# In-field operations to deliver biomass to a biorefinery

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**Abstract:** This study shows how “Satellite Storage Locations” (SSLs) can be sized and located to balance in-field hauling cost to the SSL and load-haul cost from the SSL to a biorefinery. This analysis used an in-field bale wagon to deliver bales of switchgrass to the SSL and year-round hauling from SSLs to a biorefinery with commercial equipment. An average productivity of 12 Mg $h^{-1}$ was assumed for the in-field bale wagon. Based on average operating time to haul bales from a 16 ha field, the allowable in-field to SSL haul distance was 3.2 km. The mobilization cost to move equipment to the SSL for commercial load and haul operations is a factor in minimizing total cost, in-field hauling plus highway hauling. Analysis showed that mobilization cost is not as important as limiting in-field hauling cost. This result suggests that a large number of smaller SSLs may be the desired organization as compared to a fewer number of larger SSLs.

**Keywords:** biomass, biorefinery, switchgrass, biomass logistics, in-field hauling, hauling costs, satellite storage locations

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## 1 Introduction

Distributed storage is needed for year-round delivery of herbaceous biomass. In the Southeastern USA (SE), forest biomass is harvested all 12 months. Forest biomass is “stored on the stump,” meaning it is left in the forest until it is needed and then harvested and shipped directly. Even with delayed harvest of a perennial grass, which is practical in the SE, it is possible to harvest only part of the year, thus, some material must be stored up to six months.

Due to the large volume of materials to be handled and stored, biomass storage will most likely occur at an intermediate location between the farm gate and the plant utilizing the biomass. These storage systems have been proposed under various names (Brownell and Liu, 2012). Distributed storage in Kansas is called “Satellite Depot Locations” (large square bales of corn stover) and “Roadside Storage” in Idaho (large square bales of wheat straw). In the SE (Cundiff and Grisso, 2008), the term used is “Satellite Storage Locations” (SSLs). The system uses in-field hauling equipment to deliver round bales of switchgrass to the SSL. A SSL is defined as a graveled storage yard with suitable public highway access for year-round hauling with tractor-trailer trucks.

The situation in the SE is unique because the “in-field hauling” will unavoidably require some travel on public highways. Few large fields are available, thus biomass from numerous small fields must be accumulated at an SSL. This means the equipment used to haul bales from the field must typically travel on public highways. Certain areas of the SE have land that cannot produce grain cost competitively, and this land has the highest potential for switchgrass production. It is characterized by relatively small, irregular-shaped fields on rolling terrain (Cundiff et al., 2009). Biomass from a number of these fields will need to be accumulated at a given SSL. The question becomes, what is the optimum size and/or spacing of the SSLs?

It is expected that landowners will be offered a “farm-gate” contract to supply biomass to the biorefinery. This contract will cover production (all costs associated with establishing and maintaining a stand of switchgrass),

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harvest (mowing, raking, baling and in-field hauling to an SSL), and storage (contract will pay cost to establish and maintain an SSL on the contract holder's land). It is expected that all farm-gate contracts receive the same compensation based on mass delivered to the SSL. The biorefinery can now reach out to the radius required to accumulate biomass needed to achieve their desired economy-of-scale processing cost. The increase in average highway hauling cost to gather the biomass from the larger production area is borne by the biorefinery. Thus, no contract holder is disadvantaged---all are treated equally.

If a "large SSL" option is chosen, farmers will harvest a larger number of fields and accumulate the biomass at the large SSL. This will require the in-field hauling cycle time to be longer for the fields further from this location; consequently, the equipment will move fewer Mg $h^{-1}$, and the cost ($ $Mg^{-1}$) will be higher.

On the other hand, a distribution of smaller SSLs may mean that load-haul costs will be higher for the biorefinery. The hauling contractor must move equipment from SSL to SSL, and the time lost in moving equipment reduces overall productivity (lower average Mg $h^{-1}$ for the SSL load-out operation).

The biorefinery is interested in the total delivered cost (farm-gate contract + load-haul contract) of the biomass. Thus, the biorefinery, using their contacts with both parties, will organize the biomass operations to achieve the minimum delivered cost.

The SSL optimization problem can be visualized using the database shown in Figure 1. This database was developed by using aerial photographs to determine land use within a 48-km radius of Gretna, VA. Fields with the highest probability for switchgrass production were identified and the 199 SSLs shown in Figure 1 (green crosses) were positioned such that each production field was less than 3.2 km from an SSL.

Judd et al. (2012) investigated two SSL crew operations, "stationary" and "mobile." The "stationary" option envisioned that an SSL would be a permanent location that would function like a "buying point" used in forest biomass logistics systems. Farmers would deliver biomass to this location where the biomass is stored and transshipped to the biorefinery. With the "mobile" option, load-out equipment is moved from SSL to SSL, and Judd et al. (2012) found this option to be more cost effective than the "stationary" option.

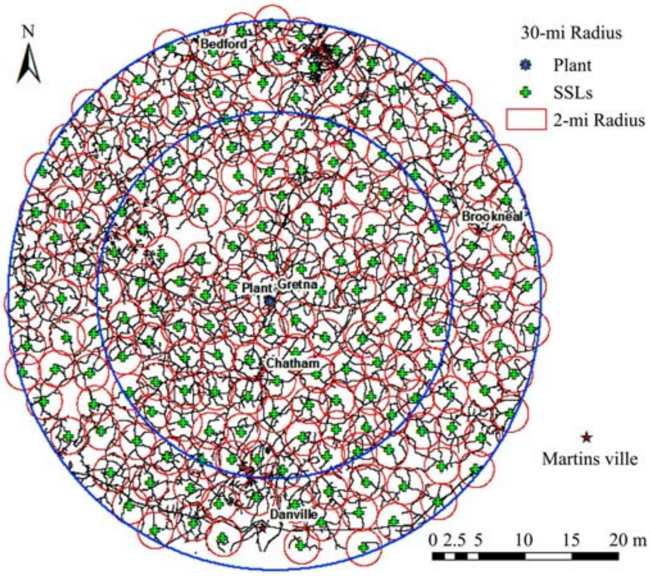


Figure 1 Concept showing SSLs located within 3.2 km of a production field

Conceptually, Figure 1 envisions that an individual SSL will be filled at given intervals by the farm-gate contractor and emptied by a hauling contractor moving in equipment and loading out all bales before moving to the next SSL. The concept envisions (Judd et al., 2012) that the loading equipment is a telehandler with special attachment to pickup two bales and insert them into a rack which remains attached to the trailer (Figure 2). Extra trailers are positioned at an SSL such that the SSL load-out crews do not wait for a truck to arrive, and the trucks do not wait to be loaded. A truck with empty trailers (racks) arrives, unhitches from the empty trailers, and then hitches to the loaded trailers that are waiting to be delivered to the biorefinery.

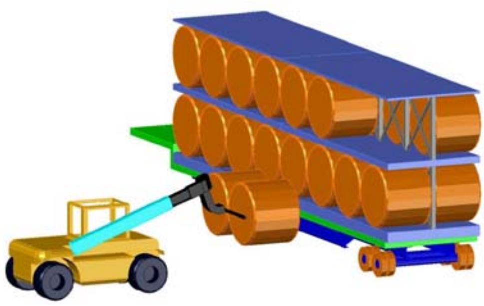

Figure 2 Concept showing rack being loaded at an SSL

The objective of this study is to show how "Satellite Storage Locations" (SSLs) can be evaluated based on in-field hauling cost to a SSL and load/hauling from a SSL to a biorefinery. The system uses a bale wagon to deliver round bales of switchgrass from the production field to the SSL and year-round hauling from the SSLs to a biorefinery using commercial delivery.

## 2 Materials and methods

### 2.1 In-field hauling

Typical unit operations used for hay harvest, in-field handling of round bales produced as livestock feed, is quite labor intensive. A farmer will carry one bale on a spear mounted on a front-end loader and a second bale on a spear on the rear 3-point hitch of their tractor. The bales are often placed in single-layer ambient storage convenient to the feeding operation. Mass moved per hour (labor and equipment productivity) is low, and the system is impractical for hauling on the highway.

A second option uses a front-end loader to load individual bales on a trailer typically pulled behind a pickup truck. The bales are unloaded individually at the storage location. This method also has low productivity, and thus is not practical for an industrial operation.

The in-field hauling option used for this study is a hypothesized system that builds on a concept first introduced in the early 1980s. The 1982 machine shown in Figure 3 self-loads eight 1.5-m diameter round bales, hauls to a location, and self-unloads (Figure 4). A modern design of this machine is hypothesized for in-field hauling of a bioenergy feedstock. This hypothesized machine will haul ten 1.2-m diameter bales. The operating parameters for the bale wagon were based in-part on data collected by New Holland [now Case New Holland (CNH)]. The operating parameters given in Table 1 were used to calculate an hourly operating cost as shown in Cundiff (2008). Estimated cost to operate this machine is \$47.60 $h^{-1}$.

Figure 3 In-field bale wagon self-loading round bales

Figure 4 In-field bale wagon self-unloading round bales

**Table 1 Operating parameters for in-field bale wagon**

| Operating parameters | Value |
|---|---|
| Purchase price | \$115,000 |
| Design life | 9,000 h |
| Annual use | 400 h $y^{-1}$ |
| Fuel (diesel) use | 3 gal $h^{-1}$ |
| Repair and maintenance factors | ASABE D497 (estimated)<br>RF1 = 0.0044; RF2 = 2.0 |
| Labor cost (including benefits) | \$20 $h^{-1}$ |

#### 2.1.1 Simulation of in-field hauling

To determine the influence of in-field hauling cost on SSL spacing, it was expedient to simulate the in-field hauling from a representative field. A 16 ha field was defined with a fairly uniform distribution of 400-kg bales (Figure 5). If the yield averaged 9 Mg $ha^{-1}$, the field would produce 356 bales, which was rounded up to 360 bales for the simulation. Each in-field load consists of 10 bales, thus the bale wagon must haul 36 loads to the SSL to remove all biomass.

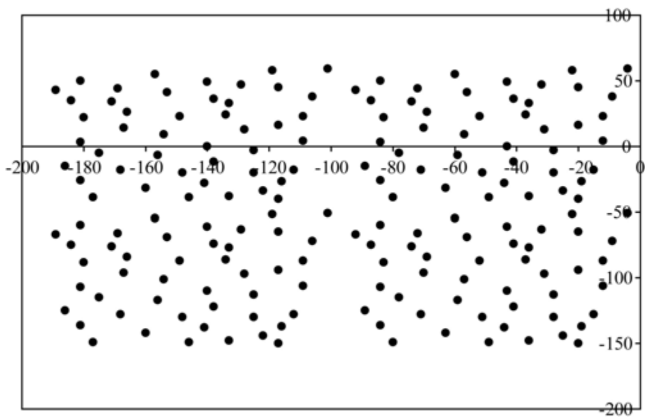


Figure 5 Distribution of bales in 16 ha field (Grid has origin at entrance to the field and the grid divisions are in m)

The following assumptions were made for the loading operation of the in-field bale wagon:

- An average of 30 sec to load a bale, which includes maneuvering the wagon into position and loading the bale.
- In-field speed between bales was 6.7 km $h^{-1}$, however this is optimistic and may be difficult to achieve in irregular-shaped fields on rolling terrain.

Cycle time is defined by:

$$C_t = t_{L10} + 2\ t_t + t_{U10} \quad (1)$$

where, $C_t$ = cycle time, h; $t_{L10}$ = time to load 10 bales, h; $t_t$ = time to travel to SSL, h; and $t_{U10}$ = time to unload 10 bales, h.

Time to travel to the SSL ($t_t$) was calculated using a highway speed of 50 km $h^{-1}$. Time to unload ($t_U$) was the time to back the machine into position at the SSL and unload. It was assumed to be a uniform time (2 min = 0.033 h).

A MATLAB program (Grisso et al., 2012) was used to calculate load time ($t_L$). As shown in Figure 5, a grid with the origin at the field entrance was established and an x-vector and y-vector was created containing the ($x$, $y$) coordinates of every bale. A distance matrix was defined:

$$d_{ij} = [(x_i - x_j)^2 + (y_i - y_j)^2]^{1/2} \quad (2)$$

where, $d_{ij}$ = distance (m) from bale i to bale $j$.

A loading sequence was established for the first 10 bales. The operator selected the 10 bales located closest to the field entrance that could be loaded in a "reasonable" sequence. The next load was selected, and this process was continued until all bales were removed. The first and last loads are shown in Figure 6.

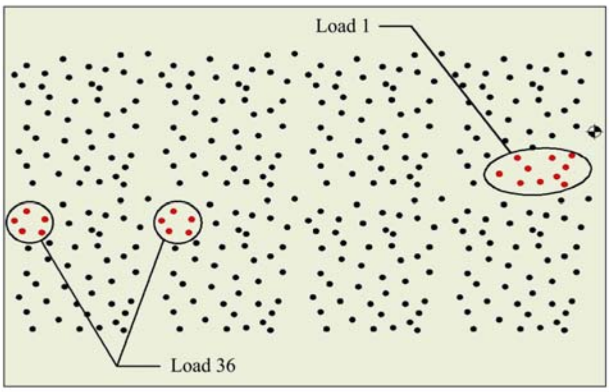


Figure 6 Field showing location of first load of 10 bales and final load of 10 bales

All bales were assigned a number. The first bale in a 10-bale load was designated $L_{start}$ and the last bale was designated $L_{stop}$. The intermediate bales were given the number $L_2$, $L_3$, $L_4$, $L_5$, $L_6$, $L_7$, $L_8$ and $L_9$. The straight-line distance from the entrance to the field (origin) to the first bale in a given load is given by:

$$d_{start} = (x_{Lstart}{}^2 + y_{Lstart}{}^2)^{1/2} \quad (3)$$

The distance from the $L_{start}$ bale to the $L_2$ bale is given by:

$$d_{start,2} = [(x_{Lstart} - x_{L2})^2 + (y_{Lstart} - y_{L2})^2]^{1/2} \quad (4)$$

In like manner, the distance from bale $L_2$ to bale $L_3$ is given by:

$$d_{2,3} = [(x_{L2} - x_{L3})^3 + (y_{L2} - y_{L3})^2]^{1/2} \quad (5)$$

Distances traveled between bales are all calculated in this manner. The straight-line distance from the $L_{stop}$ bale back to the entrance to the field is given by:

$$d_{stop} = (x_{stop}{}^2 + y_{stop}{}^2)^{1/2} \quad (6)$$

Total time to load the 10 bales is:

$$t_{L10} = (d_{start} + d_{start,\,2} + d_{2,3} + d_{3,4} + d_{4,5} + d_{5,6} + d_{6,7} + d_{7,8} + d_{8,\,9} + d_{9,stop} + d_{stop}) / v + 10\ t_L \quad (7)$$

where, $t_{L10}$ = time to load 10 bales, h; $v$ = field velocity, km $h^{-1}$; and $t_L$ = time to load individual bale, h.

In the simulation of the entire in-field hauling operation, the load time was different for each 10-bale load, but the travel time (same average highway speed used for each load to travel to the SSL and return), and unload time were the same.

2.1.2 Influence of travel distance to SSL

Travel times from the field to the SSL was calculated for distances of 0.4, 0.8 1.6 3.2, 6.4, and 12.8 km. Cycle time ($C_t$) was calculated for each load and then total time for the 36 loads was calculated.

In-field hauling cost was calculated as follows:

$$C_{ifh} = T_{ifh}\ C_{phbw} \quad (8)$$

where, $C_{ifh}$ = cost in-field hauling, \$; $T_{ifh}$ = total operating time, h; and $C_{phbw}$ = cost to operate bale wagon, \$ $h^{-1}$.

In-field hauling cost, expressed on a per-unit mass basis, is:

$$C_{pt} = C_{ifh} / M \quad (9)$$

where, $C_{pt}$ = cost in-field hauling, \$ $Mg^{-1}$; and $M$ = total mass hauled from field, Mg.

2.1.3 Simulation of SSL unload crew

The 48-km radius around Gretna, Virginia (VA) was divided into five Tours (Figure 7) to emulate the procedure described by Poorna et al. (2008), and the SSL load-out sequence for each Tour was ordered. This was done to achieve a logical sequence to minimize mobilization cost for the hauling contractor, to even flow into the at-plant storage, and to reduce the number of trucks required. Mobilization cost is defined as the total cost required to move equipment from one SSL to the next in the ordered sequence. It includes the direct cost to move equipment plus the cost for the lost time from the SSL crew's operation.

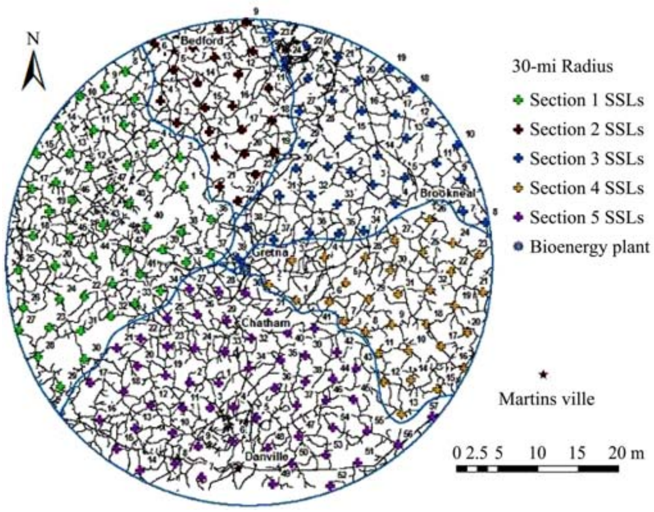


Figure 7 Tours of production area divided for operation by five hauling contactors

No optimization routine defined the five Tours; however, they contained approximately the same total biomass. Using a 9 Mg ha$^{-1}$ yield averaged across all fields, approximately the same biomass was stored in each Tour. Total equipment mobilization cost for Tour 1 was calculated as follows:

$$C_{emtot1} = C_{em12} + C_{em23} + C_{em34} + \ldots C_{emij} \qquad (10)$$

where, $C_{emtot1}$ = total mobilization cost for Tour 1, \$; $C_{em12}$ = cost to move equipment from $SSL_1$ to $SSL_2$, \$; $C_{em23}$ = cost to move equipment from $SSL_2$ to $SSL_3$, \$; $C_{emij}$ = cost to move equipment from $SSL_i$ to $SSL_j$, \$.

In like manner, the total mobilization cost was calculated for Tours 2-5. A SSL crew will have one telehandler to move over the highway to the next SSL plus the operations to position several extra empty-rack trailers at the next SSL

2.1.4 Mobilization cost assumptions

1) Telehandler – If the distance between SSLs is less than 16 km, the telehandler will be driven along the highway to the next SSL. Average travel speed for the telehandler is 27 km h$^{-1}$. Over 16 km, the telehandler was hauled on an equipment trailer. Cost for the equipment hauler is \$400 per move plus \$2.80 km$^{-1}$.

2) Empty-rack trailers – The Procurement Manager at the biorefinery will have real-time control of the entire logistics operations. The manager can send trucks to drop empty-rack trailers at the future SSL, and then these truck tractors will go to the previous SSL and pick up filled trailers. Extra truck tractor travel is estimated to be 4 × d, where "d" is the distance between the two SSLs.

3) If the biomass removal at a given SSL is completed and at least one-half of the workday remains, the equipment is moved to the next SSL. If the biomass removal is completed with less than one-half workday, the equipment is moved the next day and only 5 h (not the 10 h of a full loading workday) is achieved at the new SSL on the first day of crew operation at this new SSL.

2.1.5 SSL load-out operation assumptions

The "theoretical" productivity is 30 racks loaded (2 racks per truckload = 15 truckloads) in a 10-h workday. Mass loaded is:

$$\frac{24 \text{ bale rack}^{-1} \times 30 \text{ racks day}^{-1} \times 400 \text{ kg bale}^{-1}}{1000 \text{ kg Mg}^{-1}}$$

$$= 294 \text{ Mg day}^{-1}$$

The SSL crews are assumed to average 70% of theoretical productivity over year-round operation. Thus, the achieved productivity is 206 Mg d$^{-1}$. Filled-rack trailers at the end of the workday are hauled during the evening and replaced with empty-rack trailers so the SSL crew can begin the next workday without delay.

The simulation was run for the time required to remove all biomass in all Tours. It was assumed that all SSLs had their total biomass when the SSL crew starts removal. Biomass will be harvested and placed in SSLs at different times throughout the year. The most cost competitive management plan will fill and remove each SSL at least twice during the year. More fill/removal cycles at the SSL will reduce storage cost (\$ Mg$^{-1}$). At the completion of the simulation for load-haul of a given Tour, the total theoretical load time was defined by:

$$T_{wht1} = 10\sum_{i=1}^{n_1} N_{wdi} \qquad (11)$$

where, $T_{wht1}$ = total theoretical load time for all SSLs in Tour 1, h; $N_{wdi}$ = number of workdays required to load biomass from $SSL_i$, and $n_1$ = number of SSLs in Tour 1.

In like manner, the total theoretical load time was calculated for Tours 2-5. Actual total time ($T_{wda1}$ . . . $T_{wda5}$) was calculated using assumptions in Section 2.1.4. The operational cost (\$ $h^{-1}$) for the several pieces of equipment required for SSL load-out operations is shown in Table 2. The operational cost includes no costs for load-out or unloading at the biorefinery.

**Table 2 Total cost for SSL operations assuming 10-h workday**

| Operation | Cost (\$ dry-$Mg^{-1}$) |
|---|---|
| Telehander | 2.80 |
| Racks/Trailers | 2.39 |

The mobilization cost due to lost productivity required to move equipment and personnel from SSL to SSL was calculated as follows. If average moisture content is 15% (w.b), biomass filled per 10 h workday is: $M_{dm}$= 206 Mg $day^{-1}$ (1-0.15) = 175 dry-Mg $day^{-1}$.

$$C_{load\ SSL} = \frac{175\ \text{dry} - \text{Mg day}^{-1}\ (2.80 + 2.39)\$\ \text{dry-Mg}^{-1}}{10\ \text{h day}^{-1}} = \$90.83\ \text{h}^{-1} \quad (12)$$

Total mobilization cost due to lost productivity for Tour 1 was calculated:

$$C_{wdm1} = C_{load\ SSL}\ (T_{wha1} - T_{wht1}) \quad (13)$$

where, $C_{wdm1}$ = total cost due to lost workdays for Tour 1, \$; $C_{load\ SSL}$ = average cost for SSL loading operations [Equation (12)], \$ $h^{-1}$; $T_{wha1}$ = total actual load time for all SSLs in Tour 1, h; and $T_{wht1}$ = total theoretical load time for all SSLs in Tour 1, h.

Total biomass hauled for Tour 1 is:

$$M_1 = \sum_{i=1}^{n_1} m_i \quad (14)$$

where, $M_1$ = total biomass hauled for Tour 1, Mg; $n_1$ = number of SSLs in Tour 1, and $m_i$ = biomass stored in $i^{th}$ SSL, Mg.

Achieved loading productivity averaged across the entire Tour 1 is defined by:

$$P_{Ln} = M_1 / T_{wda1}$$

where, $P_{Ln}$ = average loading productivity for Tour 1, Mg $h^{-1}$.

Total mobilization cost for Tour 1 was:

$$C_{m1} = C_{emtot1} + C_{wdm1} \quad (15)$$

where, $C_{m1}$ = total mobilization cost for Tour 1; $C_{emtot1}$ = total equipment mobilization cost for Tour 1 [Equation (10)], \$; and $C_{wdm1}$ = total mobilization cost due to lost workdays [Equation (13)], \$.

Expressed on a per-unit-mass basis, the total mobilization cost was:

$$C_{mpM1} = C_{m1}/M_1 \quad (16)$$

In like manner the total mobilization cost was calculated for Tours 2-5.

## 3 Results and discussion

### 3.1 In-field hauling

Travel time as a percentage of total cycle time required for the in-field hauling of the 16 ha field is given in Figure 8. This result illustrates the influence of highway travel on the in-field hauling operation. Labor productivity (Mg hauled per workday), shown in Table 3, decreases at an accelerating rate as the travel distance increases.

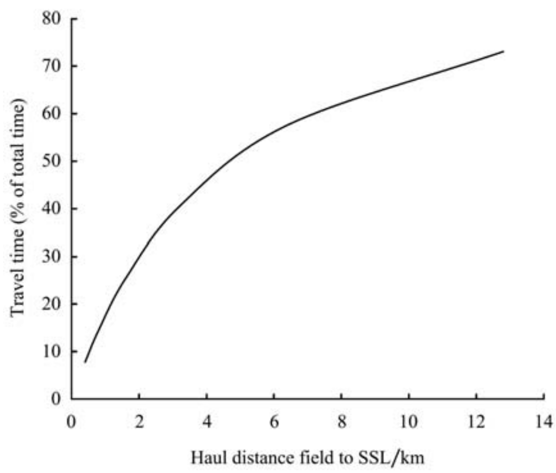


Figure 8 Total travel time to the SSL as a percentage of total time for in-field hauling bales from 16 ha field

**Table 3 Productivity and cost for in-field hauling as a function of in-field haul distance to SSL**

| Haul distance /km | Productivity /Mg $day^{-1}$ | In-field hauling cost | | Increase in cost /% |
|---|---|---|---|---|
| | | (\$ $Mg^{-1}$) | (\$ dry-$Mg^{-1}$) | |
| 0.4 | 128 | 3.59 | 4.22 | - |
| 0.8 | 120 | 3.82 | 4.49 | 6.4 |
| 1.6 | 107 | 4.29 | 5.05 | 19.5 |
| 3.2 | 88 | 5.23 | 6.15 | 45.7 |
| 6.4 | 65 | 7.10 | 8.35 | 97.8 |
| 12.8 | 42 | 10.85 | 12.76 | 202.2 |

To give a frame of reference, how far can the in-field bale wagon travel from field to SSL, if the operator is to have the same productivity (Mg $h^{-1}$) as the baling operation? Suppose that the baler can average one 0.4 Mg $bale^{-1}$ every 2 min. This gives a baler productivity rate of 12 Mg $h^{-1}$. To average a bale hauled every 2 min, the bale wagon operator must haul 30 bales $h^{-1}$.

$$30 \text{ bales h}^{-1} \times 0.4 \text{ Mg bale}^{-1} = 12 \text{ Mg h}^{-1}$$

Since an in-field haul contains 10 bales with a capacity of 30 bales $h^{-1}$, the in-field bale wagon must complete 3 loads $h^{-1}$ or a load every 20 min. To haul the 36 loads from the 16-ha field will require 12 h.

Total operating time to haul all bales from a 16 ha field is given as a function of travel distance in Figure 9. If the job is to be completed in 12 h to achieve the same productivity as the baling operation, the allowable haul distance is 3.2 km. This is why the 3.2 km in-field hauling distance was used for the SSL selection shown in Figure 1.

Average cost for in-field hauling, using the \$459.20 $day^{-1}$ total cost for the bale wagon divided by the Mg $day^{-1}$ productivity, is presented in Table 3. Cost is 19.5% higher for a 1.6 km haul as compared to a 0.4-km haul, and over 200% higher for a 12.8 km haul. This result highlights the key question, what is the optimum trade-off between increasing in-field hauling cost that results from large area SSLs and decreasing mobilization cost that results from having fewer but larger SSLs?

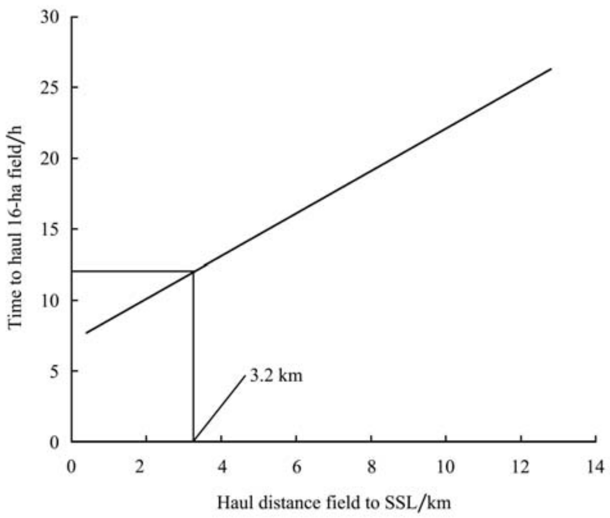


Figure 9 Allowable in-field to SSL haul distance if the travel distance is constrained such that the in-field haul productivity equals the baler productivity

### 3.2 Mobilization cost

The number of SSLs and total biomass in each of the five Tours is given in Table 4. Number of SSLs ranged from 23 in Tour 2 to 57 in Tour 5. To remove all biomass in Tour 2 requires only 23 moves, or less than half the 57 moves required for Tour 5. Mean biomass per SSL decreased from 4,200 Mg in Tour 2 to 1,600 Mg in Tour 5.

**Table 4 Total biomass hauled for each Tour**

| Tour No. | Number of SSLs | Total biomass /Mg | Average mass per SSL /Mg |
|---|---|---|---|
| 1 | 48 | 101,327 | 2,110 |
| 2 | 23 | 96,545 | 4,200 |
| 3 | 39 | 95,797 | 2,460 |
| 4 | 32 | 94,167 | 2,940 |
| 5 | 57 | 91,357 | 1,600 |
| Total | 199 | 479,375 | 2,410 |

The most interesting parameter is the total mobilization cost divided by total biomass hauled in each Tour (Table 5). Total cost (equipment hauling + extra workdays) averaged \$0.29 dry-$Mg^{-1}$ for Tour 2 and \$0.79 dry-$Mg^{-1}$ for Tour 5, which is 2.7 times higher. Average size of SSLs does significantly impact the cost of the SSL load-out operations.

Mean mobilization cost across the entire production region was \$0.52 dry-$Mg^{-1}$. Cost for Tour 2 was 44% less than the average, and cost for Tour 5 was 52% more. A hauling contractor assigned to Tour 2, if paid the same per-Mg delivered price, will earn more profit than a contractor assigned to Tour 5. This is a key issue of fair compensation for the contractors in the biomass logistics plan for the biorefinery.

Productivity of the SSL crew operation is given in Table 5. Mass hauled per operating hour (total actual workdays × 10 h $workday^{-1}$) was relatively uniform across the five Tours. The average for the entire region was 16 dry-Mg $h^{-1}$ determined by dividing total dry-Mg hauled from the five Tours by the total operating hours (total actual workdays for all five Tours × 10 h $workday^{-1}$).

The difference in total days required for mobilization as a percentage of total days to haul all biomass in the Tour is given in Table 5. The percentage ranged from 2.6% in Tour 2 with 23 SSLs to 6.4% in Tour 5 with 57 SSLs.

**Table 5 Productivity of the load-out operation, total mobilization days as a percentage of total actual days, and total mobilization cost for each Tour**

| Tour No. | Loading productivity (dry-Mg/h) | Mobilization time (% total time) | Equipment hauling ($dry-Mg$^{-1}$) | Extra workdays ($ dry-Mg$^{-1}$) | Total ($ dry-Mg$^{-1}$) |
|---|---|---|---|---|---|
| 1 | 15.9 | 4.6 | 0.29 | 0.31 | 0.60 |
| 2 | 16.2 | 2.6 | 0.14 | 0.15 | 0.29 |
| 3 | 16.0 | 4.1 | 0. 42 | 0.25 | 0.49 |
| 4 | 16.1 | 3.6 | 0.20 | 0.23 | 0.43 |
| 5 | 15.6 | 6.4 | 0.38 | 0.41 | 0.79 |
| Average | 16.0 | 4.3 | 0.25 | 0.27 | 0.52 |

The results in Table 3 suggest that a large number of smaller SSLs will minimize the average haul distance from field to SSL, and this minimizes average in-field hauling cost ($ dry-Mg$^{-1}$) for the farm-gate contractor. Conversely, the results in Table 5 suggest that a small number of larger SSLs will minimize the number of moves by the load-out contractor, and this will minimize their average mobilization cost ($ dry-Mg$^{-1}$). When the average in-field haul distance is 3.2 km, the in-field hauling cost is $6.15 dry-Mg$^{-1}$ (Table 3). This 3.2-km in-field haul distance was used to locate the 199 SSLs that was the database for the analysis in Table 5. Note that the mobilization cost for the entire 48-km region averaged $0.52 dry-Mg$^{-1}$. The $6.15 dry-Mg$^{-1}$ in-field hauling cost is almost 12 times the $0.52 dry-Mg$^{-1}$ mobilization cost. Thus, the choice to use a large number of smaller SSLs will minimize the sum of the two costs (farm-gate contract + hauling contract).

## 4 Conclusion

This analysis used an in-field bale wagon to deliver bales of switchgrass to the SSL and year-round hauling from the SSLs to a biorefinery using commercial delivery. An average productivity of 12 Mg h$^{-1}$ was assumed for the in-field bale wagon. Based on average operating time to haul bales from a 16 ha field, the allowable in-field to SSL haul distance was 3.2 km. The mobilization cost to move equipment to the SSL for commercial load and haul operations is a factor in minimizing total cost, in-field hauling plus highway hauling. Analysis showed that mobilization cost (average tour cost of $0.52 dry-Mg$^{-1}$) is not as important as limiting in-field hauling cost ($6.15 dry-Mg$^{-1}$ for 3.2 km haul distance). This result suggests that a large number of smaller SSLs may be the desired organization as compared to a fewer number of larger SSLs.

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