Choosing Forage Storage Facilities

Brian J. Holmes, Ph.D.
Professor
Biological Systems Engineering Department
University of Wisconsin-Madison

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Selection of a forage storage facility requires the producer to consider many factors. Harrison and Fransen (1991) state, "The decision on the type of storage system for ensiled forage should be based on several factors. These include: (1) type of silage, (2) herd size, (3) available labor, (4) capital investment, (5) access to equipment service, (6) feeding management, and (7) flexibility for future needs." Other factors which should be considered when the broader topic of forages are included are: (1) annual costs, (2) storage filling management, (3) marketing forage, and (4) maintaining high quality feed. Increased reliance on purchased forages and ration balancing for high milk production has heightened awareness to the value of forage quality. "Hay is just hay" is no longer true. Dairymen are willing to pay a price for hay which is commensurate with its value for maintaining the levels of milk production necessary for high profits. Since the purchase of relatively expensive feed ingredients is needed when forage feeding value is reduced, the awareness of the value of high quality is also heightened. The purchase of extra feed supplements and/or the loss of milk production due to reduced forage quality offer a cost component for comparison with the increased costs for capital and labor which may be needed to maintain feed quality. Once a forage harvest and storage system has been decided upon, the additional costs required to maintain and manage the system according to recommended practices are usually rewarded with high payback in the form of reduced dry matter (DM) loss and maintained feed quality. For example, Bolsen et al. (1993) showed a 30% higher DM loss in the top 3 feet of a bunker silo when not covered compared to when it was covered with weighted plastic film. Ruppel (1997) equates the top 3 feet of uncovered silage to a bunker silage cover and states the "silage cover is nearly 20 times more expensive than the plastic silo cover." When the cost of tires and labor to apply the cover are included, the ratio is reduced. Using 0.005 man hr/ft^2 cover and uncover labor, a 40' × 100' bunker surface, \$0.025/ft^2 plastic cost, \$10/hr labor, \$0 tire cost, \$85/TDM forage value, the cost to cover the bunker is

$300 ($100 plastic + $200 labor). The silage DM value saved by covering becomes $2142. Thus the ratio of silage saved to the total cost of covering in this case is 7 to 1. Rotz and Muck (1993) found a similar ratio to be 8 to 1. This is still a very high return on labor and plastic cost. Thus the value of following recommended practices with an existing system of storage is supported. What about the case where a producer is considering investment in a new storage system? Many studies have been conducted with the objective of determining the most economic forage storage and handling system. Rotz and Muck (1993), Rotz et al. (1989), and Rotz and Harrigan (1997) have used DAFOSYM, a computerized simulation model to analyze the costs of harvest, storage and feed delivery for a variety of forage handling systems. The model requires an accounting for all of the costs associated with these activities. This highlights the importance of how each of the cost components contributes to the total high cost of forage production and feeding. In most instances, these models presume good management, and the resultant cost comparisons are valid when good management is practiced on a farm. Thus a producer considering several forage management system alternative investments should perform a similar analysis of the system capital investments as well as annual costs based on the management to be practiced for each system. For example, if a bunker silo storage is being considered and the dreaded practice of covering with plastic and tires will not be performed, that should be factored into the analysis. Homes (1998) compared the costs of a variety of hay silage storages over a range of volumes stored. Figures 1 and 2 show the annual and total costs per TDM stored for two of those volumes. In Figure 3, the DM loss for bunker silos is changed from 13% (excellent management) to 18% (no covering), and the DM loss for piles is increased from 18% to 23%.

The cost of the bunker silo storage increases from $32.44 TDM-yr to $35.65 TDM-yr as shown in Figure 3. It is apparent from this type of analysis that a system viewed as lower in initial cost ($76/TDM stored in bunkers) is not lower in annual cost compared to the higher initial cost of stave tower silos ($129/TDM stored) at the 3072 TDM stored-size. Thus decisions about the type of storage to select should be based on annual costs incurred as the system will be operated and not just on capital investment costs or someone else's analysis which often presumes good to excellent management.

Buckmaster (1993b) and Buckmaster (1993a) have developed a spreadsheet which can be used to analyze the costs and benefits of round hay bale storage alternatives. One-use and reusable plastic coverings as well as in-barn storage were considered. The added costs ranged from about $10 to $22/ton hay compared to outside uncovered storage, but the benefits over costs ranged from $7.60 to $10.60/ton hay. Thus the added annual benefits of protecting hay from the weather outweigh the annual costs significantly.

In addition to capital and annual costs of forage handling and storage, other factors must be considered. Rapid forage harvesting capacity is an effective method of preserving forage quality. Reduced exposure to rain and timeliness of hay cutting based on maturity have helped to improve the quality of hay on many farms. Reduced alfalfa leaf loss and rain exposure, combined with TMR feeding, have resulted in a switch from dry hay to silage. Rapid silo filling reduces the period silage is exposed to air, which reduces DM losses during the filling phase.

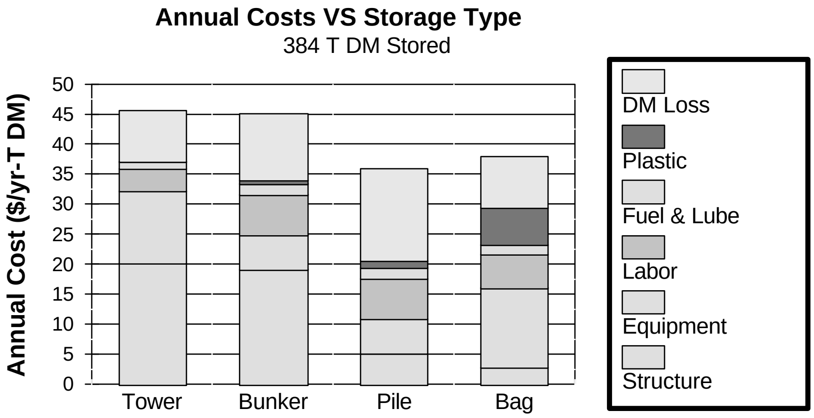

Figure 1. Annual cost/TDM for four storage types storing 384 TDM with good to excellent management.

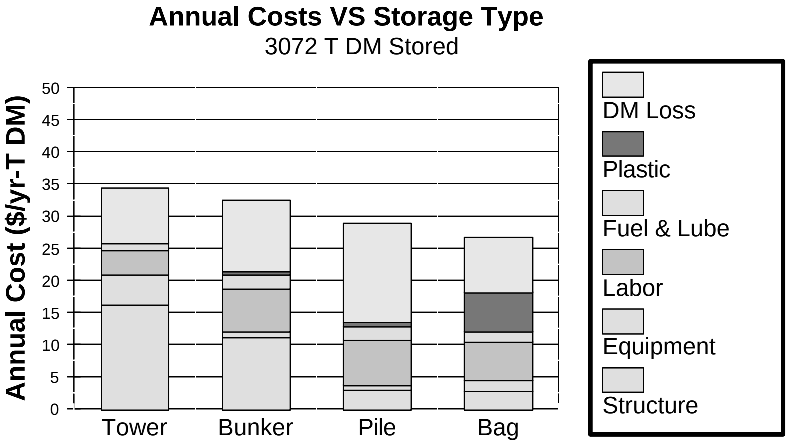

Figure 2. Annual cost/TDM for four storage types storing 3072 TDM with good/excellent management.

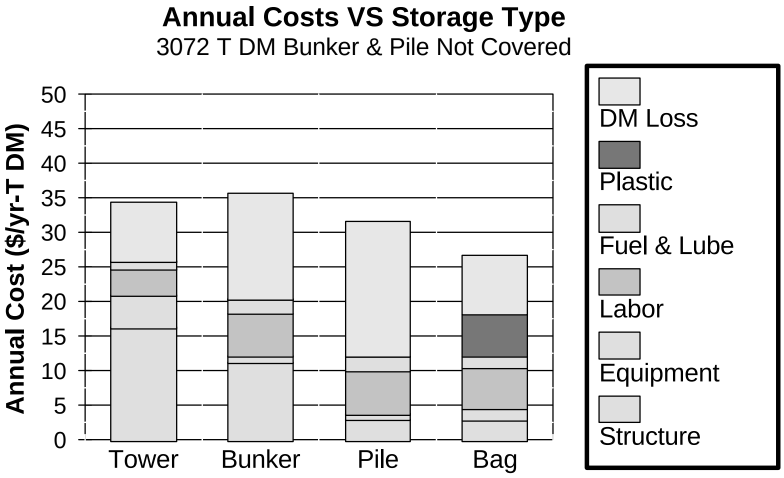

Figure 3. Annual cost/TDM for four storage types storing 3072 TDM with bunkers and piles not covered, resulting in an additional 5% DM loss compared to covering.

Rapid forage harvest and delivery to storage requires a corresponding rapid rate of storage filling. A producer selecting to use a self-propelled forage harvester may see a doubling of forage delivery rate (Table 1) compared to a large pull-behind harvester, provided transportation is also increased. This will require high capacity blowers and larger tractors at the tower silo, larger and perhaps more push-up/packing tractors at the bunker silo, and a self-feeding tray and high capacity bagging machine.

TABLE 1. Forage harvester capacity (Shinners, 1998).

Forage Harvester Type	**Capacity** (tons as fed per hour)	
	Hay	**Corn**
Pull, 200 HP	25	55
Self-propelled, 400 HP	50	120

The desire to improve feed quality drives the need to have rapid harvest and silo filling. As herd size increases, the quantity of forage harvested also increases. However, the window of harvest opportunity remains the same. Thus another reason to increase the harvest rate on many farms is also forced by an increase in herd size. Any bottlenecks in the harvest/delivery system will cause cost increases due to equipment downtime and/or forage quality losses. Some custom operators using high capacity harvesting equipment offer a complete service of harvesting through silo filling. With an adequate complement of equipment and labor force, bottlenecks found on many farms can be eliminated, and rapid harvest/delivery can be accomplished. This service will require a higher out-of-pocket cost to the producer but will be covered by the preservation of feed quality. This will pay dividends when fed in a well-balanced diet to the herd by maximizing productivity while keeping purchased feed costs to a minimum.

Labor cost and availability must be considered when selecting a feed handling and storage system. When forage harvest, transport and storage filling must be performed simultaneously, individual workers commit their labor time simultaneously. An example of this is silage making. When the forage can be stored for a time between tasks, one worker may do each task sequentially, thus reducing the number of workers required at one time. An example of this is large package hay making. Table 2 indicates the minimum number of workers which must be

TABLE 2. Minimum number of workers needed to harvest/store forage.*

Storage Type	**Task**			
	Harvest	**Transport**	**Fill Storage**	**Total Simultaneously**
	Workers Operating Simultaneously			
Bunker/Pile	1	1	1	3
Tower/Bag	1	3/4	1/4	2
Bale/Balage	1/2	1/4	1/4	1

*High harvest rates and/or long transport distances may increase these values.

available at one time. Smaller producers without access to a labor force or unwilling to find and manage a larger labor force may elect to use a forage handling system which uses fewer workers. Some smaller producers have found it beneficial to hire custom operators to perform the harvest/delivery process so as to avoid finding, hiring and managing a labor force during the short harvest windows. Equipment and labor issues become the custom operator's responsibility while the producer needs to deal with only one person.

Feeding Management

Nutritionist balance rations based on animal productivity, feed availability and feed ingredient cost. Producers deliver feed to the herd based on the balanced ration when the feed components specified in the ration are available. Cattle produce at expected levels when they consistently receive adequate quantities of a balanced ration. When the ration changes (either by design or accident), animals must adapt to the change and productivity can suffer. When the change is rapid and of a large magnitude (high quality to low quality forage with added grain supplement to balance the ration), the animal performance reduction can be significant. Consequently, sudden changes of large magnitude should be avoided. Forage storage selection and sizing can play a part in allowing a producer to avoid sudden and large-magnitude changes in ration. Forage storage factors which contribute to sudden changes in forage quality include:

(1) Depleting forage stores before the new crop is harvested and/or fermented.
(2) Forages of different type or quality stored in the same unit with sequential unloading (e.g., corn silage before hay silage, quality hay silage before rained-on hay). Abrupt changes would typically occur in tower silos, bag silos, etc.
(3) Same forages of different moisture contents stored in the same unit with sequential unloading.

Management practices have been used to warn of impending forage quality change so a new balanced ration can be adopted as soon as possible following the beginning of feed out of the different forage. Forage analysis at the time of filling allows for an estimate of forage quality before each is encountered. A measurement of the length of each quality of forage in storage can identify where a transition will occur. In tower silos where the boundary between qualities may move with settling, colored plastic strips can mark the boundary. It might be advisable to have different color plastic strips placed a foot before the boundary to give an early warning of impending change. These practices help to reduce the uncertainty about when the change will occur, which allows the operator to change the ration as close in time as possible to when it is needed. This will reduce the effect of the change on animals as soon as possible. However, the effect of the change cannot be prevented by these practices. The effect is eliminated or minimized when the change is avoided or managed to occur in a gradual manner. Gradual change occurs naturally in bunker/pile silos if they are filled by the progressive wedge method and emptied with a vertical feed-out face. Each day of feed-out results in more of the new forage and proportionately less of the former forage. The time to move through the transition depends on the filling slope, silage height and feed-out rate. With a silage height of 10 feet, a 45° filling slope and a 6-inch face removal rate, the transition will take 20 days, while a filling angle of 30° will require about 35 days to work through the transition.

Another way to avoid sudden change is to store forages of different quality in separate storages. Two or more storages, each of smaller size than one large storage, allow forages of like quality to be stored in each. As a producer anticipates a quality change (i.e., silo to become empty) less can be fed from the first while more is gradually removed from the second, producing a more gradual transition to the new feed. Through this process, adequate removal rates must be achieved from each storage surface to assure minimal DM loss during feed-out.

Storages that lend themselves to this kind of management are silo bags, silage bales and baled hay. Generally, the discrete nature of these storages make this process reasonable in cost and manageable. Characteristics of silage can be written on each bag, and transition zones can be marked on the bag as well. Similar markings can be made on bales wrapped in white plastic. Dry bales of different quality should be stored in separate areas and a storage map developed. Markers can be used to distinguish bales of different quality. Bale storage should be organized so forages of different quality are accessible without having to move other bales. Selecting two tower silos instead of one increases the initial investment and capital cost per ton. Two 90-foot long bunker silos may be less expensive than one at 180 feet long when the common walls are loaded from both sides. There may be a slightly higher capital cost for two silage piles vs. one.

Storing feeds by quality and recording quantity of each is also useful from a feed inventory perspective. At the end of the harvest season, one can estimate quantity and quality of feed which may need to be purchased and establish when the purchased feed will be needed. With adequate storage capacity or off-site storage, purchased feed can be obtained when prices are most favorable vs. when it must be purchased at current market prices toward the end of the stored feed season.

Another area that has an impact on maintaining high quality feed throughout the stored feed feeding season is the gradual loss of forage dry matter with time. Increasing amounts of purchased feed ingredients must be used to compensate for these losses. The losses are influenced by exposure of the forage to oxygen, rain and higher temperature. The longer the exposure, the larger the losses for the remaining silage. Atmospheric temperature cannot be controlled. Therefore, management of the storage is all that is within an operator's control. Temperatures below 40°F limit microbial activity. Above this temperature, the operator needs to exercise special caution when unloading and presenting feed to cattle. Microbial heating of silage can cause appreciable DM loss at the feed-off face. Rapid face removal (more than 6 in/day for bunkers, piles and bags and more than 4 in/day for tower silos) helps to keep ahead of silage spoilage organisms in warm weather. Some people will design storages with smaller unloading face areas for forage which is fed in summer. For a given amount of feed, the removal rate (in/day) will be higher for the small feed-off face. The penetration of oxygen, which supports aerobic microbial activity at the feed-off face, is influenced by the silage density at the face. This density is maximized through the packing process at filling and can be reduced by the feed removal process. Packing in a tower silo is accomplished by gravity. Maximum density is achieved at the bottom and minimum density is at the top. Bunker silos, bags and piles rely on packing equipment to make the silage dense. Little change in density due to height is found in well-packed storages of these types. This is one reason why it is important to manage for high density during the filling process. Using an effective distributer in a tower silo can increase silo capacity by as much as "30% above presently accepted values and 20 % above a commonly accepted passive distributer" (Larsen, 1986). Adjusting the machine for maximum density is important for silo bags. Bunkers and piles must be filled in thin layers (less than 6 inches before packing) and packed with a heavy tractor to achieve high density. Silage of 65-70% moisture chopped to 3/8-inch theoretical length of cut (TLC) is easiest to pack to high density. Feeding considerations may require longer fibers than is produced by 3/8-inch TLC. Extra packing time and/or weight may be required to obtain the desired 14 lbs DM/ft^3 density in a bunker or pile. Silage piles are often constructed by pushing silage up the filling surface with little to no sidewall packing. The steepness of these walls precludes their safe packing. Producers should consider constructing piles with side slopes of 3 horizontal units for each vertical unit (about 18°). These shallow side slopes are safely maneuverable, which allows packing in two directions and throughout the whole surface while filling. Shallow slopes also allow adequate weighting of the plastic cover.

A smooth, tight feed-out face helps exclude oxygen from the silage, thus promoting silage stability. Equipment and practices which promote the tight, smooth feed-out face should be used. Where bunkers/piles are wide enough, an unloading tractor can shear off a slice of silage by forcing the side of the bucket through the silage as the tractor drives from one side of the storage to the other. On narrower bunkers/piles, scraping the bucket edge down the face dislodges feed without major surface disruption. Thin layers are dislodged with this process which often frustrates the tractor operator. Ruppel (1997) suggests a method of face removal where a scoop of silage is removed from the bottom of the face. Subsequently, the edge of the bucket is used to "chip down one section at a time" sequentially into the cavity formed by first removed silage. Ruppel claims this procedure "has been successfully used by many farmers."

No storage is 100% effective at excluding oxygen from penetrating its sides. Concrete is porous to air movement through the material as well as through cracks and joints. Silo doors are porous, especially at the edges. Plastic sheets are porous throughout and are very pervious to air movement at pin holes, larger holes, joints and where it joins bunker walls and the ground. Dense packing of the silage helps to limit the spread of oxygen once it has penetrated the exterior surface barriers, but it is very important to maintain the integrity of the exterior surface barrier. Multiple wraps of plastic provide a good barrier for bale silage. The multiple wraps seal the joints and help reduce pin holes from forming as the interior plastic contacts the hay. Tower and bunker silo walls need cracks filled on a regular basis. Tower silo doors should be sealed as the doors are installed prior to filling the silo. Plastic covers and bags should be checked at 2-week intervals and holes patched. Plastic covers should be sealed well at the edges to prevent oxygen and water from entering the silage. Where the plastic meets the ground or floor of the storage, covering the plastic with soil, sandbags or other heavy, uniform weighting material can do a good job of sealing the edges as long as water can drain away from the edge.. The sides of bunker silo walls pose a more difficult sealing problem. The wall acts as a barrier to water draining over the side of the wall, and the silage settles some with time, thus causing the surface to move down the wall. This makes it difficult to affix the plastic to the wall to obtain a waterproof seal. Sloping the silage away from the wall can create a drainage channel on the silage surface which is then sealed with plastic. If no holes form in the plastic bottom of the drainage channel, water will not enter the silage. Some have tried to line the bottom of the drainage channel with scrap plastic sheets before the bigger cover is applied. Marginal success has been achieved with this method, especially when limited end to end slope is put into the drainage channel.

Sizing Storages

Several factors discussed earlier influence the procedure for sizing forage storages. Silage storages should meet the following criteria:

1. Minimize loss during storage period.
2. Minimize loss during feed-out.
3. Allow for feed inventory.
4. Allow for gradual transition between feeds.
5. Contain the feed harvested or purchased for the desired storage period.

The first criterion is met by providing as much surface area of low oxygen permeable material as possible per unit volume stored. In the case of bunker and tower silos, larger concrete walls and smaller top surface areas are preferred. Larger bags and silage bales have a lower surface area to volume ratio than do smaller units. Dry hay bales protected from rain and ground moisture minimize losses during the storage period (Table 7). Here moisture is the limiting factor for microbial activity. Minimizing loss during feed-out is a function of limiting microbial activity at the feeding face of silages and feed handling systems. Only the amount of feed used in one feeding should be removed from the silo. Excess feed removed from the silo is exposed to more air, and aerobic microbial activity will decrease its quality. Spilled feed should be cleaned up and used as quickly as possible or it will become lost feed. The silo should be designed for an adequate removal rate with some cushion added to allow some flexibility to reduce the feed-out rate as needed and still be above the minimum feed-out rate.

If the storage is sized based on average density, feed needed, face removal rate, reasonable DM loss, and storage period, the storage will automatically be large enough to contain the quantity of that feed needed for the herd. When more feed is produced than is needed, the storage will be inadequate to contain the excess. Some additional storage capacity can be obtained in bunkers and piles by adding some forage to the top. Other types of storages will have to be constructed larger to handle an overflow or another overflow storage could be used (i.e., bags as overflow when towers are the main silo).

Bunker Silo Sizing

Bodman and Holmes (1997) proposed a method of sizing bunker and trench silos. Their method assumes vertical end faces so the wall length is calculated by this system with the walls projecting part way along the end wedges of silage. The other portion of the wedge projects onto the pads on each end of the storage. The sizing procedure they recommend follows these steps.

1. Establish the herd daily feed need for the type and quality of feed adjusted up using the following equation:

$$\textit{Amount of silage to meet daily silage need}\ (lbs\ DM/herd{-}day) = \frac{\textit{total DM intake}\ (lbs/herd{-}day)}{1 - (\%\ \textit{storage loss}/100)}$$

2. Assume a face removal rate.
3. Assume a silage or wall height.
4. Calculate the silo width using this equation:

$$\textit{Bunker width}\ (ft) = \frac{\textit{daily silage need}\ (lbs\ DM/day) \times 12\ (in/ft)}{\textit{removal rate}\ (in/day) \times \textit{density}\ (lbs\ DM/ft^3) \times \textit{wall height}\ (ft)}$$

   If bunker width is less than 16 feet, return to 3. above and use a shorter wall height.

5. Assume a storage period measured in days.
6. Calculate the silo length using this equation:

$$\textit{Silo length}\ (ft) = \frac{\textit{face removal rate}\ (in/day) \times \textit{storage period}\ (days)}{12\,(in/ft)}$$

   If silo length is greater than 150 feet, consider using multiple shorter bunker silos.

Bodman and Holmes (1997) proposed a density of 14 lbs DM/ft^3 at 65% moisture. Table 3 shows a list of densities obtained from research and extension sources. The range of densities is very wide, indicating that management and the material being packed is quite variable. When sizing a storage before a person has experience with a bunker silo, the use of 14 lbs DM/ft^3 is a reasonable value. When a person has a bunker and is interested in establishing how dense the silage has been packed, Bodman and Holmes (1997) suggested marking the bunker wall at the beginning of a removal period. Sum the weight of material placed in the TMR mixer over a period of about a week. Measure silage DM content. Measure the volume of material removed during that week. Calculate the density using this equation:

$$\textit{Density}\ (lbs\,DM/ft^3) = \frac{\textit{weight removed}\ (lbs/ft^3) \times DM\ (\%)/100\ (\%)}{\textit{aver. width}\ (ft) \times \textit{aver. height}\ (ft) \times \textit{length removed}\ (ft)}$$

TABLE 3. Silage DM density in bunker silos.

Crop	Average Density (lbs DM/ft^3)	Min./Max. Density (lbs DM/ft^3)	Standard Deviation (lbs DM/ft^3)	Number of Bunkers	Reference
Alfalfa	14.8	6.3 23.5	4.30	25	Ruppel (1993) Table 2
Barley	14.6	12.1 17.3	1.53	12	Darby and Jofriet (1993)
Grass Alfalfa	16.4	11.0 21.1	2.16	9	Darby and Jofriet (1993)
Grass Packed Heavily	15.7			1	Bosma et al. (undated)
Grass Packed Lightly	14.8			1	Bosma et al. (undated)
Corn	17.7				Holter (1983)
Alfalfa	11.8				Rotz et al. (1989)
Corn	14.0				Isher et al. (undated)
Alfalfa	11.8				Isher et al. (undated)
Forage	10.5-16.8*				Alberta Agriculture (1988)
Forage	12				Cromwell et al. (1989)
Alfalfa	14.8	6.6 27.1		87	Muck and Holmes (1998)
Corn	14.5	7.8 23.6		81	Muck and Holmes (1998)
Alfalfa	16.9**			1	Shinners et al. (1994)
Alfalfa	13.4***			1	Shinners et al. (1994)
Forage	14.0				Bickert et al. (1997)

* Density increasing with height, 8- to 16-foot depth.
** 1/4-inch TLC.
*** 1-inch TLC.

Tower Silo Sizing

Tower silo sizing uses a similar procedure with at least 4 in/day removed from the most dense material (bottom). Since density varies with depth (primarily the top half of the silo), more than 4 in/day in depth will be removed from the top portions for a given quantity removed each day.

The tower sizing process is as follows:

1. The equation used in step 1 above can be used for tower silos, but the % DM loss is

probably lower for a tower than for a bunker silo.

2. If the silo will be greater than 40 feet tall, assume the density in the base of the silo will be about 21 lbs DM/ft^3.
3. Calculate the diameter needed as:

$$D = \sqrt{\frac{daily\ DM\ needed\ (lbs\ /day)\ \times\ 12\ (in\ /ft)\ \times\ 4}{3.14\ \times\ 21\ (lbs\ DM\ /ft^2)\ \times\ 4\ \ (in\ /day)}}$$

   If D > 30 feet, redo the solution for D with a removal rate greater than 4 in/day unless a silo unloader is available to handle silos of greater diameter.
   Round D down to the next even number.
4. Assume a storage period measured in days.
5. Calculate the total quantity needed to store using this equation:

$$Q\ (lbs\ DM)\ =\ daily\ DM\ needed\ (lbs\ DM\ /day)\ \times\ storage\ period\ (days)$$

6. Use a silo table to select the silo(s) that will be no larger in diameter than that calculated in step 3 above and will store at least as much as calculated in step 5 above.

When you have one silo table, you can feel confident you know what is contained in a given size silo. However, when you have a second silo table, you are not so confident. The American Society of Agricultural Engineers (1997) has a standard which contains the values listed in Table 4. These values can be found in Pitt (1990) and a modified version of the table is in Bickert et al. (1997). The International Silo Association (1993) accounted for forage type and moisture content when they developed their silo capacity (Table 5). They also have a different table for smooth-walled silos.

An example of sizing a tower silo follows:
1. Assume 2000 lbs DM/day is needed.
2. Solving for the silo diameter:

$$D = \sqrt{\frac{2000\ (lbs\ DM\ /day) \times 12\ (in\ /ft) \times 4}{3.14 \times 21\ (lbs\ DM\ /ft^2) \times 4\ (in\ /day)}}$$

$$D\ =\ 19.1\ ft$$

   Round this down to $D\ =\ 18\ ft$.
3. Assume a 300-day storage period.
4. Calculating the quantity needed as:

$$Q\ (lbs\ DM)\ =\ 2000\ (lbs\ DM\ /\ day)\ \times\ 300\ \text{days}\ =\ 600{,}000\ lbs\ DM\ =\ 300\ TDM$$

From Table 4, the following combinations of silos meet the design criteria:

Diameter (ft)	Height (ft)	Number
18	68	2
16	60	3
14	60	4

TABLE 4. Approximate DM capacity of silos in tons* (ASAE, 1997)

Silo Height (ft)	**Silo Diameter** (ft)										
	10	12	14	16	18	20	22	24	26	28	30
20	8	12	16	21	27	33	40	47	56	65	74
24	11	15	21	27	34	43	52	61	72	83	96
28	13	19	26	35	44	53	64	76	90	104	119
32	16	23	32	41	52	65	78	93	109	127	145
36	19	28	37	48	62	76	92	109	129	150	172
40	22	32	44	57	72	89	107	127	150	173	199
44		37	50	65	82	102	123	147	172	200	229
48		42	56	74	93	115	140	166	195	226	260
52			64	83	105	129	157	186	219	254	291
56			71	93	117	144	174	207	243	282	324
60			78	102	129	159	192	228	273	309	357
64					142	174	210	250	298	340	391
68					155	190	228	272	324	370	425
72								293	350	400	458
76								314	376	427	489
80								334	392	455	520

* Capacities allow one foot unused depth for settling in silos up to 30 feet high, and one additional foot for each 10 feet beyond 30 feet height.

TABLE 5. DM capacity of tower silos (International Silo Association, 1993)

Diameter (ft)	**Settled Depth** (ft)	**Moisture** (%)*	**Capacity** (TDM)								
			Alfalfa Silage					**Corn Silage**			
			50	**55**	**60**	**65**	**70**	**55**	**60**	**65**	**70**
12	30		22	22	23	24	25	21	22	22	22
	40		31	32	32	35	35	30	30	30	31
	50		39	41	41	42	43	38	39	39	40
14	40		43	44	45	46	49	41	42	42	43
	50		56	58	59	61	64	54	54	54	56
	55		62	64	66	67	71	60	61	61	62
16	50		76	79	80	82	86	73	74	74	74
	60		93	96	98	102	107	90	91	91	91
	65		102	106	108	110	117	99	99	99	99
18	50		98	102	104	106	112	95	95	95	95
	60		122	126	129	136	139	117	117	117	116
	70		145	150	154	160	166	140	140	139	138
20	60		155	160	164	168	176	148	148	147	146
	70		186	192	196	202	211	177	176	172	173
	80		217	224	230	235	246	206	204	203	200
24	60		233	241	246	257	263	219	217	216	214
	70		281	293	296	301	316	262	260	257	253
	80		330	344	348	361	369	305	302	298	293
	90		380	389	400	411	423	348	344	339	333
30	80		546	563	571	577	598	506	496	484	485
	90		631	648	657	669	686	583	572	561	556
	100		716	729	744	758	774	657	648	636	627
	110		802	819	832	852	863	738	724	716	699

* A listed tonnage does not necessarily imply suitable moisture content for stated silo size.

Bag Silo Sizing

To size a bag silo, establish the daily feed need as in step 1 of the bunker silo sizing process earlier. The DM loss for bag silos will be in the range of 8-10%.

2. Assume a DM density. Table 6 presents a list of dry matter densities from several sources. 14 lbs DM/ft^3 is a reasonable value.
3. Assume a bag diameter.
4. Calculate a face removal rate as:

$$R\,(ft\ /day) \ = \ \frac{daily\ silage\ need\ (lbs\ DM\ /day)\ \times\ 4}{density\ (lbs\ DM\ /ft^3)\ \times\ 3.14\ \times\ [\,diameter\ (ft)\,]^2}$$

   Using the 2000 lbs DM from the previous example, 14 lbs DM/ft^3 density and a 10-foot bag, the removal rate is:

$$R \ = \ \frac{2000\ (lbs\ DM\ /day)\ \times\ 4}{14\ (lbs\ DM\ /ft^3)\ \times\ [\,10\ (ft)\,]^2\ \times\ 3.14} \ = \ 1.8\,ft\ \text{»}\ 0.5\,ft$$

   This removal rate should be large enough to keep ahead of spoilage.

5. Assume a storage period, say 360 days.
6. Calculate the bag length as:

$$Silo\ length\ (ft) \ = \ face\ removal\ rate\ (ft/day)\ \times\ storage\ period\ (days)$$

   Thus the bag length needed is:

$$Silo\ length\ (ft) \ = \ 1.8\ (ft/day)\ \times\ 360\ (days) \ = \ 648\ (ft)$$

   Using 14 feet unused plastic in a bag to seal the ends and 200-foot long plastic bags, the number of bags needed is:

$$648\ ft\ /\ (200\ ft\ -\ 14\ ft) \ = \ 3.5\ bags$$

TABLE 6. Silo bag density

Bag Diameter (ft)	**Moisture Content** (%)	**Density (lbs DM /ft^3)**	**Standard Deviation** (lbs DM/ft^3)	**Condition**	**Reference**
10	- - -	2.8	1.20	Corn silage, long chop	Harrison et al. (1998)
10	- - -	2.8	1.60	Corn silage, long chop, processed	
10	- - -	2.7	1.30	Corn silage, medium chop	
10	- - -	3.2	1.26	Corn silage, medium chop, processed	
8	65	13.9	- - -	Corn silage	Derived from Rice (1998)
9	65	13.8	- - -	Corn silage	
10	65	13.4	- - -	Corn silage	
11	65	12.9	- - -	Corn silage	
12	65	13.9	- - -	Corn silage	
8	65	11.8	- - -	Alfalfa	Derived from Rice (1998)
9	65	11.7	- - -	Alfalfa	
10	65	11.4	- - -	Alfalfa	
11	65	11.0	- - -	Alfalfa	
12	65	11.8	- - -	Alfalfa	
9	70	9.1	- - -	Alfalfa	Wright (1998)
8	70	13.0	- - -	- - -	Hegge (1996)
8	65	14.0	- - -	- - -	
8	69	13.9	- - -	Corn silage	Walgenbach (1998)
8	61	13.6	- - -	Alfalfa	
8	65	15.7	- - -	Red clover	
8	59	13.7	- - -	Alfalfa	Mueller (1998)
9	63	12.4	- - -	Alfalfa	
9	54	14.3	- - -	Alfalfa	
9	65	12.4	- - -	Alfalfa	

Sizing Bale Storage

To size a bale storage area, establish daily feed need as in step 1 above of the bunker silo sizing process. DM loss will be about 4% for dry hay bales stored under roof to 50% for dry hay stored on the ground, outside and uncovered (Buckmaster 1993b; Huhnke, undated). Huhnke reports DM loss from round hay bales stored with a variety of protection methods in Table 7.

TABLE 7. Percent DM loss of round dry hay bales

Storage Method	Storage Period Up to 9 Months*	 12 to 18 Months
	DM loss (%)	
Exposed		
On ground	5 - 20	15 - 50
Elevated	3 - 15	12 - 35
Exposed		
On ground	5 - 10	10 - 15
Elevated	2 - 4	5 - 10
Under roof (open sides)	2 - 5	3 - 10
Enclosed barn	< 2	2 - 5

* If used before spring warm-up.

2. Assume an in-storage DM density. This value will be a function of bale density as well as stacking density. Tight packing of high density rectangular bales will give the maximum in-storage density. Round bales stored in single rows yield the lowest density. Tables 8 and 9 list some values of individual bale and in-storage densities for dry hay and bale silage. The in-storage values presented by Huhnke assume a large mass of bales stored with limited effects from a sloping pile edge. Values will be appreciably less for narrow piles (8-18 feet).
3. Assume a storage pad/building width and a pile height. Pile height for round bales stored on end and rectangular bales is the sum of the height of the stacking dimension. For example, two 4-foot long bales stored on end yield an 8-foot tall pile height. The pile height for round bales is listed in Table 10.
4. Assume a storage period
5. Calculate the total quantity of storage needed as:

$$Quantity\ stored\ (lbs\ DM) = daily\ need\ (lbs\ DM/day) \times storage\ period\ (days)$$

6. Calculate the length of the storage pad/building as:

$$Length\ (ft) = \frac{quantity\ stored\ (lbs\ DM) \times width\ (ft) \times height\ (ft)}{density\ (lbs\ DM/ft^3)}$$

Huhnke recommends a 2-foot space between the top of the bale pile and the bottom cord of a truss for inside storage to allow maneuvering room during bale handling. He also suggests leaving at least a 4-foot roof overhang on open walls to reduce exposure to precipitation.

TABLE 8. Table of dry bale density

Bale Type	Dimensions	Density (lbs DM/ft^3)	Conditions	Reference
Round	4' dia × 4'	10.5	Fixed chamber baler	Derived from Harrigan and Rotz (1994)
Round	4' dia × 4' 6' dia × 4'	10.0 10.1		Derived from Harrigan et al. (1994)
Round	5' dia × 4'	11.8	11.0-12.8 lbs/ft^3 range	Huhnke (1993)
Round	5' dia × 4'	6.6	4.9-8.5 lbs/ft^3 range, wet bales forced air dried to 44.7% aver. moisture	Yiljep et al. (1993)
Round	4' dia × 5' 4' dia × 5'	8.1 10.1	36 bales forced air dried, 5.2-11.4 lbs/ft^3 range 49 bales forced air dried, 5.9-14 lbs/ft^3 range	Brandemuehl et al. (1988)
Round	- - -	8.5	Varies widely; bale weight can vary as much as 100% by baler and operator	Buckmaster (1993b)
Round	5' dia × 5'		1000-1200 lb bales, on end stacking	Huhnke (undated)
		5.5-6.5*	2 high	
		5.4-6.7*	3 high	
Round	6' dia ×6'		1400-1600 lb bales, on end stacking	Huhnke (undated)
		5.2-6.2*	2 high	
		5.2-5.9*	3 high	
Round	5' dia × 5'		1000-1200 lb bales, pyramid stacking	Huhnke (undated)
		5.5-6.7*	2 high	
		5.4-6.2*	3 high	

Continued.

Bale Type	Dimensions	Density (lbs DM/ft^3)	Conditions	Reference
Continued from previous page.				
Round	6' dia × 6'		1400-1600 lb bales, pyramid stacking	Huhnke (undated)
		5.4-6.1*	2 high	
		5.2-5.8*	3 high	
Round		10.2-12.8	Hard core bales	Plue (1988)
		8.5-10.2	Soft core bales	
Rectangular large	48" × 52"	14.0-15.0		Shinners (1998)
Rectangular medium	32" × 36"	10.9		Shinners et al. (1996)
Rectangular small	14" × 18"	7.1		Shinners et al. (1996)
Rectangular small	- - -	7.1*		Stover (1952)
Rectangular small	- - -	5.2-6.3*		Sheldon et al. (1961)
Rectangular small	- - -	5.1-6.8		Plue (1988)
Rectangular small	16" × 22"	12.0-14.0		Shinners (1998)
Rectangular small	- - -	5.0-10.4*		Parker et al. (1992)
	- - -	5.1-8.5	Alfalfa	Bickert et al (1997)
	- - -	5.1-6.8	Non-legume	

* Average in-storage density of total stack.

TABLE 9. Round bale silage

Diameter (ft)	**Length** (ft)	**Weight** (lbs)	**Moisture** (%)	**Density** (lbs DM/ft^3)	**Reference**
- - -	- - -	- - -	- - -	10-15 recom-mended	Vough and Glick (undated)
4	(4)*	800-1000	55	7.2-8.9	
5	(4)*	1200-1600	55	6.9-9.2	
6	(5)*	2200-2700	55	7.0-8.6	
4	(4)*	1000-1250	65	7.0-8.7	Harrison and Fransen (1991)
5	(4)*	1500-2000	65	6.7-8.9	
6	(5)*	2800-3500	65	6.9-8.7	
5	4	- - -	53.1	6.8	Yiljep et al. (1993), harvested for forced air drying
4	4	1200	55	10.7	Plue and Haley (1988)

* Bale length assumed by this author to calculate density.

TABLE 10. Pile height of round bales

No. of Bales High	**Bale Diameter** (ft)	**Pile Height** (ft)
1	3	3.0
2	3	5.6
3	3	8.2
4	3	10.8
1	4	4.0
2	4	7.5
3	4	10.9
1	5	5.0
2	5	9.3
3	5	13.7
1	6	6.0
2	6	11.2
3	6	16.4

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