TECHNICAL NOTE:

EQUIPMENT MATCHING FOR SILAGE HARVEST

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ABSTRACT. *During forage harvest for silage, the harvesters, transport units, and equipment at the storage site (blower, bagger, or bunker packing) must work at a similar rate to avoid idle equipment and labor. Harvester power (which determines potential harvester capacity) was used as a basis for sizing transport and unloading equipment and their power units. Cycle analysis was employed to determine transport unit needs to keep the harvester fully utilized. An empirical model of transport needs was developed and guidelines for silage harvest machinery sets are provided.*

Keywords. *Analysis, Bag, Bunker, Cycle, Forage, Harvest, Logistics, Silage, Silo, Storage, System, Transport.*

Harvesting machinery and associated labor costs are a large contributor to the cost of producing and delivering forages. For example, Wisconsin custom rates for chopping, hauling, and packing whole-plant corn silage are approximately $235/ha ($95/acre; USDA, 2007); rates per hour depend largely on machinery capacities. With a typical corn silage yield of 45 Mg/ha (20 tons/acre), machinery costs to harvest, transport and store silage away are approximately $5/Mg ($5/ton); Michigan custom rates suggest up to $9/Mg ($8/ton; Stein, 2008). Harvested corn silage value is often computed as 8 to 10 times the price of shelled corn (Morrison et al., 2005); so, for the time period associated with the custom rates mentioned, silage value would have been approximately $55/Mg ($50/ton). Of the corn silage value, approximately 10% to 20% is typically due to harvest and storage machinery cost. Although the values are different for haycrop silage, the percentage is similar. Selection and sizing of equipment is important to minimize harvest cost.

In forage harvesting systems, there are significant equipment interactions as the crop moves from the field to the silo. The harvester needs to interact with the transport units to align and either unload or switch containers. Transport units need to interact at the unloading site to align and unload. The harvester is the most expensive component, so it should be kept busy to minimize production cost; avoiding bottlenecks within transport or unloading operations through matched components can significantly improve system capacity, can help avoid idle harvester situations, and can decrease the cost of producing forages.

The objectives of this work were to:

- provide benchmark figures for matching forage harvesters, transport units, and storage loading equipment such as blowers, baggers, and bunker silo packing tractors, and
- use a spreadsheet model of cycle analysis to generate a simplified transport needs model for high capacity forage harvest operations.

FORAGE HARVESTER CAPACITY

Four different factors can limit the capacity of a machine depending on field conditions and the operation. These factors are power, throughput capacity, speed, and traction. In systems where machines must interact (such as harvest, transport, and unloading), the capacity of some machines can be limited by others; this may necessitate idle time for some machines.

Of the four capacity limiting factors (power, throughput capacity, speed, and traction), power and throughput capacity are generally most limiting in forage harvest operations. (In general, forage harvest operations are not limited by speed; however, an upper bound on field speed may limit capacity in situations where there is plenty of harvester power yet a low forage yield such as a small haycrop windrow.) A well-matched pull-type harvester and tractor or a well designed self-propelled harvester should result in power and throughput yielding a similar upper bound on capacity.

Forage harvester power (and hence, specific energy) depends upon throughput, moisture content, length of cut, crop type, and knife sharpness (Srivastava et al., 2006). Overall specific energy for the entire forage harvester (cutting, blowing, locomotion, etc.) is 3.3 and 2.1 kWh/Mg (4.0 and 2.5 hph/t) for haycrop and whole-plant corn, respectively, in good field conditions (i.e., full windrows; Srivastava et al., 2006). For the eight cases included in Harrigan (2003) which had adequate transport systems, the overall specific energy of harvesters in corn silage ranged from 1.9 to 3.2 kWh/Mg (2.3 to 3.9 hph/ton) with an average of 2.4 kWh/Mg (2.9 hph/ton). For example, if transport and unloading are not bottlenecks, a 300 kW (400 hp) self-propelled harvester could harvest haycrop silage at 91 Mg/h (100 t/h) (300/3.3 = 91;400/4 = 100); this would be 32 Mg DM/h (35 t DM/h) if silage was 65% moisture. Harvesters have approximately 60% greater capacity (if

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power limited) with whole-plant corn than with haycrop silages.

Capacity into Storage

Logistics at the unloading site are critical to system performance. If forage cannot be packed, blown, or bagged fast enough, the storage site can become the bottleneck of the overall harvest system.

Silo blower manufacturers advertise maximum capacities of approximately 100 and 165 Mg/h (110 and 180 t/h) for haycrops and corn, respectively. Maximum capacity may not be maintained consistently since the blower will not be operating at 100% of capacity all of the time; also, operators may not push the capacity toward the plugging threshold. With 75% utilization, a blower and tower silo system, with adequate tractor power could store 75 Mg haycrop/h or 123 Mg corn silage/h (82 t haycrop/h or 135 t corn silage/h).

If the transport system was sufficient, a blower/tower silo system could keep a 250-kW (340-hp) harvester operating at full capacity (Buckmaster and Hilton, 2005b). An even larger harvester could be operated at full capacity if the blower had a feed table (stationary loadable platform which feeds the blower) to allow for higher utilization.

Power requirement depends on the blower type, silo height, and throughput (Rotz and Coiner, 2005). Forage blower specific energy is approximately 1.7 kWh/Mg (2.1 hph/t) with haycrops and 1.3 kWh/Mg (1.6 hph/t) with whole plant corn silage (Rotz and Coiner, 2005). The ratio of blower-specific energy to harvester-specific energy suggests that for every 1 kW (1.4 hp) of the forage harvester there should be approximately 0.5 kW (0.7 hp) available to the blower when harvesting haycrops for silage. This guideline would apply only up to approximately 130 kW (175 hp) since blower throughput capacity would be limiting beyond that point. For whole-plant corn, each 1 kW (1.4 hp) of harvester should have a match of approximately 0.6 kW (0.8 hp) available to the blower – up to approximately 150 kW (200 hp). Very large harvesters may require more than one blower operating simultaneously (likely on different silos).

Silage baggers are advertised with capacities up to and exceeding 450 Mg/h (500 t/h). Bagger capacity can be limited by the throughput capacity of the machine or available power. Baggers require approximately 1.2 kWh/Mg (1.5 hph/t) for haycrop silage and 0.8 kWh/Mg (1 hph/t) for corn silage (Rotz and Coiner, 2005); this is about 60% to 70% as much power as a forage blower. In addition to having a properly sized bagging machine, the bagger should have approximately 40% as much power available as the harvester in order to assure adequate capacity to place forage into storage. Figure 1 illustrates approximate matches for blower and bagger power for varied harvester power.

Proper packing of bunker silos, trenches, or stacks requires adequate packing weight, packing time, and a proper layering technique (Muck and Holmes, 2000). The Holmes and Muck (2002) model was used to estimate the weight (and likely power rating) of tractors required to maintain pace with harvesters with varying capacity. Forage moisture content of 65%, maximum packing layer thickness of 15 cm (6 in.), and a target density of 260 kg DM/m^3 (16 lb DM/ft^3) were used. Figure 2 illustrates the packing mass required to keep up with varying harvester power. Assuming tractors are ballasted near an upper limit at about 85 kg/kW (140 lb/hp), bunker packing tractor power rating can be estimated, also. As one example, a 225-kW (300-hp) harvester harvesting whole-plant corn for silage should be matched with a minimum of either two 19,500-kg (43,000-lb) tractors or one 27,300-kg (60,000-lb) tractor moving and packing forage in a bunker. With ballast nearing the maximum suggested by manufacturers, this would be two 230-kW (310-hp) tractors or one 320-kW (425-hp) tractor.

The blower and bagger capacity values are reasonably consistent with silo filling rates observed on 23 dairy farms; the visited farms included 22 tower silos, 23 bunker silos, and 8 bags. Of the 23 farms, 11 used self-propelled harvesters. Table 1 includes minimum, average, maximum, and “good

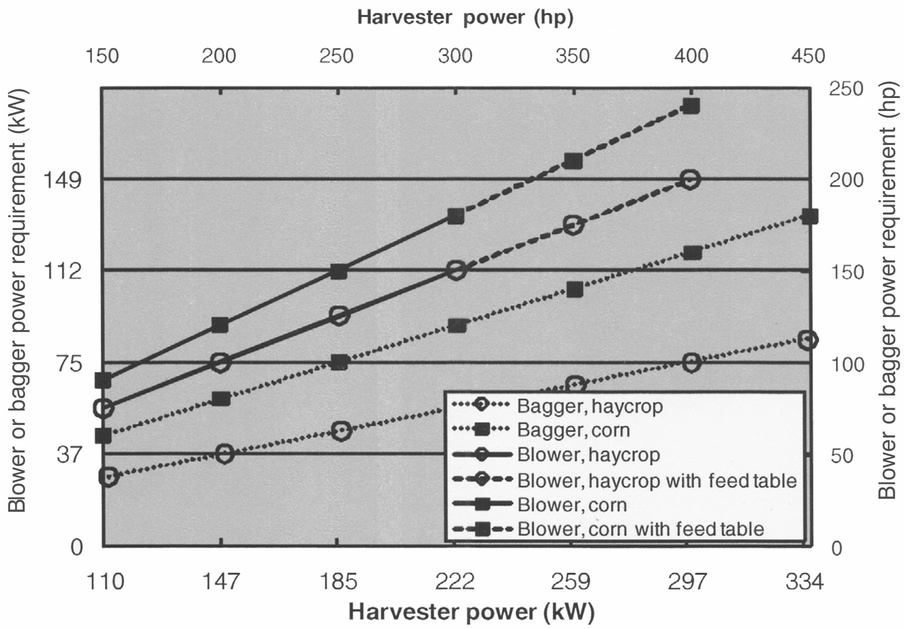

Figure 1. Approximate power required for blowers and baggers to match forage harvester capacity.

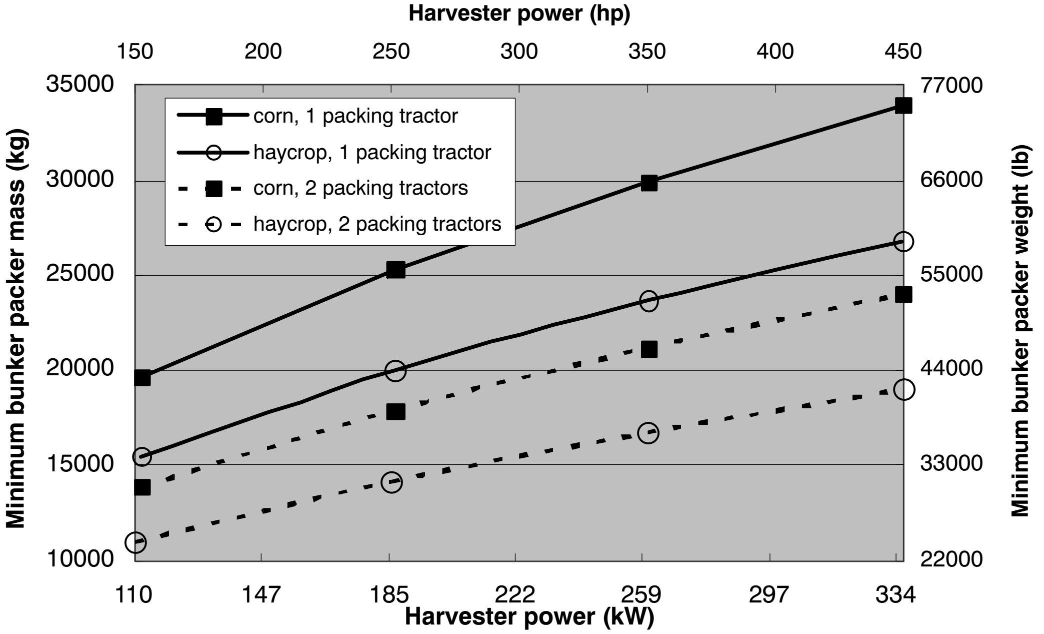

Figure 2. Nominal targets to match bunker silo tractor packing weight to forage harvester power in order to achieve a target density of 260 kg DM/m^3 (16 lb DM/ft^3).

management" benchmarks for silo filling rates based on actual farm visits. This data was collected through observation (watching stopwatch, scales, labor use, etc.) of silage harvest and silo filling (for portions of a day) and through farmer interviews/survey as needed.

It is not enough to just match the harvester capacity with that of the storage machinery; the number and size of transport units must also create a well-matched system. One method of evaluating systems with interacting machines or components is a cycle analysis. Cycle analysis accounts for all time spent by each machine in the system and can be useful to identify suitable transport systems in silage operations.

CYCLE ANALYSIS

The principles and developmental steps regarding the use of cycle diagrams were outlined by Hunt (1986). Buckmaster and Hilton (2005a) put cycle analysis in spreadsheet form providing computation of utilization of each component as well as system capacity. Their spreadsheet allows for varying system considerations such as:

- storage allowed on the harvester (such as a dump wagon or combine hopper),
- storage not allowed on the harvester (such as direct chopping into trucks),
- simultaneous harvest and transfer (such as combining while filling a wagon or cart),
- non-simultaneous harvest and transfer (such as with a dump wagon).

EXAMPLE: SELF-PROPELLED FORAGE HARVESTER

For purposes of illustrating impact of transport system on harvester utilization and system capacity, a 260-kW (350-hp) self-propelled forage harvester harvesting either haycrop or whole-plant corn silage was considered with different truck sizes. For these simulations, round trip transport distance was 9.7 km (6 miles) and unloader capacity was non-limiting at 109 Mg/h (120 t DM/h). Alignment time of the transport units with harvester and unloader were set realistically at 1 min each and average transport speeds were 40 km/h (25 mph). With the small trucks, use of a dump cart was compared to direct chopping into the trucks. Harvester utilization (time harvesting divided by total time) cannot reach 100% due to alignment and interaction time with transport units. Values near 100% are more desirable, resulting in higher system capacity and lower harvest cost.

Because of power requirement, capacity is lower (for a particular harvester) in haycrops than whole-plant corn and the appropriate number of transport units is lower. The appropriate number and size of trucks required to keep a

Table 1. Fill rates for different silo structures observed on 23 dairy farms [Mg/h and (t/h)].

Silo Type and Crop	Minimum	Average	Maximum	Good Management Benchmark[a]	Number of Observations
Tower - haycrop	18 (20)	49 (53)	73 (80)	61 (67)	13
Bunker - haycrop	14 (15)	51 (56)	113 (125)	82 (91)	9
Bag - haycrop	22 (24)	49 (54)	91 (100)	70 (77)	5
Tower - whole plant corn	15 (16)	45 (49)	100 (110)	72 (80)	9
Bunker - whole plant corn	12 (13)	62 (68)	136 (150)	99 (109)	14
Bag - whole plant corn	53 (58)	65 (72)	78 (86)	72 (79)	3

[a] Average of average and maximum.

Table 2. Effect of number of transport units on harvester utilization and system capacity with a 350-hp harvester, 6-mi round trip transport distance, and 25-mph transport speed.

Transport Unit Type[a]	Harvest Method	Transport Unit Capacity (Mg DM)	Transport Unit Capacity (t DM)	Number of Transport Units	Utilization of Harvester (h harvesting/h)	System Capacity (Mg/h)	System Capacity (t/h)
Haycrop (for silage), transport units to keep harvester as busy as possible							
Small truck	Dump cart	1.8	2	3	0.75	17.8	19.6
Small truck	Direct to truck	1.8	2	4	0.82	19.5	21.4
Medium truck	Direct to truck	3.2	3.5	3	0.89	21.1	23.2
Large truck	Direct to truck	4.5	5	3	0.92	21.8	24.0
Haycrop (for silage), one less transport unit							
Small truck	Dump cart	1.8	2	2	0.52	12.2	13.4
Small truck	Direct to truck	1.8	2	3	0.63	14.9	16.4
Medium truck	Direct to truck	3.2	3.5	2	0.62	14.5	16.0
Large truck	Direct to truck	4.5	5	2	0.76	17.9	19.7
Whole-plant corn (for silage), transport units to keep harvester as busy as possible							
Small truck	Dump cart	1.8	2	4	0.64	24.4	26.8
Small truck	Direct to truck	1.8	2	5	0.71	26.9	29.6
Medium truck	Direct to truck	3.2	3.5	4	0.83	31.6	34.8
Large truck	Direct to truck	4.5	5	3	0.83	31.4	34.5
Whole-plant corn (for silage), one less transport unit							
Small truck	Dump cart	1.8	2	3	0.48	18.3	20.1
Small truck	Direct to truck	1.8	2	4	0.57	21.5	23.7
Medium truck	Direct to truck	3.2	3.5	3	0.65	24.7	27.2
Large truck	Direct to truck	4.5	5	2	0.55	20.9	23.0

[a] Size (capacity) is indicated in columns 3 and 4.

harvester maximally utilized depends on several factors, including transport distance, transport speed, unloading rate and harvester power. The impact of a reduction in number of transport units is illustrated in table 2; several comparisons can be made using table 2 to illustrate that harvester utilization (hence production cost) is very sensitive to size and number of transport units in some situations. For example, with medium-sized trucks, system capacity was reduced from 21.1 to 14.5 Mg/h (23.2 to 16.0 t DM/h; or 31%) as the number of trucks changed from 3 to 2 during haycrop harvest and reduced from 31.6 to 24.7 Mg/h (34.8 to 27.2 t DM/h; or 22%) as the number of trucks changed from 4 to 3 during whole-plant corn harvest. In these and other cases illustrated in table 2, the marginal investment to increase transport units (and associated labor) would clearly improve profitability; capacity would increase proportionally more than the total investment (since the harvester and storage equipment would be unchanged).

FORAGE TRANSPORT REQUIREMENTS SIMPLIFIED

Buckmaster and Hilton (2005a) derived an equation to estimate the transport unit size required to keep a grain combine fully utilized. Because of the relatively low density of forages during transport, both the size and number of transport units needs to be determined. Buckmaster and Hilton (2005b) expanded the cycle analysis spreadsheet template and used it to project transport unit needs for forage and herbaceous biomass harvest. While keeping a forage harvester fully utilized (no idle time) may not be necessarily the least cost solution, it likely is a very good benchmark for consideration because of the relatively high cost of the harvester. Cycle analysis was used to run scenarios in a factorial "experiment" design with the following variables and assumptions:

- Harvesters harvested directly into transport units (trucks) or into a dump cart sized to match the trucks
- Harvester power was varied from 150 to 429 kW (200 to 575 hp) in 93-kW (125-hp) increments
- Maximum field efficiency of the harvester (system non-limiting) was 85% [Harrigan (2003) found the range to be 78 to 90% with an average of 85%.].
- Round trip transport distance was varied from 3.2 to 19.3 km (2 to 12 mi) in 3.2-km (2-mi) increments
- Capacity of transport units was 1.8, 3.2, or 4.5 Mg DM (2, 3.5, or 5 t DM)
- Speed of transport units was 16.1, 32.2, or 48.3 km (10, 20, or 30 mph)

For each scenario, the number of transport units required was determined algebraically by setting system cycle time equal to harvester cycle time and solving for the number of transport units required.

Since harvester capacity (mass/time) is proportional to harvester power (based on the specific energy term presented earlier), an expression of harvester power (power) times transport distance (length) divided by the product of transport unit capacity (mass), specific energy (power*time/mass), and transport unit speed (length/time) is dimensionless. The term of power times distance divided by transport unit capacity and speed was used to establish the functional form of an empirical model. Figure 3 illustrates the fit of the data of the resulting empirical model ($R^2 = 0.997$) for number of transport units required to keep a harvester maximally utilized. In SI units:

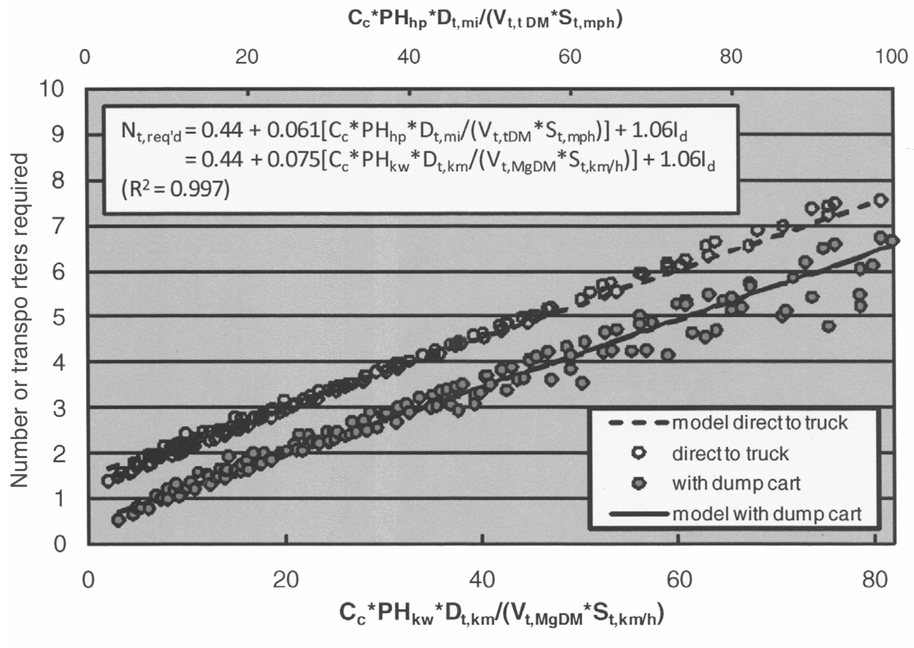

Figure 3. Empirical model for number of transport units required to keep a forage harvester fully utilized (C_c = 1.6 for whole-plant corn, 1.0 for haycrop harvest; PH is harvester power; D_t is round trip transport distance; V_t is transport unit capacity; S_t is average transport speed; I_d is 0 if a dump cart is used, 1 if not).

$$N_{t,req'd} = 0.44 + 0.0746[C_c*PH_{kW}*D_{t,km}/(V_{t,MgDM}*S_{t,km/h})] + 1.06I_d$$

Or, in English units:

$$N_{t,req'd} = 0.44 + 0.061[C_c*PH_{hp}*D_{t,mi}/(V_{t,tDM}*S_{t,mph})] + 1.06I_d$$

where

$N_{t,req'd}$ = number of transport units required to keep the harvester as busy as possible
C_c = crop coefficient (1.6 for whole-plant corn, 1.0 for haycrops)
PH = power of the harvester, kW (hp)
D_t = round trip transport distance, km (mi)
V_t = capacity of each transport unit, Mg DM (t DM)
S_t = average speed of transport units, km/h (mph)
I_d = indicator for direct chopping into transport units
= 1 if material was chopped directly into transport units
= 0 if a dump cart was used

The error of the empirical model (difference from a theoretical equation) over the range of values used in the simulated scenarios factorial experiment ranged from -21% to +31%. This reasonably simple equation will help farmers and/or custom operators match transport systems to self-propelled harvesters.

For example, with a 224-kW (300-hp) self-propelled harvester in haycrop silage chopping directly into trucks, a round trip distance of 8 km (5 mi), 2.7 Mg DM per load (3 t DM per load), and an average transport speed of 40 km/h (25 mph) yields:

$$\begin{aligned} N_{t,req'd} &= 0.44 + 0.075[1.0*224*8/(2.7*40)] + 1.06(1) \\ &= 2.7 \text{ transport units} \end{aligned}$$

or

$$\begin{aligned} N_{t,req'd} &= 0.44 + 0.061[1.0*300*5/(3*25)] + 1.06(1) \\ &= 2.7 \text{ transport units} \end{aligned}$$

With these inputs and two transport units, the harvester will have significant idle time; if three transport units were used, the transport units will have some idle time but the harvester will always be busy.

If, in an otherwise similar situation, the harvester was to harvest into a dump cart, only 1.7 transport units would be required (2 likely the best choice); however, system capacity would be lower than with the direct chop into trucks scenario because the harvester would be spending more time interacting with transport units and less time actually harvesting.

CONCLUSIONS

Without other hindrances, self-propelled forage harvesters can operate with an overall specific energy near 3.3 kWh/Mg (4 hph/t) in haycrops or 2.1 kWh/Mg (2.5 hph/t) in corn silage. To match this capacity, tower silo blowers need 50% (haycrop) or 60% (corn silage) as much power as the harvester and silage baggers need approximately 40% as much power as the harvester. A bunker packing model was used to project weight and tractor power needs so adequate packing can be ensured. Transport units were matched to the harvester using cycle analysis implemented in a spreadsheet model. The model which accounts for loading and unloading times and transportation time (affected by speed and round-trip distance) was used to generate a relatively simple empirical equation to estimate the number and/or size of transporter units required to keep up with high capacity forage harvest operations.

MODEL AVAILABILITY

The spreadsheet implementation of the cycle analysis used for this study is available at: http://cobweb.ecn.purdue.edu/~dbuckmas/research/silagesystemanalysis.xlsx. With this spreadsheet, users may vary the harvest, transport, and unload inputs to estimate the system capacity and suitability of the machinery match. Tractor recommendations for bunker packing, silo blowing, and bagging are also included.

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