MECHANIZATION: PLANNING AND SELECTION OF EQUIPMENT

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Abstract

The planning and selection of equipment for harvest and handling of forage crops can greatly impact the performance and profitability of a farm. The type and size of equipment used affects the harvested yield and nutritive value of the forage crop as well as production costs. Through interactions with other parts of the farm, these effects can impact market value of the forage, animal intake and performance, delays in other farm operations, other production costs, and ultimately farm profit. Standard procedures and relationships have been developed for determining the most appropriate equipment for a given production system. Because of the large number and complexity of the computations involved, software tools have been created to simplify the process and to develop more comprehensive evaluations that include interactions with forage yield and nutritive value and other parts of the farm. Proper planning and selection of equipment can help assure a profitable operation that meets current and future goals of the farm.

Introduction

Although much of the forage produced in the world is harvested directly by grazing animals, a major portion is mechanically harvested and carried to the animal. Mechanical harvest and storage of forage is required in many areas because cold temperatures and low rainfall prevent year around forage production. Since a continuous supply of forage is required in most animal production systems, at least some forage must be conserved for use in other parts of the year or in other geographical areas where forage production is difficult or expensive.

Mechanized forage production is also used for convenience or better control over the diet of animals. Historically, forage conservation has required considerable labor input for a relatively low value product (per unit of mass). Highly mechanized production systems available today essentially eliminate all direct harvest and handling labor. Forage can be harvested, stored, mixed with other feeds, and fed using various machines. Such harvest and handling provides large amounts of forage that is more consistent in nutritive content. This nutritive value can be measured and used to blend the forage with other feed ingredients to more optimally meet animal nutrient requirements. With better control over the diet, more efficient use of feeds and greater animal production are maintained.

Many options are available for harvest, storage, and handling of forage crops. When developing, designing, or refining the production system used on a given farm, questions often arise regarding the best processes to use and the best size and type of machines to purchase. The system used is dependent upon the climate, the desired final product or end use of the forage, the distance the forage must be transported, and personal preferences of the production manager. Each of these factors affects the cost of production and the potential profitability of the production system. Selecting the best approach and the type and size of equipment required is not an exact science, but management principles are available to guide the selection process for more optimal performance and profitable production.

Planning of Harvest Systems

All possible options available for conserving forage can be divided into two major categories: dry hay and silage systems. The major difference between these approaches is the moisture content of the feed produced. Dry hay production requires a longer field-curing period to reduce the moisture content of the forage to about 20% or less. The normal goal in silage harvest is a moisture content between 70% and 50% dependent upon the type of storage used. Silage can be produced by cutting and chopping a standing crop, or it can include a field curing period where the crop is wilted to a lower moisture content. Direct-cut or wilted forage must be placed in a silo or sealed in plastic to obtain good fermentation in an anaerobic environment.

Both forage conservation methods offer advantages and disadvantages relative to the other. Silage systems enable greater mechanization of the handling and feeding processes. With greater mechanization, less labor is required. The chopped material is also more conveniently used in total mixed rations. On the other hand, silage systems require more power or energy for harvesting, handling, and feeding and a greater investment in machinery and storage structures, both of which lead to greater production costs. Baled dry hay requires less storage volume and is easier to transport and market. Average total crop loss is 24 to 28% when hay is baled and stored in a shed or barn (Rotz and Muck, 1994). Most of this loss occurs during harvest with about 5% loss during storage. Average total loss in silage production is 14 to 24% with about half of this loss occurring during storage. Since neither system offers a clear and consistent advantage over the other, both will likely always be used in animal agriculture.

Hay systems

Many different systems or combinations of machines and processes can be used to produce dry hay. The major approaches commonly used today are illustrated in figure 1. The crop must first be mowed with some type of cutting device. The major mowing options are a cutterbar (or sicklebar) mower and a rotary disk mower. The cutterbar mower uses reciprocating knives to severe the crop from its roots. This machine provides a relatively reliable, low cost method of mowing that has been used for many years. The major disadvantage is limited mowing capacity, i.e. field speed is limited by the cutting capacity of the reciprocating knives.

This limited capacity has led to the development and wide spread use of rotary mowers. With this equipment, forage is cut with knives attached to disks rotating at a relatively high speed. This type of mowing offers virtually unlimited cutting capacity, i.e. field speed is often limited only by the operator’s ability to control the machine. The purchase cost is about 30% more per unit of cutting width, and repair costs may be greater, particularly as the machine ages. Disk mowers require about four times as much power to operate (5.0 kW/m of width compared to 1.2 kW/m for a cutterbar mower; Rotz and Muhtar, 1991). Therefore, a larger tractor is required and more fuel is consumed per hour of use. With faster field speeds, less labor and tractor time are required. All things considered, neither mower type provides a universal advantage.

Most mowing devices used in forage production today include mechanical conditioning to help speed field drying of the crop. A wide variety of conditioning devices are used, but the major options use either rolls or flails. Many different roll designs have been used. Some designs are more aggressive at damaging the crop which speeds drying, but this aggressiveness also increases field loss by disassociating leaves and other small forage particles high in nutritive content. The recommended device for conditioning alfalfa is an intermeshing rubber or plastic roll. Among the common roll devices used and with proper adjustment, little difference has been found in drying rates (Shinners et al. 1991; Rotz and Sprott 1984).

Flail conditioning devices use rotating steel or plastic tines to abrade and break forage stems. These devices were developed in Europe for use in grass forage crops. When used on alfalfa and other legumes, this type of conditioning can lead to inferior drying and/or greater leaf loss dependent upon machine adjustment. In general, roll conditioning devices are recommended for alfalfa and legume based forages and flail devices are recommended for grass-based forages.

Typical losses with well-adjusted mower-conditioners vary between 1 and 5% of dry matter (DM) yield with similar losses for the two major types of mowers (Shinners et al. 1991; Koegel et al. 1985; Rotz and Sprott 1984). Among roll-type conditioning machines, roll design does not have much effect on loss. Adjustment of roll pressure and clearance has more effect than the pattern or material used in the rolls. The difference in loss between a well-adjusted mower-conditioner and a similar mower without a conditioner is 1 to 2% of crop yield. Mowing and conditioning loss is mostly leaves causing a small decrease in the nutritive content of the remaining forage.

As forage dries in the field, the top of the swath dries more rapidly than the bottom. Manipulation of the swath can speed the drying process by moving the wetter material to the upper surface where it dries more quickly. Swath manipulation can also improve drying by spreading the hay over more of the field surface. Spreading exposes more of the crop to the radiant solar energy and drying air. There are three operations used to manipulate hay swaths: tedding, swath inversion, and raking.

Hay tedders use rotating tines to stir, spread, and fluff the swath. Dependent upon how it is used, this treatment can reduce field-curing time by up to a couple days. Tedding may also allow more uniform drying throughout the swath. Losses caused by tedding are normally between 1 and 3% of crop yield, but much greater loss can occur if the crop moisture content gets below 35%. Tedding can also cause greater raking loss. When a light crop (less than 2.5 t DM/ha) is spread over the field surface, raking loss can be more than double that when narrower swaths are raked. In alfalfa, the loss caused by tedding is often greater than the average rain loss avoided by faster drying (Rotz and Savoie, 1991). The decision to use tedding should be made by comparing the probable loss from more time lying in the field to the known loss and cost of tedding. The increased machinery, fuel, and labor costs may only justify routine use of tedding on grass crops in wet climates.

Swath inverting machines provide a more gentle method for manipulating field curing swaths. Various machine designs are used where the swath is lifted, turned, and dropped back to the soil surface inverted from its original position. Exposing the wet bottom layer of the swath speeds drying enough to reduce the average field curing time by a few hours. Although not as effective as tedding in improving drying rate, leaf shatter and the resulting loss are small. With less drying benefit though, there is less reduction in the probability of rain-induced loss. The added labor, fuel, and machinery costs of the operation are likely greater than the benefit received (Rotz and Savoie, 1991).

Raking is normally an important operation in haymaking. It is used to turn or roll together swaths for easier pickup by the baler and to speed drying. Raking hay in the morning of the day in which it is anticipated to be ready for baling can reduce the field curing time by a few hours allowing an earlier start at baling. Raking causes a loss of 1 to 20% of crop yield (Rotz and Muck, 1994). The loss increases as the crop dries, particularly below a moisture content of 30%. Greater loss is generally found with a rotary windrower compared to the more standard side-delivery rake. The rotary windrower uses rotating tines to sweep hay into a windrow. The sweeping action allows more forage material to become entangled with the stubble and lost. Side delivery rakes provide a rolling and wrapping action that reduces entanglement with the stubble and increases entanglement among the plants in the swath.

Hay balers are used to compress and package hay for easier handling. Hay balers are available that produce bales of many sizes and shapes. Advantages and disadvantages are associated with each. Small rectangular bales have been most popular over the past fifty years, but now large round and rectangular bales are becoming the predominate hay packages. Systems are sometimes used to produce small round bales, low-density stacks, and cubes, but these constitute a relatively small portion of the hay produced.

The small rectangular bale is about 36 by 46 cm in cross-section with lengths up to 130 cm. An advantage of small rectangular bales is that the 25 to 35 kg bale can be manually handled in stacking and feeding. A disadvantage though is that this bale handling is labor intensive. During a typical baling operation where hay is transported and stacked in storage simultaneous with baling, up to five people are required. A relatively small tractor of 26 to 45 kW is sufficient to power small rectangular balers. The baler pickup normally extends from the right side of the machine, so the tractor pulling the baler is driven on the left side of the windrow. In a newer design, referred to as the centerline baler, the pickup device is centered behind the tractor with the compression chamber located above the center of the pickup. The centerline design is promoted for better maneuverability and less loss during baling, but less loss has not been found (Shinners et al., 1992).

To reduce the manual labor in bale handling, several labor saving devices have been developed. A popular option is a bale thrower mounted at the exit of the baler. This device throws bales into a trailing wagon, reducing the need for handling and stacking on the wagon. At the unloading site, bales are sometimes dropped from an elevator to avoid stacking in storage. Automatic bale wagons are sometimes used in large operations. These wagons mechanically lift bales dropped on the field surface by the baler. Hydraulically driven mechanisms stack the bales and the completed stack can be transferred to storage.

Large rectangular, high-density bales are becoming more popular, particularly for hay transported long distances. These bales have a height and width of 60 to 130 cm, a length of 120 to 250 cm and a mass of 200 to 1000 kg. Special equipment is thus needed for lifting, transporting, and feeding these large bales. Balers producing these large packages offer greater baling capacity; they are capable of harvesting twice the amount of hay per hour as the small package balers. The centerline design is used in these balers. More power is required with a minimum tractor size of 90 kW recommended for the largest balers.

Large round balers produce bales 90 to 180 cm in diameter and 120 to 160 cm in length with a mass of 200 to 900 kg. Completed bales are transported to the storage site with a tractor mounted loader or a wagon. When bales are not transported simultaneous with harvest, one person can perform the entire operation. Large round balers require more power than small rectangular balers. Recommended minimum tractor sizes vary with baler size from 35 to 55 kW. The power requirement is dependent on the baler design (Rotz and Muhtar, 1991). Fuel and labor requirements with round bale harvest are largely dependent on the method of transport. When bales are hauled to a storage site on wagons, fuel use is comparable to that with small bale systems and labor use is about half. Both labor and fuel requirements can become excessive when bales are individually transported.

Typical DM losses during hay baling vary between 2 and 5% of the yield with the loss equally divided between pickup and chamber losses (Rotz and Muck, 1994). Pickup losses are high when the machine is pulled at a faster speed than the rotating speed of the pickup device. Chamber loss is largely influenced by crop moisture content with greater loss in drier material. When hay is baled at night, leaf moisture is higher, similar to stem moisture, and chamber loss can be cut in half. Chamber loss is mostly high quality leaf material; so excessive chamber loss reduces the nutritive content of the remaining forage. In large round balers, chamber loss is 40 to 300% greater than that in rectangular balers (Koegel et al., 1985). Chamber loss is very sensitive to the feed rate of hay. Excessive loss occurs at low feed rates because the bale is rolled in the chamber too much per unit of hay baled.

Hay is either stored inside a shelter or outside with varying amounts of protection from the weather. When well protected, hay is relatively stable during storage with only minor respiration by microorganisms on the hay. The respiration transforms DM to heat and gases that leave the hay causing DM loss and nutrient change. In dry hay stored under cover, little respiration occurs and DM loss over six months of storage is about 5% (Rotz and Muck, 1994). Hay stored outside and unprotected experiences the same loss as hay stored inside plus additional loss from weathering of hay on the exposed surface. Dry matter loss often increases an additional 10 to 15% with outside storage of large round bales. When hay is stored several months in a humid climate without protection from the environment, DM loss can exceed 30%.

Silage systems

Major options in silage production include field wilting and direct-cut harvest systems (Figure 2). Direct-cut harvest is most often used with corn and other annual grain crops where the standing crop can mature and dry to a moisture content suitable for ensiling (60 to 70% moisture). In very wet climates such as northern Europe, direct-cut harvest of perennial grass crops is sometimes used because field wilting is very difficult. Under these conditions moisture contained in the crop is excessively high, so special facilities are required to capture effluent moisture and plant nutrients that drain from the forage during ensiling. Organic acids are often applied to control the fermentation and improve the ensiling of very wet forage.

Wilted silage production involves the same mower-conditioning and swath manipulation operations used in hay production. Advantages and disadvantages of the various types of machines available are similar to those described above. Tedding and swath inversion type processes would normally not be used in silage production except in very humid climates. Raking is used more for combining swaths or windrows than as a method to enhance drying. For high-capacity forage chopping machines, two or more swaths or windrows are often combined to more fully use the capacity of the machine and to reduce the number of trips across the field with the heavy (soil compacting) equipment used in chopping.

Raking can be avoided by adjusting the mower conditioner to deposit forage in a relatively narrow swath, which is then picked up by the chopping operation following the field-curing period. This can eliminate the labor, fuel, and machinery costs associated with raking. This approach is most often used for a high-yielding forage crop and/or with smaller forage chopping machines.

Most silage is harvested using a precision cut harvester. This type of machine uses a pickup device to lift the crop and feed rolls to uniformly feed the crop into the chopping device. The crop is chopped using a series of knives mounted on a rotating cutterhead that pass a stationary shearbar at a very close tolerance. This type of chopping provides good control over the length-of-cut of the forage for smaller and more uniform particle sizes. Precision cut machines require considerable power. The tractor size required varies from 50 kW for a relatively small chopper to 150 kW for large choppers. Self-propelled machines come with engines that can deliver up to 400 kW for very high capacity harvest.

Forage harvesters include cut-and-throw and cut-and-blow machine designs. Cut-and-throw machines use the cutterhead to chop the forage and throw it through a spout into a trailing wagon or truck. This design is most often used in smaller, lower capacity units. In cut-and-blow machines, the forage flows from the cutterhead into a fan that blows the material through the spout to the trailing wagon or truck. This design requires more power and offers greater throughput capacity.

A flail chopping machine can also be used for forage harvest. This machine uses rotating flails to mow a standing crop or pickup a swath, to chop the forage, and to blow it through a spout into a trailing wagon. This offers a lower cost harvest method for low capacity production systems. The particle size of the harvested forage is relatively long and variable.

Chopped forage can be transported in self-unloading wagons, dump wagons, or dump trucks. The method selected depends upon the harvest capacity required and the type of unloading required at the storage facility. Tower silos require a blower to propel the forage up a pipe to the top of the silo. Self-unloading wagons are most suitable with this handling method. Dump wagons or trucks provide rapid unloading that is most convenient for bunker silo filling. Another option with increasing use is silage bags. Equipment is used to pack silage in long horizontal plastic tubs or bags. This equipment can be used with self-unloading wagons, dump wagons, or dump trucks. The size and number of transport vehicles must be set according to the transport distance and the capacity of the forage chopper. The transport system should always be sized just large enough to prevent idle time in the chopping operation.

Another option for silage production is bale silage. Forage is baled using a large round or rectangular baler at a moisture content between 40 and 60%. As in dry hay, bales must be transported either individually or by wagon. The forage must be sealed in plastic soon after baling to allow proper fermentation and stable storage. Bales can be individually wrapped, wrapped in a long tube, set in a plastic tub, or sealed in individual bags. The amount of plastic required and the cost of that plastic varies considerably dependent upon the type of wrapping used. A tight seal must be maintained throughout the storage period to obtain adequate preservation. This approach provides a more economical and versatile procedure for silage production that is particularly well suited to smaller forage producers.

Labor requirements for silage harvest are normally less than that required for hay harvest, but energy requirements are greater. Silage harvest requires a minimum of two people, one operating the forage harvester and the other conducting the transport and unloading functions. Higher capacity systems often require two transport operators. With bunker silos, an additional person is required at the unloading site to operate a tractor used to load and pack the silo. Fuel requirements range from 12 to 20 liter/t DM, about double that of typical hay harvest systems.

Losses in forage chopping vary from 2 to 6% with similar amounts lost from the pickup and by drift (Rotz and Muck, 1994). Drift losses occur as the chopped material exits the spout of the harvester and travels toward the trailing wagon or truck. Drift losses are influenced by crop moisture content, wind conditions, machine adjustment, and operator skill.

Chopped forage is ensiled in tower silos, bunker silos, or silage bags. Tower and bunker silos are permanent structures requiring a high initial investment. Use of bags eliminates the need for permanent structures and allows segregation of higher quality forage for more efficient allocation in meeting animal nutrient requirements. In silos emptied over a one year period, typical forage DM losses range from 6 to 11% in bottom-unloaded sealed silos or silage bags, 7 to 14% in top-unloaded stave silos, and 10 to 15% in well-managed bunker silos (Rotz and Muck, 1994). When effluent occurs, up to 5% additional DM is lost. The DM lost is primarily highly digestible carbohydrates, which increases the concentration of protein and fiber constituents in the remaining forage.

System selection

The first step in planning a forage production system for a given farm is to select the most appropriate harvest and storage system. As described above, one must select among many available options. Although some systems are best for certain situations, none are generally preferred for all applications. Many factors must be considered when developing a "best" system for a given farm. Factors like the investment in equipment and structures, losses and nutritive changes, and the labor and fuel requirements are important considerations. Other factors like timeliness of harvest, speeding the drying process, reducing the number of machine operations, and labor availability may also be important considerations or constraints in the decision making process.

Losses in forage production and their effect on animal intake and production should always be considered. Average harvest and storage losses are between 20 and 30% for most forage systems (Figure 3). Losses are less in direct-cut silage systems when the silage is well preserved with little effluent loss. Harvest losses are greater in hay systems compared to silage systems, but hay storage losses are less if inside storage is used. The loss in all systems is primarily leaves and soluble carbohydrates extracted from the plant tissue. The total loss typically causes a substantial gain in fiber concentration with the potential for a small loss to a small gain in crude protein concentration (Rotz and Muck 1994). These changes often increase the need for supplemental feeds, and they may limit animal intake and performance. The loss of feed value to animals consuming the forage is therefore greater than the DM loss.

The economics of forage production is perhaps the most important consideration in the selection process. Economic values can be assigned to nearly all the relevant considerations. By totaling all costs, a total cost of production can be obtained. More detail on calculating production costs will be discussed in the following sections. When a comprehensive and complete economic evaluation is done among available alternatives, normally the lowest cost or most profitable system is selected.

Although a general recommendation cannot be made across farms, general guidelines or considerations can be made for planning or selecting the most appropriate production system:

1. Cutterbar and rotary disk mowers have offsetting advantages and disadvantages. Rotary disk mowers are most useful when greater harvest capacity is needed in the mowing operation.
2. The added investment for conditioning forage can be justified in essentially all forage harvest systems in any climate.
3. For most efficient field drying, relatively wide swaths should be dropped by the mowing device and raked prior to harvest.
4. Tedding is most useful for grass-based forages harvested in cool, wet climates.
5. When environmental conditions allow the production of high quality dry hay, this hay will normally provide a more nutritious feed for high-producing animals than can be obtained in silage production.

6. Hay systems normally require a lower investment in equipment and structures compared to silage systems allowing them to be more economical for smaller operations.
7. Some type of shed or structure can normally be justified for hay storage except perhaps in very dry climates.
8. Outside storage of large round bales can be appropriate when bales are kept off the soil, the bales are relatively large in diameter, or a relatively small amount of the hay is used in animal rations (Harrigan and Rotz, 1994).
9. Systems using small rectangular bales can require twice the labor input of large bale systems. Large bales require less manual labor for lifting and handling. Fewer people can complete the harvest and transport of large round bales, but more of their time may be required.
10. When hay is transported relatively long distances, large high-density rectangular bales are generally preferred.
11. In cool or wet climates, silage production provides the most reliable and consistent feed source.
12. When forage is produced and fed on large dairy or livestock operations, silage provides a more economical, high capacity, and fully mechanized system of feed production.
13. In silage systems, manual labor is replaced by mechanical power, so substantially more fuel is required.
14. Bale silage generally has higher labor requirements and production costs than other forage production systems, but it can be preferred on smaller operations or when it is desirable to use the same equipment for both dry hay and silage production.
15. Tower silo, bunker silo, and bagged silage storage methods tend to have offsetting advantages and disadvantages. Bunker silos normally produce lower quality feed, but they are often preferred in large, high capacity silage production systems where rapid filling is required.

Selection of Equipment

After the general system for forage production is selected, the next step in the planning process is to select the most appropriate size and type of equipment. Principles and procedures for machinery selection and sizing are well developed and documented (Hunt, 1999; ASAE, 1999a; ASAE 1999b). Although a complete description of these principles is beyond the scope of this paper, a summary of the more applicable procedures for forage equipment are described.

Principles of machinery selection

Machinery is selected by determining the amount of work that must be completed in a given time period and then matching this requirement to the capacity of the equipment needed. In forage harvest, the required work is the quantity of forage that must be harvested for any given harvest. The equipment should be sized to complete the most difficult harvest. For perennial forages, the most difficult harvest is normally the first harvest in late spring or early summer. This crop normally has the highest yield, and weather conditions are generally less favorable than occur in later harvests.

The harvest capacity required is the crop yield times the land area divided by the time available for harvest. The time available is the most difficult parameter to estimate. It is related to the length of the harvest window, the number of days within that window that are suitable for harvest, and the number of hours suitable for harvest on a given suitable day. For most forage crops, an acceptable window is to complete the harvest within two weeks. The number of days suitable for harvest within that window will vary greatly dependent upon the climate. The normal procedure is to use the minimum number of suitable days available in 8 out of 10 weather years. In very dry climates, equipment can be sized assuming that 70 to 80% of the days in the window are suitable for harvest operations. In more humid areas, this value is much less, in the range of 20 to 40%. The number of hours available within a given day will also vary with the climate. In dry climates hay baling can be done for many hours of the day and night, but in humid climates suitable crop conditions may only be available for 4 to 6 hours per day.

As an example, consider 50 ha of forage yielding 4 t DM/ha harvested in a humid northern climate. If 30% of the days are suitable for harvest operations, about four days are available in a two-week period. Assuming six available hours per day, 24 h are available to complete the operation. The required capacity of the harvest system is 2.1 ha/h or 8 t DM/h.

The capacity of harvest machines is related to swath width, field speed, maximum throughput of the machine, and available power. Because harvest capacity is so variable with crop conditions, equipment suppliers normally do not provide an estimated capacity for individual machines. With experience on a given crop, a suitable field speed can be determined for a given yield and swath width. Harvest capacity can then be determined from the product of crop yield, swath width, field speed, and field efficiency (ASAE, 1999a). Field efficiency accounts for nonproductive time such as slowing to turn at the end of the field or stopping to switch wagons, unload bales, sharpen knives, adjust machines, and similar activities. Field efficiencies range from a low of about 60% for some round baling operations to as high as 90% for mowing and raking in large fields.

As an example of determining machine capacity, consider a medium sized forage harvester chopping the crop yielding 4 t DM/ha. With a swath width of 5.6 m (double windrow), a field speed of 5.5 km/h and a field efficiency of 70%, the harvest capacity is 8.6 t DM/h. This harvester would thus meet the required capacity of the above example.

After the harvester is sized, a tractor can be selected to match this machine. Often equipment suppliers list a maximum tractor size for a given machine. This provides a good guide for selecting an appropriate tractor. Generally, a tractor should be used that is within 70 to 100% of the maximum recommended size. Using a larger tractor could lead to damage of the implement. Using a smaller tractor may overload and damage the tractor, and it will slow the harvest operation.

Procedures are also available for calculating the power requirement of an operation as a function of the implements throughput capacity, implement and wagon weight, and field slope (ASAE, 1999a). Tractors can then be sized allowing for some power loss and reserve power for extra difficult conditions (ASAE, 1999b). Specific energy or power requirements have been summarized for the major forage harvest operations (Rotz and Muhtar, 1992; ASAE, 1999b). Without showing the detailed calculations, the medium-sized forage harvester above should be operated with an 80 kW tractor. This satisfies the power requirement of the harvester allowing an additional 30% for reserve power and power loss.

After the harvest equipment is selected, transport and unloading equipment must be selected to appropriately match the harvest capacity. When transport and unloading operations are done simultaneous or in parallel with harvest, the transport and unloading capacities must equal or exceed the capacity of the harvester preventing any idle time for the harvester. If transport or unloading limits harvest capacity, harvest capacity decreases and production costs increase. The number and size of transport wagons or trucks must be set considering the hauling distance and the total time required to make a full cycle for filling, transport, and unloading.

The unloading rate should also exceed the capacity of the harvester. When an unloading operation such as a forage blower is used where the transport unit must remain during unloading, then the unloading time must be included when determining the transport cycle time and the resulting transport capacity. For a dump wagon or truck, this is not necessary and thus the transport cycle time is shortened. The unloading equipment must still be able to process the load of forage before the next load arrives. For high capacity silage harvest systems, transport and dumping into a bunker silo provides a relatively high capacity operation. A common problem can still occur when large self-propelled harvesters are used. Silage flows to the silo at a high rate that does not allow adequate time for silage packing. This leads to less dense silage, poor fermentation, greater loss, and more rapid deterioration of the silage during the emptying and feeding process. To eliminate this problem, more packing tractors must be used.

For further refinement of machinery sizes and types, an economic analysis can be used. With this approach, the total cost of production of the harvest system must be determined and compared among feasible machinery options to select the least-cost option. Total cost is the sum of all ownership and operating costs for the production system. Mathematical procedures for calculating these equipment costs are available (Hunt, 1999; ASAE, 1999a). Fixed costs include the depreciation of the initial machine cost, the interest on the investment in the equipment, and a small cost for taxes, insurance, and shelter of the equipment. Considering that about 70% of a machines initial value is lost over the first 10 years of its life and an inflation adjusted interest rate of 6%/year, a reasonable estimate for annual depreciation and interest costs is 11% of the initial cost. When equipment is not taxed, an annual fixed cost can be estimated at 12% of the initial cost allowing 1% for insurance and shelter costs.

Operating costs include repairs, maintenance, fuel, labor, and material costs such as plastic and twine. Repair and maintenance cost data have been collected and summarized for many types of equipment and mathematical models have been developed to predict these costs over a machines useful life (Rotz, 1987; ASAE, 1999b). For normal use, a rough estimate of the annual repair and maintenance cost of forage equipment is 4% of the initial cost. With heavy use, this annual cost may be higher at 6 to 8%.

To determine fuel cost, fuel use must be known for the operation. Models are available for predicting fuel use as a function of tractor size and the power requirement of the operation (ASAE, 1999a). As an estimate, diesel fuel use can be determined by multiplying 0.22 liter/kW-h by the tractor size (kW) and the time (h) required to carry out the operation. Fuel cost can be increased 15% to cover the cost of lubrication oil.

Labor costs are normally the easiest to calculate. The annual labor cost of an operation is the product of the hourly wage rate, the number of people required to perform the operation, and the time required to complete the operation.

Material costs vary widely among harvest systems. Operations such as mowing and raking require no materials; others like round bale silage require considerable use of plastic. Material costs range from about $1/t DM for baling twine up to $20/t DM for plastic on individually wrapped bales of bale silage.

An additional cost is the cost of forage losses and nutritive changes that occur during harvest and storage. As an estimate of this cost, the total DM loss can be multiplied times the value of premium quality forage. This estimate would not necessarily reflect nutritive losses. The value or cost of nutritive changes is particularly difficult to estimate because it depends upon the animals fed and the type and value of other available feed ingredients. A sophisticated model of animal nutrient requirements is needed to determine this value. A ration balancing program can be useful for estimating the value of forage nutritive changes (VandeHaar et al., 1987). Because of the difficulty in determining reliable costs for nutritive losses, they are often ignored in machinery selection and planning.

To complete the economic evaluation, the timeliness cost of not getting the work done on time must be included. Otherwise, small low cost equipment would always be preferred. When equipment is too small, the crop is not harvested at its optimum yield and nutritive level. Timeliness cost is particularly difficult to estimate in forage harvest due to rapid declines in nutritive content and the affect that delay can have on later harvests. A general estimate for the timeliness cost in haymaking is 1.8% of the maximum crop value per day of delay beyond optimum harvest (ASAE, 1999b). A more accurate assessment can only be attained by monitoring or predicting changes in hay yield and nutritive value over time.

By totaling all costs for each production option, the least cost option can be selected. Calculating and comparing production costs can be laborious. Computer software tools are thus very useful for assisting this process.

Software aids for forage equipment selection

A number of software tools have been developed to assist the planning and selection of equipment systems for agricultural production. These tools can be grouped into three categories: economic models, selection models, and simulation models. Economic models are the simplest and most common type. These models calculate the total ownership and operating costs of individual machines, machine operations, or machinery systems. Normally many of the machine parameters are preset to reduce data input, thus making the model easier to use.

One particular economic model is well suited for use in evaluating and comparing forage systems. This program, developed at Oklahoma State University, is called AGMACH$, Agricultural Field Machinery Cost Estimator. The program, developed for a Windows operating system, is available on the Internet at http://www.dasnr.okstate.edu/agmach/. By providing information on machine or operation type, purchase price, operating width, field speed, and tractor size, the total cost per unit of field area and per hour of use are calculated. A sequence of several operations can be analyzed to determine the total cost of production. This tool can assist farm management decisions by providing a comparison of costs among several production systems and machines of different size. A drawback of this approach though is that the timeliness cost of not completing the work within a reasonable window of time and the cost of forage losses and nutritive changes are not considered.

Machinery selection models have been developed to select an optimum set of machinery for a given cropping system (Rotz et. al., 1983; Siemens, 1997). This type of model uses the principles of machinery sizing and economic evaluation described above to develop feasible machinery sets and to select the economically optimum set for a given farm size and crop rotation. The timeliness cost for delay in planting or harvest can be included with the production costs providing the optimum or overall least cost machinery system for completing the work. This type of model has worked well for selecting equipment for annual grain crops, but it has not been successfully applied to forage crops. The variable effects of delayed harvest on crop nutritive value and the interaction of a harvest on succeeding harvests lead to a more difficult and comprehensive modeling approach.

Simulation models provide this other approach where the impact of machinery selection and size is integrated with the whole farm. The Dairy Forage System Model (DAFOSYM) is a tool that was developed to evaluate the long-term economic and environmental impacts of alternative forage production strategies on dairy and cash crop operations (Savoie et al. 1985; Rotz et al., 1989; Borton et al., 1997). The model simulates crop production, feed use, and the return of manure nutrients back to the land over many years of weather for a given location and farm. Growth and development of alfalfa, grass, corn, small grain, and soybean crops are predicted on a daily time step from soil and weather conditions. Performance and resource use in tillage, planting, and harvest operations are functions of the size and type of machines used and the weather conditions. Field drying rate, harvest losses, and nutritive changes in crops are related to the weather, crop conditions, and machinery operations used. Losses and nutritive changes during storage are influenced by the characteristics of the harvested crop and the type and size of structures used for storage.

Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of animals making up the dairy herd. Animal diets are formulated with a cost-minimizing linear program to meet fiber, energy, and protein requirements using supplements to compliment the available forage. Nutrient flows through the farm are modeled to predict potential nutrient accumulation in the soil and loss to the environment.

Simulated performance is used to predict production costs, income, and net return or profit of representative farms for each weather year. By modeling several alternatives, the effects of system changes can be compared including resource use, production efficiency, environmental impact, and profitability. The distribution of annual values obtained can be used to assess the risk in using a particular technology or strategy as weather conditions vary. DAFOSYM is available on the Internet at http://pswmrl.arsup.psu.edu. This program also functions in a Windows operating system.

DAFOSYM can be used in the planning and selection of forage production systems by comparing long-term farm profitability for several options. This profitability integrates production costs with the impact of timeliness on forage nutritive value and the interactions between forage production and other parts of the farm. The model can be used to compare a wide range of options including machine type and size, bale type and size, production method (hay vs. silage), and storage method (Rotz et al., 1989; Harrigan et al., 1994; Rotz et al., 1993).

General guidelines for equipment selection

The planning and selection of the appropriate equipment for forage conservation must be specific to an individual farm. The type and size of machinery used is dependant upon climatic conditions, type of forage grown, nutrient requirements of animals fed, marketing requirements of forage sold, interactions with other cropping enterprises on the farm, preferences of the farm manger or management team, and the availability of capital, labor, and other resources. Normally a forage enterprise is developed in steps, building upon current practices. Therefore, the “best” next step may not lead toward the overall “best” system. Good planning requires much thought along with some calculations or the use of management tools as described above. Such planning should always consider the long-term goal of the operation, i.e. not just meeting the needs of the immediate problem or challenge. The best decisions will be made using an objective assessment of the needs of the operation rather than a subjective approach that relies on personal preferences and marketing tactics.

Although equipment selection should be done specific to the needs of the farm, general guidelines can be made for the most suitable type and size of equipment needed to harvest various amounts of forage (Tables 1 and 2). The equipment used in these systems is that commonly available in developed countries at the current time. Information provided for each system includes the range in annual forage production that justifies the use of the equipment set, the range in labor required to harvest and handle the hay, and a range in the total cost of production for each system. This information was generated through a series of simulations and analyses using the DAFOSYM and AGMACH$ software packages described above.

Eight equipment systems are listed in Table 1 for producing quantities of dry hay over the range of 100 to 5000 t DM per year. These include small rectangular bale, large round bale, and large rectangular bale systems. As an example for a farm producing 500 t DM of forage per year, a large mower-conditioner (4.0 to 4.3 m cutting width), a tandem rake and a large baler would satisfactorily complete the work. The baler could be either a small rectangular or round bale type depending upon the handling and feeding requirements of the farm. If forage production on the farm is growing, the smaller of the large rectangular bale systems should be considered. It may not provide the lowest production cost at the current time, but it would position the farm for growth and the addition of more forage production.

A comparison of capacities, labor requirements, and production costs for a variety of silage harvest and handling systems are listed in Table 2. Round bale silage systems are best suited to the smaller, low-capacity operations. They are particularly well suited to those operations where it is desirable to use the same equipment for both dry hay and wilted silage production. Although the labor requirement and production costs are high, this system eliminates the need for a silo. Silo storage costs are typically in the range of $15 to 20/t DM of forage stored in the structure. Direct-cut silage systems offer a little higher capacity, lower labor requirement, and lower production cost compared to wilted silage systems. As described above though, direct-cut harvest is only suitable for the harvest of certain crops or under certain crop and climatic conditions. In North America, corn silage is commonly harvested using a direct-cut system, whereas harvest of alfalfa, grass, and small grain forages normally includes field wilting.

More than one type of forage production may be used on a given farm, and this should be considered in equipment selection. Often, both dry hay and wilted silage are produced, perhaps from the same crop. This may justify the use of a larger mower-conditioner or rake than would be required for either forage type alone. Likewise, a direct-cut system may be used for corn silage while a wilted silage system is used for alfalfa and grass crops. This could justify the use of a larger chopper, transport vehicles, and unloading equipment then would be recommended for either crop alone. Thus as the total amount of forage produced on the farm increases, larger equipment can generally be justified and the production cost per unit of forage can be reduced.

Conclusions

1. Planning and selection of forage equipment is a complex process that must consider the productivity of the whole equipment system, costs of production, the effect on forage yield and quality, and the interactions between forage production and other parts of the farm.
2. Standard procedures and mathematical relationships have been developed to assist the selection and sizing of equipment for forage production (ASAE, 1999a; ASAE 1999b).
3. Software tools are available that help reduce the mathematical computation, improve the accuracy, and include the less tangible costs in equipment selection such as timeliness effects on forage yield and nutritive value and the interaction between forage production and other parts of the farm.

4. Equipment selection is farm specific but general guidelines on the capacity, labor requirements, and production costs of various dry hay and silage harvest systems can assist this selection process.

References

ASAE Standards, 46th Ed. (1999a). EP496, Agricultural machinery management. St. Joseph, MI:ASAE.

ASAE Standards, 46th Ed. (1999b). D497, Agricultural machinery management data. St. Joseph, MI:ASAE.

Borton, L.R., Rotz C.A., Black J.R., Allen M.S. and Lloyd J.W. (1997). Alfalfa and corn silage systems compared on Michigan dairy farms. Journal of Dairy Science, **80:** 1813-1826.

Harrigan, T.M., Rotz C.A. and Black J.R. (1994). A comparison of large round bale storage and feeding systems on dairy farms. Applied Engineering in Agriculture, **10:** 479-491.

HUNT, D. (1999). Farm power and machinery management, 9th edition. Ames: Iowa State University Press.

Koegel, R.G., Straub R.J. and Walgenbach R.P. (1985). Quantification of mechanical losses in forage harvesting. Transactions of the ASAE, **28:** 1047-1051.

Rotz, C.A. (1987). A standard model for repair costs of agricultural machinery. Applied Engineering in Agriculture, **3:** 3-9.

Rotz, C.A. (1995). Loss models for forage harvest. Transactions of the ASAE, 38, 1621-1631.

Rotz, C.A., Abrams S.M. and Davis R.J. (1987). Alfalfa drying, loss and quality as influenced by mechanical and chemical conditioning. Transactions of the ASAE, **30:** 630-635.

Rotz, C.A., Borton L.R. and Black J.R. (1991). Harvest and storage losses with alternative forage harvesting methods. Proceedings Forage and Grassland Conference, American Forage and Grassland Council. Georgetown, TX, 1991. pp. 210-213

Rotz, C.A., Black J.R., Mertens D.R. and Buckmaster D.R. (1989). DAFOSYM: A model of the dairy forage system. Journal of Production Agriculture, **2:** 83-91.

Rotz, C.A. and Muck R.E. (1994). Changes in forage quality during harvest and storage. In: Fahey G.C. et al. (eds) Forage quality, evaluation and utilization. American Society of Agronomy, Madison, WI. pp. 828-868.

Rotz, C.A. and Muhtar H.A. (1992). Rotary power requirements for harvesting and handling equipment. Applied Engineering in Agriculture, **8:** 751-757.

Rotz, C.A., Muhtar H.A. and Black J.R. (1983). A multiple crop machinery selection algorithm. Transactions of the ASAE, **26:** 1644-1649.

Rotz, C.A., Pitt R.E., Muck R.E., Allen M.S. and Buckmaster D.R. (1993). Direct-cut harvest and storage of alfalfa on the dairy farm. Transactions of the ASAE, **36:** 621-628.

Rotz, C.A. and Savoie P. (1991). Economics of swath manipulation during field curing of alfalfa. Applied Engineering in Agriculture, **7:** 316-323.

Rotz, C.A. and Sprott D.J. (1984). Drying rates, losses and fuel requirements for mowing and conditioning alfalfa. Transactions of the ASAE, **27:** 715-720.

Savoie, P. (1988). Hay tedding losses. Canadian Agricultural Engineering, 30, 39-42.

Savoie, P. and Beauregard S. (1990). Hay windrow inversion. Applied Engineering in Agriculture, **6:** 138-142.

Savoie, P., Parsch L.D, Rotz C.A., Brook R.C. and Black J.R. (1985). Simulation of forage harvest and conservation on dairy farms. Agricultural Systems, **17:** 117-131.

Siemens, J.C. (1997). Field machinery selection using simulation and optimization. In Peart and Curry (eds) Agricultural Systems Modeling and Simulation, Marcel Dekker, pp. 543-566.
Shinners, K.J., Koegel R.G. and Straub R.J. (1991). Leaf loss and drying rate of alfalfa as affected by conditioning roll type. Applied Engineering in Agriculture, **7:** 46-49.
Shinners, K.J., Straub R.J. and Koegel R.G. (1992). Performance of two small rectangular baler configurations. Applied Engineering in Agriculture, **8:** 309-313.
Vandehaar, M., Bucholtz H., Beverly R., Emery R., Allen M., Sniffen C. and Black R. (1987). Spartan Dairy Ration Evaluator/Balancer version 2.01, User's manual. Cooperative Extension Service, Michigan State University, East Lansing.

Table 1 - Harvest capacities, labor requirements, and costs of typical hay harvest systems.

Harvest system	Capacity* t DM/yr	Labor† hrs/t DM	Cost‡ $/t DM
Small rectangular bale systems			
Mower-cond. (2.8-3.0 m), rake, small baler, 2 wagons	100 - 300	2.3 - 1.5	76 - 46
Mower-cond. (3.7-4.0 m), tandem rake, medium baler, 3 wagons	200 - 400	1.6 - 1.1	57 - 40
Mower-cond. (4.0-4.3 m), tandem rake, large baler, 4 wagons or automatic bale wagon	300 - 600	1.1 - 0.6	45 - 32
Round bale systems			
Mower-cond. (2.8-3.0 m), rake, small baler, wagon	100 - 300	1.5 - 1.3	74 - 49
Mower-cond. (3.7-4.0 m), tandem rake, medium baler, 1-2 wagons	300 - 500	1.2 - 1.0	47 - 40
Mower-cond. (4.0-4.3 m), tandem rake, large baler, 2 wagons or truck	500 - 800	1.0 - 0.8	36 - 31
Large rectangular bale systems			
Self-propelled (SP) windrower (4.9 m), tandem, Rake, mid-size baler, bale wagons or truck	500 - 3000	0.8 - 0.5	43 - 20
Two SP windrowers (4.9 m), heavy duty tandem rake, large baler, bale wagons or truck	2000 - 5000	0.5 - 0.3	34 - 26

* Total annual production of dry hay.
† Total labor requirement in person-hours/t DM of dry hay produced.
‡ Total production cost including equipment depreciation, interest on equipment investment, insurance, shelter, repairs, maintenance, fuel, labor, and material (twine) costs.

Table 2 - Harvest capacities, labor requirements and costs of typical silage harvest systems.

Harvest system	Capacity* t DM/yr	Labor† hrs/t DM	Cost‡ $/t DM
Round bale silage systems			
Mower-conditioner (2.8 m), rake, medium baler, wagon, bale wrapper	200 - 500	1.9 - 1.5	100 - 85§
Mower-conditioner (3.7-4.0 m), tandem rake, large baler, 2 wagons or truck, bale wrapper	500 - 800	1.3 - 1.1	60 - 50§
Wilted silage systems			
Mower-conditioner (2.8-3.0 m), rake, small chopper, 2 wagons, blower	200 - 500	1.3 - 1.0	65 - 45
Mower-conditioner (3.7-4.0 m), tandem rake, medium chopper, 3 wagons, bunker packing	400 - 800	1.1 - 0.9	57 - 40
Mower-conditioner (4.0-4.3 m), tandem rake, large chopper, 3 wagons, bunker packing	500 - 1500	0.9 - 0.7	41 - 29
Self-propelled (SP) windrower (4.9 m), tandem rake, large SP chopper, dump trucks, bunker packing	1000 - 3000	0.7 - 0.6	54 - 32
Direct cut silage systems (corn silage)			
Small chopper (1 row), 2 wagons, blower or bunker packing	200 - 800	0.7 - 0.5	44 - 27
Medium chopper (2 row), 3 wagons, blower or bunker packing	400 - 1200	0.7 - 0.5	32 - 22
Large chopper (3 row), 3 wagons or 2 dump trucks, blower or bunker packing	800 - 2000	0.5 - 0.4	23 - 18
Large SP chopper (4-6 row), 3 dump trucks, 2 bunker packing tractors	2000 - 5000	0.3 - 0.2	20 - 15

* Total annual production of silage.

† Total labor requirement in person-hours/t DM of silage produced.

‡ Total production cost including equipment depreciation, interest on equipment investment, insurance, shelter, repairs, maintenance, fuel, labor, and material (plastic) costs.

§ Includes cost of plastic wrap. For comparison to other systems, include a silo cost of $15 to 20/t DM of stored silage in wilted and direct cut silage system costs.

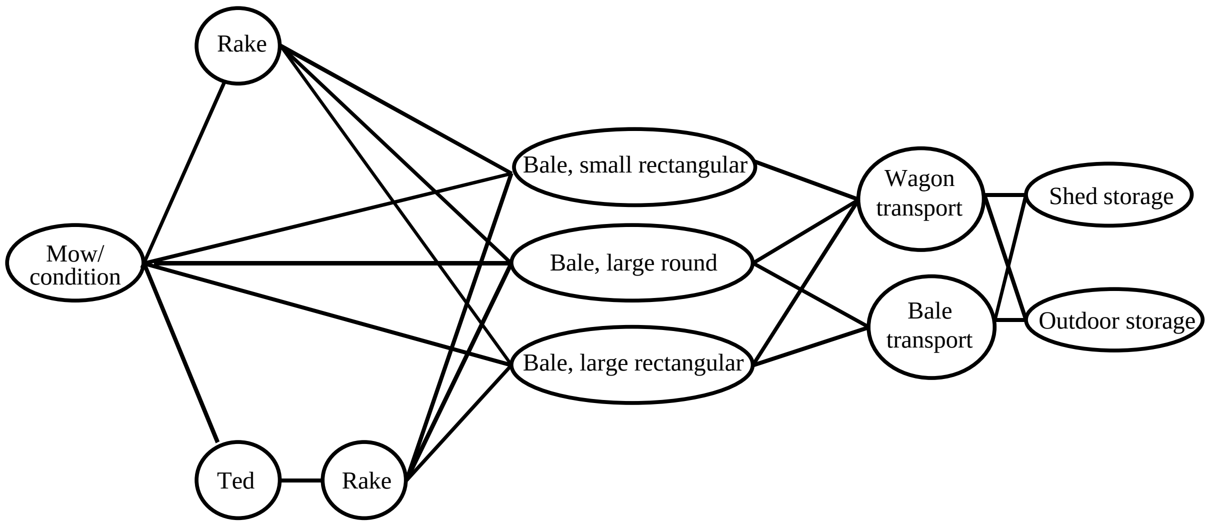

Figure 1 - Major options for harvest and handling of field-cured dry hay.

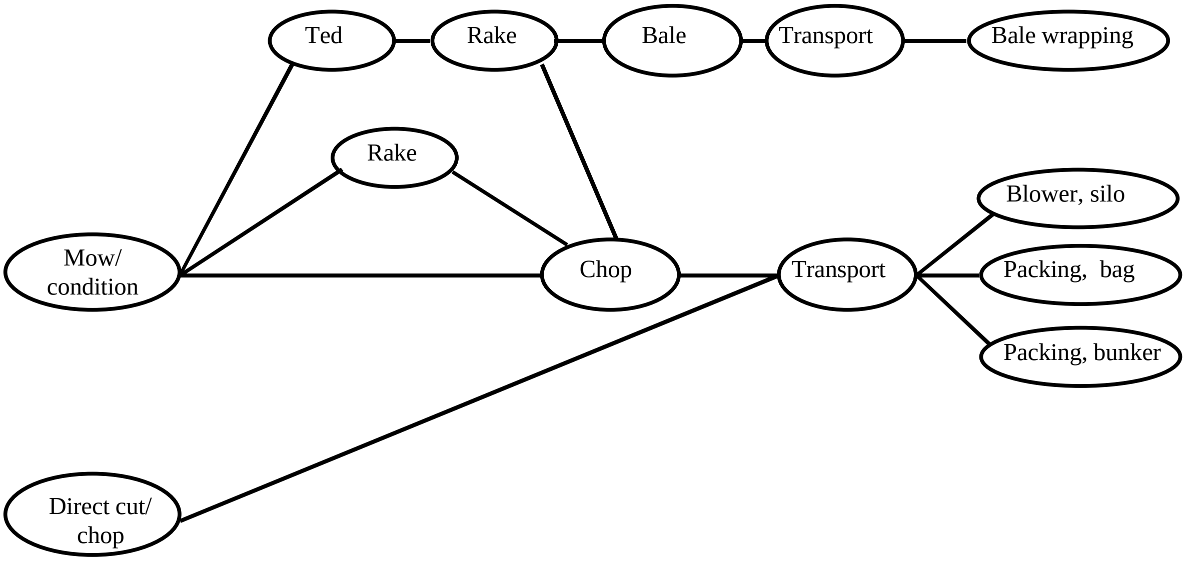

Figure 2 - Major options for harvest and handling of silage.

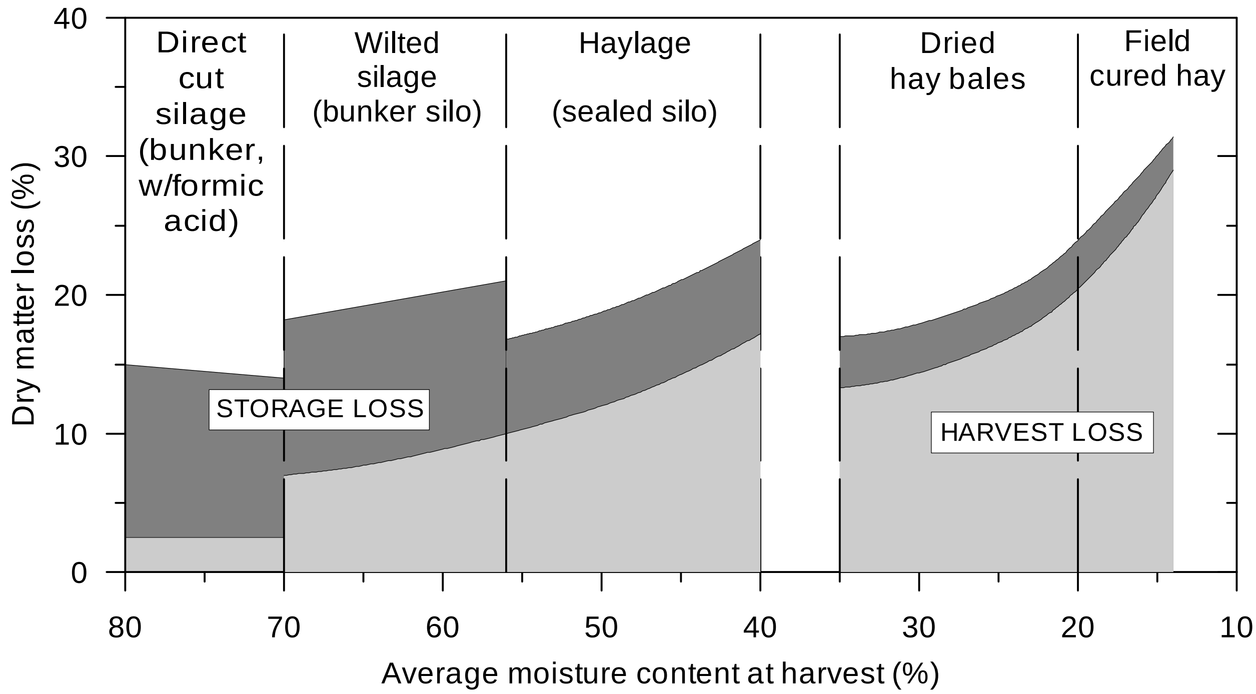

Figure 3 - Typical dry matter losses during the harvest and storage of different types of forage (Rotz et al., 1991).