




Optimization of herbaceous feedstock delivery to a network of supply depots for a biorefinery in the Piedmont, USA

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Abstract: The southeastern USA has the potential to be a significant producer of bio-based products; however, research is still needed to demonstrate the most cost-effective feedstock delivery system for this region. A logistic system that has shown promise is one utilizing a network of supply depots. This study calculated the cost to produce a stream of size-reduced herbaceous biomass (i.e., switchgrass) for five theoretical depots in the Piedmont province. Three depots were located in south central Virginia and two in north central North Carolina. A logistics system with a 20-bale handling unit was used for load-out operations at 199 theoretical satellite storage locations (SSLs) within a 48 km radius of each depot location. The distribution of potential production fields and the transportation distance from SSLs to the depots were determined with spatial and network analyses. Based on an analysis of potential land cover available for feedstock production, the annual capacity per depot ranged from 80 839 to 170 830 Mg, resulting in a total annual capacity of 555 195 Mg for all five depots. Cost to deliver feedstock for 24/7 operation, 48 weeks per year ranged from 46.03 to 62.86 USD Mg⁻¹ annual capacity. At the low end, these costs were: SSL operation (22%), truck (29%), receiving facility (26%), and debaling-size-reduction (23%). The principle economy-of-scale factors were the receiving facility and debaling-size-reduction costs. To minimize per-Mg cost, depot capacity should be chosen such that equipment can be operated as close to 80% of design capacity as possible. © 2023 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: herbaceous; feedstock; logistics; modeling; spatial analysis; depots; biorefinery

Introduction

Certain biorefinery designs require high capacity to achieve the necessary economy of scale. It is often not practical to meet the feedstock demand by hauling low-bulk-density biomass from the surrounding

production area, since transportation costs would be too high. Consequently, the US Department of Energy (DOE) introduced a concept where a network of depots producing an intermediate feedstock (i.e., material at higher bulk density and higher energy density) would supply a biorefinery.^{1,2} The application of this concept was the motivation for this study



of five depot locations supplying a theoretical biorefinery in the Piedmont, a physiographic province in the southeastern USA.

The southeast has historically been an underutilized region of the USA for biofuel production. According to the US DOE and the United States Department of Agriculture (USDA), as of 2022, the total annual ethanol biofuel production in the USA was about 17 billion gallons from 192 biorefineries.³ The southeast only contributed 346 million gallons, or 2%, of this total from six biorefineries located in Tennessee, Kentucky, and North Carolina.³ However, this region has been shown to have the natural resources available, such as the proper climate, soils, and land use, to potentially produce a significant amount of the country's demand for biofuel.⁴ Resop and Cundiff⁵ previously identified 34 multi-county production zones in the Piedmont province with potential annual production of switchgrass for biofuel ranging from 50 000 Mg to 360 000 Mg per zone. Switchgrass (*Panicum virgatum* L.), a perennial, warm-season grass, as the potential biofuel feedstock was selected again for this study due to a long history of research that has shown it to be a flexible and resilient crop that can be grown under many diverse climates.⁶

The use of a biomass depot system, proposed by the US DOE,^{1,2} as the logistics system for managing the delivery of feedstock to a biorefinery has shown promise in recent studies. Lamers *et al.*⁷ compared the traditional feedstock supply system, where biomass is transported directly from the growers to the biorefinery, to the depot system. They found that a network of feedstock supply depots can help mitigate the risk of supply shortages and variabilities that pilot-scale biorefinery operations have experienced with the traditional system.⁷ However, much of their cost analysis focused on existing biofuel industries in the Midwest, and

this analysis needs to be expanded to explore the potential for application of this depot system to underutilized regions like the southeast.

Toba *et al.*⁸ simulated the use of supply depots, assuming a woody feedstock for a biorefinery located in the Piedmont region of South Carolina. First, they used a fuzzy suitability analysis to determine ideal locations for production fields based on environmental factors such as land use, slope, and soil properties. Then, they performed cluster and network analyses to determine the most suitable sites for depots, resulting in a two-depot scenario and a three-depot scenario. They found the more decentralized depot system provided greater potential for a more ecologically sustainable, and more economically efficient, supply system in terms of total distance traveled from fields to depots,⁸ however, a more detailed cost analysis of the depot system is needed.

A key point to be made is that the 'front end' for any bioenergy industry is the same whether the product is an intermediate at a depot or a final product processed at a biorefinery. Either way, the customer requires a stream of size-reduced material for continuous operation (Fig. 1). For this study, it is assumed that feedstock producers store feedstock in satellite storage locations (SSLs), defined as a gravel storage area with suitable road access, until it is transported to the receiving facility.^{9,10} The SSL logistics model has been applied in several other biofuel feedstock delivery studies previously.^{11–15} This material may have different preprocessing steps to meet the required removal of foreign material, moisture content, and other specifications, which will ultimately be part of the logistics design. However, these preprocessing steps will not be part of this study, which ends with a stream of size-reduced material for continuous annual operation.

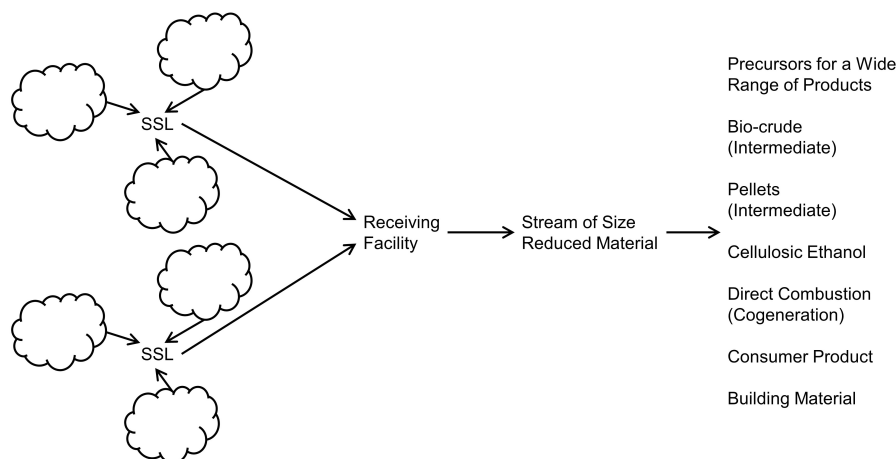


Figure 1. Supply chain for a feedstock delivery from fields to satellite storage locations (SSLs), and subsequent delivery to a receiving facility (either a depot or biorefinery).



This study assumed five feedstock depots that produce an intermediate product for ultimate delivery to a biorefinery producing some final product or a bulk precursor to some final product. The objectives of this study were: (1) to site the depots and a potential biorefinery based on suitable criteria; (2) to estimate the potential production of feedstock delivered to each depot; and (3) to calculate the costs to deliver feedstock to the depot and process it into a continuous stream of size-reduced material for 24/7 operation, 48 weeks per year.

Methodology

Study area

The depot sites were chosen from 34 potential biorefinery locations, defined as multi-county production zones, in the Piedmont province.⁵ The study area was chosen to encompass a region that has already undergone extensive research into the logistics for delivery of herbaceous feedstock from SSLs to a potential biorefinery centered in Gretna, Virginia.^{11,16} Three zones were selected from the south central Virginia Piedmont (VA5, VA6, VA7) and two zones were selected from the north central North Carolina Piedmont (NC2, NC3)⁵ (Fig. 2).

Criteria for locating depots and biorefinery site

For the purposes of this study, a cellulosic ethanol biorefinery location was chosen where the deliveries from the five depots would be received. The biorefinery was located with

convenient access to a four-lane highway and the site had an existing rail siding. Ideally, it would be collocated with one of the fuel blending depots in the region currently operated by Osage (Glen Allen, Virginia), a company that brings in rail tanker cars carrying ethanol from the Midwest and blends with gasoline for delivery to their customers.¹⁷

Many constraints have been used in the literature to define the feedstock supply radius (i.e., the distance between the production fields and a biorefinery). Gustafson *et al.*¹⁸ used a 161 km (100-mile) radius to define the supply of wheat straw and corn stover to a potential biorefinery. Holder *et al.*¹⁹ assumed an 80 km (50 mile) radius for corn feedstock biorefineries. Lynch and Satrio²⁰ used a 97 km (60 mile) radius to define the distance between switchgrass fields and a theoretical biorefinery. Thus, for this study, the five depots were located within a 97 km radius of the chosen biorefinery site.

A site for a potential biorefinery was selected near South Boston, Virginia (Fig. 3). A 97 km radius buffer was created around the biorefinery to select the sites for the five depots. The depots were placed near the center of each respective production zone (VA5, VA6, VA7, NC2, or NC3), at a location with open land cover and access to a primary or secondary road (Fig. 3).

Potential feedstock production available for the five depots

Potential switchgrass feedstock production was estimated from current land cover within a 48 km (30 mile) radius

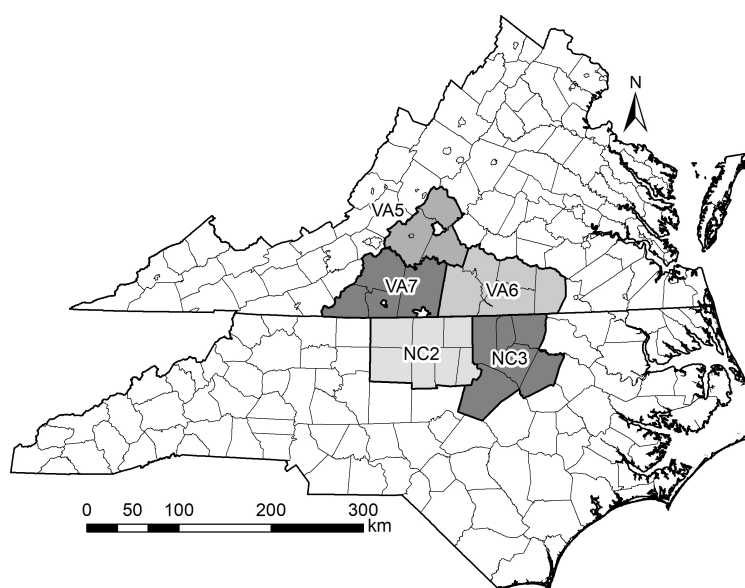


Figure 2. The proposed areas for the five theoretical depots used for this study based on multi-county production zones in the Piedmont, USA.

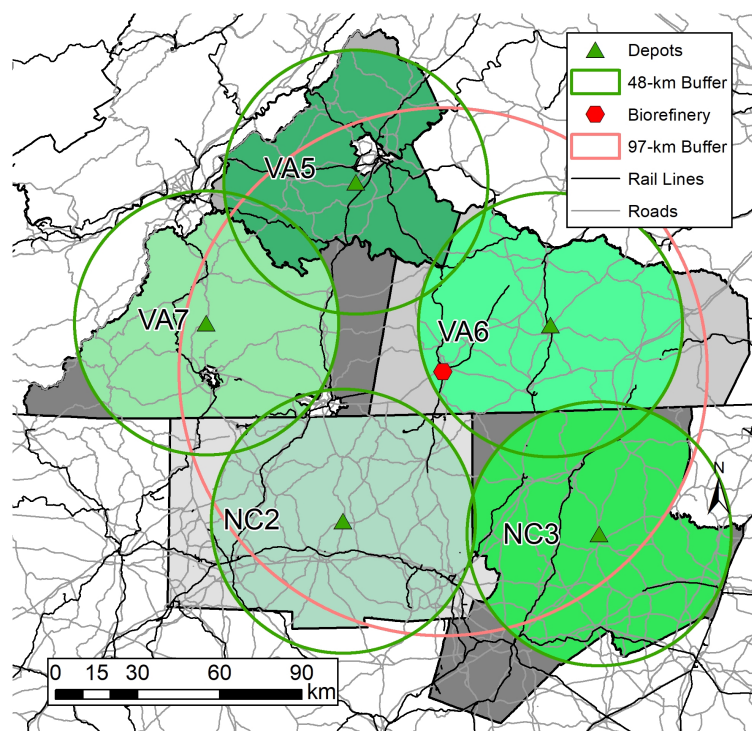


Figure 3. Sites selected for the theoretical biorefinery and five depots. The switchgrass feedstock production area for each depot was defined as the 48 km radius around each depot location.

Table 1. The total area and potential feedstock production based on the available land cover for each depot within a 48 km radius in each production zone.

Depot	Total area (ha)	Grassland and scrubland (ha)	Feedstock production (Mg)
VA5	437 895	30 077	80 607
VA6	561 864	63 572	170 372
VA7	509 820	37 683	100 989
NC2	641 175	30 224	81 000
NC3	648 182	45 681	122 425

around each depot, the same production area used by the Gretna study.^{11,16} The total area for each depot was defined as a 48 km buffer around each site (Fig. 3). These buffered areas were then clipped to the multi-county production zones, defined by Resop and Cundiff,⁵ so the production area for each depot did not overlap (Fig. 3). All spatial analyses and geoprocessing were performed using ArcGIS 10.6 (Redlands, CA, USA). The total area defined by each depot is shown in Table 1.

Current land cover was derived from the 2019 National Land Cover Database (NLCD).²¹ The NLCD is a widely used 30 m resolution land cover raster produced by the United

States Geological Survey and updated every few years. Land cover was divided into two classes based on their priority for attracting into herbaceous feedstock production: (A) high priority (scrubland and grassland, i.e., open land not currently used for agriculture) and (B) low priority (cropland and pastureland, i.e., land currently in agricultural production), similar to the land cover classes developed by Resop *et al.*¹¹ for the Gretna dataset using the 2006 NLCD. For this study, only one land cover scenario was considered, which assumed 40% of the available scrubland and grassland (i.e., high priority land) could be attracted into switchgrass production. This scenario was selected to represent a fairly conservative land-cover scenario, leaving more optimistic scenarios for future research.

The herbaceous feedstock was assumed to be switchgrass (*Panicum virgatum* L.), which is a perennial warm-season grass that has been shown to have significant potential as feedstock for a biorefinery.^{6,20} Switchgrass was also used to define the feedstock production database for the Gretna study.¹¹ The switchgrass feedstock was assumed to be harvested from fields and stored at SSLs in round bales with an average moisture content of 15%.¹¹ An average switchgrass yield of 6.7 Mg ha⁻¹ was assumed over the entire study area.²² The total annual production for each depot was calculated as:

$$Q_z = A_z \text{ yld} \quad (1)$$



where:

Q_z = the total annual production (Mg) for one of the five production zones z ;

A_z = the total feedstock production area (ha) within a 48-km radius around the depot within production zone z as defined by the land cover scenario;

yld = the average switchgrass yield across the entire zone (Mg ha^{-1}).

In each production zone, the total potential area was calculated based on the high priority land cover classes (i.e., scrubland and grassland). Figure 4 shows the potential feedstock density within each production zone, calculated in ArcGIS, using focal statistics on the available land cover to give a sense of the spatial variability of production within the study area. A 3.2 km (2 mile) radius was selected for estimating feedstock density because this distance was used to calculate the feedstock supply radius for each SSL in the Gretna study.¹¹

The land cover area, ranging from 30 077 to 63 572 ha, was multiplied by the percentage of the area expected to be attracted into switchgrass production (40%) and then multiplied by the assumed average switchgrass yield (6.7 Mg ha^{-1}) to estimate the annual production for each depot (Table 1). The potential annual production ranged

from 80 607 Mg (VA5) to 170 372 Mg (VA6), resulting in a total production of 555 393 Mg, which could potentially be delivered annually to a biorefinery.

Procedure for analysis of satellite storage location (SSL) databases

The database for each depot was assumed to contain 199 SSLs. The location of each SSL, relative to the depot location (i.e., the center of the 48 km radius), was defined in the Gretna database,¹¹ and used for all five depot databases in this study. A feedstock density multiplication factor (F_d) was defined as:

$$F_d = \frac{Q_z}{Q_b}$$

where:

Q_z = the total annual production (Mg) for one of the five production zones z (Table 1);

Q_b = the total annual production defined for the Gretna study (152 526 Mg).^{11,16}

The feedstock density multiplication factor was determined for each of the five depots (Table 2). The same SSL database developed for the Gretna study¹¹ was used for the five

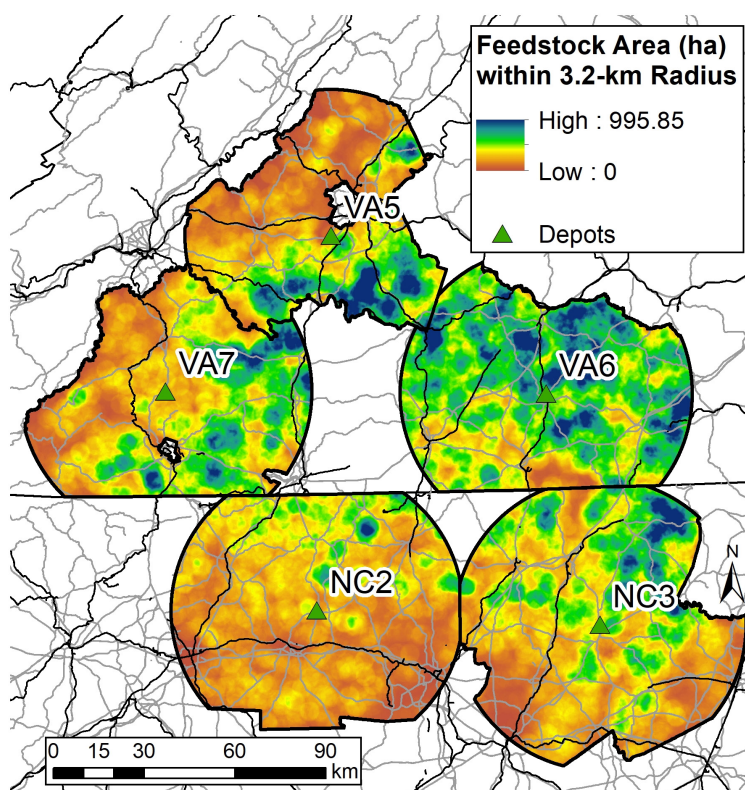


Figure 4. The potential feedstock density within each production zone based on areas identified from scrubland and grassland in the 2019 National Land Cover Database (NLCD).



Table 2. The feedstock density multiplication factor (F_d) for the five depots.

Depot	Feedstock density multiplication factor
VA5	0.53
VA6	1.12
VA7	0.66
NC2	0.53
NC3	0.80

databases in this study. The only change was the quantity of biomass harvested and stored at each SSL. These quantities were increased or decreased at each of the 199 SSLs in the Gretna database using the feedstock density factor defined above. Repeating this key point, the quantity stored at each SSL was changed, but the distribution of SSLs was unchanged. Ideally, one would use the distribution of potential feedstock (Fig. 4) to create a separate set of SSLs for each depot database based on the spatial variability of switchgrass fields, similar to the method used by Resop *et al.*¹¹ to create the Gretna database. For this study, the Gretna distribution of 199 SSLs was used to simplify the analysis. Future research could explore the impact that SSL distribution ultimately has on feedstock delivery costs, but it is expected that this uncertainty is not significant.

Resop *et al.*¹⁶ analyzed a set of 199 SSLs within a 48 km radius of the potential biorefinery and estimated the feedstock delivered to the biorefinery for each week in a 49 week annual operation. The same methodology was used for each of the five depot databases in this study, except the annual operation was 48, not 49 weeks. The procedure used to calculate the load-out and truck productivity for the delivery of round bales from the SSLs to a depot also used a different number of load-out operations operating simultaneously for each of the five depot databases. It was assumed that the hauling for load-out operations would consist of two 20-bale handling units per truck.¹⁵ Modern balers can produce 5×4 round bales of switchgrass, which weigh about 0.4 Mg, resulting in about 16 Mg per truckload.¹⁶

To obtain an estimate of the minimum number of load-out operations required to supply each depot, the following design constraints were used. The average expected load-out productivity was assumed to be 60 Mg day^{-1} , based on a previous study of load-out operations for the Gretna database.¹⁶ However, it is expected that the achieved productivity will vary from depot to depot depending on the number of load-out operations and the amount of feedstock in storage. The hauling season was assumed to occur over 45 weeks with six production days per week. The annual production of each load-out operation was estimated as:

$$60 \frac{\text{Mg}}{d} \left(6 \frac{d}{wk} \right) (45 wk) = 16,200 \text{ Mg} \quad (2)$$

For each depot, the total estimated feedstock production (Table 1) was divided by the annual production per load-out operation (16 200 Mg) to calculate the minimum number of load-outs.

The method for scheduling moves between SSLs in the load-out sequence was described by Resop *et al.*¹⁶ The time allowed for moves between SSLs was assumed to be constant (0.5 day per move). Continuous operation was used for the simulations, one simulation for each of the five depot databases. Each simulation was performed with a separate MATLAB program (Portola Valley, CA, USA). No delays due to weather, holidays, or major breakdowns were scheduled. These events were handled as 'contingency days'. For example, if the simulation predicts the load-out sequence for a load-out operation is completed in 45 weeks, then the contingency days for a 48-week season is $48 - 45 = 3$ weeks \times 6 days per week = 18 days, or an average of 0.4 day per week.

Results

Simulation results for SSL databases created for the five depots

The results for the load-out operations are given in Table 3. The key variable is the achieved average productivity over the

Table 3. Comparison of the achieved average load-out productivity results for the five depots.

Depot	Feedstock stored in SSLs (Mg)	Avg. SSL size (Mg)	No. load-outs	Load-out productivity (Mg day^{-1})	Contingency (days per week per load-out)
VA5	80 839	406.2	5	54.2	0.55
VA6	170 830	858.4	10	59.3	0.49
VA7	100 667	505.9	6	56.5	0.42
NC2	80 839	406.2	5	54.2	0.55
NC3	122 020	613.2	7	50.0	0.27

**Table 4. Comparison of the feedstock hauling results for the five depots.**

Depot	Total truck loads	Total mass hauled (Mg)	Clean up (%)
VA5	4878	78048	3.5
VA6	10 458	167 328	2.0
VA7	6102	97 632	3.0
NC2	4878	78048	3.5
NC3	7434	118944	2.5

48 week season. Generally, the depot with the lowest average size SSL had the lowest productivity. This is logical because there is more time required to move between SSLs to deliver the annual capacity. The ‘outlier’ is the NC3 depot where a productivity of only 50 Mg day⁻¹ was calculated, which is unexplained at this time. Note that the contingency for this depot was only 0.27 day per week per load-out, which is lower than the authors recommend.

Total loads hauled for each depot is given in Table 4. No partial loads were hauled, thus a few bales are typically left at the SSL when a load-out is completed. The feedstock contractor wants to sell all the feedstock they produce and put in storage, so the business plan envisions a ‘clean-up’ operation that will haul any remaining bales. The amount left for cleanup ranged from 2% to 3.5% of the total stored feedstock. Cost for this operation is not considered in this study.

Computation of feedstock delivery costs for the five depots

Load-out operation costs

The plan presented here envisions that one worker will work four 10 hour days, for example from Monday to Thursday, then a second operator will work Friday to Saturday and Monday and Tuesday of the next week, and this rotation will continue, to provide a 60 hour work week over the 48 week season.

The same equipment operation at the SSL (telehandler and bale loader) used by Resop *et al.*,¹⁶ was used for this study. The telehandler was estimated to operate 1852 hours per year of the total 10 hours per day × 6 days per week × 48 weeks per year = 2880 hours per year of load-out operation. This means the equipment operates, on average, for 64.3% of each operating day. Telehandler cost (21.19 USD hour⁻¹) and bale loader cost (10.34 USD hour⁻¹) were the same as the costs calculated in Resop *et al.*¹⁶ For this study, labor cost for the load-out worker was assumed to be 25 USD hour⁻¹ with 25% benefits, thus the labor cost was 25 (1 + 0.25) = 31.25 USD hour⁻¹. The load-out cost per operating day was determined as:

$$C_{lo} = [C_{theq}(0.643) + C_{bleq}(0.643) + L_{lo}] \left(10 \frac{h}{d}\right) \quad (3)$$

where:

C_{lo} = total cost for load-out operations at SSL (USD day⁻¹);

C_{theq} = telehandler equipment cost (USD hour⁻¹);

C_{bleq} = bale loader equipment cost (USD hour⁻¹);

L_{lo} = labor cost for load-out worker (USD hour⁻¹).

Load-out worker travel reimbursement

It is specified that the load-out worker provides their own transportation and reports for work to the SSL being unloaded that day. (This is the procedure used for construction workers who report to construction sites to begin work.)

Reimbursement for the worker’s transportation was computed as follows. The total payment to a specific load-out worker (USD) was calculated for a round trip each day to the SSL being unloaded that day (j th SSL). The distance was measured from the base (i.e., the depot) to the SSL, thus it was the same as the haul distance in the database. A column matrix was defined for the sequence of SSLs unloaded by each load-out. Load-out 1 is shown as an example. The number of rows in this matrix is n_j , the number of SSLs unloaded. The column matrix, $jlo1(i)$, was defined by the load-out sequence for Load-out 1, and so forth for all load-outs in the dataset. The total annual travel payment (USD) for a worker at Load-out 1 was calculated as:

$$C_{trl(1)} = \sum_{i=1}^{n_j} [j = jlo1(i)] n_{day_j} (2hd_j) T_f \quad (4)$$

where:

n_{day_j} = number of unload days for j th SSL;

hd_j = haul distance (km) for j th SSL;

T_f = travel payment parameter = 0.364 USD km⁻¹.

The total travel payment for each load-out worker was calculated in like manner. Dividing the total travel payment by the mass of all loads hauled by the individual load-out gives the load-out worker’s travel cost per Mg hauled. This was calculated for all load-outs supplying the five depots. The costs for the service truck (used to support the load-out operations) and equipment hauler (used to move equipment between SSLs) were calculated using the procedures defined by Resop *et al.*¹⁶ (Table 5). The ‘SSL Operations’ cost (USD Mg⁻¹) was obtained by dividing the USD day⁻¹ cost (equipment and labor) by the achieved average productivity (Mg day⁻¹) (Table 3).

Truck costs

The ideal truck cycle time (T_i) was calculated based on the following assumptions:

**Table 5. Comparison of the annual load-out operation costs (in USD Mg⁻¹) for the five depots.**

Depot	SSL operations	SSL worker travel	Service truck	Equipment hauler	Total
VA5	7.37	0.49	2.72	0.74	11.32
VA6	6.98	0.46	2.47	0.35	10.26
VA7	7.10	0.48	2.58	0.58	11.04
NC2	7.37	0.49	2.72	0.74	11.32
NC3	6.84	0.48	2.27	0.48	10.07

1. Load time was defined as the total time to unhook a trailer set with empty racks and hook a trailer set with full racks at the SSL. For this study, the 'load time' averaged 15 min.
2. Unload time was defined as the time to weigh in a truck at the receiving facility, sample for quality, lift off full racks from the trailer set and replace them with empty racks, and then weigh out. For this study, the 'unload time' averaged 20 min.
3. Travel speed over rural roads averaged 70 km hour⁻¹.

A multiplier of 1.4 was used to obtain truck *achieved* average cycle time (T_a), defined as:

$$T_a = 1.4 T_i \quad (5)$$

This multiplier accounted for delays in loading (*e.g.*, waiting at SSL) and unloading (*e.g.*, waiting at receiving facility), plus delays due to traffic (particularly for travel through towns). This is an ambitious achieved cycle time, but it does lead to a 'baseline' truck fleet size.

The truck cost included three categories: truck tractor rental, driver labor, and fuel. As defined by Resop *et al.*,¹⁶ the truck fleet operation and productivity was assumed to be the responsibility of a Feedstock Manager at the biorefinery. All maintenance for the truck tractors was covered by the rental contract. No cost was included for insurance or for a fueling station at the biorefinery. The cost of the racks and rack trailers was not included in the truck cost, but was added later.

The current rental cost for a single-drive-axle, pintle-hitch truck tractor is 845 USD week⁻¹, thus the annual rental cost for a 48-week season was calculated as:

$$845 \frac{\text{USD}}{\text{week}} \left(48 \frac{\text{weeks}}{\text{year}} \right) = 40\,560 \frac{\text{USD}}{\text{year}} \quad (6)$$

The labor cost for an operator, including benefits, was assumed to be 31.25 USD hour⁻¹. A shift-work plan must be used to operate a 12 hour haul day, 6 days per week. The annual labor cost for a 48 week season with six 12 hour workdays each week was calculated as 108 000 USD per truck per year.

Table 6. Comparison of the truck costs (in USD Mg⁻¹) for the five depots.

Depot	No. trucks	Rental cost	Labor	Fuel	Total
VA5	5	2.51	6.68	3.82	13.01
VA6	11	2.61	6.95	3.82	13.38
VA7	7	2.82	7.51	3.83	14.16
NC2	5	2.51	6.68	3.82	13.01
NC3	8	2.60	7.08	3.84	13.52

The only cost component that varies with annual use is the fuel cost. The total fuel cost (based on 1.7 km L⁻¹ consumption, at 1.31 USD L⁻¹) was calculated as:

$$FC = \frac{T_{hd}}{1.7 \frac{\text{km}}{\text{L}}} \left(1.3 \frac{\text{USD}}{\text{L}} \right) \quad (7)$$

where:

FC = fuel cost (USD);

T_{hd} = total haul distance for annual operation of truck fleet (km).

Total truck cost is given Table 6. It is interesting that labor is about 50% of the total, and fuel is about 30%. The same distribution of feedstock across the production area was used for all depots, so the fuel cost (USD Mg⁻¹) was approximately the same.

Receiving facility costs

The design parameters for the five depots are given in Table 7. The designation '2 day, 1 night' in the forklift column denotes that two forklifts operate during the 12 hour haul day, 6 days per week and one forklift operates 24/7 to insure the biorefinery has a continuous supply of bales. The forklifts were used to capacity for the VA6 depot (170 830 Mg year⁻¹), but were not used to full capacity for the smaller depots. Another key parameter is the number of rack unloaders. One unloader had the capacity required for all depots except VA6; two were specified for this depot. It is not good design procedure to have only one rack unloader. If this equipment is out of service, there is no way to supply bales to the size

**Table 7. Design parameters for the logistics system required for the five depots.**

Depot	No. racks	No. rack trailers	No. forklifts at receiving facility	Storage area at receiving facility (m ²)	No. rack unloaders
VA5	61	10	2 day, 1 night	6290	1
VA6	133	21	2 day, 1 night	8930	2
VA7	75	13	2 day, 1 night	6805	1
NC2	61	10	2 day, 1 night	6290	1
NC3	88	15	2 day, 1 night	7275	1

Table 8. Cost estimates (in USD Mg⁻¹) for equipment and facilities required for the five depots.

Depot	Racks	Rack trailers	Receiving facility forklifts	Operating and rack storage area	Rack unloader
VA5	3.17	3.08	8.15	0.58	1.46
VA6	3.28	3.07	3.86	0.35	1.38
VA7	3.13	3.12	6.55	0.45	1.17
NC2	3.17	3.08	8.15	0.58	1.46
NC3	3.03	3.08	5.40	0.41	0.97

reduction operation and production stops. It is likely that two unloaders would be specified even though their full capacity is not utilized.

The cost procedures given by Grisso²³ were used to obtain the cost estimates for each of the five depots (Table 8) based on the design parameters defined in Table 7.

Debaling size-reduction costs

For this study, a 'debaler' was defined as a machine which removes the net and shears the bale in half for delivery into an initial size reduction operation. A prototype machine for debaling round bales was developed by Vermeer (Pella, IA, USA)²⁴ and estimated operation parameters for this machine are used here to calculate cost. The unit was assumed to be powered with a 37 kW (50 hp) electric motor. Cost to own and operate the debaler is given in Appendix A.

Initial size reduction was performed with a horizontal grinder powered with two 224 kW (300 hp) electric motors. Cost to own and operate the horizontal grinder is given in Appendix B.

It was estimated that a crew of two would be required to operate the rack unloader, debaler, and size reduction. (This assumption presumes expected automation of the various machines.) The labor allocation was 25% for the rack unloader, 25% for the debaler, and 50% for the horizontal grinder. Annual cost to operate the debaler and horizontal grinder (24/7, 48 weeks per year) was 294 262 USD and 1 491 634 USD, respectively. The costs on a per Mg annual capacity for each depot are given in Table 9. These results illustrate a key issue in receiving facility design. The most

Table 9. Cost estimates (in USD Mg⁻¹) for debaling and size reduction at the five depots.

Depot	Debaler	Size reduction
VA5	3.64	18.45
VA6	1.72	8.73
VA7	2.92	14.82
NC2	3.64	18.45
NC3	2.41	12.22

cost-effective operation can be achieved when the equipment is operated near 80% of design capacity.

Total cost to produce a stream of size-reduced material at depot for 24/7 operation

The total cost to produce a continuous stream of size-reduced material at the five depots is given in Table 10. The difference in SSL operation costs and truck costs was slight across the annual capacity range for these five depots. This suggests that these two operations can be organized for efficient logistics over the given capacity range (at least 2 to 1) within a 48 km radius.

The key issues in the total cost are the receiving facility and debaling-size-reduction costs. Here the per-Mg cost is dependent on operation of equipment as close to the design capacity as possible. Two examples are:

1. The design must use an integer number of forklifts at the receiving facility. If one forklift cannot unload trucks and supply the rack unloader at the production

**Table 10. Total cost (in USD Mg⁻¹) to produce a continuous stream of material at the five depots.**

Depot	SSL operations	Truck	Receiving facility	Debaling-size-reduction	Total
VA5	11.32	13.01	16.44	22.09	62.86
VA6	10.26	13.38	11.94	10.45	46.03
VA7	11.04	14.16	14.42	17.75	57.37
NC2	11.32	13.01	16.44	22.09	62.86
NC3	10.07	13.54	12.89	14.63	51.13

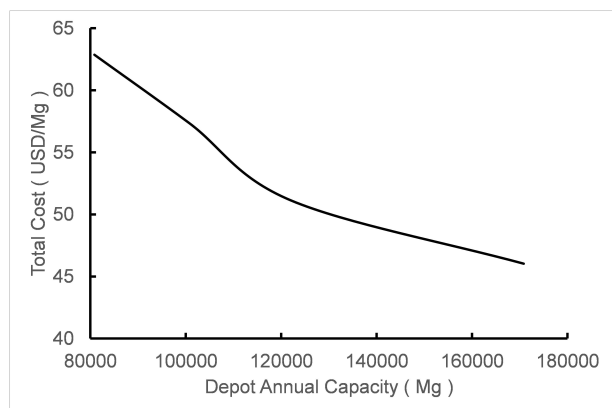


Figure 5. Total cost (in USD Mg⁻¹) as a function of depot annual capacity (in Mg).

rate required, then two must be used, even though the second will be operated at less than full capacity.

2. A debaler is required for all five depots. The capacity of the Vermeer prototype is 1.3 bales min⁻¹, and the required capacity ranges from 0.4 bales min⁻¹ (32% design capacity) for the VA5 depot, to 0.9 bales min⁻¹ (70% of design capacity) for the VA6 depot. The approximate cost to own and operate the debaler for 48 weeks of operation is the same for all five depots, thus the per-Mg cost is higher for the smaller depots.

The total cost (USD Mg⁻¹) calculated for each depot as a function of annual depot capacity (Mg) is plotted in Fig. 5. A cost reduction per Mg as depot annual capacity increases was expected. However, the rate of this decrease was more than expected.

Conclusions

This study calculated the cost to produce a continuous stream of size-reduced herbaceous biomass (i.e., switchgrass) for five depots in the Piedmont, USA. Based on previous research, which defined a series of multi-county production zones in the Piedmont province,⁵ three of the depots (VA5, VA6, VA7) were in Virginia and two were in

North Carolina. Annual capacity ranged from 80 839 Mg (VA5) to 170 830 Mg (VA6). The five depots have a total annual production of 555 195 Mg, which could be delivered to a biorefinery for producing a product, such as cellulosic ethanol, or some other product requiring an herbaceous feedstock. A logistics system with a 20-bale handling unit was used for load-out operations at 199 satellite storage locations (SSLs) within a 48 km radius of each depot location. The distribution of potential switchgrass production fields around each depot was determined based on the density of scrubland and grassland from the 2019 NLCD. Cost to deliver feedstock for 24/7 operation, 48 weeks per year ranged from 62.86 USD Mg⁻¹ annual capacity (VA5) to 46.03 USD Mg⁻¹ (VA6). For the VA6 depot these costs were SSL operation (22%), truck (29%), receiving facility (26%), and debaling-size reduction (23%).

The following conclusions are offered for the depot capacity range studied here, nominally 80 000 to 170 000 Mg year⁻¹:

1. The load-out and truck costs were approximately constant on a per-Mg annual basis.
2. The two significant economy-of-scale factors were receiving facility and debaling-size reduction. The depots should be sized such that the available equipment can be operated as close as possible (~80%) to design capacity to give the lowest cost on a per-Mg basis.

References

1. Hess JR, Kenney KL, Ovard LP, Searcy EM and Wright CT, Commodity-scale production of an infrastructure-compatible bulk solid from herbaceous lignocellulosic biomass. *Idaho National Laboratory, Idaho Falls, ID* 6:163 (2009).
2. Hess JR, Wright CT, Kenney KL and Searcy EM, Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass – Executive Summary Idaho National Lab. (INL), Idaho Falls, ID (United States); 2009 Apr [cited 2022 May 20]. Report No.: INL/EXT-09-15423 <https://www.osti.gov/biblio/971374>. Available from:
3. Ramsey S. USDA ERS-U.S. Bioenergy Statistics, U.S. Statistics (2023 Available from). <https://www.ers.usda.gov/data-products/u-s-bioenergy-statistics/>.



4. O'Brien D and Suszkiw J, Finding the right biofuels for the southeast: a range of alternatives. *Agric Res* **60**:10 (2012).
5. Resop JP and Cundiff JS, Assessment of herbaceous feedstock supply for locating biorefineries in the Piedmont, USA. *Biofuels Bioprod Biorefin* **16**:43–53 (2022).
6. Fike JH, Parrish DJ, Wolf DD, Balasko JA, Green JT, Rasnake M *et al.*, Long-term yield potential of switchgrass-for-biofuel systems. *Biomass Bioenergy* **30**:198–206 (2006).
7. Lamers P, Tan ECD, Searcy EM, Scarlata CJ, Cafferty KG and Jacobson JJ, Strategic supply system design – a holistic evaluation of operational and production cost for a biorefinery supply chain. *Biofuels Bioprod Biorefin* **9**:648–660 (2015).
8. Toba AL, Paudel R, Lin Y, Mendadhala RV and Hartley DS, Integrated land suitability assessment for depots siting in a sustainable biomass supply chain. *Sensors* **23**:2421 (2023).
9. Cundiff JS, Grisso RD and Judd J, Operations at satellite storage locations (SSL) to deliver round bales to a biorefinery plant. *ASABE* **2009**:1 (2009 Reno, Nevada, June 21–June 24, 2009).
10. Brownell DK and Liu J, Managing biomass feedstocks: selection of satellite storage locations for different harvesting systems. *Agric Eng Int: CIGR J* **14**:74–81 (2012).
11. Resop JP, Cundiff JS and Heatwole CD, Spatial analysis to site satellite storage locations for herbaceous biomass in the piedmont of the southeast. *Appl Eng Agric* **27**:25–32 (2011).
12. Judd JD, Sarin SC and Cundiff JS, Design, modeling, and analysis of a feedstock logistics system. *Bioresour Technol* **103**:209–218 (2012).
13. Grisso RD, McCullough D, Cundiff JS and Judd JD, Harvest schedule to fill storage for year-round delivery of grasses to biorefinery. *Biomass Bioenergy* **55**:331–338 (2013).
14. An H, Optimal daily scheduling of mobile machines to transport cellulosic biomass from satellite storage locations to a bioenergy plant. *Appl Energy* **236**:231–243 (2019).
15. Grisso RD, Cundiff JS and Comer K, Multi-bale handling unit for efficient logistics. *AgriEngineering* **2**:336–349 (2020).
16. Resop JP, Cundiff JS and Grisso RD, Central control for optimized herbaceous feedstock delivery to a biorefinery from satellite storage locations. *AgriEngineering* **4**:544–565 (2022).
17. Osage. 2023. Available from: <https://www.osageinc.net/>
18. Gustafson C, Maung T, Saxowsky D, Nowatzki J and Miljkovic T, Economics of Sourcing Cellulosic Feedstock for Energy Production (2011).
19. Holder CT, Cleland JC, LeDuc SD, Andereck Z, Hogan C and Martin KM, Generating a geospatial database of U.S. regional feedstock production for use in evaluating the environmental footprint of biofuels. *J Air Waste Manage Assoc* **66**:356–365 (2016).
20. Lynch MN and Satrio JA, Utilization of grassy biomass grown in heavy-metal contaminated soil as feedstock for bioenergy production—an LCA study. *IOP Conf Ser: Earth Environ Sci* **1034**:12022 (2022).
21. Dewitz J and National Land Cover Database (NLCD), Products (2019). US Geological Survey 2021.
22. Fike JH, Pease JW, Owens VN, Farris RL, Hansen JL, Heaton EA *et al.*, Switchgrass nitrogen response and estimated production costs on diverse sites. *GCB Bioenergy* **9**:1526–1542 (2017).
23. Grisso RD, Cundiff JS and Sarin SC, Rapid truck loading for efficient feedstock logistics. *AgriEngineering* **3**:158–167 (2021).
24. Vermeer. 2023. Available from: <https://www.vermeer.com/na>

**Jonathan P. Resop**

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**John S. Cundiff**

John S. Cundiff was elected a Fellow in the American Society of Agricultural and Biological Engineers in 2000. Upon his retirement, he was appointed professor emeritus of biological systems engineering at Virginia Tech in 2010. Since that time, he has continued to publish studies to advance opportunities for development of a biorefinery industry in the Piedmont.

Appendix A

Cost to Operate Debaler

Vermeer built a prototype debaler and conducted tests processing over 40 000 bales. A 'second evolution' prototype was designed but not built. The purchase price used here is the estimated cost for a production machine. The hydraulics are powered with a 50 hp (37 kW) electric motor.

- Purchase price (PP): 330 000 USD
- Design life: 25 000 h
- Interest rate: 6.25% ($r=0.0625$)
- Insurance rate: 0.80 USD per 100 USD value per year

$$\frac{330\,000}{100} (0.80) = 2\,640 \text{ USD / year}$$

Annual hours of operation (assuming 24/7 operation for 48 weeks per year) are defined as:

$$24 \text{ hours / day (7 days / week) (46 weeks / year) = 8\,064 \text{ hours / year}$$

The lifespan of a single debaler can be calculated as:

$$n = \frac{25\,000 \text{ hours}}{8\,064 \text{ hours / year}} = 3.1 \text{ years}$$



- Tax rate: 1%
- Repair and maintenance factor (R/M): 3.00 USD hour⁻¹
- Labor cost (including benefits): 31.25 USD hour⁻¹

The cost recovery factor (CRF) is defined as:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

where:

r = interest rate (decimal percent);

n = design life (year).

$$CRF = \frac{0.0625(1+0.0625)^{3.1}}{(1+0.0625)^{3.1} - 1} = 0.365$$

The rack unloader is powered with a 37 kW (50 hp) electric motor. The cost to purchase and install this motor with needed infrastructure and controls is 15 000 USD.

The maximum power consumption is for operation of the shear. Shear operation is less than 20% of the total operating time. Energy use, assuming a power factor of 50%, is estimated as:

$$37 \text{ kW} (8\ 064 \text{ h}) (0.50) = 149\ 184 \text{ kWh/year}$$

The annual ownership cost for a debaler and electric motor is calculated as:

$$\text{cost recovery} + \text{insurance} + \text{taxes} = \text{ownership} \\ (330\ 000 + 15\ 000) (0.365 + 0.008 + 0.01) = 132\ 135 \text{ USD/year}$$

It is assumed that two operators operate the rack unloader, debaler, and grinder. For this analysis, 25% of the operator time is allocated to the debaler. The energy cost is \$0.08 kWh⁻¹. The annual operating cost is calculated as:

$$\text{maintenance} + \text{energy} + \text{labor} = \text{operating} \\ 3.00 (8064) + 149\ 184 (0.08) + 31.25 (8064) (2) (0.25) = \\ 24\ 192 + 11\ 935 + 126\ 000 = 162\ 127 \text{ USD/year.}$$

The total annual cost is calculated from the ownership cost and operating cost as:

$$\text{ownership} + \text{operating} = \text{total} \\ 132\ 135 + 162\ 127 = 294\ 262 \text{ USD/year.}$$

Appendix B

Cost to Operate Horizontal Grinder

The chosen machine is a Vermeer Model HG6000E horizontal grinder. This machine is most often used to grind wood; however there are applications where it is used to grind

herbaceous biomass. It has two 300 hp (224 kW) electric motors.

- Purchase price: 723 257 USD
- Design life: 25 000 h
- Interest rate: 6.25% ($r = 0.0625$)
- Insurance rate: 0.80 USD per 100 USD value per year

$$\frac{723\ 257}{100} (0.80) = 5\ 786 \text{ USD/year}$$

- Tax rate: 1%
- Repair and maintenance factor (R/M): 90 USD hour⁻¹
- Labor cost (including benefits): 31.25 USD hour⁻¹

Assuming there are two workers operating the rack unloader, debaler, and horizontal grinder, the labor cost for these workers is allocated as: 25% rack unloader, 25% debaler, and 50% grinder.

Cost recovery factor:

where:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

r = interest rate (decimal percent);

n = design life (year).

Annual hours of operation (assuming 24/7 operation for 48 weeks per year) is defined as:

The design life of a single grinder can be calculated as:

$$24 \text{ hours/day} (7 \text{ days/week}) (46 \text{ weeks/year}) = 8\ 064 \text{ hours/year.}$$

The grinder is powered with two electric motor. The cost to

$$n = \frac{25\ 000 \text{ hours}}{8\ 064 \text{ hours/year}} = 3.1 \text{ years}$$

$$CRF = \frac{0.0625(1+0.0625)^{3.1}}{(1+0.0625)^{3.1} - 1} = 0.365$$

purchase and install the electric power infrastructure is estimated at 15 000 USD.

Annual energy use, assuming a power factor of 80% for continuous operation is calculated as:

$$224 \text{ kW/motor} (2 \text{ motors}) (8\ 064 \text{ hours}) (0.80) \\ = 2\ 890\ 140 \text{ kWh/year.}$$

The annual ownership cost for a rack unloader and electric motor is calculated as:

$$\text{cost recovery} + \text{insurance} + \text{taxes} = \text{ownership} \\ (723\ 257 + 15\ 000) (0.365 + 0.008 + 0.01) = 282\ 753 \text{ USD/year}$$



The annual operating cost, assuming an energy cost of \$0.08 per kW-h, is calculated as:

$$\begin{aligned} \text{maintenance} + \text{energy} + \text{labor} &= \text{operating} \\ 90 (8064) + 2890140 (0.08) + 31.25 (8064) (2) (0.5) &= \\ 725760 + 231212 + 252000 &= 1208881 \text{ USD/year} \end{aligned}$$

The total annual cost is calculated from the ownership cost and operating cost as:

$$\begin{aligned} \text{ownership} + \text{operating} &= \text{total} \\ 282753 + 1208881 &= 1491634 \text{ USD/year} \end{aligned}$$