

SIZING FORAGE MACHINERY

Dennis R. Buckmaster
Associate Professor of Agricultural and Biological Engineering
Purdue University

A comparison of typical custom rates for forage harvest operations to the value of the hay or silage harvested illustrates the importance of correct machine sizing and operation. Hay and silage harvesting machinery and associated labor costs are often the single largest contributor to the cost of producing and delivering forages. Furthermore, because of the weather interdependence, machinery capacity affects losses, forage quality, and subsequent growth.

This manuscript covers some basic machinery management principles and provides some benchmark figures for traction is not limiting. Here are a few examples of these factors limiting capacity.

- Power limited: high capacity baler with a 75 hp tractor attempting to harvest a high yield windrow
- Power limited: 9 ft disc mower-conditioner with a 50 hp tractor
- Throughput capacity limited: 140 hp tractor with a relatively low-capacity twine-tie baler in a high yield windrow situation
- Speed limited: high capacity baler with suitably sized tractor, but the windrow originated from a 9 ft mower (without raking 2 together) in a low yield situation (you can only drive so fast before the pickup lags)

selecting haying machinery. Topics of capacity, equipment matching, and power requirements are addressed. The focus is size and capacity, with some content related to machinery features; paint color is not addressed.

Hay Making Capacities and cost

There are four factors which can limit the capacity or productivity of any agricultural machine: power, throughput capacity, speed, and/or traction. Hopefully in hay and silage operations,

- Speed limited: sickle bar mower-conditioner (at some speed, cut quality will deteriorate)
- Speed limited: raking at excessively high speeds may increase losses

Somewhat analogous to economic analysis of supply and demand, there are two views toward capacity: 1. What capacity is needed? and 2. What capacity does a machine (or machinery set) have? Area capacity has units of acres/hour while material capacity has units of tons/hour. Area capacity ($C_{a,ac/hr}$) required is a function of land area to be covered (A_{ac}), calendar days available to accomplish the work (B_{days}), working hours per day ($G_{hrs/day}$), and probability of being able to do the work on any random day ($PWD_{decimal}$) (ASABE 2007a, 2007b, 2007c). Required area

capacity is:

$$C_{a,ac/hr} = \frac{A_{ac}}{B_{days} G_{hrs/day} PWD_{decimal}} \quad [1]$$

The probability of a working day for hay making is affected by soil conditions, the operation to be performed and weather. A complicating factor for haying operations is that baling requires mowing and raking to be completed. The probability of a working day for baling, then, is lower than the PWD for either previous operation. Because baling and raking require more particular crop conditions (i.e., moisture), there will also be less time per day available for these than for mowing. As one direct consequence of these facts, a baler must have a higher capacity than the mower or rake.

Area capacity of a machine is a function of operating speed (S_{mph}), width (W_{ft}), and field efficiency ($E_{f,decimal}$). consequence rather than an input; one example would be a baler with a limited throughput capacity or limited power available. Once the capacity requirement is estimated (equation 1), finding a reasonably suitably sized machine is straightforward (use equation 2 and solve for width).

Power requirement is affected by throughput required (or throughput is affected by power available), so power must be considered. Yield may affect the optimal swath manipulation choices so that speed is not limiting capacity significantly (see 4th example above). Table 1 illustrates several hay machinery set examples for different operations. Included are benchmark labor requirements and costs. Another source

$$C_{a,ac/hr} = \frac{S_{mph} W_{ft} E_{f,decimal}}{8.25} \quad [2]$$

Field efficiency for forage operations typically range from 0.65 to 0.8 and account for turning, breaks, overlaps, and other factors which keep one from achieving 100% of the machine's capacity 100% of the time. Field efficiency of round balers is relatively low because they need to regularly stop to tie or wrap and eject bales.

Throughput (or material) capacity is area capacity (computed for a machine or as the requirement) times yield ($Y_{tons/ac}$).

$$C_{m,tons/hr} = C_{a,ac/hr} Y_{tons/ac} \quad [3]$$

In some instances, material capacity may be the limit and speed becomes a

of benchmarks for cost is published custom rates. According to Indiana custom rates of 2007, to mow-condition, rake, and bale hay with 2 tons DM/acre yield, the cost is about \$35/ton DM for small square bales and \$30/ton DM for net wrapped large round bales.

Features and matching

Wise machinery selection requires an evaluation of crop conditions and capacity requirements. Sometimes it boils down to personal preferences, dealer inventory, and service. A visit with a knowledgeable salesperson is often required. A proper match of tractors to mower, rakes, and balers requires some study of the advertising literature or operators manuals.

Operation & size	Mower	Rake	Baler	Transport system	Labor (hrs/ton DM)	Cost (\$/ton DM)
Small square bales 20 to 60 acres 100 to 300 tons DM/year	9 ft	Single rake	Low capacity	2 wagons	1.4 to 2.1	42 to 69
Small square bales 40 to 80 acres 200 to 400 tons DM/year	8 to 12 ft	Tandem rake	Medium capacity	3 wagons	1.0 to 1.4	36 to 52
Small square bales 60 to 120 acres 300 to 600 tons DM/year	12 to 14 ft	Tandem rake	High capacity	4 wagons or auto bale wagon	0.5 to 1.0	29 to 41
Large round bales 20 to 60 acres 100 to 300 tons DM/year	9 ft	Single rake	Low capacity	1 wagon	1.2 to 1.4	44 to 67
Large round bales 40 to 80 acres 200 to 400 tons DM/year	8 to 12 ft	Tandem rake	Medium capacity	1-2 wagons	0.9 to 1.1	36 to 43
Large round bales 60 to 120 acres 300 to 600 tons DM/year	12 to 14 ft	Tandem rake	High capacity	2 wagons or truck	0.7 to 0.9	28 to 33

Table 1. Typical haying machinery sets with benchmark labor requirements and costs (Rotz, 2001).

The following features information may help identify questions to ask.

Mower-conditioners can have different cut and condition combinations. In general, sickle mowers require less power and cut cleaner, but they have a

lower “speed limit”. Although disc mowers require more power, their capacity is higher, they can cut lodged crops, and, if there is enough power available, practically never plug. Figure 1 illustrates the power requirement ranges for the two types of mowers.

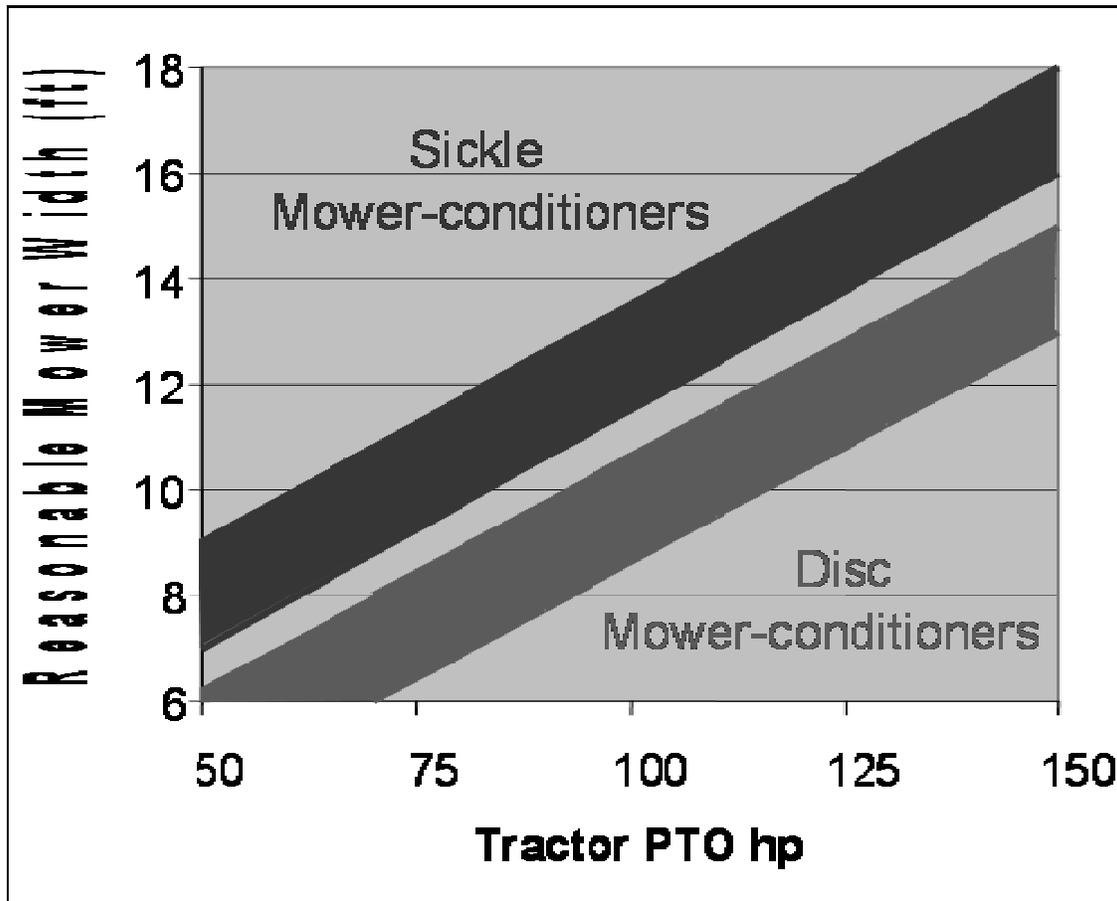


Figure 1. Tractor power requirements for sickle and disc mower-conditioners.

Conditioners speed the rate of forage drying by generating more pathways for moisture to leave the crop (primarily stems). Roll conditioners (rubber or steel) are good in legumes which have thick stems. Flail conditioners scuff the plant; they are more appropriate in grasses because the flails can cause high leaf loss in legumes. Regardless of the conditioning mechanism, more aggressive conditioning will increase

drying rate, but also potentially increase losses.

Of the three common types of rakes, parallel bar rakes result in the lowest loss; they can be ground or hydraulically driven. Wheel rakes can allow higher speeds, but may result in more rock movement. Rotary rakes are becoming more common and will not result in large losses if properly set and operated.

Round balers now have several options worth serious consideration. These include bale slicing, net wrap, silage special options (for heavier, “sticky” bales), variable speed pick-up, automatic controls, integrated plastic wrapping (for silage). Although net wrap is more expensive, the increase in productivity can often pay for the difference (which leaves the other benefits of net over twine as pure gain). Some round balers can be safely operated with as little as 45 hp while others may be able to fully utilize over 100 hp; check the operator’s manuals or advertising literature. Round balers, even with net wrap, have a relatively low field efficiency. A relatively high capacity round baler with throughput capacity near 30 tons/hr will likely lead to a day-long average near 15 tons/hr; this is because the operator will not “run on the edge” of plugging and the wrap/eject cycle keeps field efficiency (time actually picking up and baling) below 70%.

Large rectangular balers have throughput capacities approaching 50 tons/hr. They require more power than round balers, but because they do not need to stop for wrapping and ejecting, field efficiency is typically 15% higher. Power requirements range from 90 to 200 hp. With high capacity balers, more windrow planning is required. For example, if a large rectangular baler is expected to harvest a crop yielding 2.5 tons/acre at 40 tons/hr with a travel speed of 6 mph and a field efficiency of 0.85, the baler needs to cover 16 acres/hr. This requires the effective cut width to be 26 ft; two or three swaths must be raked together.

Bulk Silage Harvest Harvester power and capacity

Of the four capacity limiting factors (power, throughput capacity, speed, and traction), power and throughput capacity are generally most applicable to silage harvest operations. Hopefully, forage harvest operations are not traction limited; that is, the soil is firm enough for the machines to move without excessive slip. In general, forage harvest operations are not speed limited, either. An upper bound on field speed may be a capacity limit in situations where there is plenty of harvester power with a small haycrop windrow to pick up and chop. Capacity in forage harvest situations, then, is most often limited by power or machine throughput capacity. A well matched pull-type harvester and tractor or a well designed self-propelled harvester should result in these two potentially limiting factors yielding a similar upper bound on capacity.

A good rule-of-thumb is that harvester throughput ($C_{m, \text{tons/hr}}$) in grasses and legumes can approach harvester horsepower divided by 4 in good field conditions (full windrows; Buckmaster, 2006). For example, if transport and unloading are not bottlenecks, a 400 hp self-propelled harvester could harvest 100 tons of haycrop silage per hour; this would be 35 tons DM/hr if the silage was 65% moisture. Harvester power efficiency for corn silage is, at best approximately 2.5 hphr/ton; this corresponds to 60% more capacity (per unit power) than with haycrop silages. A 400 hp harvester can harvest approximately 160 tons of corn silage per hour ($400/2.5$).

Silage into storage: blower, bagger, & bunker packer

Logistics at the unloading site are critical to system performance. If silage 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 capacity of approximately 110 tons/h with haycrop silage and 180 tons/hour with corn silage. Maximum capacity may not be maintained consistently throughout a day or longer since the blower will not be operating at 100% 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 82 tons haycrop/hr or 135 tons corn silage/hr. These values are consistent with silo filling rates we observed on farms. If the transport system was sufficient, a blower/tower silo system could keep a 340 hp harvester operating at full capacity. An even larger harvester could be operated at full capacity if the blower had a receiving platform to allow for higher utilization.

Blower power requirement will depend on the blower type, silo height, and throughput (Rotz and Coiner, 2005). Forage blower power efficiency is approximately 2.1 hphr/ton with haycrops and 1.6 hphr/ton with corn silage. The ratio of blower power efficiency to harvester power efficiency suggests that for every 1 hp of the forage harvester in haycrop silage, there should be approximately 0.5 hp available to the blower. This guideline would apply

only up to approximately 175 hp since blower throughput capacity would be limiting if more power was available. For corn silage, each 1 hp of harvester should have a match of approximately 0.6 hp available to the blower – up to approximately 200 hp.

Silage baggers are advertised with capacities exceeding 500 tons/hour. Bagger capacity can be limited by the throughput capability of the machine or available power. Baggers require approximately 1.5 hphr/ton for haycrop silage and 1 hphr/ton for corn silage; this is about 60-70% as much power as a forage blower (Rotz and Coiner, 2005). 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 silage into storage.

Proper packing of silage into bunker silos, trenches, or stacks requires adequate packing weight, packing time, and a proper layering technique. 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. Good management practices of 65% moisture silage, maximum packing layer thickness of 6 in, and a target density of 16 lb DM/ft³ were assumed. Figure 2 illustrates the packing mass required to achieve the target density while keeping up with varying harvester power levels. As one example, a 300 hp harvester harvesting corn silage should be matched with a minimum of either two 43,000 lb tractors or one 60,000 lb tractor (off the chart) moving and packing silage in a bunker. Packing with less tractor weight

will result in lower density (higher losses, less capacity). There is a practical limit of approximately 160 lb per PTO hp rating; weighting a tractor more than this may cause premature axle or transmission failure (check operators manuals). The 160 lb/PTO hp was used to generate the right axis of Figure 2.

Figure 2 slightly overestimates packing weight required; although a 300 hp harvester (previous example) has capacity of 120 tons corn silage/hr, silage will arrive at the bunker at a slightly lower rate due to field efficiency and transporter interactions.

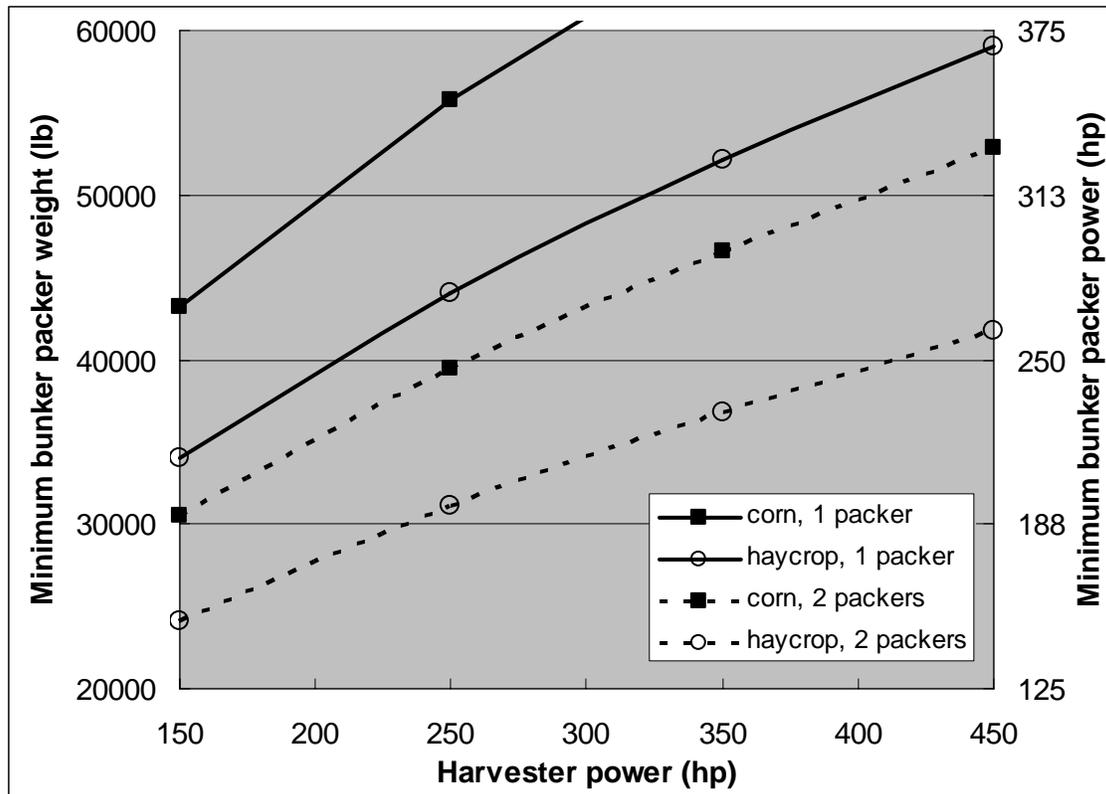


Figure 2. Tractor weight requirements for adequate bunker silo packing (right axis assumes total ballast of 160 lb/hp – refer to operators manual for limitations).

Tools availability

For a limited time, attendees of the 2008 Indiana Forage Day may access and download some tools and further information on this topic. The URL is: <http://cobweb.ecn.purdue.edu/~dbuckmas/INFOR08>

Available there are:

- *Haying machinery aids.xls* which is an Excel workbook containing a simple capacity estimator and a simple tractor cost calculator
- *Benchmarking tractor costs.pdf* which is documentation for the tractor cost calculator
- *IN custom rates EC-130-W.pdf* which is Indiana the 2007 custom rates fact sheet printed by Purdue University
- *Mach_FORAGE_field_Operations_2005.pdf* which is a

University of Illinois fact sheet
related to machinery costs

References

- ASABE. 2007a. S495: Uniform terminology for agricultural machinery management. Standards of the Amer. Soc. Agr. and Biol. Engineers. St. Joseph, MI.
- ASABE. 2007b. EP496.2: Agricultural machinery management. Standards of the Amer. Soc. Agr. and Biol. Engineers. St. Joseph, MI.
- ASABE. 2007c. D497.4. Agricultural machinery management data. Standards of the Amer. Soc. Agr. and Biol. Engineers. St. Joseph, MI.
- Holmes, B.J. and R.E. Muck. 2002. Documentation of bunker silo silage density calculator. University of Wisconsin, Madison. URL:
<http://www.uwex.edu/ces/crops/uforage/bunkdens-Doc.PDF>
- Hunt, D.R. 1986. *Engineering Models for Agricultural Production*. Westport, CT: AVI Publishing.
- Rotz, C.A. 2001. Mechanization: planning and selection of equipment. In: *Proc. XIX International Grassland Congress*. San Pedro, Sao Paulo, Brazil 763-768.
- Rotz, C.A. and C.U. Coiner. 2005. The integrated farm system model reference manual. USDA Pasture Systems and Watershed Research Laboratory. URL:
<http://www.ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference.pdf>. IFSM is available at:
<http://www.ars.usda.gov/Main/docs.htm?docid=8519>
- Spreadsheet is available at:
http://www.uwex.edu/ces/crops/uforage/Bunker_Density_Calculator_%20English-Metric-Espanol4-21-05.xls