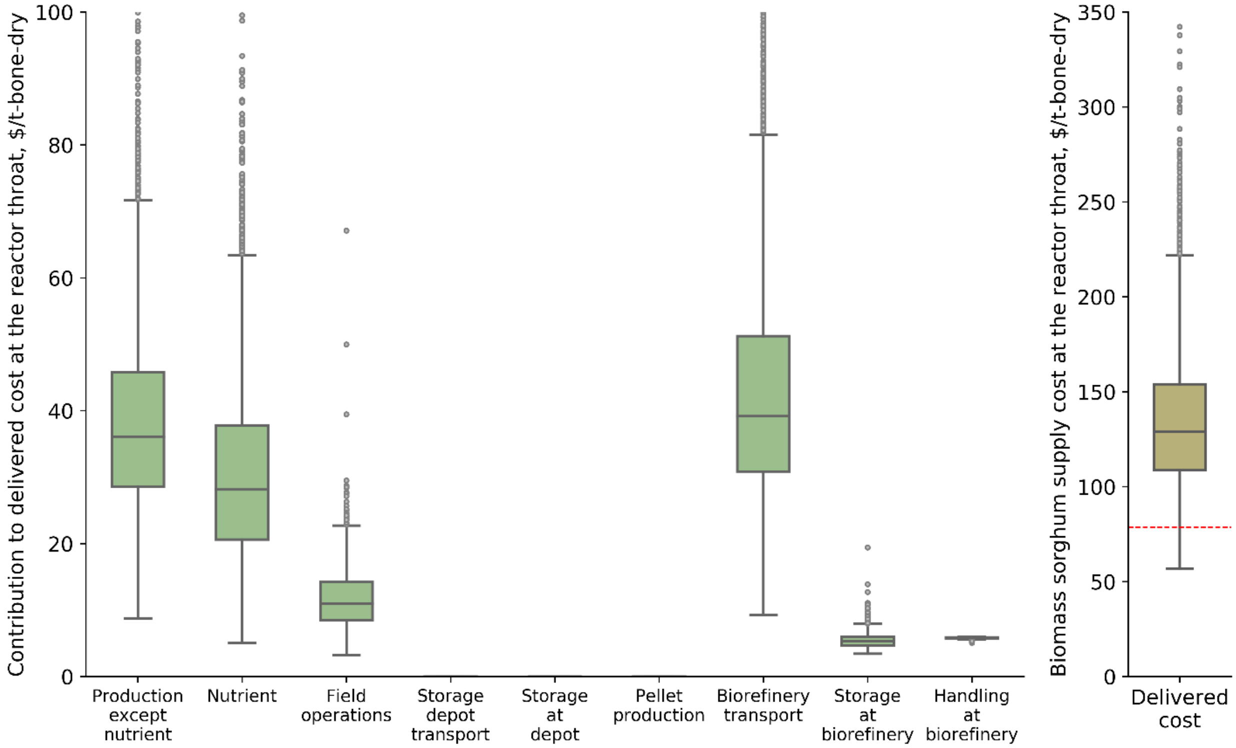


Figure S9. Uncertainties in the overall biomass sorghum supply cost and contribution from each stage of the supply chain. **t** = metric ton.

b. Chopped biomass and pellet system

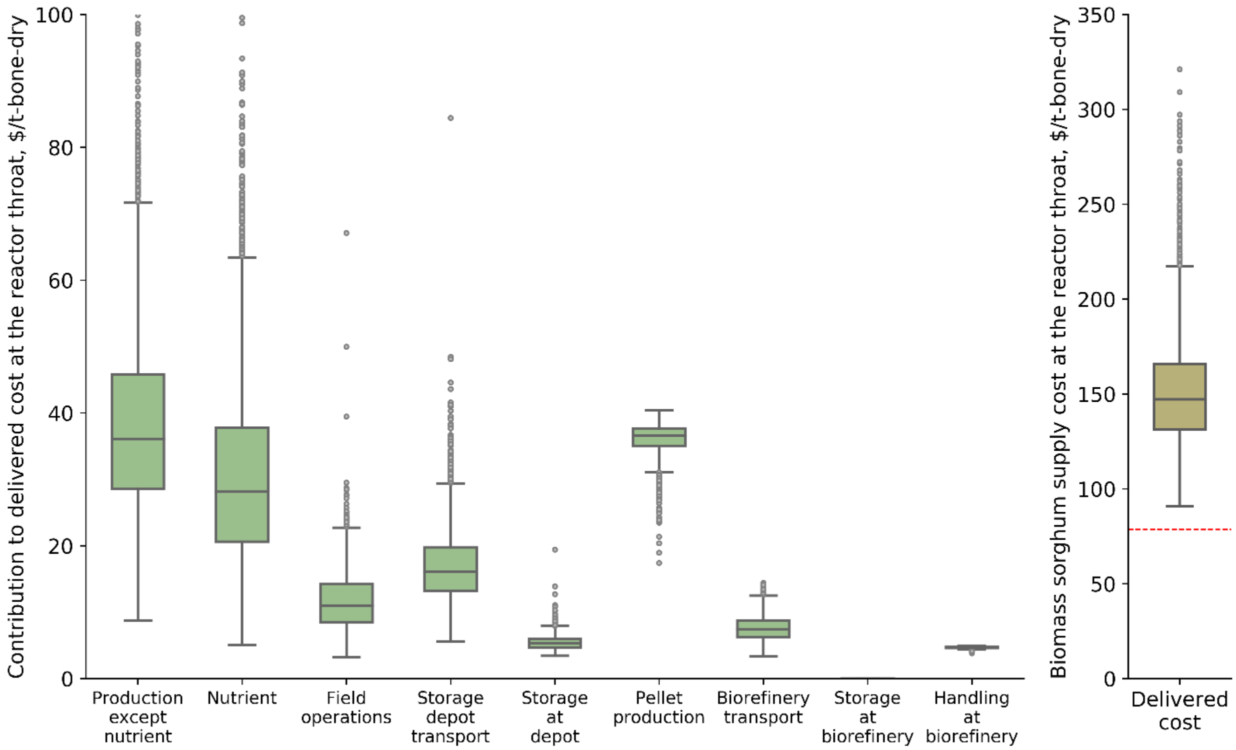


Figure S10. Uncertainties in the overall biomass sorghum supply cost and contribution from each stage of the supply chain. **t** = metric ton.

c. Direct transportation of module to the biorefinery

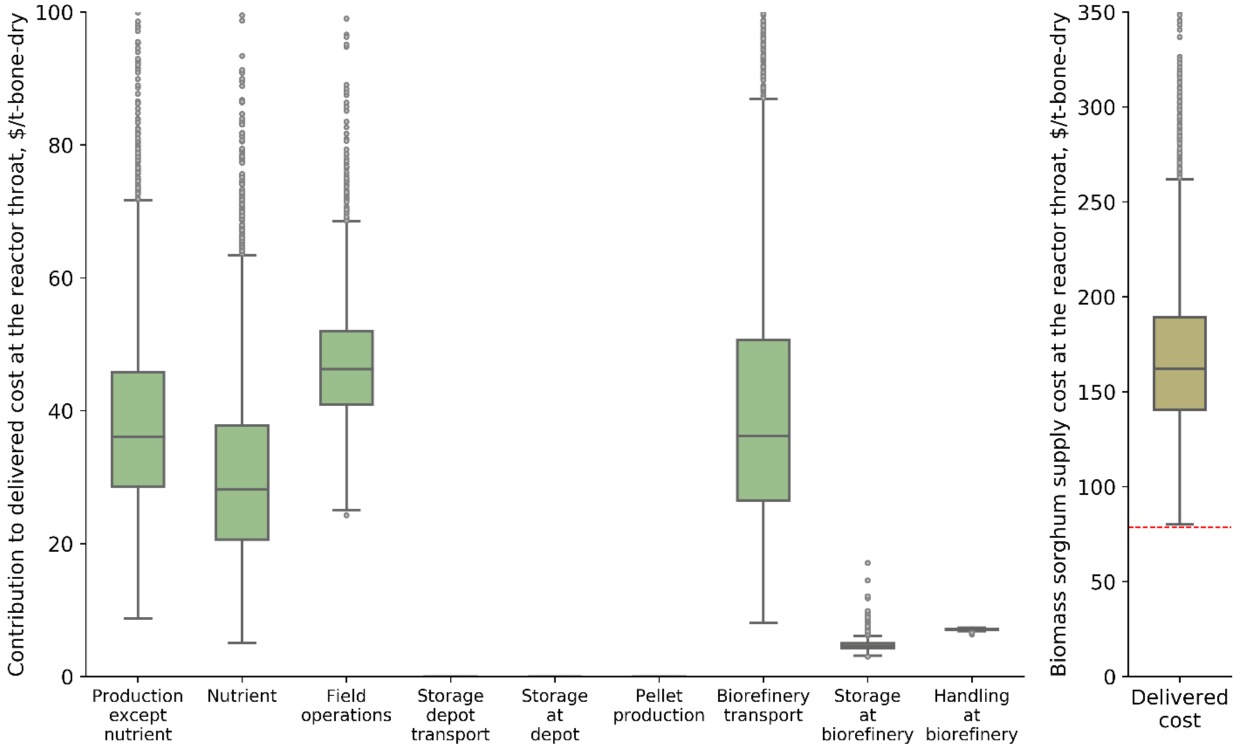


Figure S11. Uncertainties in the overall biomass sorghum supply cost and contribution from each stage of the supply chain. **t** = metric ton.

d. Module and pellet system

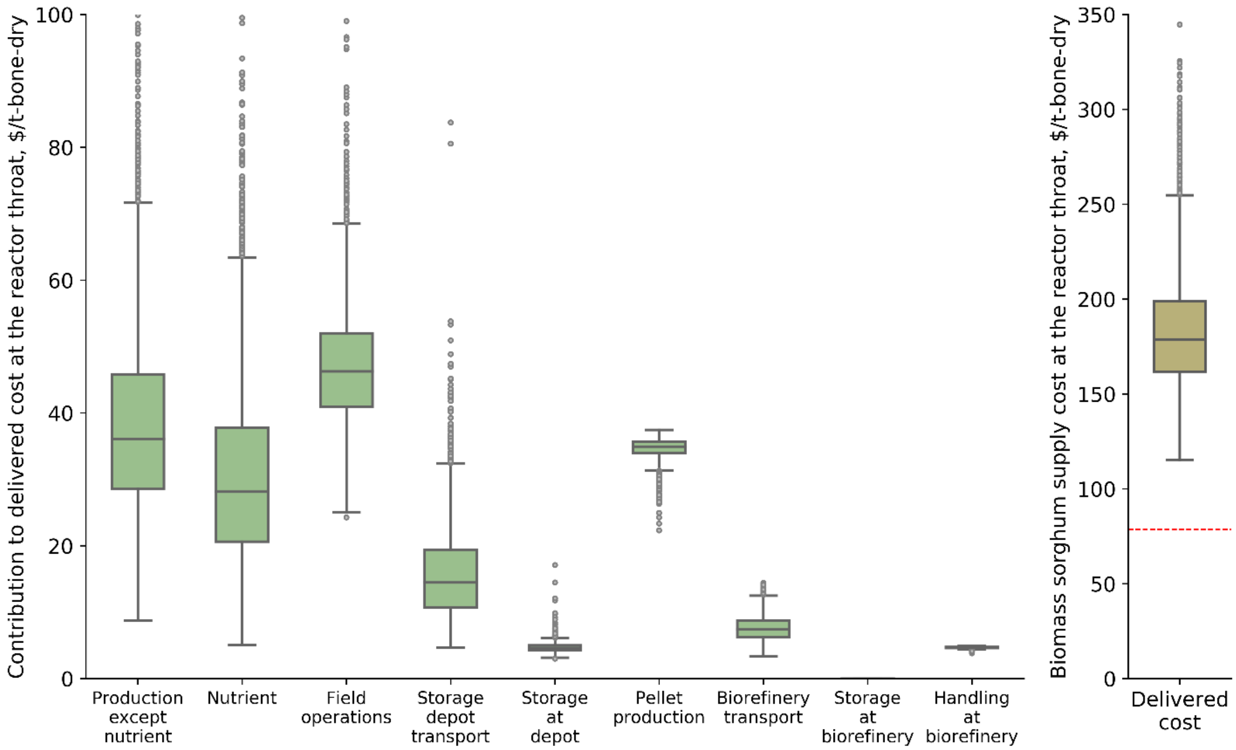


Figure S12. Uncertainties in the overall biomass sorghum supply cost and contribution from each stage of the supply chain. **t** = metric ton.

e. Direct transportation of bale to the biorefinery

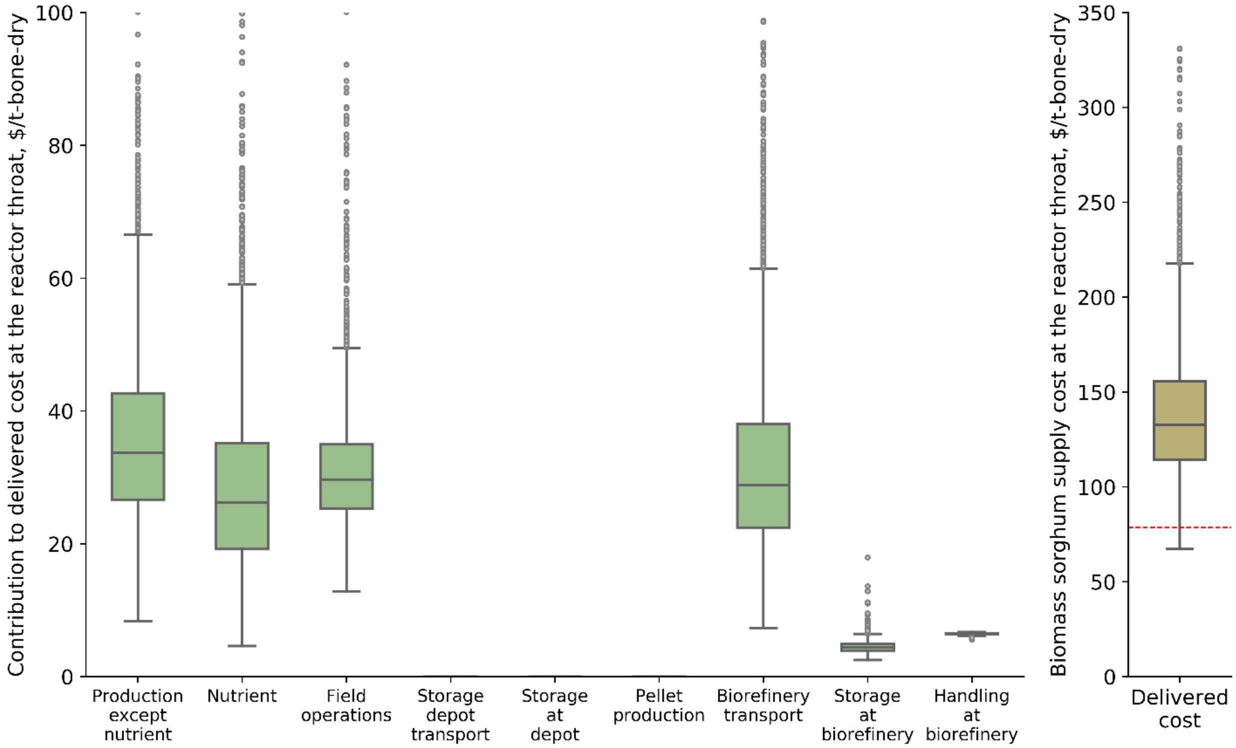


Figure S13. Uncertainties in the overall biomass sorghum supply cost and contribution from each stage of the supply chain. **t** = metric ton.

f. Bale and pellet system

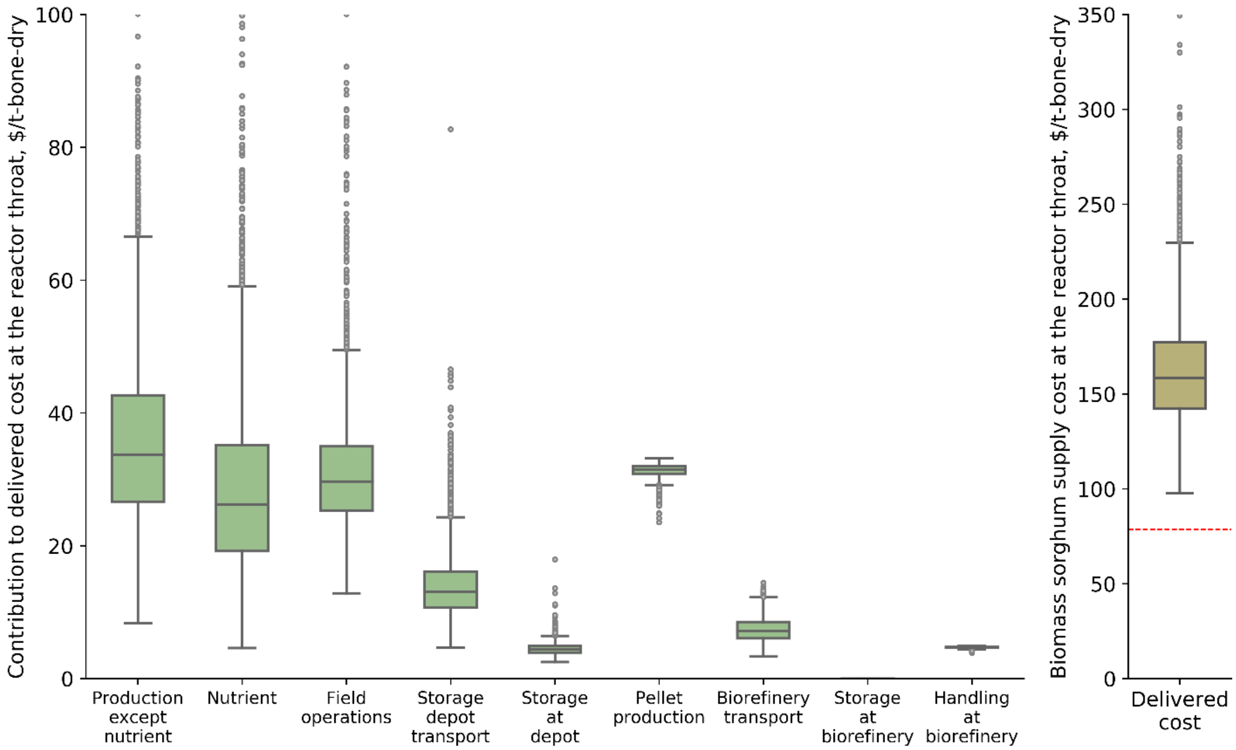
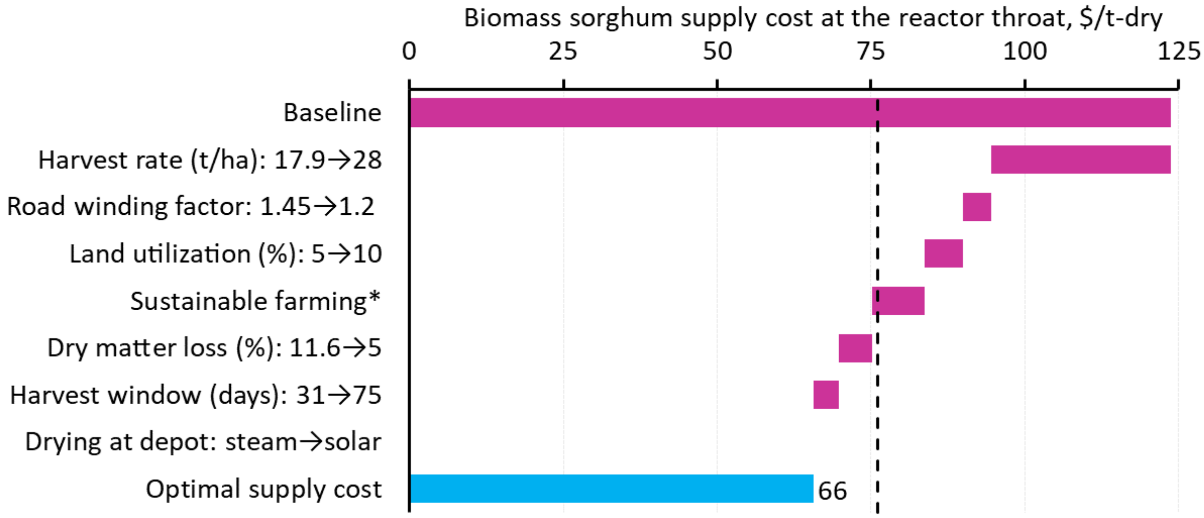


Figure S14. Uncertainties in the overall biomass sorghum supply cost and contribution from each stage of the supply chain. **t** = metric ton.

S6. Optimal biomass sorghum feedstock supply cost

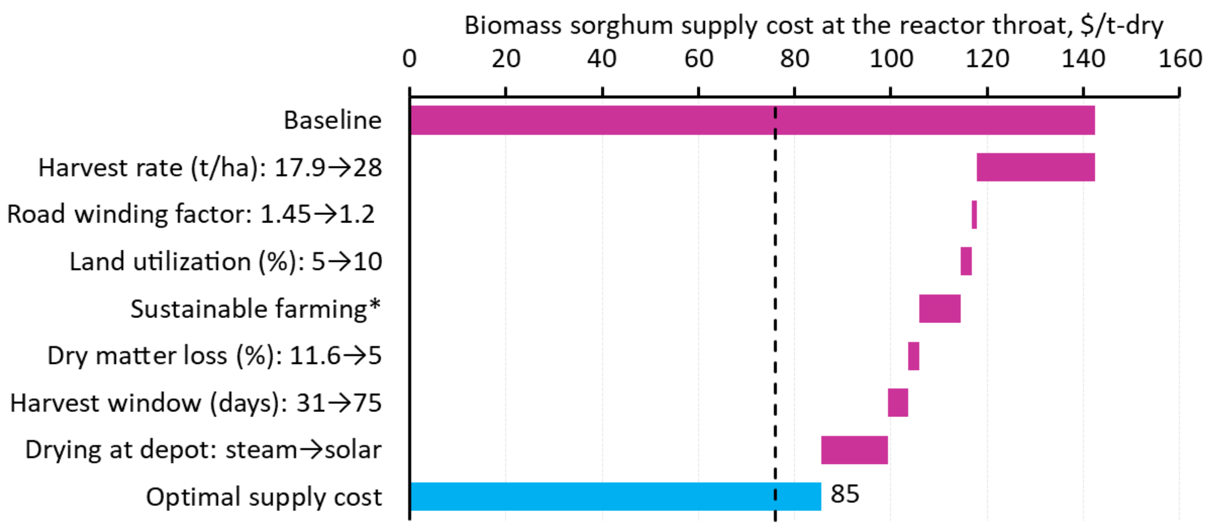
a. Direct transportation of chopped ensiled biomass to the biorefinery



**N-131→100; P-34→20; & K-212→75*
(Table S2; all data are in 'kg/ha')

Figure S15. Optimal chopped ensiled biomass supply cost without preprocessing depot. Sustainable farming practices include low- or no-till strategies that can reduce costs by minimizing nutrient inputs and use of machinery. **t** = metric ton.

b. Chopped ensiled biomass and pellet system



**N-131→100; P-34→20; & K-212→75*
(Table S2; all data are in 'kg/ha')

Figure S16. Optimal chopped ensiled biomass supply cost with preprocessing depot. Sustainable farming practices include low- or no-till strategies that can reduce costs by minimizing nutrient inputs and use of machinery. **t** = metric ton.

c. Direct transportation of module to the biorefinery

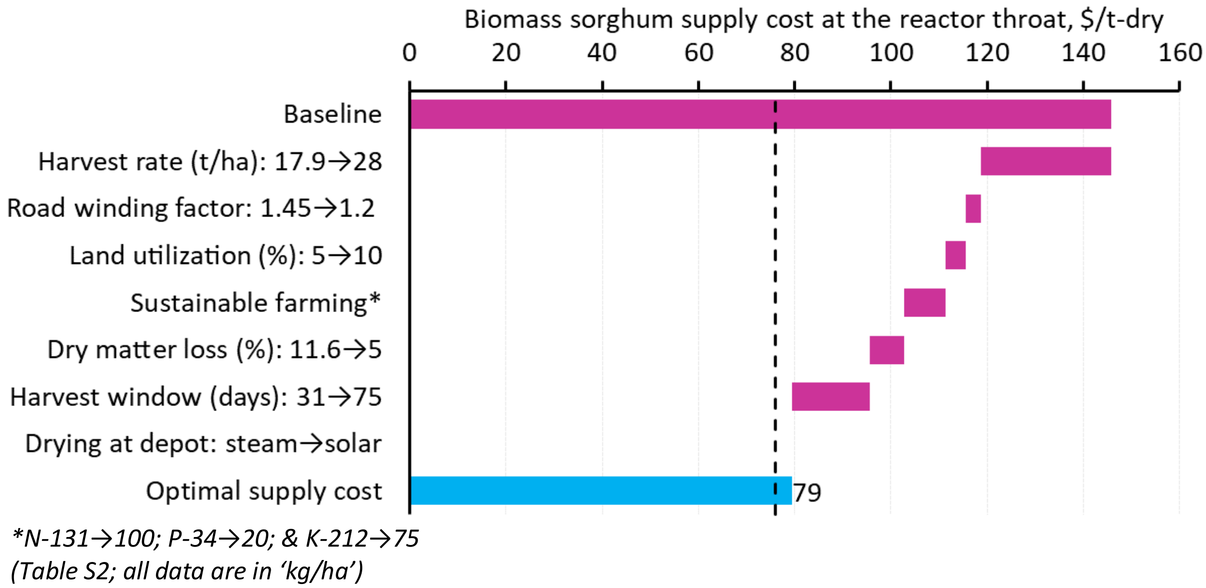


Figure S17. Optimal biomass module supply cost without preprocessing depot. Sustainable farming practices include low- or no-till strategies that can reduce costs by minimizing nutrient inputs and use of machinery. **t** = metric ton.

d. Module and pellet system

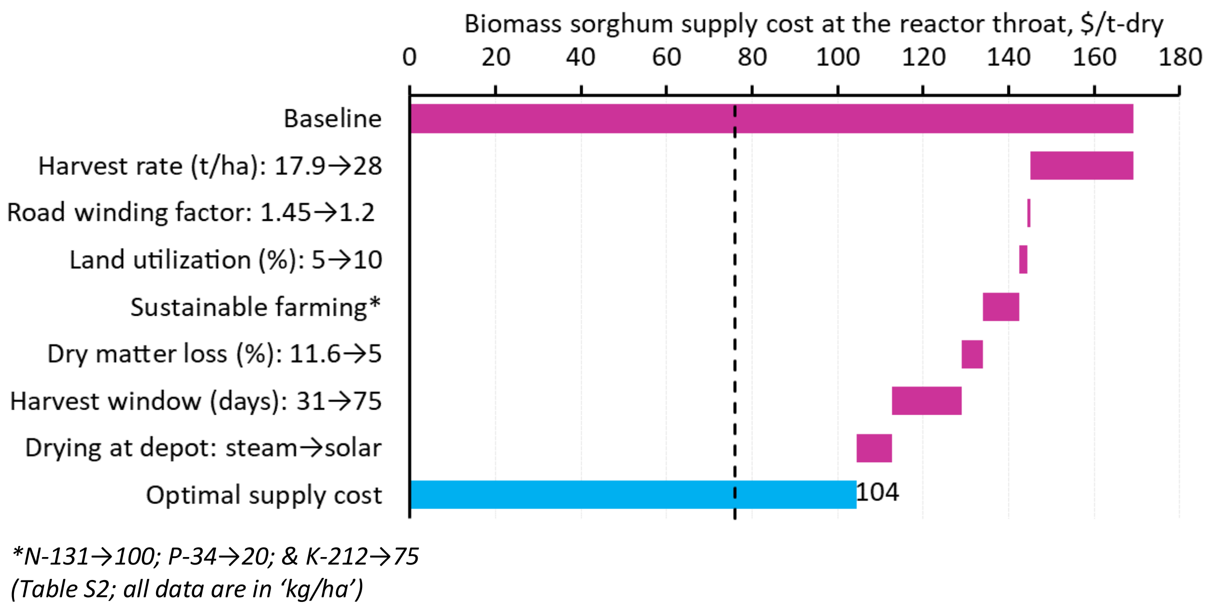
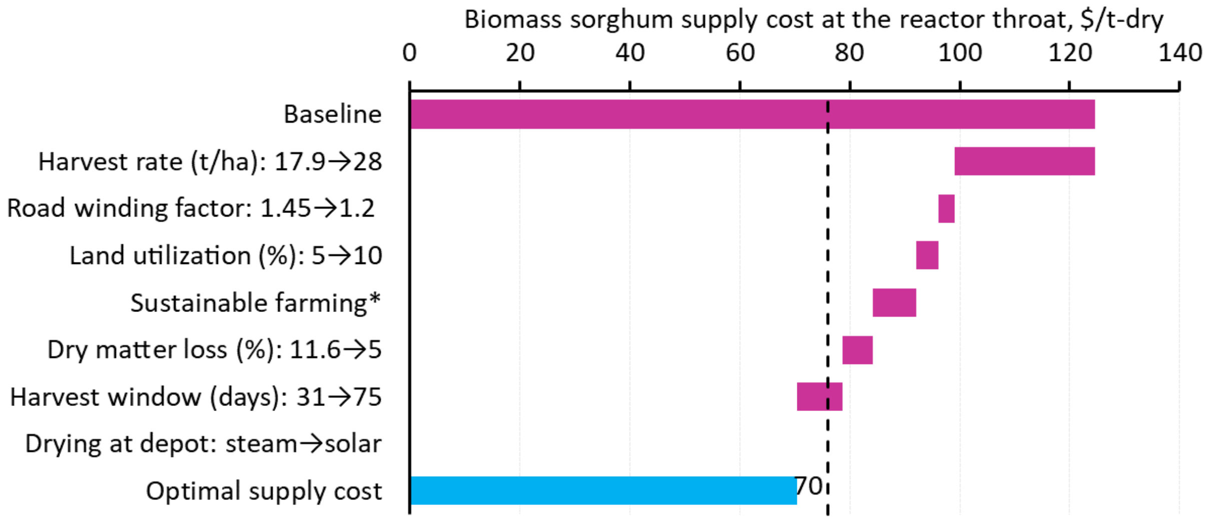


Figure S18. Optimal biomass module supply cost with preprocessing depot. Sustainable farming practices include low- or no-till strategies that can reduce costs by minimizing nutrient inputs and use of machinery. **t** = metric ton.

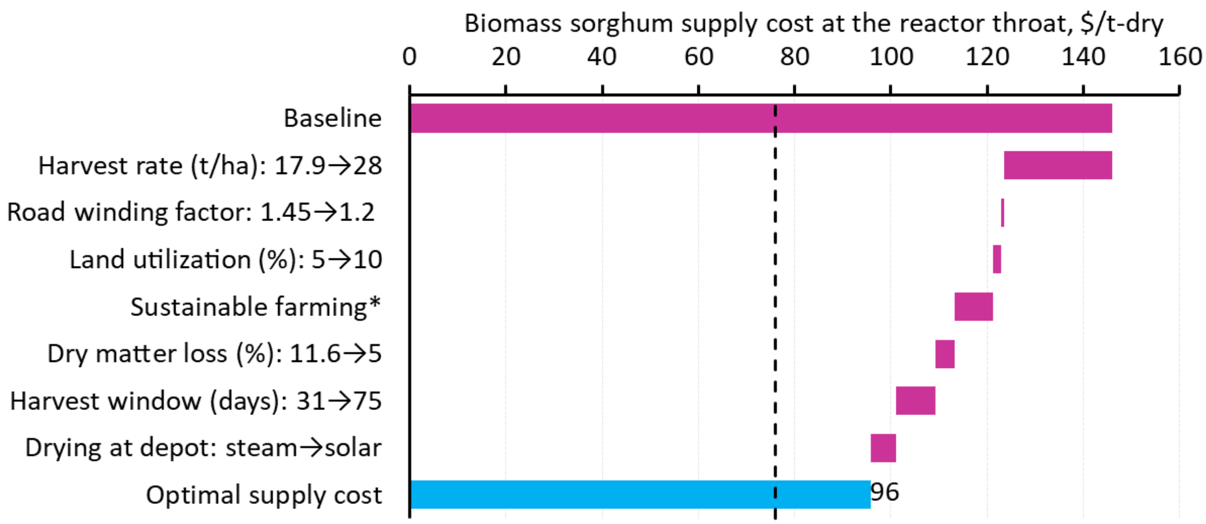
e. Direct transportation of bale to the biorefinery



**N-131→100; P-34→20; & K-212→75*
(Table S2; all data are in 'kg/ha')

Figure S19. Optimal biomass bale supply cost without preprocessing depot. Sustainable farming practices include low- or no-till strategies that can reduce costs by minimizing nutrient inputs and use of machinery. **t** = metric ton.

e. Bale and pellet system



**N-131→100; P-34→20; & K-212→75*
(Table S2; all data are in 'kg/ha')

Figure S20. Optimal biomass bale supply cost with preprocessing depot. Sustainable farming practices include low- or no-till strategies that can reduce costs by minimizing nutrient inputs and use of machinery. **t** = metric ton.

S7. Sensitivity to the GHG emissions associated with biomass feedstock supply chain

a. Direct transportation of chopped ensiled biomass to the biorefinery

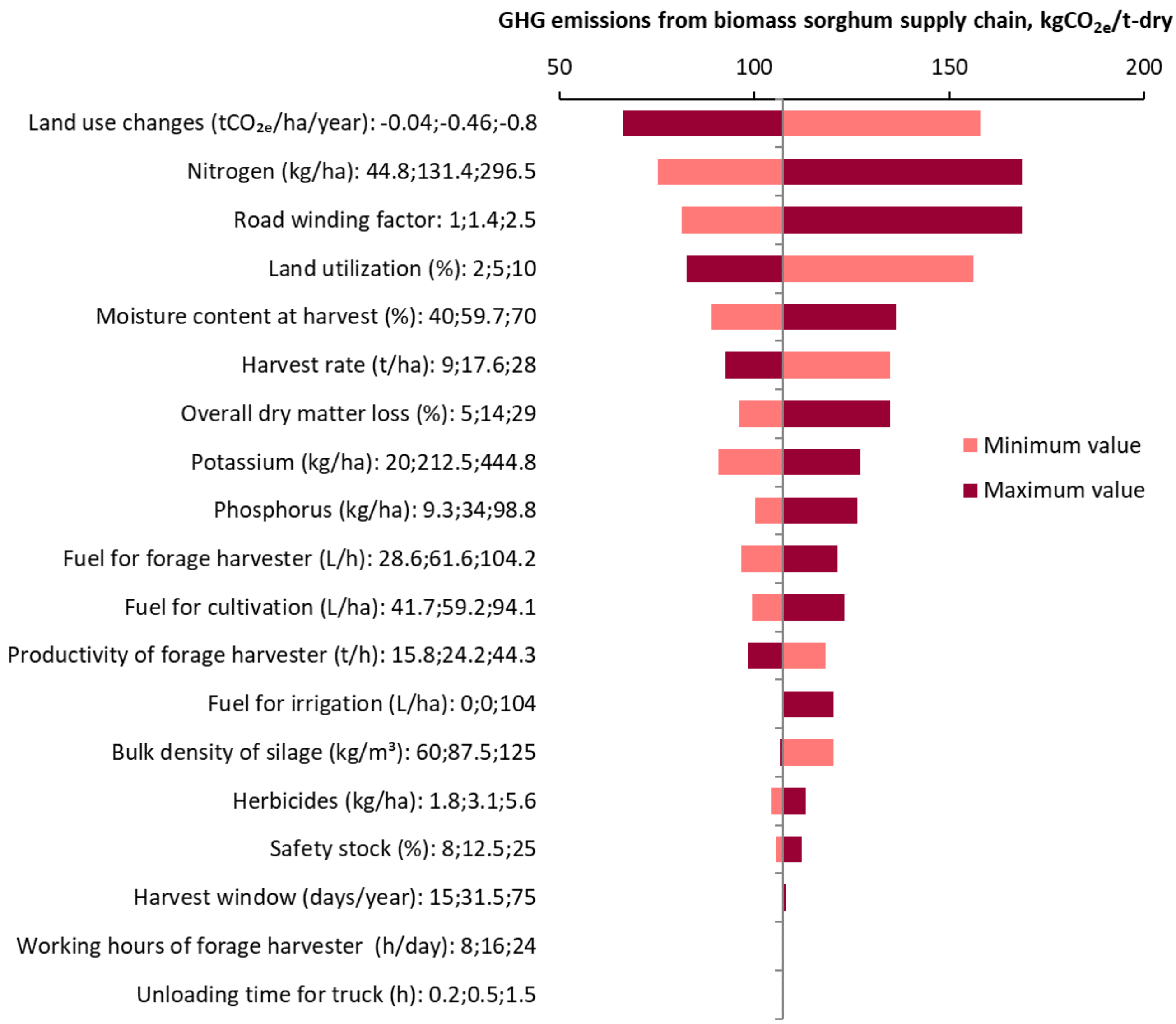


Figure S21. Sensitivity to the GHG emissions for the chopped biomass supply system without preprocessing depot. **t** = metric ton.

b. Chopped ensiled biomass and pellet system

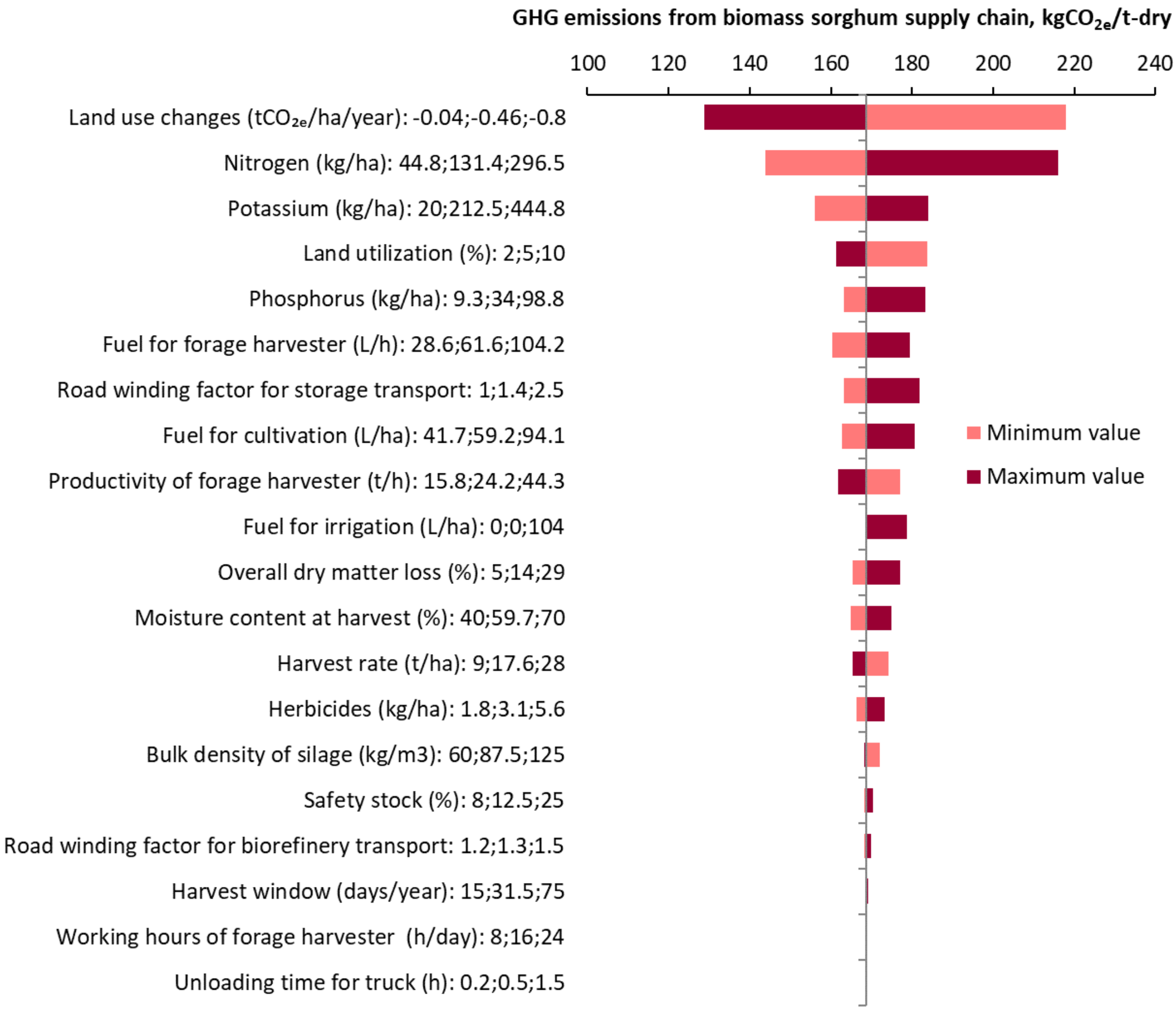


Figure S22. Sensitivity to the GHG emissions for the chopped biomass supply system with preprocessing depot. **t** = metric ton.

c. Direct transportation of module to the biorefinery

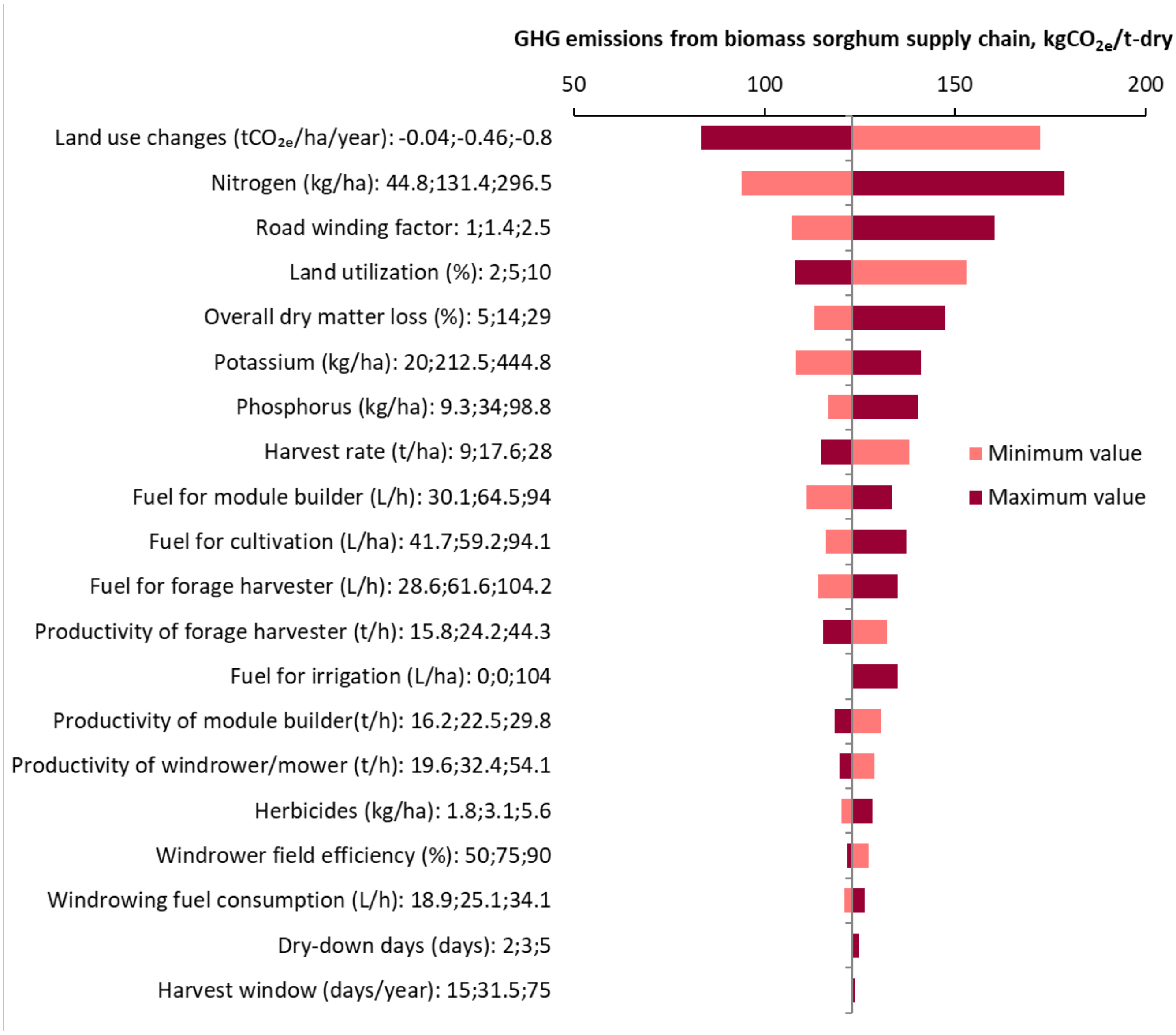


Figure S23. Sensitivity to the GHG emissions for the biomass module supply system without preprocessing depot. **t** = metric ton.

d. Module and pellet system

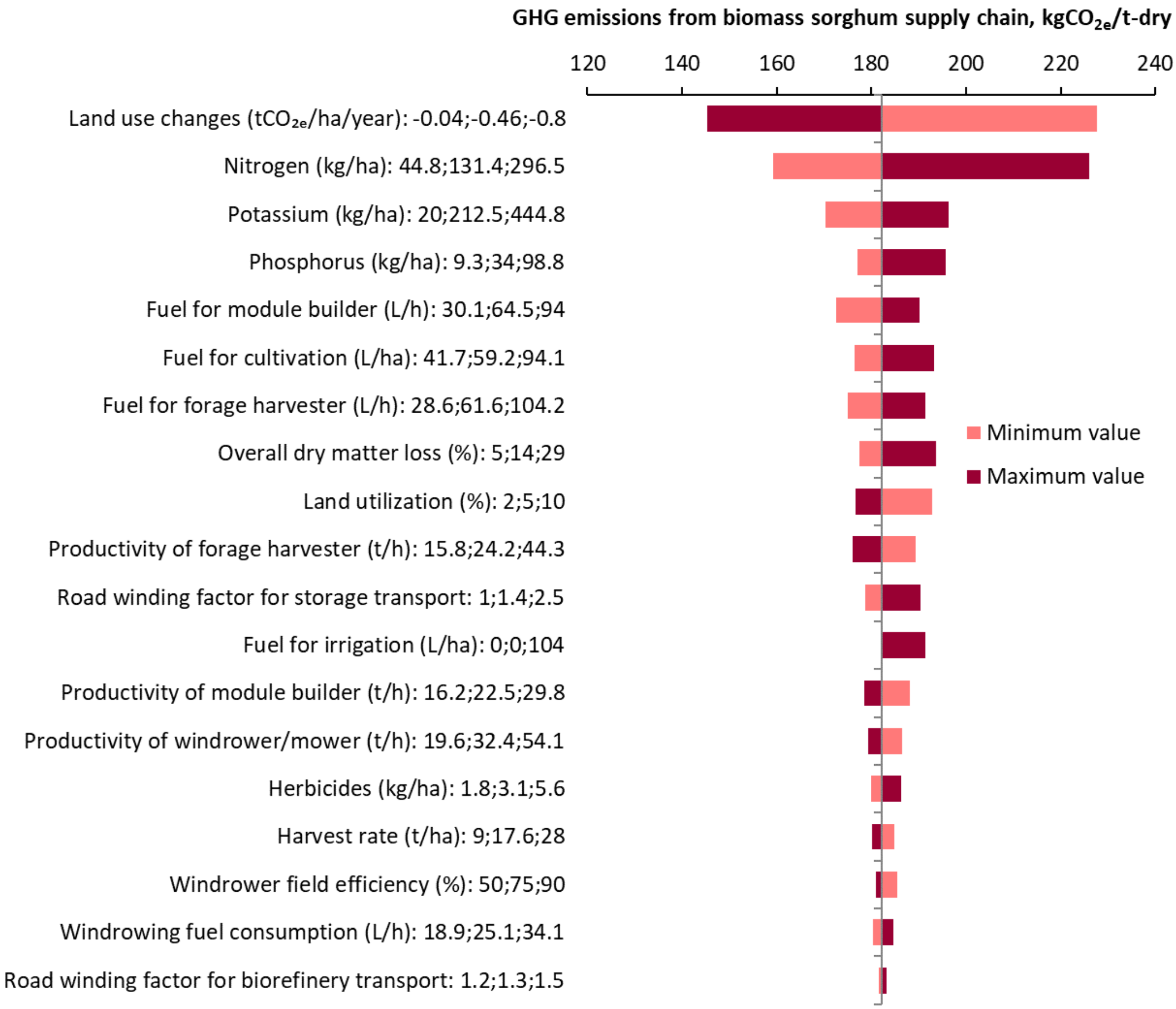


Figure S24. Sensitivity to the GHG emissions for the biomass module supply system with preprocessing depot. **t** = metric ton.

e. Direct transportation of bale to the biorefinery

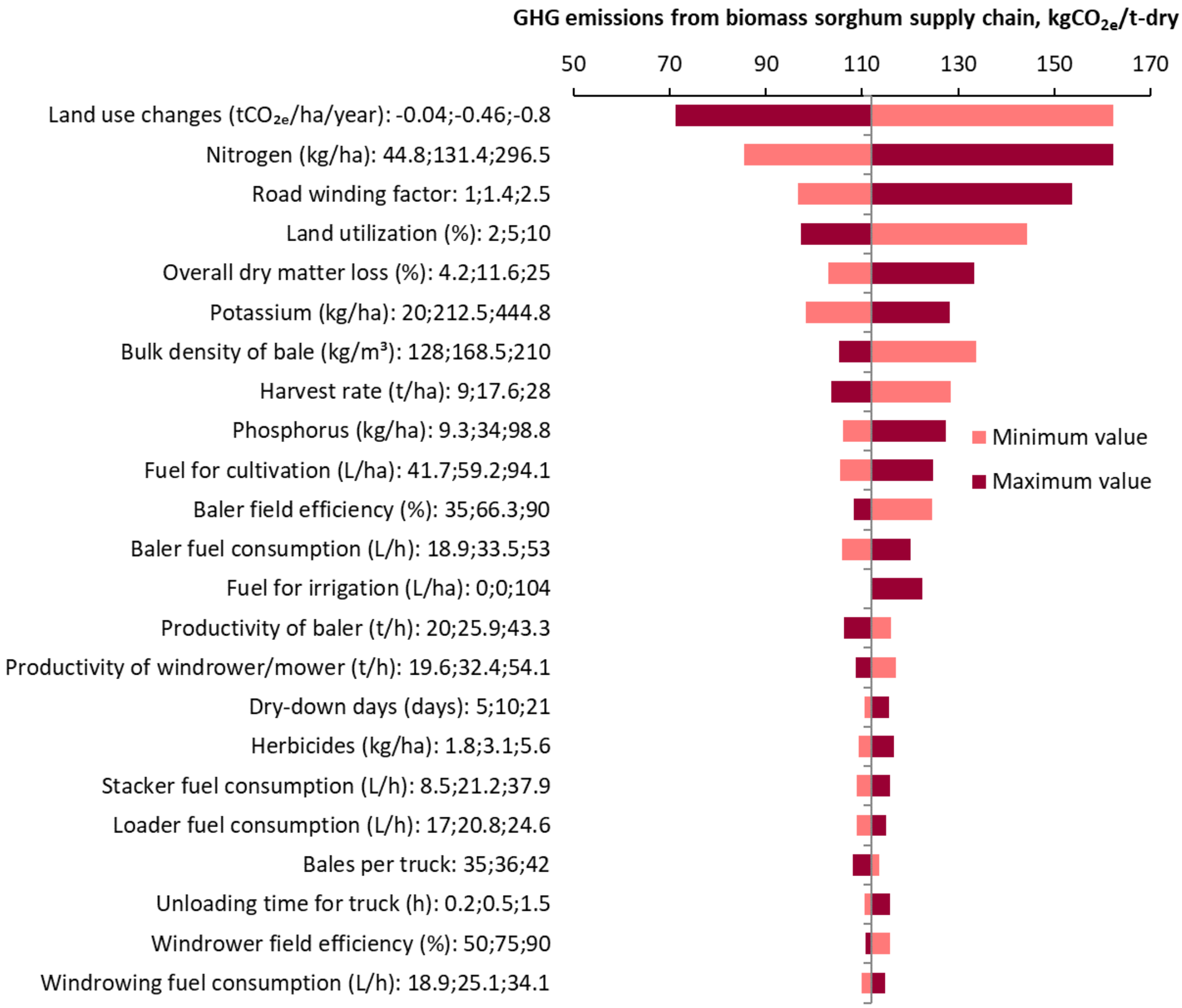


Figure S25. Sensitivity to the GHG emissions for the biomass bale supply system without preprocessing depot. **t** = metric ton.

e. Bale and pellet system

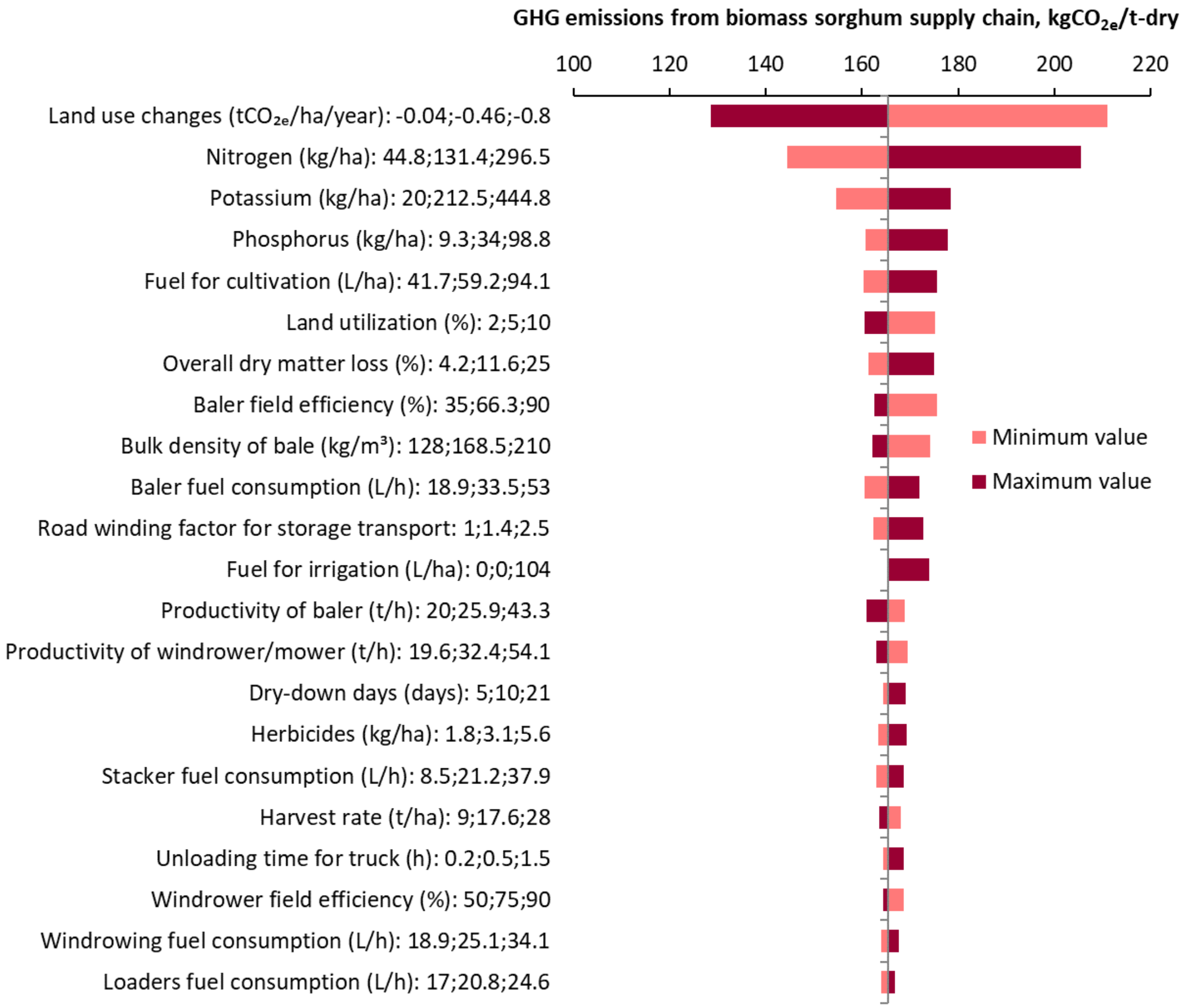


Figure S26. Sensitivity to the GHG emissions for the biomass bale supply system with preprocessing depot. **t** = metric ton.

S8. Impact of dry matter loss on delivered cost of sorghum and carbon footprint

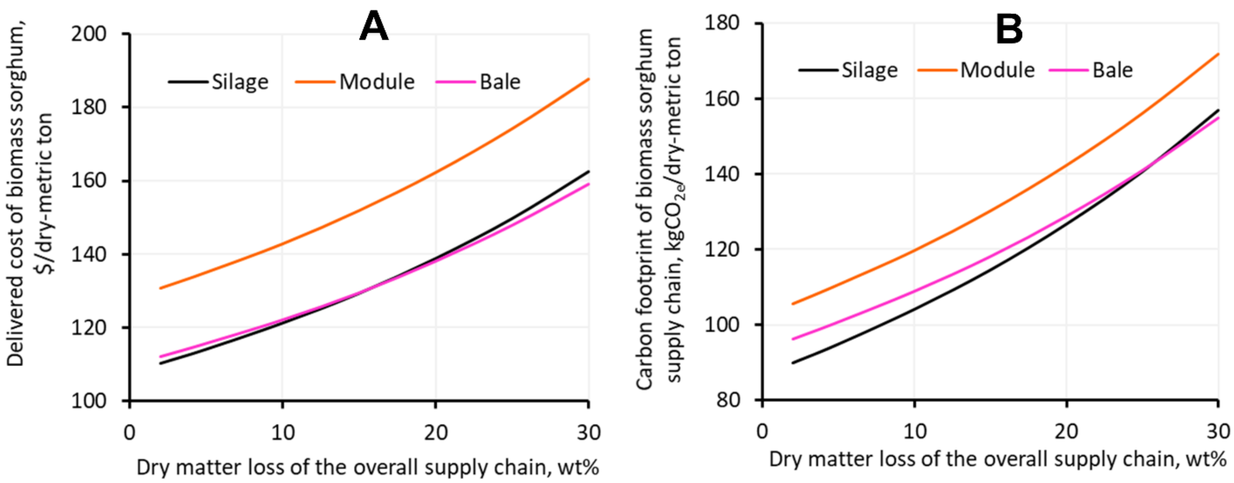


Figure S27. Delivered cost of sorghum (A) and associated GHG emissions (B) as a function of dry matter loss.

S9. Uncertainties associated with GHG emissions from biomass feedstock supply chain

a. Direct transportation of chopped ensiled biomass to the biorefinery

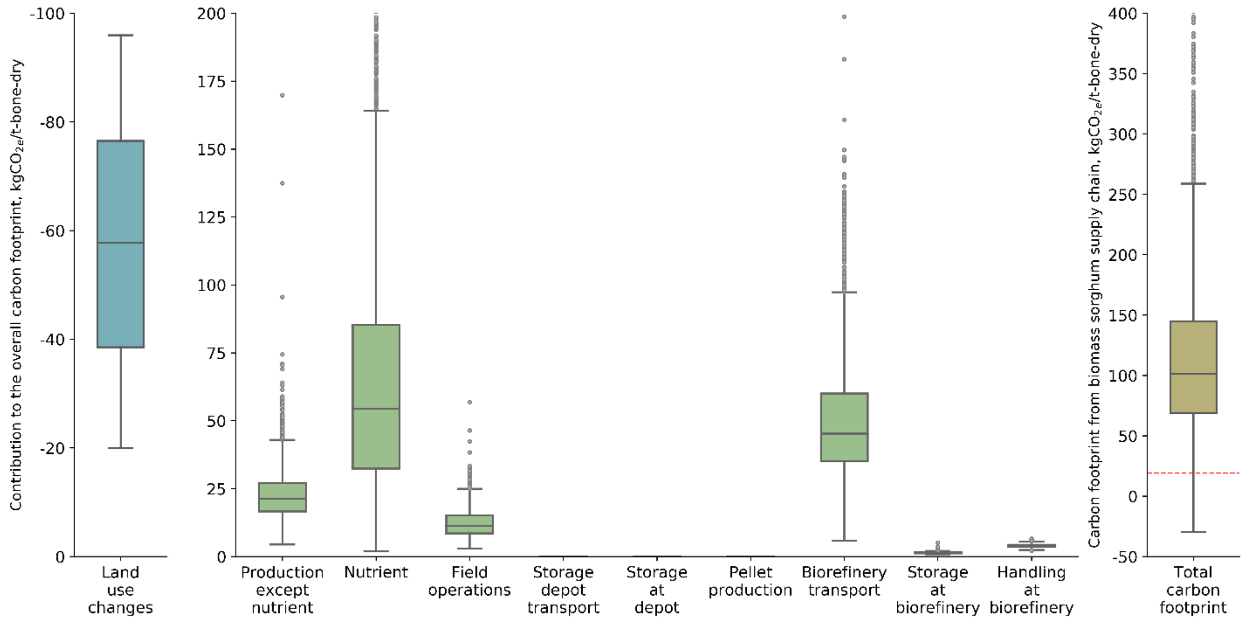


Figure S28. Uncertainties in the overall GHG emissions and contribution from each stage of the supply chain. **t** = metric ton.

b. Chopped biomass and pellet system

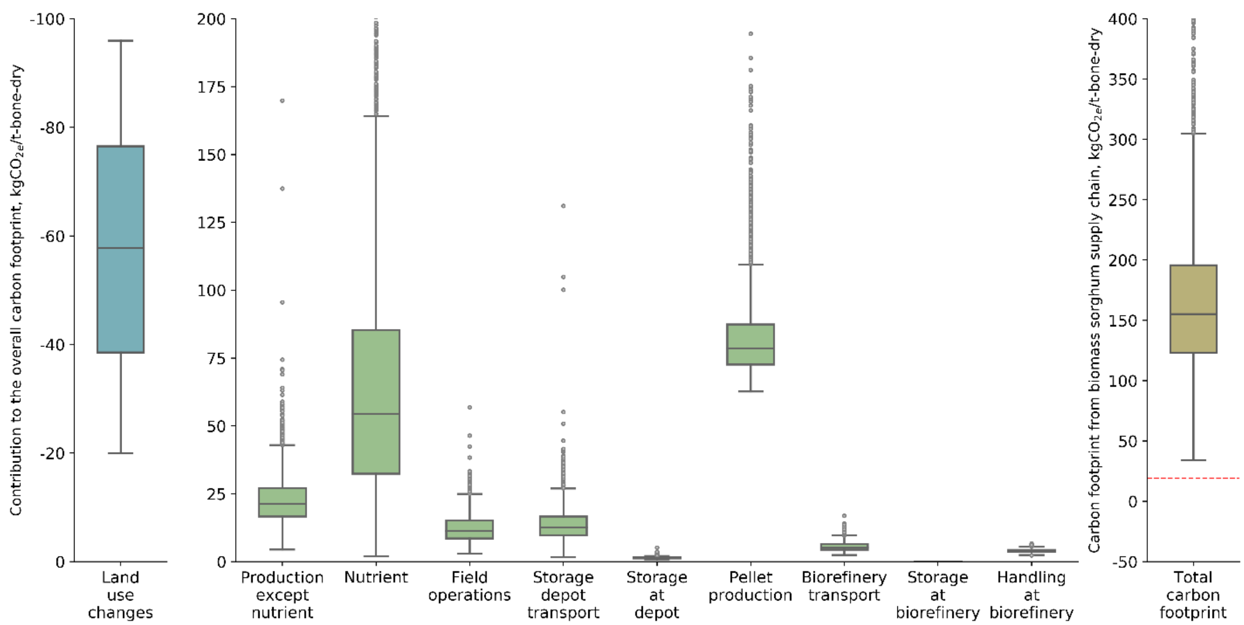


Figure S29. Uncertainties in the overall GHG emissions and contribution from each stage of the supply chain. **t** = metric ton.

c. Direct transportation of module to the biorefinery

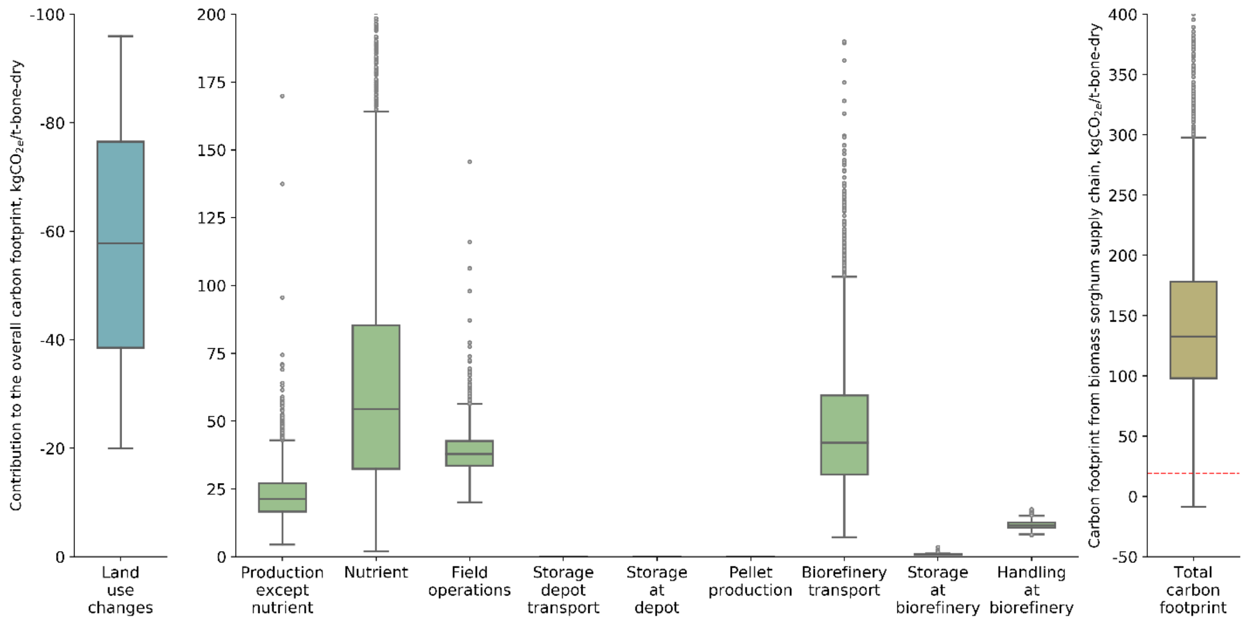


Figure S30. Uncertainties in the overall GHG emissions and contribution from each stage of the supply chain. **t** = metric ton.

d. Module and pellet system

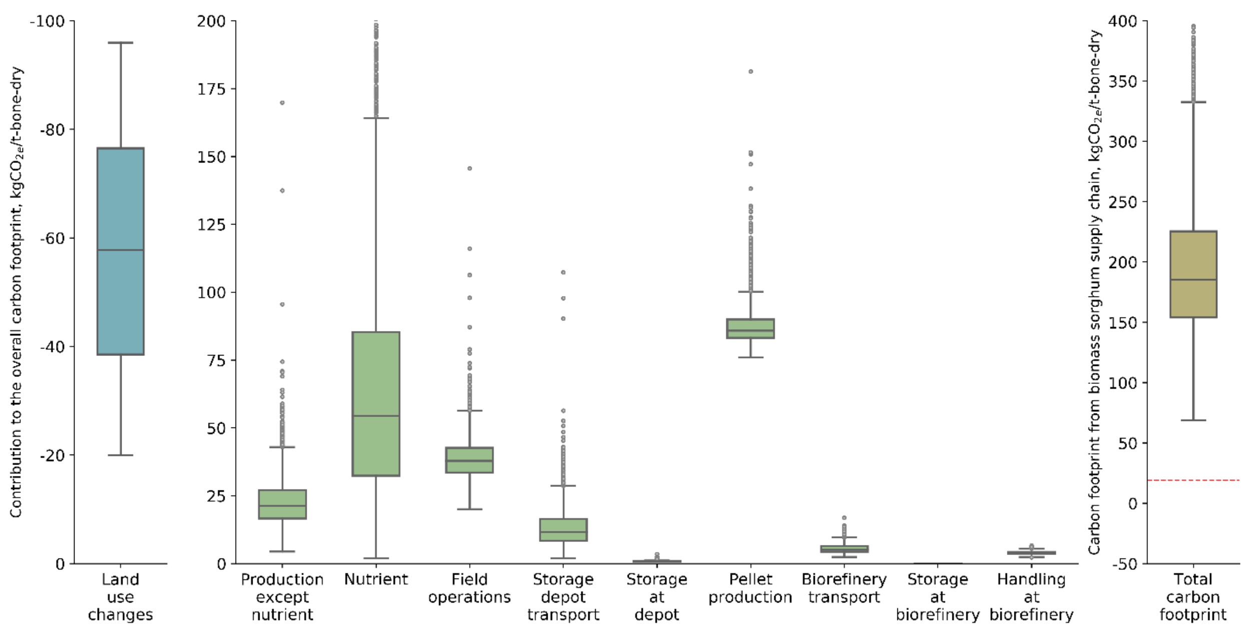


Figure S31. Uncertainties in the overall GHG emissions and contribution from each stage of the supply chain. **t** = metric ton.

e. Direct transportation of bale to the biorefinery

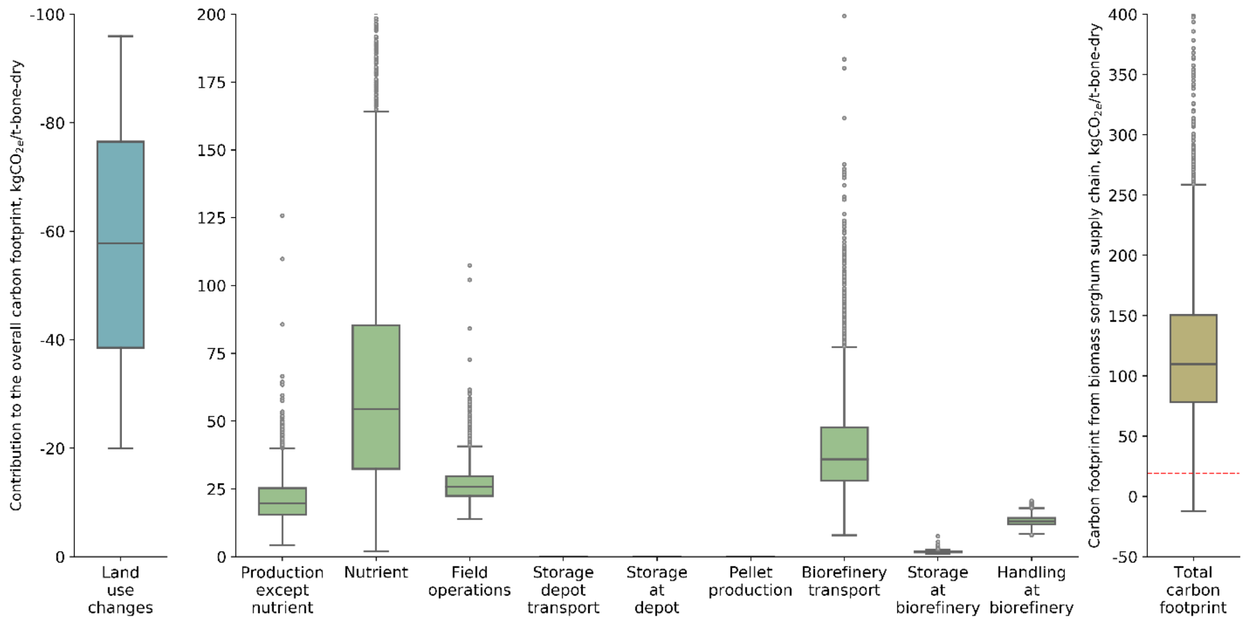


Figure S32. Uncertainties in the overall GHG emissions and contribution from each stage of the supply chain. **t** = metric ton.

f. Bale and pellet system

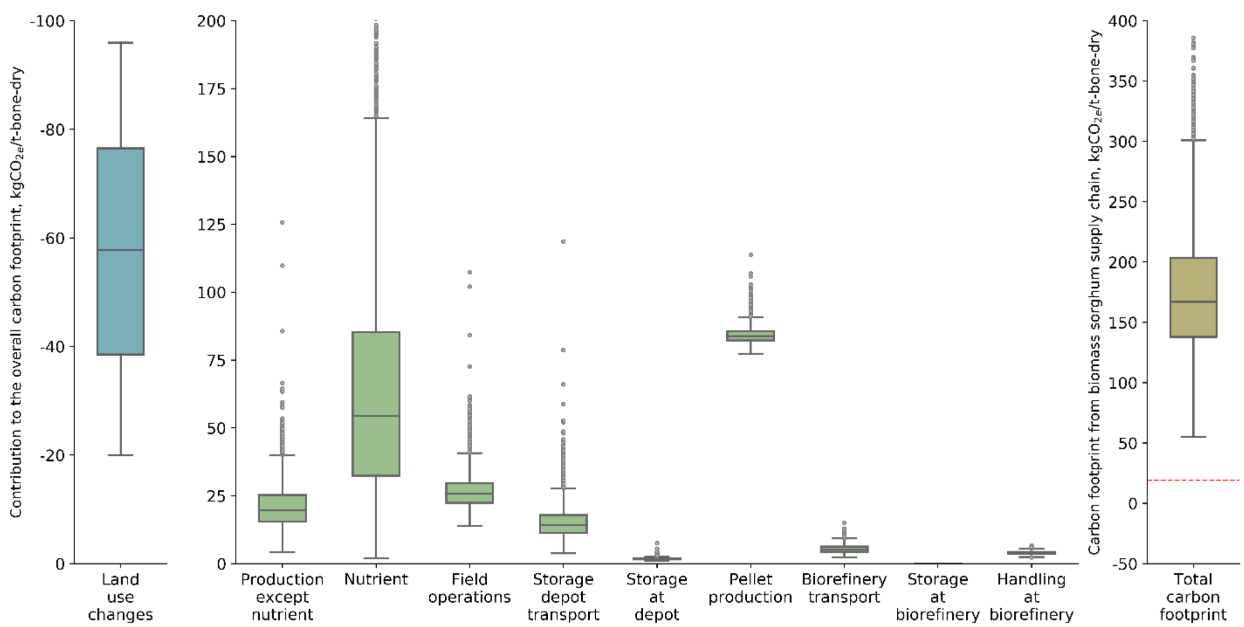
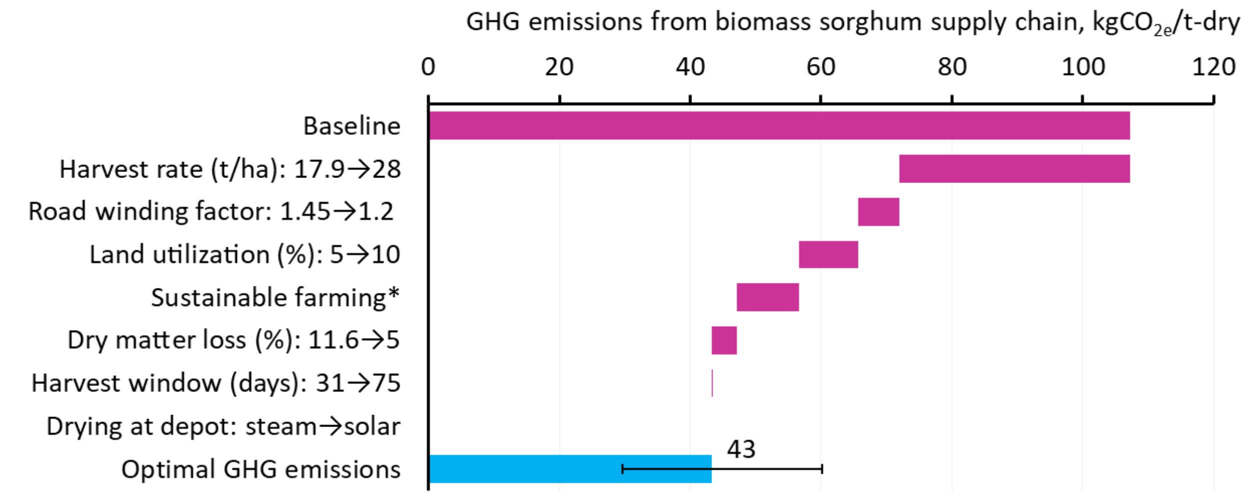


Figure S33. Uncertainties in the overall GHG emissions and contribution from each stage of the supply chain. **t** = metric ton.

S10. Optimal GHG emissions

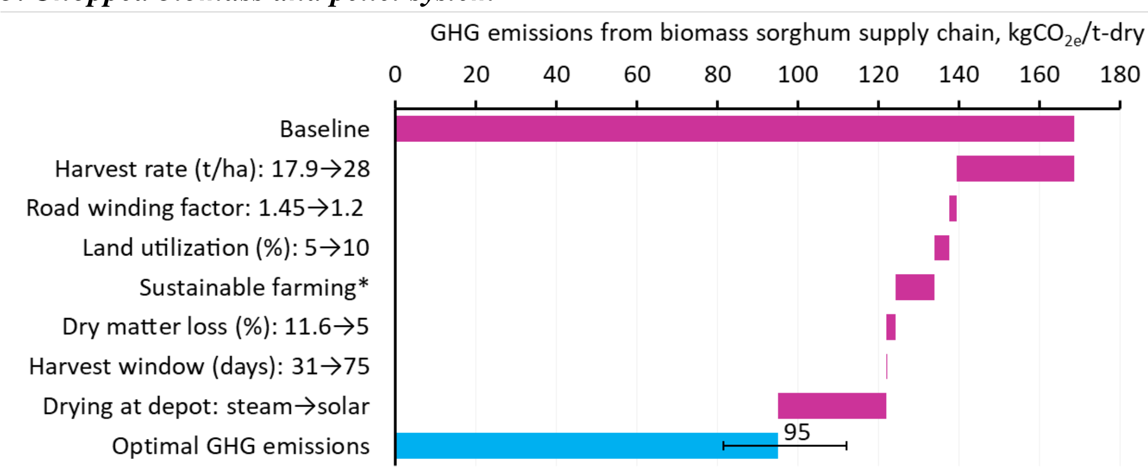
a. Direct transportation of chopped ensiled biomass to the biorefinery



**N-131→100; P-34→20; & K-212→75*
(Table S2; all data are in 'kg/ha')

Figure S34. Optimal GHG emissions from chopped ensiled biomass supply chain without preprocessing depot. The sensitivity bar represents the variation in the GHG emissions due to the variabilities present in the soil organic carbon sequestration potential of biomass sorghum. Sustainable farming practices include low- or no-till strategies that can reduce GHG emissions by minimizing nutrient inputs and use of machinery (fuel). **t** = metric ton.

b. Chopped biomass and pellet system



**N-131→100; P-34→20; & K-212→75*
(Table S2; all data are in 'kg/ha')

Figure S35. Optimal GHG emissions from chopped ensiled biomass supply chain with preprocessing depot. The sensitivity bar represents the variation in the GHG emissions due to the variabilities present in the soil organic carbon sequestration potential of biomass sorghum. Sustainable farming practices include low- or no-till strategies that can reduce GHG emissions by minimizing nutrient inputs and use of machinery (fuel). **t** = metric ton.

c. Direct transportation of module to the biorefinery

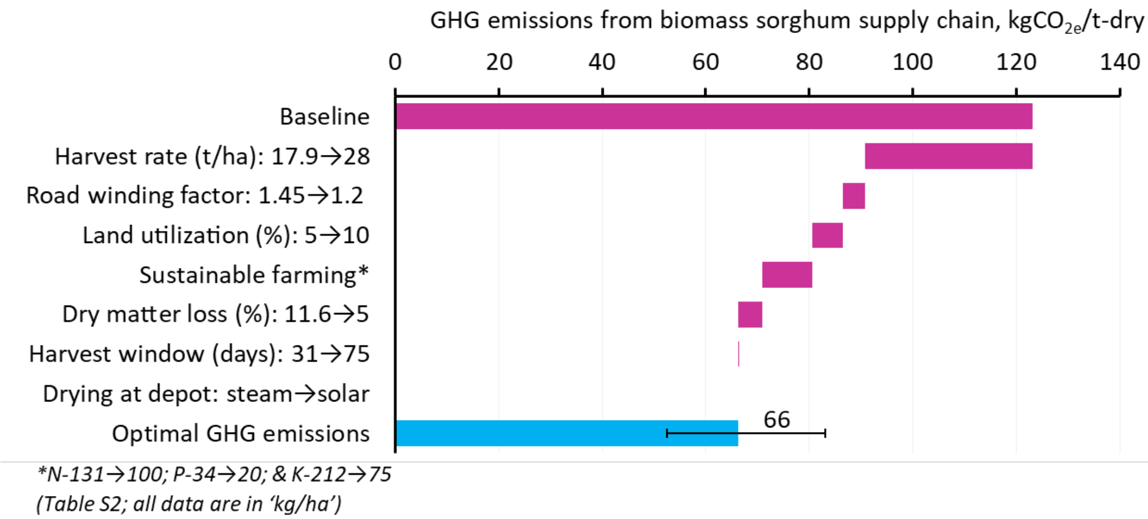


Figure S36. Optimal GHG emissions from biomass module supply chain without preprocessing depot. The sensitivity bar represents the variation in the GHG emissions due to the variabilities present in the soil organic carbon sequestration potential of biomass sorghum. Sustainable farming practices include low- or no-till strategies that can reduce GHG emissions by minimizing nutrient inputs and use of machinery (fuel). **t** = metric ton.

d. Module and pellet system

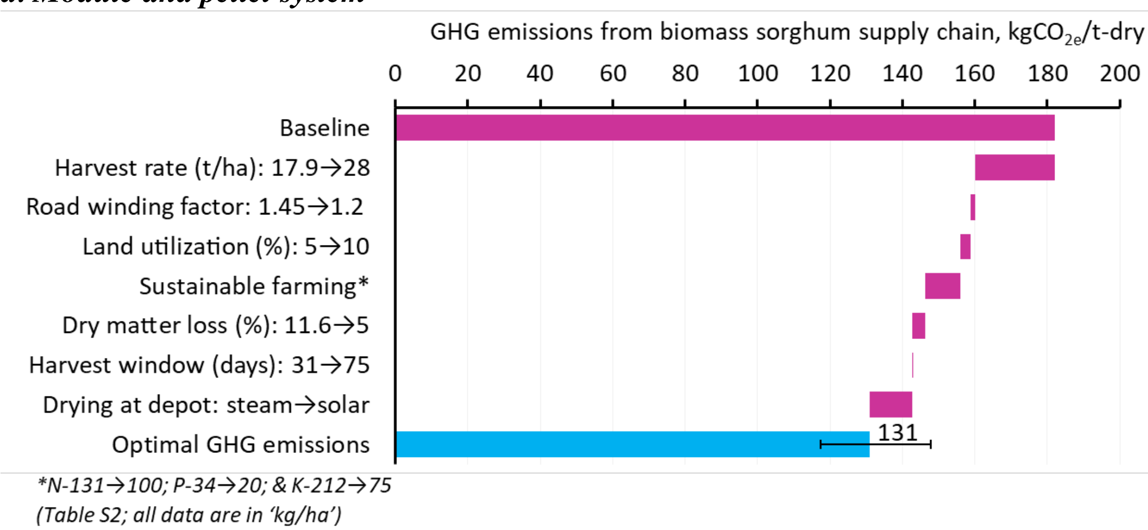


Figure S37. Optimal GHG emissions from biomass module supply chain with preprocessing depot. The sensitivity bar represents the variation in the GHG emissions due to the variabilities present in the soil organic carbon sequestration potential of biomass sorghum. Sustainable farming practices include low- or no-till strategies that can reduce GHG emissions by minimizing nutrient inputs and use of machinery (fuel). **t** = metric ton.

e. Direct transportation of bale to the biorefinery

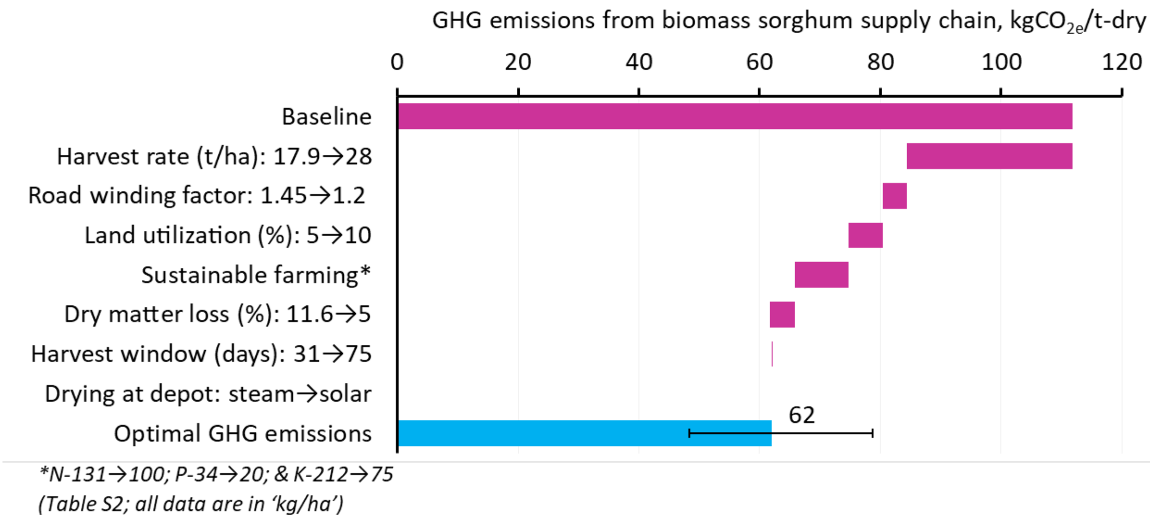


Figure S38. Optimal GHG emissions from biomass bale supply chain without preprocessing depot. The sensitivity bar represents the variation in the GHG emissions due to the variabilities present in the soil organic carbon sequestration potential of biomass sorghum. Sustainable farming practices include low- or no-till strategies that can reduce GHG emissions by minimizing nutrient inputs and use of machinery (fuel). **t** = metric ton.

f. Bale and pellet system

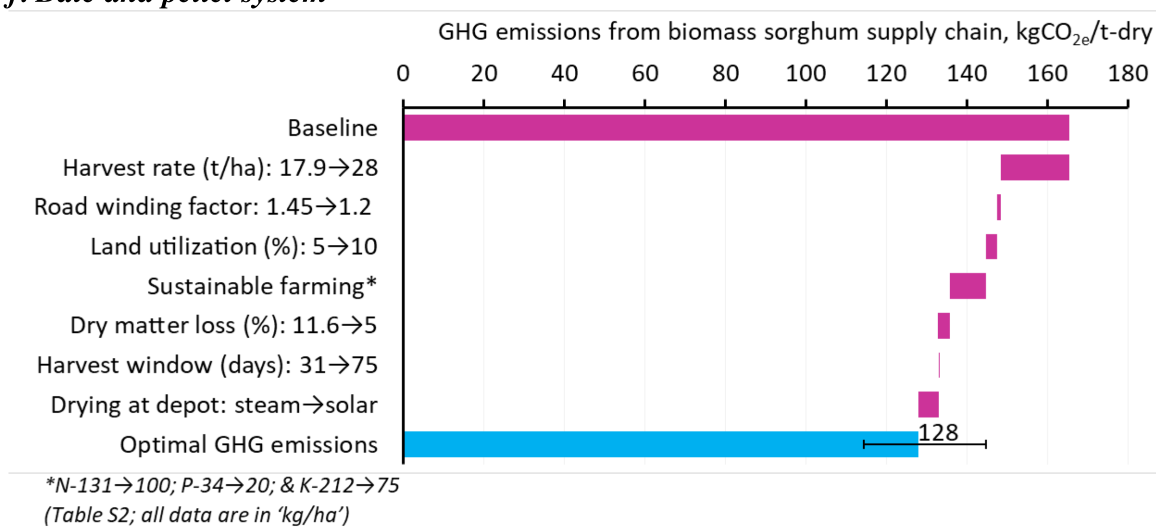


Figure S39. Optimal GHG emissions from biomass bale supply chain with preprocessing depot. The sensitivity bar represents the variation in the GHG emissions due to the variabilities present in the soil organic carbon sequestration potential of biomass sorghum. Sustainable farming practices include low- or no-till strategies that can reduce GHG emissions by minimizing nutrient inputs and use of machinery (fuel). **t** = metric ton.

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