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Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs

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Abstract: The *2011 US Billion-Ton Update*[1] estimates that there are enough agricultural and forest resources to sustainably provide enough biomass to displace approximately 30% of the country's current petroleum consumption. A portion of these resources are inaccessible at current cost targets with conventional feedstock supply systems because of their remoteness or low yields. Reliable analyses and projections of US biofuels production depend on assumptions about the supply system and biorefinery capacity, which, in turn, depend on economics, feedstock logistics, and sustainability. A cross-functional team has examined optimal combinations of advances in feedstock supply systems and biorefinery capacities with rigorous design information, improved crop yield and agronomic practices, and improved estimates of sustainable biomass availability. Biochemical-conversion-to-ethanol is analyzed for conventional bale-based system and advanced uniform-format feedstock supply system designs. The latter involves 'pre-processing' biomass into a higher-density, aerobically stable, easily transportable format that can supply large-scale biorefineries. Feedstock supply costs, logistics and processing costs are analyzed and compared, taking into account environmental sustainability metrics. © 2013 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: biochemical ethanol process; biorefinery size; advanced uniform format; conventional bale system; LCA; water footprint

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Introduction

The study began by examining issues between biorefinery capacity, reliable feedstock logistics, sustainability, and life cycle assessment. This initial study focused on the conversion of herbaceous feedstock to ethanol via a biochemical conversion process.

Biorefinery sizing assumptions used in previous design reports are evaluated by incorporating new data from feedstock supply studies and new information on biorefinery costs. At the same time, selected sustainability metrics are examined to determine how different sizing assumptions affect process sustainability.

In 1991, the National Renewable Energy Laboratory (NREL) published a case study that compared a 2000 dry metric tons per day (DMT/day) facility against a large 9000 DMT/day facility based on assumed feedstock production using conventional-bale systems.[2] They determined that the 2000 DMT/day was approximately optimal.

In 2002, NREL and the Oak Ridge National Laboratory (ORNL) performed a more rigorous analysis to determine the most appropriate cellulosic ethanol plant size. Based on this study, they again determined that 2000 DMT/day was appropriately optimal.[3] Their analysis took into account the increased feedstock transportation costs associated with a larger collection radius and the economy-of-scale advantages derived from increased plant capacity. Again, as in the previous study, they assumed a conventional-bale supply system.

Reasons to unconstrain biorefinery capacity

Ongoing R&D has suggested that a biorefinery capacity of 2000 DMT/day and feedstock collection radius of 50 miles may no longer be optimal. The following factors support re-visiting the biorefinery-sizing assumptions:

- Improved biorefinery cost estimates based on more rigorous process-design information.[4]
- Improved crop yields and agronomic practices have led to increased biomass availability and better tools have expanded the amount of biomass that may be sustainably harvested and supplied to biorefineries.
- Enhanced data and modeling tools have increased the spatial resolution of potentially available biomass resources from agricultural systems.
- Limiting the feedstock collection radius to 50 miles may cause difficulty in meeting biofuels production goals because fragmented resources, such as low-density or small-acreage plots, may not be economically viable within that radius.[5]
- Instead of a conventional-bale system (CBS), a 2009 Idaho National Laboratory (INL) study showed that there are a variety cost and supply advantages offered by an advanced uniform design (AUD), which involves 'pre-processing' the biomass into a higher-density, aerobically stable, easily transportable format. After pre-processing, the AUD biomass can be treated as a commodity – bought and sold in a market and transported like commodity-scale grains – greatly increasing feedstock availability and providing a continuous, consistent, and economic feedstock supply to large-scale biorefineries.[6]

Advanced uniform design

Local biorefineries generally only process a single or small number of feedstock types, which means that in a local area around a biorefinery, crop rotation is not always feasible. As such, co-locating the biorefinery with the feedstock supply does not nessessarily encourage sustainable agriculture practices.

On the other hand, AUD largely decouples biorefinery location from feedstock location. Because pre-processed feedstock is more easily and efficiently transported to the biorefinery (via rail), access to isolated and low yield areas is increased thereby increasing the volume of material that can cost effectively enter the system. In addition, AUD facilitates sustainable land practices and allows biorefineries to be efficiently sited and optimized for market demand, distribution infrastructure, proximity to utilities, and access to skilled workers.

AUD also mitigates risk associated with feedstock outages, such as those associated with local weather, pests, and diseases. Since feedstocks are processed as commodities in an AUD system, the biorefinery should be less vulnerable to price volatility and may not need to contract directly with feedstock producers.

AUD pre-processed feedstock has consistent physical properties, thus allowing it to use standardized, high-efficiency, high-volume grain handling and transport systems and equipment. Standardization of feedstocks also allows biorefineries to establish tight operating specifications and optimize the conversion process based on narrow feedstock characteristics.

The AUD puts active controls in the supply system to manage moisture. Active moisture controls are a key element of current grain commodity systems. AUD pre-processing stabilizes feedstock material and facilitates commodity scale distribution of the biomass materials. The ability to manage moisture allows more biomass into

the supply system and reduced risk for the biorefinery in feedstock quality. Furthermore, AUD pre-processing reducing the storage footprint and environmental impacts, such as the fire hazards, rodent infestation, and localized odors normally associated with large-scale storage of non-aerobically stable feedstock that are typical of using CBS.

Finally, the AUD provides additional market options for geographically stranded feedstock producers (i.e. fragmented feedstock, not within a 50-mile biorefinery radius, that can not be collected economically with CBS), letting them sell excess product in a commodity market.

Illustrative cases

In order to highlight the advantages of the AUD, three illustrative cases where biorefinery capacities ranged from 500 to 10 000 DMT/day were examined in this study. POLYSYS, an agricultural land-use simulation model from the Agricultural Policy Analysis Center at the University of Tennessee, was used to forecast the biomass-feedstock supply for all three cases in the 2017 time frame. Both CBS and AUD logistics systems were analyzed using INL's Biomass Logistics Model (BLM).[7] All three cases used a biochemical-conversion biorefinery that is based on published designs.[4] A complete listing of the modeling tools used in this analysis is included in Table 1.

- Case 1: Iowa corn stover feedstock collected using CBS logistics and evaluated for biorefinery capacities ranging from 500 to 2000 DMT/day. (Note: 2000 DMT/day was the maximum size analyzed due to constraints on delivery traffic congestion.)
- Case 2: Iowa corn stover collected using AUD logistics and evaluated for biorefinery capacities ranging from 500 to 10 000 DMT/day.
- Case 3: Georgia herbaceous feedstock mix collected using AUD logistics and evaluated for biorefinery capacities ranging from 500 to 10 000 DMT/day. (Note: Although POLYSYS modeled a mix of herbaceous feedstocks, for simplicity of calculations, we assumed 100%-switchgrass (SWG) for all downstream-of-feedstock-production calculations.)

For all three cases, the biomass supply included in this study is documented in detail in Langholtz *et al.*[8]

Feedstock supply

Feedstock supply analyses were performed using the POLYSYS model, which operates as a mathematical displacement model and is tied to historical agricultural-production and land-use patterns. National production forecasts are disaggregated to the county level using trailing averages of production data from the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS).[9] The conditions under which bioenergy crops or crop residues are supplied are a function of the maximum net expected returns of traditional and cellulosic crops after the demands established for current uses in the USDA baseline are met.[10]

Through an iterative process of model executions, a biomass farm-gate price of $60.63 per DMT (2007$) was determined to supply sufficient biomass to meet the RFS2 cellulosic ethanol targets and projected biopower demand levels.[8,11,12] In this scenario, contracts begin for corn stover collection in 2012 and estimates on tillage behavior, traditional crop yields, and adoption assumptions are consistent with the analysis supporting the *Billion-ton Update* report.[1] Farmgate price of a feedstock includes the total cost of production, harvest, and delivery to the roadside. Farmgate

Table 1. Summary of modeling and analysis tools used for this study.

Biofuel System Element	Modeling Tool	Description
Feedstock Production	POLYSYS	An agricultural land-use simulation model used to forecast biomass-feedstock supply.[9]
Feedstock Logistics (INL's BLM)	Powersim System Dynamics Framework	A systems dynamic model used to design and simulate biomass preprocessing and supply chain (logistics) infrastructure.[7]
Ethanol Conversion	Aspen Plus	A chemical process modeling system used to design the biomass-to-ethanol conversion plant.[4]
Life Cycle Analysis	SimaPro	A life cycle assessment and carbon footprinting model used to analyze environmental performance.[36]
Water Resources	SWAT	A river basin scale model developed to quantify the impact of land management practices in large, complex watersheds.[28,29]
Water Resources	SPARROW	A modeling tool for regional interpretation of water-quality monitoring data.[26,27]

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Table 2. Summary of overall Iowa (IA) and Georgia (GA) residue and energy crop biomass feedstock supply modeled by POLYSYS.

Residue/Energy Crop	Yield (DMT/ha)	Total ha Planted/ Harvested	Total Production (DMT)	Growers Payment (2007$/DMT)
IOWA				
Corn stover	4.13	5,726,650	23,620,508	$46.90
Wheat straw	0.13	6,041	7,985	$37.36
Total	***4.08***	***5,778,203***	***23,628,493***	***$46.90***
GEORGIA				
Corn stover	1.51	111,034	167,307	$44.96
Wheat straw	0.96	60,318	57,700	$35.84
Total residues	***1.31***	***171,351***	***225,007***	***$42.62***
Switchgrass	11.22	135,023	1,514,474	$33.66
Total	***11.22***	***135,023***	***1,514,474***	***$33.66***

price also includes profit required to incentivize production of energy crops. For dedicated feedstocks to be competitive, farmers must be paid above the expected returns, i.e. the opportunity cost, of an alternative crop. For residues, farmgate price also compensates producers for nutrients and organic matter embodied in the residues which must be replaced in the soil. This paper identifies feedstock supply available when the offered farmgate price of biomass is $61 per DMT. 'Grower payment' is the price required for rights to harvest material from the field. Succinctly, grower payment is farmgate price minus harvest cost for both dedicated feedstocks and residues. Average grower payments of participating producers and a summary of the feedstock supply results are reported in Table 2.

Switchgrass production budgets are estimated for a 10-year planning horizon with no-till establishment on cropland, cropland pasture, and permanent pasture. For permanent pasture, a one-time breaking fee is incurred in the establishment year. Crop residues include corn stover and wheat straw. Crop residue yields are estimated after requirements for soil carbon and wind and water erosion are met. Both crop residue and switchgrass supplies are estimated using a cumulative harvest efficiency of 0.81 from standing yield to farm-gate yield.

Supply projections were limited to the feedstock price level determined in Langholtz *et al.*[8] to meet EISA and projected state biopower mandates. Because there is insufficient feedstock at a farmgate price of $60.63 per DMT in the state of GA to support a biorefinery capacity of 7500 or 10 000 DMT/day, we assumed that herbaceous feedstock will be available in adjacent states at the same grower payment as Georgia and the feedstock will be transported further for Case 3 in these scenarios.

The current analysis does not explore whether or not feedstocks would be produced on different land types when comparing the AUD with the CBS. Nor does it explore the opportunity to increase feedstock prices to procure more supplies within a given area.

Logistics

Feedstock logistics analyses were performed utilizing the INL Biomass Logistics Model (BLM).[7] The BLM is developed on a system dynamics modeling platform (Powersim) and accounts for all capital and operational elements when evaluating a feedstock supply system design. The BLM is not used to site depots, terminals, or biorefineries in the logistics analysis scenarios in this paper; instead, it assumes a central location within the biomass supply in the CBS designs and a specified distance from the biomass in the AUD designs. The BLM simulates the flow of biomass through the entire supply chain, tracking changes in feedstock characteristics (i.e. moisture content, dry matter, ash content, and dry bulk density) as influenced by the various operations (i.e. harvesting, transportation, storage, …) in the supply chain.

Case 1 analysis

The first scenario is based on using a CBS for cornstover in Iowa which is a high yield area. The CBS uses currently available, commercial equipment and processes (Fig. 1). Multi-pass harvest systems first move the field-dried feedstock into a windrow and then bale the windrow into large square bales (3' × 4' × 8'). Bales are collected and moved

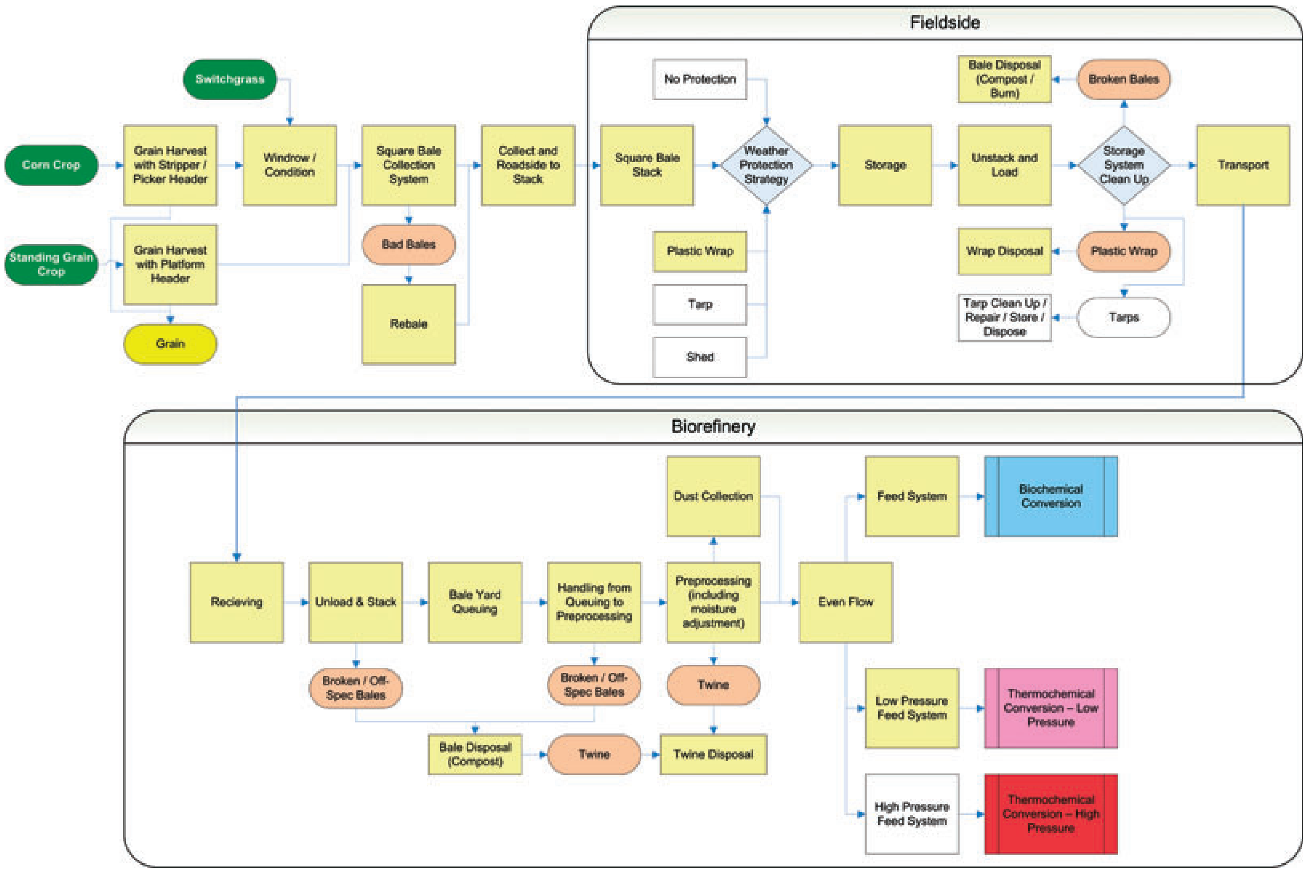

Figure 1. Engineering design schematic of the CBS.

to field-side storage stacks where they are protected with tarps. When needed at the biorefinery, bales are delivered via flatbed semi-trucks to biorefinery short-term storage. At the biorefinery, the bales are queued as needed through a grinding process that reduces the feedstock to ¼-inch particle size bulk material. This bulk material is then fed into the conversion reactor.

Constraints

One of the major drawbacks of the CBS design is that it provides limited opportunity to stabilize material or alter material specifications, which means that only material containing less than 15% moisture, which meets the conversion process moisture specification, should be baled. This constraint limits the availability of feedstocks and impacts system performance across climate ranges, different harvest seasons, and different crops.

In the case of switchgrass, moisture at harvest can be managed primarily by delaying cutting of the crop until the material has dried appropriately. However, a corn stover harvest presents a very different challenge as stover is a secondary crop to the corn grain. The harvest window, and subsequently the material properties of the stover at harvest, is driven by grain harvest decisions.

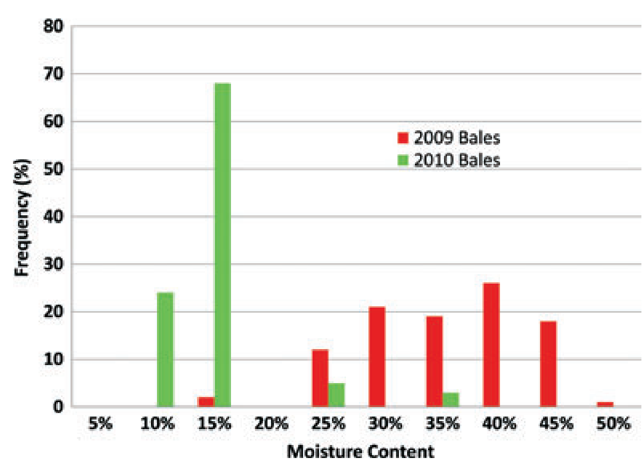

Figure 2. Moisture content of bales entering storage was vastly different for each year according to an INL-conducted northwest Iowa storage study (internal INL data, not included here).

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Climate conditions have a major impact on the field drying of stover. Figure 2 shows moisture distribution as measured in an INL storage study of bales that were collected in northwest Iowa in 2009 and 2010. In 2010, approximately 95% of the bales collected met the CBS criteria of 15% moisture or below, whereasin 2009, more than 97% of the bales collected were at 25% moisture or above. Moving and storing material with high-moisture content significantly impacts stability and logistics costs.

Analysis parameters

The logistics assessments for the CBS in this analysis are limited to 2000 DMT/day and smaller biorefineries because the current system design cannot be scaled to larger biorefineries without significant design changes across multiple elements. For example, an entirely new infrastructure would be required to support and manage movement of 60 or more trucks per hour as required in the large biorefinery capacity scenarios. Following is a breakdown of model parameters used in the Case 1 logistics analyses.

- **10-year average assessment:** Using 10 years of harvest progress data, coupled with climate data and field drying data, an analysis was performed to develop a 10-year average assessment of the corn stover available to bale in Iowa at 15% moisture. The resultant algorithm was tested against Boone County, in the center of Iowa, and showed that, on average, approximately 36% of the corn stover acres could be baled at 15% moisture or below. This percentage was used to set the 10-year average for Iowa that was used in the Case 1 logistics analysis. It's important to note that calculating an impact of climate across years or for larger geographical areas can result in an average that does not necessarily represent individual years in the dataset.
- **Harvesting system:** The analysis accounts for collection limitations stemming from using a multi-pass harvest system to collect corn stover in CBS. INL field tests demonstrated that collection rate is capped at 6.72 DMT/ha by the practical limits for this type of equipment. Harvest windows of 19 harvest days are also assumed for the conventional system.
- **Field-side storage:** Collection system models assume field-side storage at a fixed stack size. The distance to the stack input into the collection model is determined by using the county yield and implementing a radial geometric mean formula to establish the transport distance from the field to the local stack. Storage system bale stacks are assumed to be 2000 DMT. The moisture content of the bales when put into storage is assumed to be 15%. Dry matter losses in storage are modeled at 5%.
- **Transportation to biorefinery:** Transportation distance to the biorefinery is solved through a series of spatial operations. First the feedstock density for a given county is normalized with the density of all counties that have area within a 25-mile radius of the subject county's centroid. This normalization is performed to simulate the potential movement of feedstock across county boundaries for delivery to the biorefinery. The density calculation, accounting for yield and acres participating in stover collection, provides a DMT/mile^2 density. With the normalized feedstock density calculated for the county, a radial geometric mean formula is employed to establish an average biorefinery transport distance for the county.
- **Biorefinery pre-processing:** Pre-processing operations in the CBS are exclusively performed within the biorefinery gates. A two-stage grinder is used in the model to size-reduce the stover bales to ¼-inch material, which is then fed through an even-flow queuing system and fed to the biochemical conversion reactor.

Case 1 results

Using INL's BLM, the various supply system components – harvest, collection, and transportation – were systematically run for the available biomass from each of the counties within Iowa. The total supply costs were estimated by summing all of the system components. The results of the statewide county-by-county analysis are shown in Fig. 3.

As can be seen in Fig. 3 there is a wide range of logistics costs (approximately $45–$88/DMT) using the CBS (Case 1). Cost variations are mainly due to low-yield areas, which, in turn, have a high impact on the overall logistics costs.

Case 2 and Case 3: AUD analyses

The AUD system utilizes equipment and processes that are, in some cases, commercially available now and, in others, at bench and pilot scales, and will likely be commercially available in 2017. In the latter case, production-sized equipment is scaled from current bench and pilot scale data.

In an AUD process (Fig. 4), a single-pass harvesting system collects the grain and corn stover at the same time and the corn stover is fed directly to a baler. The corn

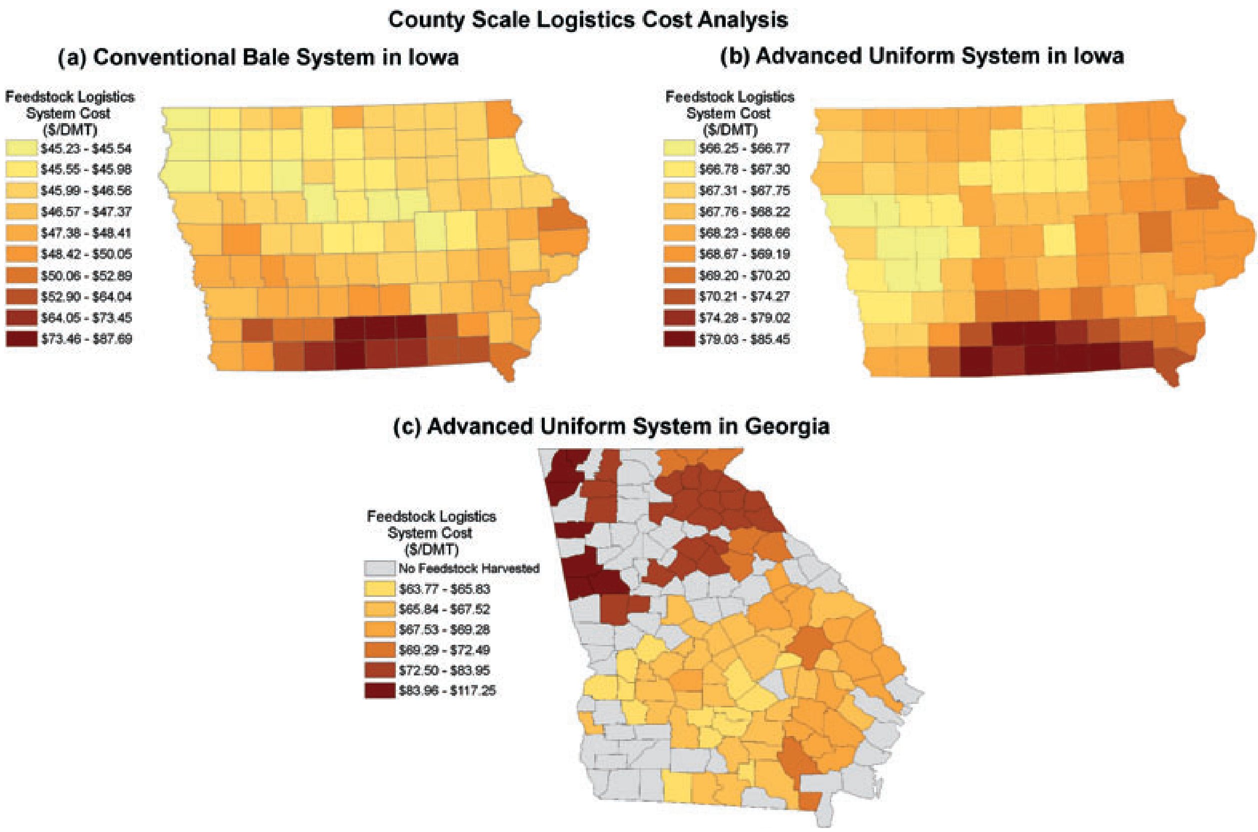

Figure 3. Breakdown of total Case 1 and 2 logistics costs for each county in Iowa based on removable stover limits, and total Case 3 logistics costs for each county in Georgia based on removable switchgrass limits.

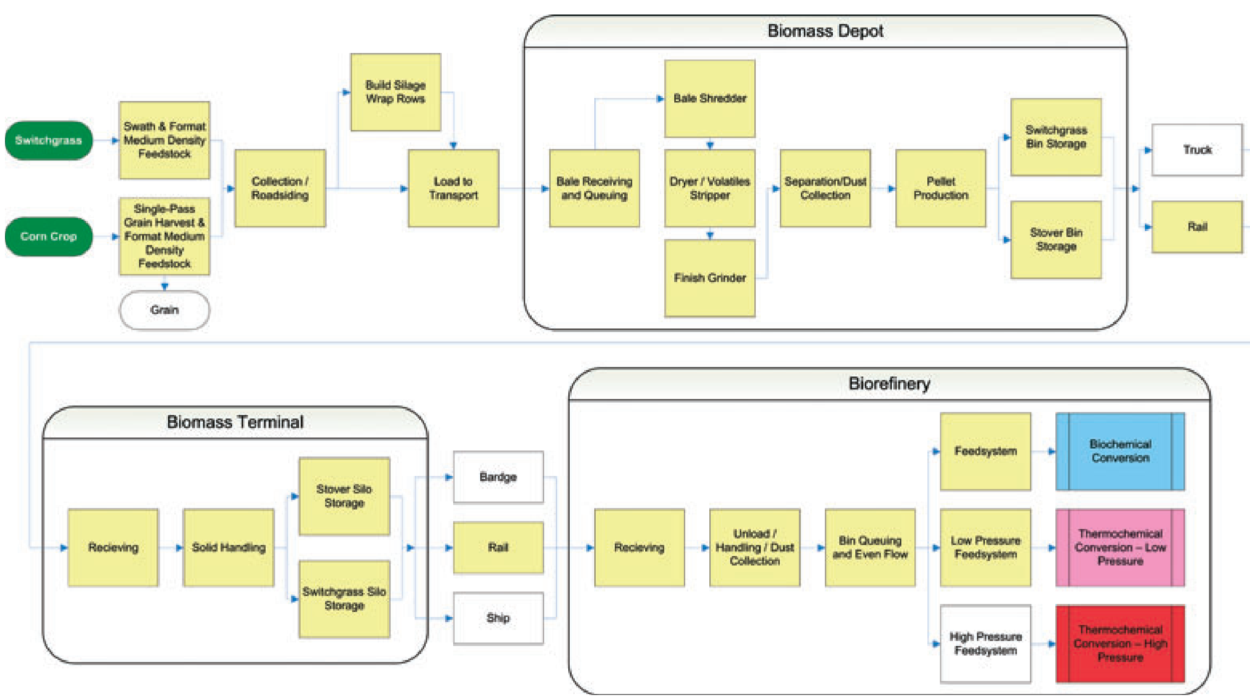

Figure 4. The AUD supply system uses distributed pre-processing depots to stabilize and densify feedstock, providing a lignocellulosic commodity material compatible with the infrastructure.

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stover bales are collected and moved to field-side stacks where they are protected with plastic wrap and stored. Plastic wrap was chosen to protect the bales because of the concern that the high moisture content would lead to unacceptable dry matter losses if the bales were protected with tarps similar to that in Case 1. When needed, stacks are delivered via flatbed semi-trucks to the depot for short-term storage and processing. Again as needed, the bales are sent through a drying, grinding, and densification process that dries the material to <10% moisture, reduces the feedstock to ¼-inch particle size bulk material, and then densifies the material to a pellet with density >30 lb/ft^3. The densified material is then shipped to the terminal for blending and later transported to the biorefinery.

Analysis parameters

The key feature of AUD is the pre-processing of biomass at an early stage in the supply system (Fig. 4). Pre-processing depots produce a final uniform material that is compatible with the grain storage and handling infrastructure.

- **Field-side storage:** Collection system models assume field-side storage at a fixed stack size. The distance to the stack input into the collection model is determined by using the county yield and implementing a radial geometric mean formula to establish the transport distance from the field to the local stack.
- **Bale moisture content:** Storage system bale stacks are assumed to be 2000 DMT. Moisture content of the bales when put into storage is assumed to be >20% due to baling of the material directly from the combine without field drying. Due to the high moisture content, the bales are wrapped in plastic to reduce the dry matter losses. Dry matter losses in storage are modeled at 7.8%.
- **Trucking feedstock from field-side to depot**: Depot size is based on the throughput capacity of the grinder, which is the most capital-intensive piece of equipment at the depot. The transportation distance is solved through a series of spatial operations much like the field-side-to-biorefinery delivery in a CBS.
- **Trucking from depot to blending terminal:** This distance is again solved through a series of spatial operations based on a terminal size of 3 600 000 DMT/year.
- **Shipping by rail from blending terminal to biorefinery:** This operation is based on a predetermined distance of 100 miles since, by rail, the majority of costs are fixed and the variable cost per mile is minimal.

In Case 3, the logistics design in Georgia assumes that the feedstock is 100% switchgrass. For the 7500 and 10 000 DMT/day biorefinery-capacity scenarios, the terminal-to-biorefinery distance was increased to 300 miles to accommodate the need for feedstock outside of Georgia.

The AUD feedstock design incorporates a blending facility (terminal) where different feedstocks can be blended to meet a conversion facility's feedstock design requirements.

AUD's impact is that the average supply system cost is higher, but the spatial and temporal variability are much lower. Where a CBS has low control over delivered biomass feedstock specifications, AUD has high control. Also, AUD is able to access material from low-yield counties that would typically be stranded and not able to enter the supply system at affordable costs.

Case 2 results

Case 2 uses the AUD for corn stover collection in Iowa. The results of the county-by-county analysis of feedstock logistics costs are shown in Fig. 3. The figure shows that while on average the total logistic cost is higher, the range of variability ($66–$85 per DMT) is lower than that for the CBS ($45–$88 per DMT).

Case 3 results

Case 3 uses the AUD for switchgrass in Georgia. The results of the county-by-county analysis of feedstock logistics costs are shown in Fig. 3. The figure shows that while on the average the total logistics cost is higher, the range of variability of the total cost is relatively low ($64–$117 per DMT) and much less for the AUD that for the CBS (internal INL data, not included here).

Overall logistics results

The overall conclusions regarding the effects of feedstock logistics design on total cost are the following:

- The CBS demonstrates high spatial variability in costs, even in highly productive regions such as Iowa. The local ranges in feedstock cost were from $45 to $88 per DMT. Additionally, the CBS has very limited control on the feedstock specifications delivered to the biorefinery.

The AUD has higher average supply system costs, but it does demonstrate reduced spatial and temporal variability. The average costs were much more stable, ranging from $66 to $85 per DMT for Iowa corn stover. The AUD also allows material from areas with low yields to enter into the system, whereas under the conventional supply

Table 3. Breakdown of feedstock logistics costs by unit operations for CBS and AUD system designs in Boone County, IA (a, b) and AUD system design in Telfair County, GA (c).

a) Conventional bale system costs in Boone County, IA for 2000 DMT/day biorefinery

Harvest & Collection	Storage	Transportation (~45 km)	Preprocessing	Handling & Queuing	Total Logistics
$15.61	$5.95	$8.86	$14.94	$0.83	$46.20

b) Advanced uniform system costs in Boone County, IA

Harvest & Collection	Storage	Depot Transport (~17 km)	Depot Preprocessing	Terminal Transport (~80 km)	Terminal	Biorefinery Transport (~170 km)	Handling & Queuing	Total Logistics
$16.15	$6.60	$6.01	$24.79	$3.14	$1.54	$8.95	$0.83	$68.01

c) Advanced uniform system costs in Telfair County, GA

Harvest & Collection	Storage	Depot Transport (~17 km)	Depot Preprocessing	Terminal Transport (~80 km)	Terminal	Biorefinery Transport (~170 km)	Handling & Queuing	Total Logistics
$16.37	$5.54	$6.23	$23.29	$4.96	$1.54	$8.95	$0.83	$67.71

Table 4. Summary of feedstock and average logistics costs (weight averaged) used in biorefinery sizing and sustainability study.

Case	Location	Feed	Logistics	Distance to Biorefinery (mi)	Biorefinery Size (DMT/d)	Grower Payment ($/DMT)	Logistics ($/DMT)	Total Feedstock Cost ($/DMT)
1	IA	Corn stover	CBS	15	500	$46.89	$44.81	$91.70
				21	1,000	$46.89	$45.40	$92.29
				30	2,000	$46.89	$46.20	$93.09
2	IA	Corn stover	AUD	100	500 to 10,000	$46.90	$68.01	$114.91
3	GA	SWG	AUD	100	500 to 5,000	$33.93	$67.71	$101.64
				300	7,500 to 10,000	$33.93	$73.77	$107.70

system these resources would be stranded and inaccessible. An example of the breakdown of total logistics cost for all cases are included in Table 3. AUD pre-processing costs are higher than those for CBS costs mainly because of higher pre-processing costs (drying, pellitization) and additional transportation steps.

Feedstock supply and logistics summary

A summary of the feedstock supply costs (grower payment + average logistic costs) for the work included in this study is displayed in Table 4. Using CBS logistics for Iowa corn stover (Case 1), the feedstock supply cost increases with increasing biorefinery size, as a greater collection radius is required. In contrast, using AUD logistics for Iowa corn stover (Case 2), biorefinery capacities in excess of 10 000 DMT/day are possible with a terminal located 100 miles from the biorefinery; thus, the feedstock supply cost is constant for Case 2. Similarly, the feedstock supply cost is constant for biorefinery capacities ranging from 500 to 5000 DMT/day for Georgia switchgrass (Case 3). However, at biorefinery capacities of 7500 and 10 000 DMT/day for Georgia switchgrass, a larger cropping area, and thus a larger terminal-to-biorefinery distance (300 miles), is required.

Conversion to ethanol

Conversion methods

Techno-economic analyses for the biochemical process of making ethanol from corn stover or switchgrass were performed by scaling the biochemical process design model for corn stover that was developed at NREL.[4]

For this study, we assumed that the feedstock convertibility is the same for similar feedstock types (i.e. corn stover and switchgrass) as well as between the feedstock formats (i.e. CBS and AUD). All conversion data are based on those reported for corn stover (using CBS),[4] using the feedstock composition data displayed in Table 5.

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Table 5. Corn stover and switchgrass compositions used for this study.

Component	IA Corn Stover (dry wt %)	GA Switchgrass (dry wt %)
Glucan	35.05	35.00
Xylan	19.53	22.50
Lignin	15.76	22.60
Ash	4.93	3.30
Acetate	1.81	1.80
Protein	3.10	1.20
Extractives	14.65	9.70
Arabinan	2.38	3.10
Galactan	1.43	0.50
Mannan	0.60	0.30
Sucrose	0.77	0.00
Total structural carbohydrates	58.99	61.40
	IA Corn Stover (bulk wt%)	GA Switchgrass (bulk wt%)
Moisture	12	15

The minimum ethanol selling prices (MESP) to give a 10% after-tax internal rate of return were calculated using a standard discounted cash flow rate of return analysis and the financial assumptions included in an earlier NREL report.[4]

Results

Figure 5 shows the breakdown of the MESP (biorefinery only) as a function of biorefinery plant size for each case.

In all cases, MESP decreases as biorefinery size increased. AUD logistics and processing costs are essentially constant for Iowa corn stover; thus, rising feedstock costs do not limit the economies-of-scale for biorefineries in excess of 10 000 DMT/day. In the case of lower-yielding feedstock (county-yield), such as Georgia switchgrass, increases in feedstock costs start to balance biorefinery economies-of-scale at biorefinery capacities in excess of >5000 DMT/day.

Due to the higher logistics costs, the MESP for AUD corn stover (Case 2) is approximately $0.25/gal higher than that for CBS (Case 1) at small biorefinery capacities (<2000 DMT/day). However, this study suggests that increasing the biorefinery size to 5000 DMT/day will more than offset the MESP increase associated with more expensive AUD pre-processed feedstock. Biorefinery capacities in excess of 10 000 DMT/day are only possible with AUD, and the resulting MESPs are substantially lower than that with CBS.

As the biorefinery size increases from 500 to 10 000 DMT/day with AUD logistics, the MESP decreases from $3.72 to $2.25 per gallon for IA-corn stover and $3.37 to $2.04 per gallon for GA-switchgrass. The lower MESP for switchgrass compared to that for corn stover is attributed to lower feedstock cost, higher ethanol yield, and higher byproduct electricity credit.

Water

In this section, the water resource use and the impact on water quality are analyzed. Water resource analysis

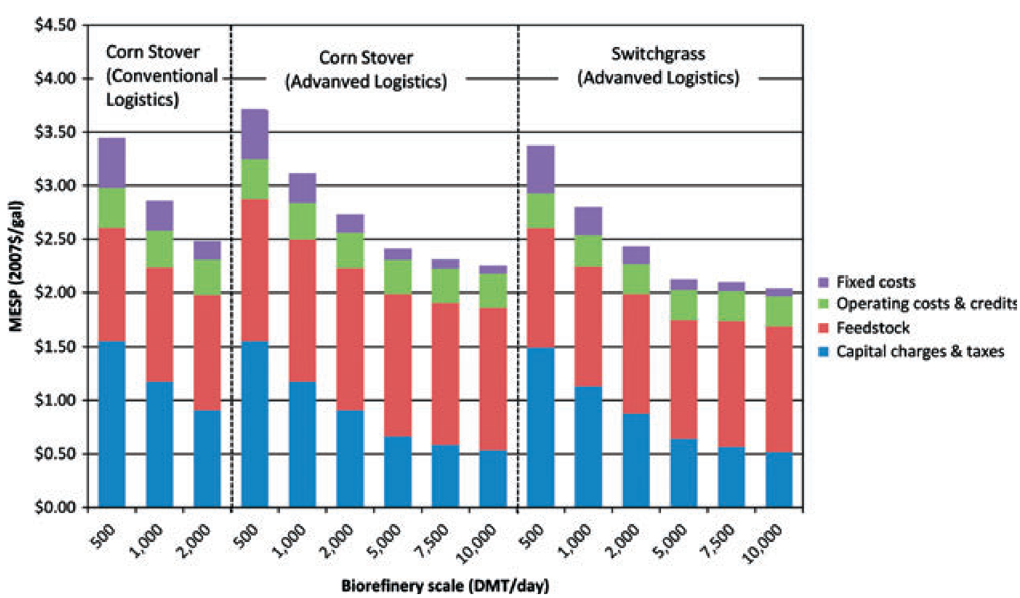

Figure 5. Minimum ethanol selling price (MESP) as a function of plant size.

focuses on the consumptive use of rainfall (green water) and of surface and ground water (blue water) through irrigation and process water use. Water quality analysis focuses on discharged water from fields containing fertilizer and process water discharge (grey water). The water footprint for the three types of water is considered for the feedstock growing stage and conversion stage for the process described earlier. Detailed methodologies of the water footprint assessment for the green, blue and grey water are described elsewhere.[13,30]

Data sources and assumptions

We used public data sources for this work including government reports and open literature. In the case that data were not available, we relied on a combination of model simulation and statistical regression. We assumed that soil moisture level is sufficient to meet the lowest water demand for switchgrass, so that irrigation is not required in the state of Georgia.

Climate, irrigation, crop, and nutrient loading data

Water footprint calculation relies heavily on climate, agricultural and hydrological data. All of the climate data used in this study were derived from the National Climate Data Center of NOAA for the period from 1970 to 2000.[14] Agricultural data for crop harvested acreage were from USDA NASS.[15] Irrigation application data were acquired from the 2002 and 2007 Census of Agriculture,[16,17] and the Farm and Ranch Irrigation Survey[18,19] published by the USDA and USGS.[20] The crop coefficient K_c, used in estimating evapotranspiration *(ET, the loss of water from the soil by evaporation and by transpiration from the crops)*, was compiled from the High Plains Regional Climate Center,[21] the Texas High Plains Evapotranspiration network,[22] and the previous studies of Kiniry *et al.*[23,24] Climate in 2017 was assumed to remain the same as the historical average from 1970 to 2000. However, the irrigation demand was further adjusted from historical values to reflect the increase of corn acreage and yield[25] (Table 6). Nitrogen loading (data not included here), a key component of interest in grey water, in IA and GA was estimated using results from SPARROW model.[26,27] Nitrogen fertilizer input rates for switchgrass were estimated by POLYSYS. Regular corn field fertilizer input were simulated by a SWAT hydrologic model based on USDA state-level data,[28,29] while supplemental fertilizer inputs were provided by POLYSYS. A natural background nitrogen concentration, C_N, was compiled from USGS.[30] Nutrient loading for SWG was estimated from alfalfa.[27] Based on the historical monitoring data sets for total nitrogen and nitrate (USGS[30]), C_N is assumed to be 95% of the total nitrogen concentration in stream water. Nitrogen fertilizer input data are included in Table 7. A comparison of the SWAT and SPARROW model in the studied areas showed good agreement for average values, while SPARROW projected less veriabilities.[31] All of the watershed-scale calculations in this study were further converted into county-level data using the zonal statistics tool in ArcGIS.

Water allocation

Corn plants produce grain and stover, both of which can be used as biofuel feedstock. During its growth, corn grain and stover each appropriate a fraction of the total water requirement. The same fraction was assumed in partioning the water footprint associated with stover based biofuel production. The blue water and green water of corn is partitioned between grain and stover by applying a crop harvest index.[32]

Conversion process water use

Consumptive water use at the biorefinery is estimated from the process model described earlier. Depending on the production scale and feedstock, the normalized process water use ranges from 5.3 to 5.6 L/L ethanol produced. The conversion process water is supplied from surface and ground water sources, and therefore its use contributes only to the blue water footprint.

In the conversion process, more bio-electricity is produced than that needed for the biorefinery, and thus the excess power is sold to the grid. A water use credit from the export electricity is considered using a system expansion approach. Electricity generation water consumption factors from electricity generation mix in IA (0.5279 gal water/Kwh) and GA (0.6403 gal water/Kwh) were adopted from a Power-Water tool.[33,34]

Results

In general, the blue water footprint of corn stover- and of switchgrass-derived ethanol ranged from 4.3 to 7.3 gal per gallon ethanol (Fig. 6), similar to that of conventional oil sands production.[35] Switchgrass-derived ethanol (Case 3) requires less blue water than corn stover-derived ethanol (Case 1 or 2) because of savings from switchgrass irrigation. Export bioelectricity contributes a 1 gal/gal water credit to the blue water footprint, reducing total blue water use by 12–20%.

Table 6. Projected corn irrigation volume by 2017.

FIPS	Case 1	Case 2	Case 1	Case 2	Irrigated Area Fraction	Case 1	Case 2
	Corn Yield		Harvested Acreage			Irrigation Water Use Volume	
	DMT/ac		1000 Acre		%	MGY	
19017	2.12	2.17	29	81	0.6%	28.2	77.7
19033	2.23	2.55	55	152	0.6%	44.3	122.0
19057	1.75	1.80	19	52	1.8%	48.7	133.9
19059	2.03	2.04	30	84	0.8%	41.2	113.5
19065	1.83	1.91	62	170	0.6%	55.7	153.3
19067	2.15	2.46	43	119	0.7%	41.8	115.0
19071	1.75	1.75	29	79	3.2%	166.3	457.9
19077	1.78	1.78	37	102	1.4%	85.2	234.6
19081	2.31	2.57	50	139	0.7%	52.0	143.1
19085	1.84	1.84	65	179	12.1%	1371.4	3775.6
19099	2.33	2.48	41	112	0.6%	29.2	80.3
19103	1.57	1.57	45	123	1.3%	69.5	191.3
19109	2.19	2.20	48	131	0.6%	40.1	110.4
19111	1.37	1.37	14	38	1.4%	26.4	72.6
19115	1.67	1.74	31	84	5.0%	250.4	689.5
19119	2.28	2.37	61	169	0.7%	92.7	255.2
19125	1.69	1.69	25	70	0.7%	32.8	90.2
19127	2.49	2.77	57	158	0.6%	45.8	126.0
19131	2.40	2.85	49	135	0.9%	55.4	152.5
19133	1.84	1.86	41	114	21.6%	1940.3	5342.0
19139	1.73	1.85	31	85	2.6%	114.6	315.6
19143	2.28	2.30	39	109	1.1%	73.4	202.0
19147	2.12	2.16	49	134	1.4%	106.0	291.8
19149	2.07	2.11	89	245	1.0%	165.5	455.7
19155	2.18	2.18	77	211	0.8%	119.8	329.9
19161	2.41	2.81	54	148	0.7%	56.2	154.7
19163	2.02	2.16	31	85	0.9%	35.1	96.6
19167	2.39	2.57	82	226	1.8%	308.0	847.9
19193	2.72	2.72	64	176	2.7%	371.0	1021.4
19195	2.40	2.84	45	125	0.7%	18.1	49.7
19197	2.44	2.89	64	175	0.5%	44.4	122.2

* Counties might not require irrigation if not listed in the table.

Green water contributes the most to the overall water footprint in both Case 1 and Case 2, and its relative contribution is significantly larger in Case 3 (Fig. 7) due to the climate differences between GA and IA. In particular, GA has higher evapotransporation than IA,[28] Additionally, green and blue water in Case 1 and Case 2 represent only the portion of water allocated to corn stover and the water use in the biorefinery, whereas in Case 3 the results represent all water associated with the entire above-ground switchgrass plant in addition to biorefinery blue water use (Fig. 7).

Grey water for the corn stover cases (Case 1 and Case 2) is attributable to the fraction of fertilizer required during the corn growth and supplemental fertilizer application to replace nutrients lost with stover removal. The average grey water in Case 1 and Case 2 is estimated at

Table 7. Nitrogen fertilizer application rate on stover (Cases 1 and 2) at Iowa, and switchgrass at Georgia (Case 3). The unit is in kg N per stover or switchgrass harvested acreage.

FIPS (IA)	Case 1 Supplement Fertilizer	Case 2 Supplement Fertilizer	Corn Fertilizer	FIPS (GA)	Case 3 SWG Fertilizer	FIPS (GA)	Case 3 SWG Fertilizer
	kg/ac	kg/ac	kg/ac		kg/ac		kg/ac
19001	12.89	12.89	54.68	13001	65.86	13201	–
19003	10.98	10.98	26.71	13003	75.22	13205	–
19005	10.52	10.52	55.21	13005	70.48	13207	78.00
19007	6.08	6.08	55.32	13007	–	13209	58.34
19009	18.21	18.21	54.85	13009	–	13211	78.00
19011	13.84	14.40	59.65	13011	35.45	13213	78.00
19013	13.30	13.92	59.63	13013	–	13215	–
19015	15.97	16.20	58.15	13015	78.00	13217	58.53
19017	15.71	16.09	59.67	13017	75.39	13219	78.00
19019	9.56	9.82	59.82	13019	70.44	13221	78.00
19021	16.45	17.25	53.64	13021	67.09	13223	–
19023	16.16	18.30	58.75	13023	69.21	13225	78.00
19025	16.05	18.25	53.88	13025	58.40	13227	–
19027	18.38	21.16	54.48	13027	62.79	13229	66.22
19029	15.93	15.93	26.71	13029	69.83	13231	65.61
19031	13.55	14.07	58.98	13031	61.79	13233	78.00
19033	16.52	18.89	58.45	13033	78.00	13235	63.18
19035	17.90	19.28	26.71	13035	–	13237	–
19037	13.23	13.36	59.25	13037	–	13239	–
19039	4.36	4.36	54.67	13039	–	13241	58.45
19041	16.36	17.13	56.44	13043	60.90	13243	–
19043	14.74	14.74	56.83	13045	47.67	13245	–
19045	11.56	11.61	59.76	13047	78.00	13247	–
19047	18.62	18.62	26.71	13049	–	13249	78.00
19049	12.32	12.92	55.09	13051	–	13251	78.00
19051	5.22	5.22	56.92	13053	–	13253	–
19053	7.00	7.00	26.71	13055	67.45	13255	–
19055	13.67	14.06	59.66	13057	–	13257	–
19057	12.96	13.32	60.44	13059	–	13259	77.72
19059	15.04	15.12	55.98	13061	78.00	13261	78.00
19061	13.52	13.52	58.29	13063	–	13263	–
19063	16.02	16.41	57.57	13065	58.40	13265	–
19065	13.55	14.10	58.45	13067	–	13267	58.38
19067	15.95	18.24	58.66	13069	58.19	13269	71.01
19069	17.89	21.42	59.37	13071	–	13271	72.39
19071	12.92	12.92	26.71	13073	–	13273	78.00
19073	16.97	19.98	54.17	13075	–	13275	70.80
19075	17.42	18.51	59.73	13077	78.00	13277	74.56
19077	13.14	13.14	54.81	13079	–	13279	64.83
19079	16.41	16.72	60.36	13081	72.23	13281	52.89

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Table 7. (Continued.)

FIPS (IA)	Case 1 Supplement Fertilizer	Case 2 Supplement Fertilizer	Corn Fertilizer	FIPS (GA)	Case 3 SWG Fertilizer	FIPS (GA)	Case 3 SWG Fertilizer
	kg/ac	kg/ac	kg/ac		kg/ac		kg/ac
19081	17.07	19.04	60.40	13083	–	13283	69.59
19083	16.03	16.45	60.81	13085	–	13285	–
19085	13.63	13.63	26.71	13087	–	13287	68.41
19087	12.64	12.64	57.11	13089	–	13289	66.91
19089	13.75	14.46	58.28	13091	73.67	13291	41.11
19091	18.04	21.69	58.80	13093	58.14	13293	–
19093	18.49	20.33	26.71	13095	–	13295	78.00
19095	12.87	12.87	59.43	13097	–	13297	58.53
19097	10.74	10.74	60.33	13099	–	13299	66.52
19099	17.24	18.39	59.01	13101	–	13301	68.75
19101	12.02	12.02	56.63	13103	78.00	13303	68.71
19103	11.59	11.59	59.31	13105	71.50	13305	58.27
19105	11.18	11.35	59.55	13107	58.19	13307	78.00
19107	13.14	13.14	58.54	13109	78.00	13309	–
19109	16.18	16.27	60.18	13111	–	13311	60.07
19111	10.14	10.14	57.94	13113	–	13313	–
19113	10.00	10.08	59.49	13115	–	13315	76.10
19115	12.39	12.89	59.61	13117	52.89	13317	78.00
19117	5.26	5.26	54.08	13119	78.00	13319	78.00
19119	16.90	17.51	26.71	13121	–	13321	76.56
19121	10.89	10.89	54.66	13123	–		
19123	12.95	13.16	57.13	13125	58.35		
19125	12.51	12.51	54.76	13127	–		
19127	18.40	20.52	59.88	13129	78.00		
19129	14.74	14.74	26.71	13131	–		
19131	17.75	21.09	59.44	13133	78.00		
19133	13.64	13.75	26.71	13135	–		
19135	7.51	7.51	52.97	13137	58.45		
19137	13.39	13.39	26.71	13139	59.29		
19139	12.80	13.69	59.96	13141	–		
19141	16.97	17.08	26.71	13143	–		
19143	16.88	17.05	26.71	13145	–		
19145	11.78	11.78	26.71	13147	78.00		
19147	15.70	15.99	56.42	13149	78.00		
19149	15.35	15.61	26.71	13151	78.00		
19151	16.83	17.37	56.19	13153	74.24		
19153	13.08	14.05	56.41	13155	74.80		
19155	16.16	16.16	26.71	13157	58.53		
19157	15.48	15.77	59.30	13159	–		
19159	5.40	5.40	26.71	13161	67.24		
19161	17.84	20.78	53.64	13163	71.96		

Table 7. (Continued.)

FIPS (IA)	Case 1 Supplement Fertilizer	Case 2 Supplement Fertilizer	Corn Fertilizer	FIPS (GA)	Case 3 SWG Fertilizer	FIPS (GA)	Case 3 SWG Fertilizer
	kg/ac	kg/ac	kg/ac		kg/ac		kg/ac
19163	14.94	15.96	60.00	13165	78.00		
19165	16.60	16.60	26.71	13167	62.71		
19167	17.66	18.99	26.71	13169	–		
19169	15.61	15.66	59.96	13171	–		
19171	15.12	15.14	59.78	13173	64.69		
19173	6.29	6.29	26.71	13175	72.13		
19175	7.37	7.37	54.67	13177	78.00		
19177	6.46	6.46	54.18	13179	–		
19179	10.99	10.99	54.55	13181	–		
19181	12.90	12.90	54.67	13183	58.44		
19183	16.65	17.08	58.24	13185	58.68		
19185	5.52	5.52	26.71	13187	48.95		
19187	16.64	16.68	57.03	13189	–		
19189	15.99	15.99	59.09	13191	–		
19191	12.49	12.53	57.93	13193	78.00		
19193	20.13	20.13	26.71	13195	58.53		
19195	17.78	21.02	58.41	13197	78.00		
19197	18.03	21.36	60.81	13199	78.00		

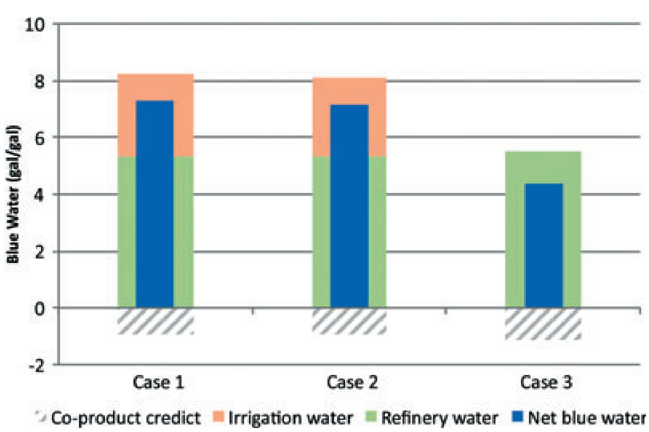

Figure 6. Blue water footprint of cellulosic ethanol produced from corn stover (Cases 1 and 2) and switchgrass (Case 3) by production stage at refinery scale of 2000 DMT/day in 2017.

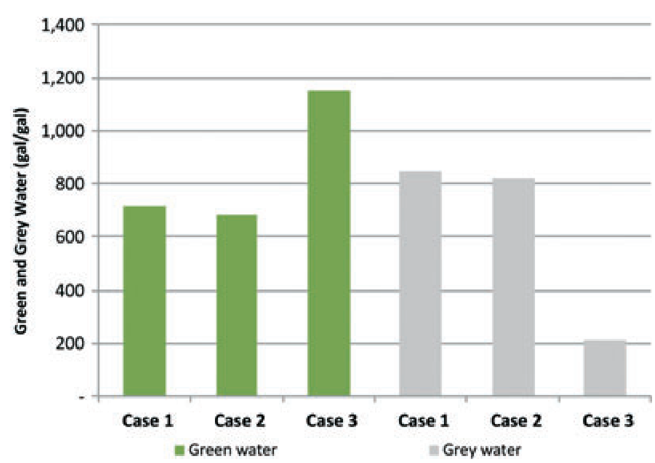

Figure 7. Green and grey water footprint of cellulosic ethanol produced from corn stover (Cases 1 and 2) and switchgrass (Case 3) by production stage at refinery scale of 2000 DMT/day in 2017.

850 and 820 gallons water per gallon ethanol, respectively. The average grey water in Case 3, which accounts for assimilating the total fertilizer applied during the entire growth period, is only 210 gallons water per gallon ethanol. Results clearly indicate the unique ability of switchgrass to capture nutrient runoff in addition to lower fertilizer input requirements thereby reducing grey water loadings. Historically, switchgrass has been used in conservation programs to contain the fertilizer loss to water body from crop land.

At the same refinery capacity, choice of feedstock and location could have significant impacts on types of water footprint of the cellulosic biofuel. Since a majority of

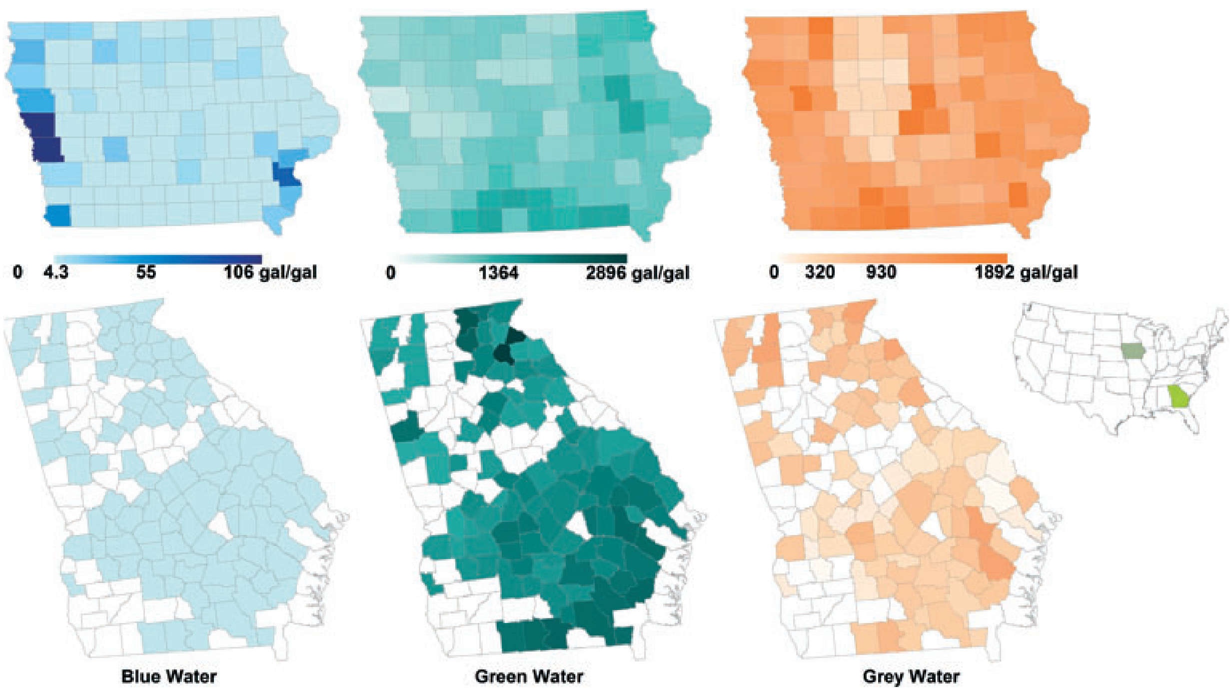

Figure 8. County-level distributions of blue, green, and grey water footprint for a 2000 DMT/d biorefinery in 2017 to produced biofuel from (a) corn stover grown in Iowa via advanced logistic system (Case 2) and (b) switchgrass grown in Georgia via advanced logistic system (Case 3).

water requirements in the biofuel life cycle are from the feedstock growing stage, the water footprint of a particular biofuel is largely determined by regional climate. For example, with the same advanced logistic system cellulosic ethanol produced from switchgrass in biorefineries located in Georgia (Case 3) requires 39% less blue water footprint than that for Iowa stover in Case 2 (Fig. 6). Since the total water requirement for crop growth would be satisfied either from rainfall (green water) or irrigation (blue water), lower green water footprint often means increased blue water footprint for the same plant species (Fig. 8).

Switchgrass is a high yield perennial which requires substantial evapotransporation to support its growth. Switchgrass can be cultivated in many regions in the USA without irrigation, and thus producing rain-fed switchgrass could have less impact on regional blue water use than other crops requiring irrigation.

Biorefinery water supply is entirely blue water, and biorefinery water demand is concentrated in a single local area. Thus, a biorefinery built in an area where the local feedstock is blue-water-intensive would likely lead to an increased burden on the local water resources as compare to a biorefinery built in an area with less blue-water-intensive feedstocks. Therefore it is environmentally beneficial to develop switchgrass or other perennial feedstock plantations in regions with sufficient green water supply to ensure sustainable water use for the feedstock and the biorefinery.

From a whole biorefinery production perspective, the resource needs for blue water becomes more pronounced as biorefinery scale increases. Further, CBS logistics systems dictate that the biorefinery be located near the biomass feedstock production, whereas AUD logistics effectively decouple biorefinery location from feedstock production. Therefore, we expect that CBS logistics would stress a local water resource to a greater extent than AUD logistics. Figure 8 further shows the extensive geographical variability of blue andf green water footprint even within a state, which would affect the choice of feedstock thereby influence the refinery siting consideration.

Sustainability metrics and life cycle assessment

SimaPro v.7.3 life cycle assessment modeling software was used to develop and link unit processes using established methods.[36] In the absence of primary, publicly available data, we used the Ecoinvent v.2.0 and, to a lesser extent, the US Life Cycle Inventory (US LCI) processes. We modified the Ecoinvent processes to be reflective of

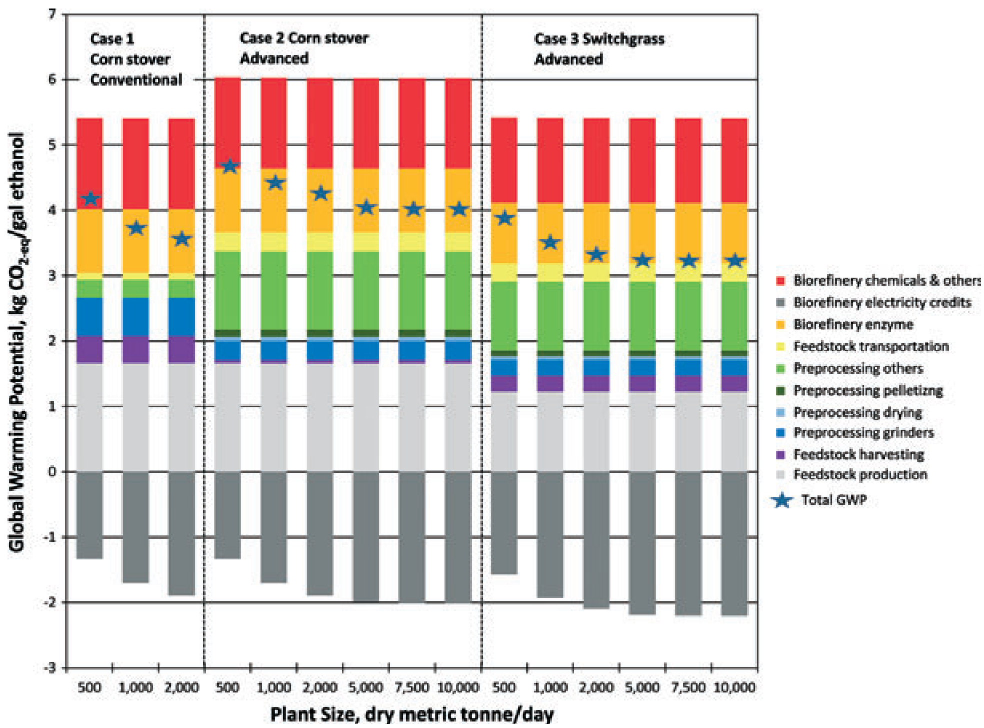

Figure 9. GHG emissions LCA results for Case 1: Iowa corn stover, CBS; Case 2: Iowa corn stover, AUD; and Case 3: Georgia switchgrass, AUD.

U.S. conditions and the US LCI processes to account for embodied emissions and energy flows.

Modeling approach and assumptions

The modeling boundary for this study is from field to refinery gate, including embodied energy and material flows using the methods described elsewhere.[36] The functional unit is 1 gallon of ethanol produced in the year 2017. Avoided impacts are accounted for using product displacement (also termed boundary system expansion).[15] For products that share inputs (e.g. corn grain and corn stover), burdens are allocated between products based on a 'product-purpose' approach. Inputs to multi-year cropping systems (i.e. switchgrass) are likewise annualized by the length of the cropping rotation. Impacts from direct and indirect land use change are not considered in this study. Feedstock processing and transport are modeled according to INL's CBS and AUD.

LCA modeling results

A breakdown of the GHG emission (in terms of CO_2 equivalent) for each of the cases is displayed graphically in Fig. 9. When comparing AUD to CBS, moderate increases in GHG emissions observed in the Iowa corn stover biochemical conversion-to-ethanol are associated with additional field-to-depot and depot-to-terminal transportation steps ('Pre-processing other' category in Fig. 9) and increased transportation contribution to the biorefinery ('Feedstock transportation' category). The small increases in normalized (per gallon of ethanol) electricity credit with increasing biorefinery scale are associated with increased electricity generation efficiency. As expected, we observe small feedstock differences in GHG emissions for Iowa corn stover and Georgia switchgrass.

Conclusions

As expected, we demonstrated that CBS has lower average logistics costs than AUD. AUD logistic costs are higher than CBS costs primarily due to increased pre-processing costs and increased transportation costs (with multiple transportation step). Likewise and similar to earlier studies,[3] we also show that, with CBS, logistic costs increase as either biorefinery capacity or feedstock collection radius increase. AUD mitigates many of the CBS feedstock-supply risks and, while resulting in modestly higher logistics costs, dramatically reduces both the temporal and spatial biomass-cost variability and allows access to substantially larger quantities of biomass.

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1. AUD effectively disconnects the feedstock from the biorefinery in terms of both scale and location. Single or multiple terminals can supply single or multiple biorefineries of varying scale. Biorefinery locations can be optimized for logistics, distribution, water resources, or other project-specific constraints.
2. AUD promotes more sustainable cropping practices, whereas, with CBS, there is always pressure to produce the same crop.
3. AUD providers have much tighter control on biomass production specifications than is possible with CBS.

Iowa corn stover supply costs with CBS increase as biorefinery capacity increases from 500 to 2000 DMT/day; however, the biorefinery economy-of-scale impact is larger in magnitude, and the overall MESP decreases from $3.45/gal to $2.48/gal going from 500 to 2000 DMT/day biorefinery scale. It must be noted that CBS was not considered for biorefinery capacities of 5000 DMT or greater as the existing models do not capture the substantial additional infrastructure required to manage the high throughput of trucks through the biorefinery.

Iowa corn stover supply costs with the AUD are constant for biorefineries ranging from 500 to >10 000 DMT/day, and, as a result, the MESP is reduced from $3.72/gal to $2.25/gal. Similar to Iowa corn stover, Georgia switchgrass feedstock supply costs are constant using the AUD for biorefineries ranging from 500 to 5000 DMT/day; however, for biorefineries larger than ~5000 DMT/day, the terminal-to-biorefinery distance needs to be increased from 100 miles to 300 miles to supply the larger capacities. As a result, the MESP for Georgia decreases from $3.37/gal to approximately $2.04/gal as the biorefinery capacity is increased from 500 DMT/day to 10 000 DMT/day. Only small, if any, cost reductions are expected for capacities greater than 10 000 DMT/day. Results of this study show that biochemical ethanol production using a CBS results in the lowest MESP at small biorefinery scales. At larger biorefineries (>5000 DMT/day), these analyses suggest that AUD logistics result in production costs lower than those possible with conventional systems.

Our results show no detrimental effects on water sustainability metrics when comparing AUD to CBS. Nevertheless, feedstock location and feedstock type do affect water use and quality, so if biorefineries use different feedstocks or pull feedstocks from different locations than those modeled here, the results will change. This study also did not consider the local impact on water resources when siting a large biorefinery. We expect that large biorefineries, such as those enabled by the AUD, will require a water footprint commensurate to their scale and hence may stress the water resources of a specific area where the biorefinery is located.

Our results show that AUD logistics result in modestly higher GHG emissions (10–15%) than CBS, mainly due to additional field-to-depot and depot-to-terminal transportation ('Pre-processing other' category in Fig. 9) steps and increased transportation contribution to the biorefinery ('Feedstock transportation' category).

One potential issue not addressed in this work is that biomass resulting from AUD pre-processing are substantially changed physically and potentially chemically compared to materials collected using CBS (e.g. lignin is plasticized). This may affect biorefinery yield, operability, and production costs; and thus, future work will need to experimentally verify and quantify biochemical conversion of these materials, and adapt the models/analyses accordingly.

Acknowledgement

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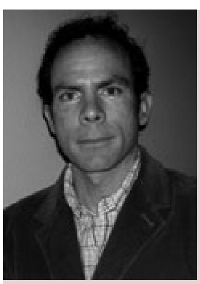

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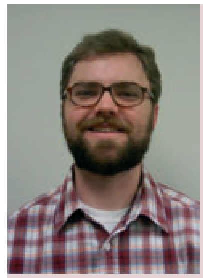

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