11 Silages in Farming Systems

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Silage is normally produced and used in a farming system where it interacts with many other farm components. Silage from corn (*Zea mays* L.), alfalfa (*Medicago sativa* L.), perennial forage grass, and small grain crops can be produced on the same farm along with grain crops where they are used to feed one or more types of animals. In addition to silage, some of the forage can be grazed or conserved as dry hay. The many aspects of forage production and use along with the other aspects of farm production create a complex system. Thus, silage production cannot be studied in isolation from other parts of the farm.

Pasture, dry hay, and silage each offer advantages in certain climates and applications. When pasture is available, a well-managed grazing scheme provides low cost forage that is high in protein and other nutrients required by ruminant animals. The major disadvantage of pasture is that in many climatic regions of the world, pasture crops are only available 4 to 6 mo of the year. To feed animals during the remainder of the year, forage crops must be conserved as dry hay or silage.

Silage production can complement or enhance pasture systems. Pastures grow rapidly in the spring, often producing more forage then can be consumed by grazing animals. Silage production can be used to remove this excess forage, which allows the regrowth of the pasture forage to maintain a higher nutritive value.

Compared with silage, dry hay requires more time in the field for curing or drying. During this time, losses occur due to rain damage, microbial respiration, and additional machine operations such as raking and tedding. In cooler climates with frequent rainfall, field drying to an acceptable moisture level for stable hay storage is difficult. Thus, silage production is often preferred to reduce harvest losses. Silage harvest also removes the crop from the field faster, speeding regrowth and

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thereby increasing the yield in subsequent harvests. Compared with dry hay though, storage losses are relatively high in silage production. These losses are normally the more digestible portion of the feed, which reduces the nutritive value to the animal. Silage is the only option for some forage crops. Cereal crops such as corn, barley (*Hordeum* spp.), and rye (*Secale* spp.) produce high quality forage when ensiled, and drying these crops for hay storage and use is not practical.

Silage can provide better consistency of nutrient content compared with other forages. Nutrient levels in pastures often vary from week to week throughout the grazing season, which makes it difficult for the manager to maintain the appropriate feed supplementation for consistent animal production. Dry hay also tends to be more variable in nutritive content as crop maturity and harvest losses vary throughout the season. Due to faster harvesting and better blending in storage, silage (particularly that stored in bunker silos) provides less variation in nutritive content throughout extended feeding periods.

Silage production offers other advantages and disadvantages relative to hay. A major advantage in feeding silage is the ease of handling and preparing animal rations. Silage blends well with other feed supplements to form a total mixed ration (TMR) that efficiently meets the nutritional needs of the animal. Disadvantages of silage systems are that a greater investment is required in equipment and structures, more energy is needed to harvest and handle the crop, and the cost per unit of feed dry matter produced is often greater.

When all advantages and disadvantages are considered, silage production has an important role in animal agriculture. Dairy and beef are major industries that depend on a reliable and consistent source of high quality forage. The use of silage in these production systems is likely to continue to grow as farm size continues to increase. On larger farms, greater harvest and feeding capacity is required, and this capacity is most easily met through silage production. More producers are also using mixed rations, and silage provides a good base for blending feeds.

There are many methods for producing silage. Harvest methods can be categorized as direct-cut and wilted silage systems. Through field wilting, some of the crop moisture is removed to reduce storage losses and enhance preservation. Harvesting devices include a range of equipment from flail machines that produce a relatively long and variable length of cut to precision cutting machines that produce a relatively short and controlled length of cut. Storage options include bunker silos, tower silos, silage bags, and stacks. In recent years, interest has grown in baling high-moisture forage in large bales that are sealed in a plastic wrap for ensiling. Any of these options or some combination can be appropriate for a given farm depending on the forage crop produced, type of animals fed, climate, farm size, and other management factors.

Because of the complex relationship between forage production and other farm components, an evaluation of silage systems must be viewed in the context of the whole-farm system. Major linkages among components include the competition among farm activities for available time, labor, equipment, capital, and other resources. The harvest and storage methods are linked or interrelated to the land, crop, and animal components of a farm through the flow of nutrients from the crop to the animal and back to the land. These links and associated interactions cause effects that are often not obvious or well understood. Only by taking a systematic look at the whole farm, its components, and their interactions can one fully understand the role of silage in a farming system.

This chapter addresses major issues and considerations in viewing silage as a component of a farming system. Silage production systems, including equipment, energy, labor, and other resource requirements and forage losses, will be examined. Next, the economics of silage production will be discussed. This discussion will be expanded to include interactions between silage production and other farm components, modeling of silage systems, silage system selection, and the evaluation of silage production systems.

PRODUCTION SYSTEMS

Silage production involves a complex set of operations and processes from crop establishment to the feeding of the animals. Many physical, biological, and chemical processes affect the overall system performance. The linkage or interdependence among these components requires a comprehensive look at the production system.

Crop Establishment

Crop establishment normally requires a sequence of tillage and planting operations with inputs of fertilizer, pesticide, and seed. These requirements can vary widely depending on the establishment method, which ranges from no-till frost seeding to a conventional tillage system requiring several operations. Given a similar method of establishment, the machinery, energy, chemical requirements, and costs for establishing silage crops are comparable to those of other crops. For perennial forage crops, however, annual input requirements and costs averaged over a 3- to 7-yr stand life are considerably less per unit of harvested crop than those obtained with annual crops.

Major cropping inputs consist of seed, fertilizer, and pesticides. The amount and type required depends on the type of silage crop (annual or perennial). Production requirements for various crops are covered in other chapters of this book. Typical seed requirements for silage production are listed in Table 11–1, and Table 11–2 gives nutrient removal in forage crops. Nutrient removal is an indication of fertilizer requirements, but these requirements depend on current soil status, efficiency of nutrient uptake, and climatic factors. Values shown in these tables represent the minimum long-term average inputs required.

Seed, fertilizer, and pesticide inputs are site specific; they must be used in compliance with the capability of the land and target yields. As much as possible, nutrient inputs should match anticipated plant uptake for optimal whole-farm nutrient balance. This requires good control of the timing and rates of chemical application. For more detail on these inputs for specific soil and climatic conditions, an agronomic specialist and available resource materials for your region should be consulted.

Perennial forage crop establishment can be accomplished using a prepared seedbed or no-till seeding. The method used has advantages and disadvantages that

Table 11–1. Typical seed requirements for silage production (Hall, 1997; Roth, 1997).

Species	Seeding rate	Seed cost
	kg ha^{-1}	\$ kg^{-1}
Alfalfa in pure stand	17–20	3.80–6.80
Alfalfa in mixture		
Alfalfa	11	3.80–6.80
Perennial forage grass	3–9	1.60–8.80
Birdsfoot trefoil in pure stand	11	9.70–9.90
Birdsfoot trefoil in mixture		
Birdsfoot trefoil	7	9.70–9.90
Perennial forage grass	2–7	1.60–8.80
Red clover in pure stand	11–13	8.80–10.40
Red clover in mixture		
Red clover	4–7	8.80–10.40
Perennial forage grass	4–13	1.60–8.80
Perennial forage grasses in pure stand	9–16	1.60–8.80
Sudangrass or sorghum × sudangrass hybrid	28–33	0.77–1.10
Small grains	56	0.22–0.77
Corn silage	6–9 seeds m^{-2}	\$0.70–1.60 per 1000 seeds

are dependent on prior use of the land, seeding date, soil type, and other factors. In a prepared seedbed, the soil is tilled to control weeds and create an optimal environment for seed germination and emergence. The machinery required for preparing a seedbed may include a moldboard or chisel plow, disk harrow, field cultivator, and other specially designed tillage implements. Although the equipment list may be long, the investment is normally "shared" with other crop enterprises on a farm.

No-till establishment reduces the machinery investment and labor inputs by reducing the number of trips over a field. Due to the challenge of seed placement

Table 11–2. Typical annual nutrient removals by several forage crops and nutrient replacement costs (Follett & Wilkinson, 1995).

Crop	Dry matter yield	N	P	K
	t DM ha^{-1}		kg ha^{-1}	
Legumes†				
Alfalfa	18	500	39	450
Red clover	8	195	26	240
Korean lespedeza	7	185	27	160
Cool-season grasses				
Orchardgrass	13	325	48	335
Smooth bromegrass	11	185	32	230
Timothy	9	170	27	235
Tall fescue	9	180	37	190
Warm-season grasses				
Coastal bermudagrass	22	550	67	385
Carpetgrass	3.5	56	9	280
Pensacola bahiagrass	11	175	25	110
Annual Crops				
Corn silage	27	270	49	280
Sorghum–sudan	18	360	61	450
Typical replacement cost of nutrients		\$0.55 kg^{-1} N	\$1.32 kg^{-1} P	\$0.44 kg^{-1} K

† Since legumes normally fix the N they require, N replacement is not required.

in untilled soil, the investment in a no-till seeder is often greater than that for a seeder designed for tilled soil. For weed control, a good plan of chemical application (including timing) is important. Here, as in many cases regarding silage production, there are tradeoffs between machinery investment and the use of energy, labor, and chemicals.

Establishment of annual crops, such as corn, for silage can also be performed with or without prior tillage. The general set of equipment is the same, but the final condition of the seedbed may not be as critical. Due to the physiology of the seed and its greater store of energy for use during germination and emergence, annual crops do not require as much seedbed preparation as perennial legumes and grasses. The larger seeds of annual crops can be planted at deeper and less uniform depths. For corn, alternatives for post-emergence weed control include mechanical cultivation and chemical control. There is again a tradeoff involving machinery investment, energy, labor, and chemical application.

Harvest Systems

The capital investment in silage harvesting machinery depends on the type of harvest and storage used. Forage activity flowcharts document many of the alternatives used to move the standing crop to the feed bunk (Kjelgaard, 1979; Tseng & Mears, 1975). Different machinery investments are required for systems using tower silos, bunker silos, tubes, and wrapped bales. Machinery for transport and placement into storage must interface with the harvesting machinery and that required for storage. Figure 11–1 illustrates the major options for silage harvest and transport (more detail on harvest equipment is available in Chapter 8, Shinners, 2003). An example of the investment required in silage harvest equipment is illustrated in Table 11–3 for two farm sizes.

The first major choice among existing methods for harvesting and storing of silage is between direct-cut and wilted silage (Fig. 11–1). In a direct-cut system, the standing crop is cut, chopped, and conveyed to a truck or wagon for hauling. A major issue in direct-cut systems is crop moisture concentration. For good ensiling and preservation, the moisture concentration must be <750 g moisture kg^{-1}. Greater moisture concentrations lead to poor fermentation and excessive production of effluent, which result in excessive losses of dry matter (DM) and nutrients. Direct-cut harvest is normally used for corn silage where standing corn can obtain a suitable ensiling moisture level of 600 to 700 g moisture kg^{-1} (Roth et al., 1995).

Direct-cut silage harvest requires less equipment, energy, and labor input than wilted silage harvest. With direct-cut harvest, the major investments include the harvester (and an associated tractor unless it is a self-propelled machine), transport equipment, and equipment for placing silage into the storage unit. Wilted silage harvest requires a separate mowing operation and a field drying period before the chopping operation. This requires an additional investment in a mower or mower–conditioner, a rake, and perhaps a tedder or other swath manipulation device to speed the drying process.

For perennial grass, alfalfa, and small grain forage crops, field wilting is normally required to remove some of the moisture. Silage must be wilted from a standing crop moisture level of 750 to 850 g moisture kg^{-1} down to 500 to 750 g mois-

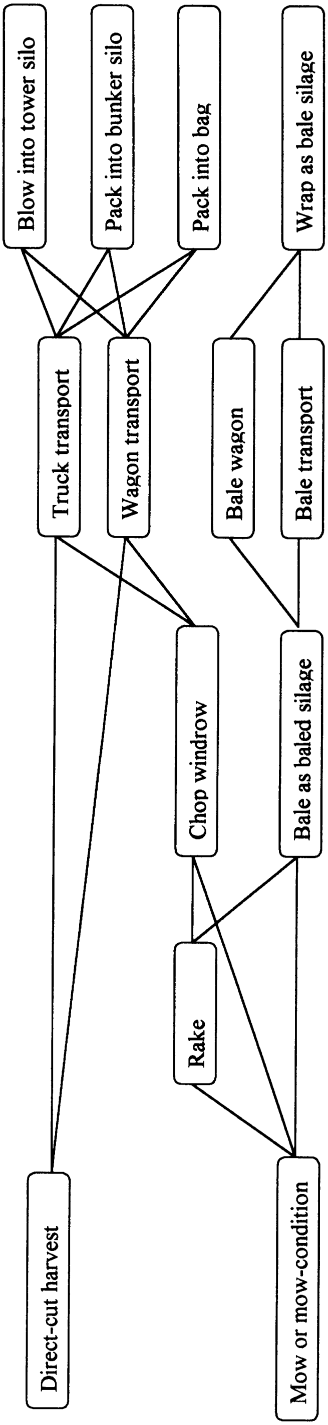

Fig. 11–1. Activity flowchart for silage harvest.

Table 11–3. Typical investments in forage harvest systems for two sizes of dairy farms (Rotz & Harrigan, 1997).

101-ha crop area		486-ha crop area	
Mower–conditioner	$12 000	Two mower–conditioners	$34 000
Rake	$10 800	Rake	$10 800
Round-baler	$11 200	--	
Bale wagon	$4 500	--	
Forage harvester	$24 100	Self-propelled harvester	$155 100
Two dump wagons	$19 800	Three used trucks	$60 000
Tractor (50% of initial cost)	$51 300	Tractor (50% of initial cost)	$136 200
Total	$133 700		$396 100
Total per hectare	$1 324		$815

ture kg^{-1}. The target moisture depends on the type of storage unit, additives used, and the specific crop. Direct-cut systems for these crops require a chemical additive such as formic acid to improve or control fermentation for adequate preservation (Rotz et al., 1993).

Storage and Handling Systems

Forage can be ensiled and stored in a variety of structures and packages. Structures include bunker (horizontal) and tower silos. Other options include bags, stacks, and bales. Bunker silos normally are constructed with concrete sides, but they may be made of wood. A trench silo is similar, with sides formed by an earthen embankment. Tower silos are formed with concrete staves, poured concrete, or steel panels. Poured concrete and steel silos may be sealed to reduce the infiltration of O_2 through the walls. Although sealed silos are more costly, they do reduce storage losses. Bags may be placed on a concrete, paved, or stone pad to facilitate emptying of bags during wet and cold weather conditions. Sometimes silage is simply dumped into a large stack with little or no packing. Even with a cover, losses from a stack can be very high, a tradeoff considering the low investment. A more detailed description of storage options is available in Chapter 9 (Savoie & Jofriet, 2003).

Machinery investment for transport and placement into storage depends on the storage unit and other farm operations. As transport distance or harvest capacity increases, use of trucks for transportation becomes more common. Dump trucks and tractor-drawn dump wagons are better suited for filling bunker silos where rapid unloading is desired. Self-unloading wagons can be used with tower and bag storage units when metered unloading is desired. Bunker silos require the use of a tractor to distribute and compress the forage. Tower silos require a blower, tubes or bags require a bag-packing unit, and bale silage requires a bale wrapper.

With the many options of ensiling forage, the range in investment for storage is large. Initial capital investment is not always proportional to storage capacity because some silos are filled more than once per year and there are economies of scale (a lower cost per unit with larger structures). The initial cost for tower silos depends largely on silo capacity, the amount of sealing used to prevent O_2 infiltration, and whether bottom or top unloading is used. Typical initial costs range from \$120 to \$500 t^{-1} DM stored, with the cost decreasing as silo size increases (Ishler et al., 1991). Investments for concrete bunker silos fall in the same range, but the average cost is lower because a dedicated unloader is not needed. Trench silos can be constructed at a much lower cost, but a suitable site must exist. Also, silage unloading is not as convenient or clean as that obtained with a concrete unit. Bagged silage systems can include a small initial investment for site preparation or paving (about \$5 m^{-2}) to improve unloading conditions.

Methods for emptying silos vary with the type of silo (Fig. 11–2). Tower silos normally use a mechanical unloader that slices silage from the top or bottom surface and conveys it from the silo. Sealed silos normally use a bottom unloader, while other tower silos use top unloaders. Bunker silos, bagged silage, and stack silos are normally emptied using a tractor with a front-end loader. Block cutters are sometimes used to slice a layer or block off the silage face. This maintains a smoother face that is less susceptible to O_2 penetration and thus reduces storage loss. However, this approach is less feasible for larger operations because of the higher cost for the equipment and a lower unloading capacity (Muck & Rotz, 1996).

To make baled silage, forage at a moisture level of 400 to 700 g moisture kg^{-1} is baled in large bales that are individually wrapped in plastic or aligned in a plastic tube or wrap for ensiling. When a tight seal is maintained during storage, relatively good preservation and low storage loss can be obtained. Baled silage is handled and fed using large bale handling equipment (Fig. 11–2). A bale processing operation such as grinding or chopping may be required to reduce feeding loss and enable better mixing with other feeds. An advantage of this system, particularly for smaller farms, is that the same equipment can be used for both dry hay and silage making. Individual bales provide more flexibility in feeding according to forage quality, but bale silage quality is more variable than that in a silo.

Feeding is the last major component of silage production systems. Poststorage handling of forages is important because optimal animal productivity depends on optimal allocation and delivery of the forage. Major feeding options are individual feeding of forages and grains or the use of a mixer for blending silage and feed supplements into a TMR (Fig. 11–2). Mixing options include stationary mixers or mobile mixers used to carry the feed to the feed bunk. Regardless of the feeding approach, optimal production requires blended feed rations that provide nutritive characteristics that match the nutritive requirements of the animals fed.

Resource Requirements

The major inputs in silage production are energy, labor, polyethylene covers, and silage additives. Following the various flow paths of Fig. 11–1 and 11–2, there are different combinations of machines, energy, and labor used to harvest, store, and deliver silage. Optimal use of energy or labor is not necessarily minimal use of energy or labor. For example, if additional energy used to process silage results in improved animal performance such that the value of these improvements exceed the cost of processing, the additional energy is expended wisely. Similarly, if additional labor yields economic benefits beyond the added marginal cost, it should be considered.

Most energy used in silage production is in the form of engine fuel. The exception is electrical energy used with silo unloaders and stationary feeding units.

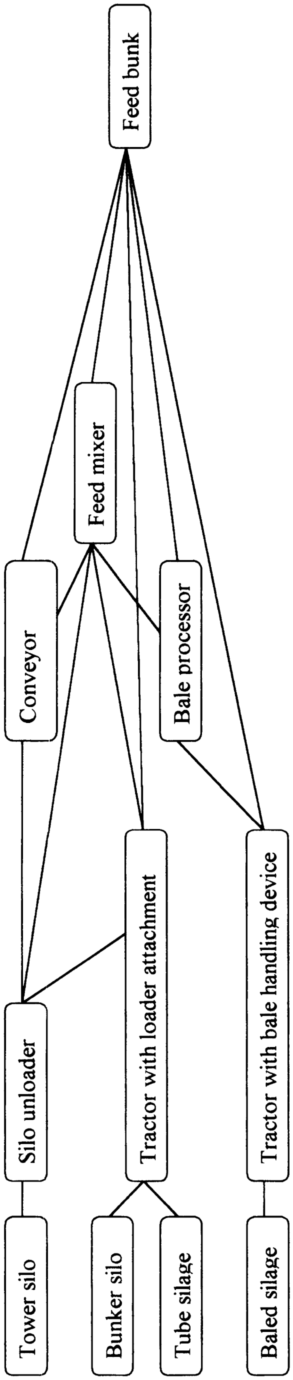

Fig. 11–2. Activity flowchart for silage feeding and delivery.

Kjelgaard (1979) reported energy consumption from field to silo of 12.4 to 26.6 MJ t^{-1}. Energy input was 40% lower for direct-cut silage harvest and transport compared with wilted silage, and tower silo systems required 15 to 20% more energy than bunker silo systems. Energy inputs for silage feeding ranged from 2 to 3.6 MJ t^{-1} (Kjelgaard, 1979). Miller and Rotz (1995) reported typical fuel requirements (include efficiency in energy conversion and energy losses) for mowing and chopping to be 1.5 and 7.0 L t^{-1} DM (20 and 100 MJ t^{-1}), respectively. Total requirements for well-managed harvest and unloading into storage were 10 L t^{-1} DM (150 MJ t^{-1}) for wilted silage and 7 L t^{-1} DM (100 MJ t^{-1}) for direct-cut systems. These requirements can vary by 100% depending on the number of operations used, travel distance, swath width, and machine capacity.

Labor inputs vary among silage systems and the associated type and size of machinery used. Typical labor requirements for harvesting and handling range from 0.4 to 0.6 h t^{-1} DM for corn silage and 0.6 to 0.8 h t^{-1} DM for wilted alfalfa or grass silage (Kjelgaard, 1979; Miller & Rotz, 1995). Most of this labor is required for chopping, transporting, and loading into storage. Labor inputs can also vary by more than 100% depending on the management conditions.

Polyethylene covers are often used to improve preservation. In bunker or tower silos, plastic covers provide a much needed barrier to air infiltration into the top surface of the silage mass to reduce respiration loss (Buckmaster et al., 1989). For bagged and baled silage, the plastic provides the only seal to allow extended anaerobic conditions (Vough & Glick, 1993). Plastic requirements vary considerably among storage options. For tower silos, the amount of plastic needed is minimal. Bunker silos need between 1 and 2 m^2 t^{-1} DM to cover the top surface of stored silage, and silage bags require about 8 m^2 t^{-1} DM of silage. When round bales are aligned in a tube, 14 to 21 m^2 t^{-1} DM are required. A thinner plastic may be used for individually wrapped bales, but the requirement is very high at 100 to 200 m^2 t^{-1} DM of stored silage.

Biological and chemical additives for silage include bacterial inoculants, enzymes, anhydrous ammonia, and organic or mineral acids (Muck & Kung, 1997). Additives can improve preservation by increasing the rate and extent of fermentation, and they may improve the stability of the silage once removed from storage. Anhydrous ammonia also increases protein levels. The potential benefit of different additives varies among annual and perennial crops and those harvested as wilted or direct-cut silage (Chapter 7, Kung et al., 2003). Application rates and costs of additives vary widely among the types and brands of additives.

Silage System Losses

Substantial losses and nutritive changes occur during the harvest, handling, storage, and delivery of silage (Chapters 6, Muck et al., 2003; 7, Kung et al., 2003; 8, Shinners, 2003; and 9, Savoie & Jofriet, 2003). A comprehensive review by Rotz and Muck (1994) summarized much of the literature regarding DM losses and nutrient changes in forages. They presented typical ranges in DM loss caused by various factors and the resulting changes in crude protein (CP), neutral detergent fiber (NDF), and total digestible nutrients (TDN) associated with these losses. The discussion here is limited to the interrelationship of losses and the accumulation of total system losses and nutritive changes.

Respiration, rain, and harvest equipment cause DM losses and nutrient changes in the field. Respiration during field drying results in a loss of carbohydrates, which leads to a lower energy value entering storage and a greater concentration of the other plant components such as fiber and protein. Rain can cause losses by three mechanisms: (i) additional respiration loss from plant and microbial processes, (ii) leaching of soluble nutrients, and (iii) the disassociation of leaves and small plant particles. All losses reduce nutritive value, but leaching of nonstructural carbohydrate and protein generally causes the greatest reduction.

Harvest equipment such as mowers, rakes, and forage harvesters induce some loss via mechanical damage (Chapter 8, Shinners, 2003). The value of these losses varies widely with the specific conditions of climate, management, crop, and equipment used. For leafy legumes, the effect of the loss is more pronounced because the more nutrient-rich components of the plant (leaves) are most susceptible to mechanical damage and loss. Plant respiration, occasional rain damage, and added machine operations cause greater harvest losses with wilted silage harvest than direct-cut harvest. However, wilting reduces storage losses, resulting in similar losses overall for wilted silage and direct-cut harvest systems (Rotz et al., 1993).

During storage, DM loss and changes in nutritive value occur due to respiration, fermentation, protein breakdown, and effluent production (Chapters 3, Rooke & Hatfield, 2003; 6, Muck et al., 2003; and 9, Savoie & Jofriet, 2003). Respiration occurs during and immediately following filling because some O_2 is entrapped with the forage. Ongoing infiltration of O_2 throughout the storage period continues respiration to a limited extent. During feedout, the surface of the silage is again exposed to O_2 and respiration increases. Effluent production occurs in high-moisture silage that is packed at pressures beyond that needed to cause saturation of the silage. The effluent is rich in nutrients, containing many soluble compounds such as sugars and protein (Rotz & Muck, 1994). Losses in silage storage vary with the type and size of storage used (Table 11–4). A final point of loss is in delivery

Table 11–4. Typical storage and feeding losses for major forage production methods.

Storage system	Cross et al. (1997) Storage loss	Rotz & Muck (1994) Storage loss	Ishler et al. (1991) Storage loss	Ishler et al. (1991) Feeding loss	Ishler et al. (1991) Total loss†
	% DM				
Perennial forage hay:					
Inside shed	3	5	4	5	9
Outside	16	15	14	15	29
Perennial forage silage:					
Concrete upright	9	10	10	11	21
Oxygen-limiting	5	8	8	11	19
Bunker	12	12	14	11	25
Trench	15	na‡	na	na	26
Corn silage	na	na	6	4	10
Bags	5	na	na	na	10§

† Assumptions made on missing observations.

‡ Not applicable.

§ From Garthe and Hall (1992).

and feeding. Generally 3 to 5% of stored silage does not make it into the animals fed due to spills, loss from the feed bunk, and sorting of feeds by the livestock.

Because silage must undergo several processes between the field and feed bunk, these individually small, yet collectively large, losses and nutritive changes have considerable impact on silage production efficiency and economics. Even with efficient silage production, the collective losses from mowing (typically 2%), respiration (3–5%), rain (0–20%), chopping (3%), storage (10–12%), and feeding (3–5%) are important and should be minimized (Buckmaster et al., 1990; Rotz et al., 1991; Rotz & Muck, 1994).

A total system loss is often estimated by summing the losses of individual processes. This overestimates loss by overlooking the cumulative effect of one loss on the others. At each stage of production, the portion of forage retained is one minus the loss. The product of the amounts retained in all stages gives the final portion of silage retained as animal feed. One minus this amount gives the total system loss. For example, a typical silage harvest may include the following fractional losses: mowing (0.02), respiration (0.04), rain damage (0.05), raking (0.03), chopping (0.03), storage (0.12), and feeding (0.05). The amount retained as animal feed is 0.98(0.96)(0.95)(0.97)(0.97)(0.88)(0.95) = 0.70 for a total system loss of 0.3, or 30%. Typical DM losses during harvest and storage are illustrated for major forage harvest options in Fig. 11–3.

Dry matter loss does not fully represent the loss in silage value. The lost portion of the crop is not equal in nutritive value to the retained portion. Also, in the fermentation phase of ensiling, quality is changed with very little direct DM loss. Buckmaster et al. (1990) determined the economic value of forage losses considering the combined effects of DM loss and nutritive changes. They found that for silage systems, the largest value loss occurred during storage ($8.80 t^{-1} DM). The value of mower–conditioner and forage harvester losses combined ($4.90 t^{-1} DM) was larger than the average rain-induced loss ($3.10 t^{-1} DM). Further breakdown

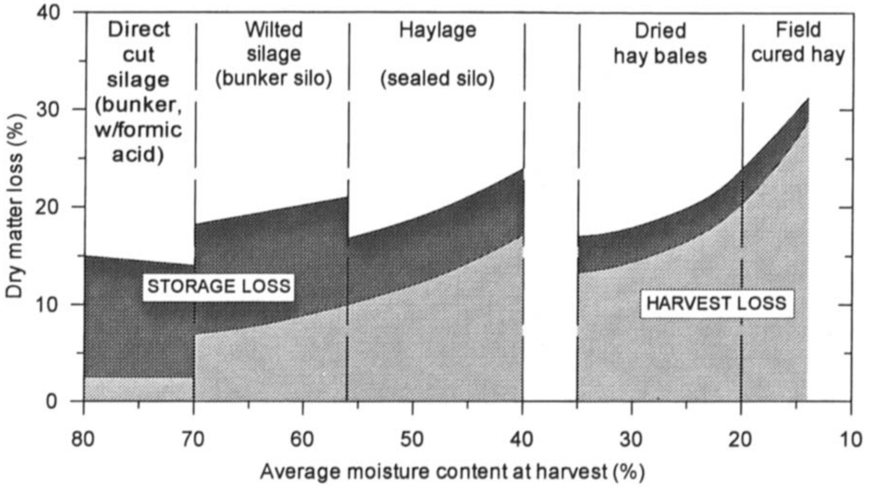

Fig. 11–3. Typical dry matter losses during the harvest and storage of different types of forage (Rotz et al., 1991).

of the value of changes during ensiling suggested that respiration allowed by ongoing O_2 infiltration and the exposed surface during feedout contributed most to the loss in value during silage storage (\$3.80 and \$4.00 t^{-1} DM, respectively).

SILAGE ECONOMICS

A comprehensive economic analysis should consider all aspects of silage production along with their effects on other farm components. For simplicity, an accounting approach is often used to value inputs and outputs measured for annual production years. To be accurate, this approach must include the establishment cost of perennial forage stands in preproductive years and the costs associated with postharvest handling and storage.

Costs of silage production for all crops vary by geographical region, the production system used, the scale of enterprise involved, and farm-specific characteristics. Silage economics for any particular farming system are unique relative to other farms. Therefore, costs and returns presented in this section should be viewed as examples only. The assumptions used rely on budgets prepared at the University of Tennessee (Cross et al., 1997). The use of models that integrate silage production with the whole-farm system for a more comprehensive economic analysis will be addressed later in this chapter.

Establishment Costs

Annual forage crops such as corn silage have establishment costs in each production year. Perennial grass and alfalfa crops, however, are generally established with less production during the first year. They then have a number of subsequent full production years determined by the longevity and persistence of the forage crop. Establishment costs for perennial crops are substantial, with totals ranging from 35 to 50% of annual production costs.

A preferred method for the allocation of these costs is illustrated in Table 11–5. Example establishment costs are shown for alfalfa hay, alfalfa silage, perennial grass hay, and perennial grass silage (Cross et al., 1997). Establishment costs include all seed, fertilizer, chemical, labor, and machinery costs incurred in the establishment year. The value of the harvested crops in that first year is deducted from the establishment costs, resulting in a net cost that must be allocated to each future year in the life of the forage stand. This allocation is performed using annuity factors that

Table 11–5. Example establishment costs for forages grown in Tennessee (Cross et al., 1997).

	Alfalfa		Perennial grass	
	Hay	Silage	Hay	Silage
Establishment cost, \$ ha^{-1}	573	573	257	257
Offsetting hay income (net of harvest cost), \$ ha^{-1}	272	272	0	0
Net establishment cost, \$ ha^{-1}	301	301	257	257
Number of years to distribute costs, yr	4	4	6	6
Annuity factor (assuming 10% discount rate)	0.316	0.316	0.230	0.230
Annual share of establishment cost, \$ ha^{-1}	95	95	59	59

account for the time value of money to distribute the first year net cost over the life of the stand (Boehlje & Eidman, 1984). In Table 11–5, each hectare of alfalfa hay in full production must have $95 additional annual cost of production added to account for the unrecovered costs associated with the establishment of that crop. Note that the annual establishment cost for alfalfa is higher than that of grass because grass costs less to establish and the stand life is longer.

Harvest Costs

Annual costs of production include the annualized cost of establishment, the allocation of fixed costs of machinery used in production, and direct costs of inputs used in the annual production and harvest of silage. Example budget amounts of all costs associated with forage production are presented in Table 11–6. Yields used in this example represent harvested yields and therefore account for differences in harvest losses.

Fixed costs of capital asset ownership are those incurred even if the asset is not used. They include depreciation, interest, insurance, housing of machinery, and property taxes. All of these costs are essentially proportional to the value of the asset. The purchase of capital assets occurs at a point in time, with the asset intended for use several years into the future. Therefore, ownership costs of a capital asset must be allocated over the economic life of that asset to equitably reflect each year's cost of production.

Depreciation is a measure of annual loss in value of an asset through use or ownership. Depreciation in this sense is an economic measure that is different from tax depreciation. Interest refers to the opportunity cost of having funds tied up in the asset and not necessarily the interest paid on a loan for the asset. Annual insurance, housing, and tangible property taxes are incurred every year and are independent of the use the asset receives. All farms face ownership costs of depreciation and interest on their assets, but many forego the direct cost of insurance and housing of machinery. These costs may still occur through loss or more rapid depreciation of the asset. Taxes on tangible assets are determined locally and are not levied in many areas. Complete procedures for calculating each of these fixed

Table 11–6. Breakdown of annual costs of forage establishment and harvest (Cross et al., 1997).

	Corn silage	Alfalfa silage	Grass silage	Alfalfa hay
Establishment share, \$ ha^{-1}	0	95	59	95
Chemicals, \$ ha^{-1}	111	121	17	121
Fertilizer, \$ ha^{-1}	173	116	101	116
Fuel, \$ ha^{-1}	20	49	37	30
Repairs, \$ ha^{-1}	49	156	119	67
Machinery fixed costs, \$ ha^{-1}	126	385	294	146
Labor expense, \$ ha^{-1}	69	215	146	116
Other, \$ ha^{-1}	79†	22	17	126‡
Total, \$ ha^{-1}	627	1159	790	817
Yield, t DM ha^{-1}	12.7	9.7	5.6	9.0
Cost per unit, \$ t^{-1} DM	49	119	141	91

† Seed is included in other costs for corn silage.

‡ Hay preservative is included in other costs for hay production.

costs are described in farm management texts (e.g., Hunt, 1999; Boehlje & Eidman, 1984).

The total investment in silage harvest equipment can be high. Example investments are presented in Table 11–3 for different systems and farm sizes (Rotz & Harrigan, 1997). The investment in tractors is included assuming that 50% of their use is in harvest activities. Total machinery investment per unit of land area is 38% less for the larger operation. Amounts shown in Table 11–3 are also consistent with system investments outlined in Roth et al. (1995).

If timely harvest for optimal forage quality is constrained by available machinery or labor, increases in machinery investment can have a positive effect on farm profit. With a delay in harvest, the crop yield may increase, but the concentration of most nutrients decreases. An investment in larger machinery to achieve higher quality (less mature) forage can then improve profit. If not harvested at the appropriate stage of maturity, the change in forage yield and nutritive content can create a timeliness cost of up to 1.8% of the maximum crop value per day of delay beyond optimum harvest (ASAE, 2000). For a 5-d delay, this could be worth up to \$15 t^{-1} DM. Thus, improved forage quality through a more timely harvest may pay for a substantial additional investment in harvest machinery. As an example, applying this potential loss in value to a crop yielding 6 t DM ha^{-1} results in a loss of \$90 ha^{-1}. Dividing \$90 by an annuity factor reflecting a 6-yr machine life (Table 11–5) indicates that an additional machinery investment of up to \$390 ha^{-1} is justified to eliminate delay.

Actual fixed costs per hectare or unit of silage produced depend on the amount produced with the equipment. Spreading annual fixed costs of production over more units, either through more production area or higher yields, reduces the fixed costs per unit. Budget-based calculations of fixed costs are often used to estimate costs over a range of farms. Budget values, however, are determined assuming an annual use in hours, land area, or units of forage harvested. The use of budget information on a farm that uses more (or less) than that assumed in the preparation of the budget overestimates (or underestimates) true machinery fixed costs per unit. Therefore, care must be taken using budget information to assure that the assumptions on which machinery costs were based are known and are consistent with the way they are applied.

Machinery ownership costs can account for 18 to 38% of each crop's total cost of production (Table 11–6). Machinery costs for alfalfa and grass silage systems are often higher than that for corn silage because operations are required for mowing and field wilting. They are also higher than those for dry hay production because the equipment required for harvest and handling of wilted silage requires a greater investment.

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 (ASAE, 2000). 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 6 to 8%.

To determine fuel cost, fuel use must be known for each operation. As an estimate, diesel fuel use can be determined by multiplying 0.22 L $(kW\ h)^{-1}$ by the tractor size (kW) and the time (h) required to perform the operation. Fuel cost can be increased 15% to cover the cost of lubrication oil. 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 amounts of plastic. Material costs are as much as \$20 t^{-1} DM for plastic on individually wrapped bales of silage.

Use of contract or custom operators can reduce the farmer's financial risk by reducing the investment in machinery and the machinery ownership and operating costs. Contract harvest operations are suited for farms with small-to medium-sized forage enterprises that cannot support a full machinery complement. The use of contract operators may also reduce the farm manager's control over the timing of farm operations. This can increase the risk of not having forage cut and stored in a timely fashion for optimal quality. Users of contract operators should have a contractual arrangement that stipulates when crops will be harvested, and a clear understanding of that arrangement.

Storage Costs

The cost of storing silage varies substantially among storage methods. Estimates of storage costs are presented in Table 11–7 from two sources (Cross et al., 1997; Ishler et al., 1991). These are fixed costs of storage that do not include differences in handling or feeding costs. Costs from Ishler et al. (1991) include insurance, taxes, and repairs. A range of costs is presented for each type of storage to reflect differences in structure size with each used to full capacity. Differences in local costs, the life of the structure, and the opportunity cost of funds invested in the structure also contribute to the variability. The cost will be less when a silo is filled more than once during the year because more forage is processed and stored with the same initial investment.

Garthe and Hall (1992) estimated large round-bale silage costs to be similar to costs for bagged silage. Excluding labor costs, their estimates totaled \$22 to \$29 t^{-1} DM for wrapped bales and \$31 to \$33 t^{-1} for bagged silage. The variation in the ranges reflects differences in the size of equipment used and the amount of forage stored.

Table 11–7. Estimated forage storage costs.

Storage structure	Cross et al. (1997)	Ishler et al. (1991)†
	$ t^{-1} DM	
Sealed tower silo	42–77	21–100
Concrete stave tower silo	25–41	19–43
Bunker silo	6–10	17–35
Trench	4–6	na‡
Bagged silage	12–20	22–57
Shed for dry hay	12–15	na

† Includes costs of insurance, taxes, and repairs.

‡ Not applicable.

Feeding losses must be included to determine the total cost of the forage actually available for animal consumption. For example, if a forage costs \$110 t^{-1} DM to produce and there is a 10% storage and feeding loss, only 0.9 t DM of the forage is eaten by the animal, giving an actual cost of \$122 t^{-1} DM. Adding storage costs to production costs and adjusting harvested yield to that actually consumed results in significantly higher costs of feed than typically discussed. Examples for corn silage, alfalfa silage, and alfalfa hay are presented in Table 11–8 using assumptions on storage losses and costs from Tables 11–4 and 11–7, respectively.

After accounting for all costs and losses associated with the forage systems presented in Table 11–8, corn silage appears to provide the least costly systems. The costs presented in this analysis rely heavily on assumptions about prices, yields, input levels, farm scale, and farm-specific storage, handling, and feeding systems. Therefore, the information presented should only be used as a guide for farm planning, rather than an absolute statement regarding the benefits of corn silage–based forage-livestock systems.

Valuing Forage Nutrient Content

The remaining cost in forage production is the value of nutrient changes due to losses and timeliness of harvest. Nutritional value is difficult to estimate and it varies with plant species, production system, and the intended use of the forage. Beef cattle (*Bos taurus*), for example, have different nutritional requirements than high-producing dairy cows. The basis for any forage valuation is the difference in net returns among systems using forages of different nutrient concentrations. The magnitude of this difference depends on the management approach of the producer. If a change in nutrient content is not considered in ration formulation, the "cost" is equal to the value of reduced animal productivity, that is, less meat or milk. For example, assume that feeding 10 kg d^{-1} cow^{-1} of poor quality silage reduces daily milk production 0.3 L d^{-1} cow^{-1} from a level maintained with better quality forage. If the net value of milk is \$0.30 L^{-1}, then the net cost of having fed the poor quality silage is \$0.09 d^{-1} cow^{-1}, or \$0.009 kg^{-1} of silage fed. Thus, the poor quality silage has \$9 t^{-1} less value than the better silage.

Another approach is to test the forage and balance the ration based on the actual nutrient concentration in the forage. The manager would adjust the ration to maintain production, thus avoiding the cost of lost production. There would still be

Table 11–8. Example forage feed costs accounting for storage costs and losses.

	Corn silage		Alfalfa silage		Alfalfa hay
Storage type	Tower silo	Bunker silo	Tower silo	Bunker silo	Stored inside
Cost of production, \$ t^{-1} DM†	49	49	119	119	91
Storage cost, \$ t^{-1} DM	28	17	28	17	13
Total cost, \$ t^{-1} DM	77	66	147	136	104
Storage and feeding loss, %	10	10	21	25	9
Remaining DM, %	90	90	79	75	91
Cost of remaining DM, \$ t^{-1} DM	86	73	186	181	114

† From Table 11–6.

Table 11–9. Examples of silage value varying with dry matter, net energy, and protein content.

Silage	High price scenario†	Low price scenario†
	$\$$ t^{-1}	
Average legume silage‡	$66.20	$49.27
Decreased dry matter, 50 g DM kg^{-1}	$58.85	$43.79
Increased protein, 20 g kg^{-1} DM	$70.08	$52.90
Increased net energy, 0.12 Mcal kg^{-1} DM	$69.18	$50.85
Increased protein and increased net energy	$73.07	$54.47
Increased protein, increased net energy, and decreased dry matter	$64.95	$48.42

† High price scenario assumes corn at $118 t^{-1}, soybean meal at $275 t^{-1}, and hay at $132 t^{-1}. Low price scenario assumes corn at $98 t^{-1}, soybean meal at $242 t^{-1}, and hay at $99 t^{-1}.

‡ Silage content is 193 g CP kg^{-1} DM, 1.26 Mcal NE$_L$ kg^{-1} DM, 510 g NDF kg^{-1} DM, and 450 g DM kg^{-1}.

an additional cost to the dairy ration to compensate for the lack of quality forage. If an extra 0.3 kg d^{-1} of corn is required to correct the ration for each cow and that corn costs $0.10 kg^{-1}, the resulting cost is $0.003 kg^{-1} of silage. The reduced silage value is then $3 t^{-1}. In the previous example, the same nutritive changes reduced the silage value by $9 t^{-1}. This illustrates that the value of forage quality depends greatly on how the forage is fed. In practice, the true value of forage quality varies between these two extremes depending on the feeding strategy used and animals fed.

The above example illustrates that the value of silage nutrient content is different among producers feeding the same forage to different breeds of animals or animals at different levels of production. The true value of a given silage, therefore, is best obtained by working the silage into a feed ration to determine cost difference relative to alfalfa hay at a given market price. This provides a value for a specific animal and feeding strategy.

To obtain a value that is independent of feeding practices, many animal scientists and economists prefer use a feed factor approach (Petersen, 1932). This approach relies on an implied market determination of the value of nutritional components of the forage. Imputed prices for energy, protein, and fiber are determined from market values of corn, soybean [*Glycine max* (L.) Merr.] meal, and alfalfa hay (Adams et al., 1995). With this approach, the focus is on the value of the forage, rather than the specific animal to which it is fed. An example of differences in the value of alfalfa silages differing in nutritive composition is presented in Table 11–9. The value of silage varies positively with DM, protein, and energy concentrations. The value of an additional10 g kg^{-1} of protein is $1.94 t^{-1} of silage for the high price example and $1.82 t^{-1} for the low price example.

Including feed values to the analysis in Table 11–8 more accurately determines the relative profitability of each forage type (Table 11–10). Under the assumptions used in this discussion, corn silage stored in a bunker and alfalfa hay stored inside are more profitable than the other silage alternatives. Again, these results are dependent solely on the cost, price, loss, and nutritional composition assumptions used in this discussion. The analysis assumes higher protein and energy values for alfalfa silage over alfalfa hay, but lower digestibility. Facility effects on silage qual-

Table 11–10. Example feed value calculations and net feed value over total costs.

	Corn silage		Alfalfa silage		Alfalfa hay
Storage type	Tower silo	Bunker silo	Tower silo	Bunker silo	Inside storage
Dry matter, g kg^{-1}	330	330	450	450	900
Crude protein, g kg^{-1} DM	88	88	193	193	186
NE_L, Mcal kg^{-1} DM	1.52	1.52	1.26	1.26	1.32
NDF, g kg^{-1} DM	490	490	510	510	477
Feed value, \$ t^{-1} as fed†	26	26	55	55	110
Feed value, \$ t^{-1} DM	78	78	123	123	122
Cost of remaining forage, \$ t^{-1} DM‡	86	73	186	181	114
Feed value less costs, \$ t^{-1} DM	–8	5	–63	–58	8

† Corn nutritional composition is 100 g CP kg^{-1} DM, 1.98 Mcal NE_L kg^{-1} DM, 90 g NDF kg^{-1} DM, and 880 g DM kg^{-1}. Soybean meal nutritional composition is 500 g CP kg^{-1} DM, 1.94 Mcal NE_L kg^{-1} DM, 140 g NDF kg^{-1} DM, and 900 g DM kg^{-1}. The calculated feed value of each forage is based on a \$98 t^{-1} corn price, \$275 t^{-1} for 44% soybean meal, and \$110 t^{-1} for alfalfa hay.

‡ From Table 11–8.

ity were not addressed in Table 11–10. Comparisons between tower and bunker silos may also show increases in protein concentration in the bunker silo over the tower silo, but decreases in digestibility and energy (Rotz & Muck, 1994). The value of these differences in nutrient concentrations should also be considered if one is comparing the effects of silo type.

Marketing Silage

The physical density of silage, its perishable nature, and its specialized market for livestock producers combine to create significant marketing challenges for the grower who wishes to sell silage. Purchasers of silage are livestock feeders, primarily producers of beef and dairy cattle. Market demand for silage is therefore more likely to exist in areas with many or large dairy and feeder cattle operations.

High water contents create a challenge for the economical transport of silage. This water content increases the amount of material transported and reduces the stability of the forage. Therefore, silage producers must look nearby to find profitable market opportunities. The exact proximity of production to end-use depends on a number of factors related to individual sales arrangements and pricing. In general, the greater the distance from producer to buyer, the greater the likelihood that the buyer will find alternative supplies of silage or other feeds that are more price-competitive. Forage production generally takes place near the livestock producers who use the feed (Moore & Nelson, 1995).

Marketable silage can take several different product forms. First, silage can be sold standing in the field, to be harvested by the buyer. Silage can also be sold at harvest (green chop) delivered to the buyer's farm, or it can be stored on the producer's farm and sold after the ensiling process. A variation of these last two options is wrapped, ensiled round bales. Finally, silage can be sold as part of a value-added TMR. Mixed rations can be formulated from available silage to the nutritional specifications of multiple producers and then delivered to each customer on a daily basis.

Silage transportation costs vary due to variability in the silage form, DM concentration, transport distance, and equipment used. Transportation of silage to the buyer's farm normally involves silage wagons for short distances or trucks for distances greater than about 3 km (Roth et al., 1995). Mixed rations may be transported in mixer wagons for very short distances or transferred into trucks for longer hauls. Transport costs can be estimated from comparable loads. For example, contract grain hauling in Pennsylvania costs about \$5 t^{-1} for local hauling and more than twice that for long distance hauling (Nielsen, 1997). A silage hauling cost of \$5 t^{-1} gives a cost of \$10 to \$15 t^{-1} DM dependent on the DM concentration of the forage.

Transporting silage over long distances at the time of harvest requires the use of additional tractors and wagons or trucks to enable timely, uninterrupted harvest. Although the purchase of additional machinery is expensive, a more costly alternative is an untimely harvest of poorer quality forage. Hauling silage at harvest to fill the buyer's storage facility will involve the hauling of more silage than if the silage is stored in the seller's facility. Storage losses reduce the harvested yield by 8 to 15% (Table 11–4), and this should reduce the transportation costs by the same amount.

Silage price is determined by forage supply and demand conditions at both the buyer and seller's locations. The seller cannot assume to charge and receive the local price for silage plus transportation costs; the buyer may have another forage source that is cheaper. Silage must also be priced to be competitive with alternative feeds. As illustrated in Table 11–9, DM concentration and nutritional composition affect silage value. Generally, silage is priced relative to dry hay, adjusted for DM concentration and the value of the corn and soybean meal required to equate the energy and protein contents of the two forages. Alfalfa or grass hay is used as a base because there is a more well-defined market for hay. Forage analysis should be obtained on all marketed silage to document DM and nutritional composition.

Product form also affects the pricing of silage. Silage is typically priced after ensiling, so equivalent pricing must include the costs associated with silo storage and ensiling losses. If corn silage sells for \$28 t^{-1}, harvest, hauling, and fill costs are \$8 t^{-1}, and there is an expected storage loss of 10%, then the price of corn in the field is \$18 t^{-1}. Silage delivered out of the silo is priced at the silo and then transportation costs are negotiated between buyer and seller. The pricing of a TMR must include costs for other feed ingredients, labor involved in mixing and feed acquisition, and a service component in addition to the price of the silage. The silage portion of the TMR should be priced in a manner consistent with the principles discussed above.

SILAGE PRODUCTION IN THE FARM SYSTEM

To properly select, evaluate, and compare silage systems, all components of the system and their interaction with other farm components must be considered. Major linkages occur between crop growth, harvest, storage, feeding, and animal performance. These links mean that changes in one component often affect most or all other components. A comprehensive analysis is needed to integrate the effects on all components of the farm system.

The Farm and Its Environment

Silage is normally consumed on the farm where it is produced. As such, silage production can be viewed as part of a farming system where crop DM and nutrients are produced, harvested, stored, fed, and returned back to the land on an annual cycle (Fig. 11–4). Silage production is closely linked to other processes such as the establishment and growth of the crop, animal intake and production, and manure handling. In addition, silage production is linked to other crop production systems on the farm through effects on soil structure and composition and the scheduling of operations as constrained by available machinery, labor, and suitable weather.

A major external force or input in crop production is weather (Fig. 11–4). Weather influences crop growth, the timing of many production activities, and the DM and nutrient losses that occur during harvest. The most important weather parameters are solar radiation, air temperature, and rainfall. Photosynthesis and the resulting growth of the crop are primarily related to solar radiation and ambient air temperature. Solar radiation and temperature are also major factors controlling the drying rate during field wilting. Rain supplies the soil moisture used through evapotranspiration of the crop. When rain occurs during field wilting, valuable nutrients are leached from the crop, causing a loss in DM and nutritive value.

Crop growth requires soil moisture and nutrients; lack of either during critical growth periods limits yield and the nutrient content of the crop. Most of the nutrients extracted from the soil must be replenished with chemical fertilizers or manure. In the case of legumes, N taken from the air can be fixed and used by the legume and perhaps other grass species growing with the legume (Miller & Heichel, 1995). When a field is rotated from a legume to another crop, a substantial amount

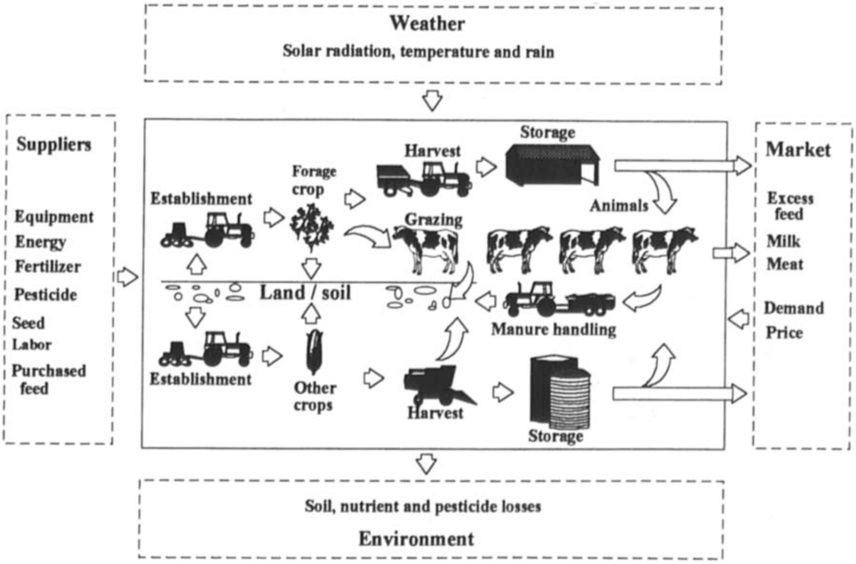

Fig. 11–4. Silage production in a farming system interacts with other crop components, animal components, and the environment to produce marketable animal and feed products.

of N in the decaying plant material is available to the new crop. A small amount of N is also added to the farm through rainfall.

As discussed in the following chapters, silage can be made from corn, small grains, perennial grasses, and legumes. When soil conservation is a critical factor determining crop rotation, use of perennial crops for silage can have a large impact on the farm nutrient balance and soil protection (or even improvement) while supplying animal feed. There are many considerations among species and cultivars, but forage crops are often productive on soils and in climates when other crops cannot meet production requirements.

Nearly all crops used to make silage can be harvested in another form. Corn can be harvested for grain, small grains can be harvested for grain and straw, and perennial grasses and legumes can be harvested as hay. The choice to use these crops for silage is primarily determined by the climate of a region and the agricultural products and markets for that region. Use of corn harvested as silage rather than grain is primarily an issue of feed requirements. By utilizing the whole plant rather than just the grain, the efficiency of using the land to produce livestock feed is increased. Of course, the economically optimum solution changes as the opportunity cost of selling the corn grain varies across years and within years.

Harvest of small grains as silage can be driven by economic, location, or logistic factors. In some instances, small grains may be planted with the intent of producing grain. As economic conditions change, it may become more profitable to harvest the whole plant as silage to add value through the feeding of livestock. In some locations, small grains are planted with the intent to produce silage because they have a growing season and harvest window that complements other crops grown on the farm. This can be advantageous by distributing machine and labor use, distributing nutrient uptake throughout the year, and providing adequate feed supply with limited storage capacity. In some climates, winter small grain crops can be double cropped with corn to capture and recycle more manure nutrients and increase annual silage production.

A major interaction occurs between the growth and development of crops and the rate of harvest. With a low harvest rate, the crop can mature during harvest, increasing yield and reducing nutritive value. Harvest rate is a function of the size of the harvest equipment, the efficiency of the harvest system, and the availability of suitable weather. Forage harvest operations may also compete with other operations, such as tillage, planting, and grain harvest, for available labor, machinery, and suitable weather. When there is a conflict over these resources, one or more of the operations is delayed and thus there is an impact on the performance of the total farm system. For example, a delay in corn planting will reduce the time available for corn growth and development, which may reduce yield, delay maturity, and thus affect silage nutritive value and animal performance.

Harvest inputs include machinery, labor, and energy. The investment in machinery is a major input in silage production. If machinery is not properly selected and apportioned among farm operations, machinery costs can be excessive, sometimes exceeding the value of the harvested forage crop.

Forages may be processed and sold as silage; however, most silage is stored and used on the farm as animal feed. With good silo management, storage losses range from 5 to 15% of crop DM (Table 11–4), and these losses reduce digestible DM and increase fiber concentration in the forage (Rotz & Muck, 1994). Another major loss is the breakdown of true protein to nonprotein N, which is less effectively used by the animal (Muck, 1987). These changes during storage ultimately affect the need for supplemental feed and the intake and performance of animals consuming the forage.

Feeding is linked with other components of silage production by the particle size distribution and nutrient contents in the forage. Particle size is an important consideration in the silo and in the feed. Finely chopped silage packs better in the silo, but when forage is chopped too fine, additional roughage from hay may be needed in the diet to promote proper rumination in animals. Animal nutrient requirements must be met by feeding supplemental feeds that complement the available forage. Total mixed rations blend all feed ingredients for a group of animals with similar requirements into a single feed ration. This method requires more energy but less labor input than manual feeding. Although computer-controlled individual-animal feeders provide the ultimate control over animal diets, they are not widely used due to a higher cost and little benefit over a properly used TMR.

Losses and nutritive changes during silage harvest and storage potentially reduce animal intake and the resulting production. This interaction depends on the initial nutritive value of the forage, the type and size of animals fed, their potential production, and the feeding strategy used. When forage with the highest nutrient content is fed to animals with the highest nutrient requirements and the lower quality forage is fed to animals with lower needs, harvest losses may have less effect on animal performance.

The major nutritional needs of forage-consuming animals are protein, fiber, and energy. These nutritional needs are the primary link between the animal and feed production components of the farm. Forage protein includes degradable, undegradable, and unavailable fractions (National Research Council, 1989). Degradable protein is that utilized by microbes in the rumen. Undegradable protein resists breakdown in the rumen and passes on to the intestinal tract where it is utilized. Animals have different requirements of these protein fractions depending on species, age, and stage of lactation (National Research Council, 1989). Unavailable protein, or that bound to plant fiber, is not easily digested and thus is essentially unavailable to the animal. Forages vary widely in both total protein concentration and protein fractions because of differences in crop species, stage of maturity, losses, harvest methods, and storage conditions. A disadvantage or challenge with silage is that the large quantities of nonprotein N formed in the silo generally provide excess degradable protein that is not well utilized by animals. In an integrated production system, protein available in the forage and supplemental feeds must be matched to animal needs.

In general, animal productivity is directly related to feed intake. Animals consume available feed until either their energy requirement or physical fill is met (Mertens, 1987). Physical fill is related primarily to the rate of fiber digestion. With rations high in forage fiber, particularly less digestible fiber, fiber digestion limits intake and the animal may not consume enough energy to meet requirements. With a diet low in forage fiber, poor animal health and a resulting decrease in production are concerns. The moisture content of silage may also affect intake. When silage has a high moisture content, such as in direct-cut silage, intake may be reduced. If intake is constrained, milk production and growth are likely reduced.

For growing and lactating animals with higher energy needs, the proper balance of energy and fiber in the diet is critical to maintain maximum production. Energy and fiber concentrations in forages vary with species and crop maturity (National Research Council, 1989). Within species, energy and fiber concentrations tend to be inversely related. Harvest and storage losses also affect these nutritive characteristics. Plant components lost, particularly through respiration, are those high in energy and low in fiber (Rotz & Muck, 1994).

Animals produce large quantities of manure, and the handling and use of the manure form major links with crop production. Handling is linked through available time, machinery, and labor. When scheduling farm operations, manure handling can compete with tillage, planting, and harvest for these resources. When properly integrated with the crop component, manure nutrients provide a valuable resource for crop growth in a sustainable farming system. Manure nutrients must be well utilized by crops to reduce nutrient loss to the environment.

Major outputs from farming systems include crop and animal products sold (Fig. 11–4). On a regional or national scale, there is an interaction between the market and the quantity of material produced. When more produce is available than the market demands, the price drops and vice versa. For the individual producer this relationship is less strong. Production obtained on an individual farm is generally related to what occurs in that region (i.e., adverse weather normally affects large regions). Differences will occur though due to variations in weather, soil, and other cropping practices and the interaction of these factors. Silage is different from many other farm products because of its relatively low value per unit volume or mass. This limits the practical distance for transporting the feed, so silage price is more sensitive to a smaller market area.

Farming systems can have undesirable outputs such as soil, nutrient, and pesticide losses to the environment. Up to one-half of the N in fresh manure can be lost through NH_3 volatilization in the barn, during storage, and following land application. Other nutrient losses primarily occur when intense or excessive rainfall causes surface runoff into streams and other waterways. Excess moisture also leaches through the soil profile, carrying dissolved nutrients (primarily N) and pesticides into the groundwater. These losses represent externalities (i.e., activities that are not reflected in market transactions). Costs for removing damage or restoring the environment can represent a substantial cost over normal production costs. Quantification and analysis of externalities is an infant science, but procedures are being developed (Steiner et al., 1995). As externalities are better documented, future policy may require producers or society to bear a greater portion of their cost.

Silage Production Models

The complexity of silage production and the interaction with weather and other farm components has led to the development and use of models for the evaluation and comparison of systems. The first modeling of silage in a farming system began about 40 yr ago. Linear programming techniques were used to select forage-handling practices that maximized family income from a dairy farm while considering effects on the entire farm organization (Armstrong et al., 1962). Various methods of hay making, rotational grazing, and silage production were compared on well-managed, high-producing dairy farms in the Midwest. Differences in farm income among forage alternatives were small, indicating that other organizational factors had more effect on incomes than the choice of forage handling method.

Most modeling of forage systems has used simulation techniques in which the performance of the farm system is tracked through time. Cloud et al. (1968) developed a simulation model to represent forage harvesting, feeding of dairy cows, selling or buying of forage, and output of milk. Forage production was simulated over a range of weather patterns to study the effects of harvest date, grain feeding method, and herd size on farm income. A perennial grass silage system was determined to be less profitable than most dry hay systems, but more profitable than heated drying of high-moisture hay.

Following this work, more sophisticated forage harvest and transport models were developed and applied. Millier and Rehkugler (1972) used a simulation approach to study the effects of harvest starting date, harvest rate, and weather on the value of forage for dairy cows. Because of a high harvest rate, silage harvest systems were beneficial in maximizing milk production, but costs of production and other economic issues were not addressed. Russell et al. (1983) developed a stochastic simulation model with a detailed machinery component to evaluate the effect of machine performance. Harvest system effects were measured by changes in total feed costs in an 18-yr simulation. Kjelgaard and Quade (1975) used a model to evaluate forage transport and handling. A transport cycle was simulated to determine the capacity and labor and energy requirements of various handling methods.

A relatively sophisticated field-curing model was developed by Parke et al. (1978) to simulate a single-harvest forage conservation method over 10 yr of historical weather. The model was developed to evaluate the effects of machine performance, crop growth characteristics, climatic differences, and management policy on the nutrient concentration of conserved forage. Pitt (1982) developed a field-curing model with a similar level of detail. Long-term average yield and the variance in yield were determined for forage harvesting systems considering the probabilistic influence of weather. A criterion was developed for evaluating proposed harvest systems in terms of yield vs. energy use.

Lovering and McIsaac (1981a) developed the first simulation model that linked all the major components of a forage–dairy system. Crop growth and harvest were simulated over 5 yr of weather to obtain typical forage production values. Storage losses, milk production, milking and feeding of cows, manure disposal, production costs, and economic return were then determined for a typical annual production cycle. They used this model to evaluate several management practices for eastern Canadian dairy farms, including a comparison of tower, bunker, and stack silos (Lovering & McIsaac, 1981b). Wilted and direct-cut silage systems were also compared with dry hay production on timothy (*Phleum pratense* L.) grass–based dairy farms (McIsaac & Lovering, 1982).

An important component in modeling silage systems is the ensiling process. McIsaac and Lovering (1980) used relatively simple empirical functions to describe

DM loss as a function of the silage DM concentration entering the silo and the type of silo. Pitt et al. (1985) developed the first mechanistic simulation model of the major microbial and biochemical processes during ensiling. These processes included aerobic respiration, hydrolysis of hemicellulose, growth and death of lactic acid bacteria and their production of lactic and acetic acids, reduction in pH, change in soluble sugar concentration, increase in osmotic potential, and proteolysis. The effects of using silage inoculants on silage fermentation and aerobic stability where studied with the model (Pitt & Leibensperger, 1987; Pitt, 1990; Pitt et al., 1991; Pitt, 1997). This model was then extended to a more comprehensive silo model that included all aerobic processes from filling to emptying of the silo (Buckmaster et al., 1989).

From this history of development, two models evolved that have been extensively used to compare forage systems. McGechan (1990a) developed a simulation model of perennial grass–based dairy farms in northern Europe. Ten-year simulations of grass growth, harvest, storage, and feeding were used to evaluate the performance and production costs of forage conservation methods. Alternative policies in grass silage production were evaluated, including wilted and direct-cut harvest, periodic tedding, maceration and mat making, and the use of silage additives (McGechan, 1990b,c; McGechan et al., 1993). Other harvest options included a precision chop harvester, a double chop harvester, a flail harvester, and silage baling.

The other major modeling effort was directed toward dairy farms in North America. A model of the dairy forage system was created that simulated alfalfa and corn production, crop harvest, feed storage, and animal production over many years of weather (Savoie et al., 1985; Rotz et al., 1989). The model was expanded to represent a whole farm by adding manure handling, tillage, and planting components (Borton et al., 1995; Harrigan et al., 1996), and nutrient flows were included to predict potential nutrient accumulation and loss to the environment (Rotz et al., 1999c). The animal component was extended to relate animal intake and performance to the nutritive value of several available forages and many supplemental feeds (Rotz et al., 1999b). Recent work added perennial grass, soybean, wheat (*Triticum* spp.), barley, rye, and oat (*Avena sativa* L.) crops to enable the analysis of more grain and silage crop options (Rotz et al., 2001, 2002).

This model has been used to evaluate many forage systems, including field drying techniques (Rotz, 1985; Rotz & Savoie, 1991; Rotz et al., 1990), hay preservation methods (Rotz et al., 1992), direct-cut alfalfa silage (Rotz et al., 1993), and corn silage vs. alfalfa systems (Borton et al., 1997). Farm performance was simulated over many weather years to predict resource use, production efficiency, environmental impact, production costs, income, and net return or farm profit. The distribution of annual values provided a measure of the risk involved in alternative technologies or strategies as influenced by weather.

Silage System Selection

The choice or selection of a silage system affects the management of the entire farm operation. Often the effects are positive in one area, but negative in another. For a given farm, a silage system should be selected that meets the requirements of the farm, integrates well with other components of the farm, and maximizes profit. Major considerations in the selection of a silage system include economic issues, labor requirements, land use, and risk.

Forage systems affect farm economics in many ways, as discussed above in this chapter. Total investment in forage systems can exceed $100 000 even on modest livestock farms. Given that the crop is harvested in a timely manner, reducing investment through the choice of less capital-intensive forage systems can help reduce the financial risk faced by the farmer and improve cash flow. Achieving a similar income with a lower investment also improves the rate of return to assets and equity. Procedures for selecting the most economical forage equipment will be discussed in the following section of this chapter.

Labor requirements vary significantly according to the chosen system. Of the four forage crops presented in Table 11–6, alfalfa silage requires three times as much labor as corn silage, grass silage requires twice the labor as corn silage, and alfalfa hay requires 68% more labor than corn silage. Other estimates have shown round-bale hay to have labor requirements 13% less than those for wilted silage, but 17% more than direct-cut silage (Miller & Rotz, 1995). Increased labor use in silage production is often offset by lower labor requirements for feeding. Silage feeding typically requires less labor than dry hay. Feeding hay to small herds may require two to three times as much labor as feeding silage (Bath et al., 1985). When large rectangular bales are fed on larger farms, labor requirements are similar to silage. The choice of forage system depends on farm size and scale, as well as capital and labor requirements.

The opportunity cost and availability of labor must also be considered. Reducing chore labor can allow more time for management. When the farm owner or manager has more time to evaluate and plan production options, better decisions are made which lead to greater profit. Often, quality labor is not available, so the investment in machinery may be a cheaper and more reliable alternative.

Land often becomes a limiting factor as livestock farms expand. Land is then transferred from grain crops into forage crops because of the importance of forages in livestock production. As land becomes even more limiting, the choice of forage crop depends largely on relative DM yields. In that case, corn silage becomes an attractive option. The decision as to which crop to grow is not always straightforward, however, because of local market conditions for protein feeds and the environmental concerns associated with continuous corn production.

The remaining whole-farm consideration in the choice of forage system is risk, or the annual variation in farm profitability. Crop diversification is a generally accepted management strategy to reduce risk on a farm. Diversification works when the risky activities are negatively correlated (i.e., when one crop does poorly, the others do well). However, the risk of one option may be so low relative to the others, or positively correlated with the effects of other options, that this option is a less risky alternative when all economic effects are considered.

Silage systems generally offer less risk than other forage options. For most climates, harvest losses in dry hay production are highly variable, causing greater variability in farm production and profit (Savoie et al., 1985). Seasonal and annual weather effects on pasture growth are also variable. Silage production and the associated economics tend to be more stable across years, but this varies with crop and harvest procedures. For example, the net returns of an all-alfalfa system may outperform alfalfa–corn silage combinations under risk because of less need for purchased concentrates (Borton et al., 1997). Of course, this conclusion depends on geographically specific climate and soil conditions, relative crop yields, and concentrate prices. A more comprehensive comparison of many forage system options is presented later in this chapter.

Equipment Selection

Along with choosing the most appropriate forage system for a given farm, the appropriate equipment must be selected. The type and size of forage harvest equipment used can have a substantial impact on farm performance and profitability. For most silage operations, a range in equipment sizes is available. Equipment sizes should be selected to meet the required capacity at the lowest cost or greatest economical return to the producer (Rotz, 2001).

The selection of the appropriate system for silage production is specific to an individual farm. The optimum type and size of machinery is dependant on 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 on current practices. The best next step may not lead to the overall best system. Good planning should always consider the long-term goal of the operation, that is, 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.

Principles and procedures for machinery selection and sizing are well developed and documented (Hunt, 1999; ASAE, 2000). 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. In silage harvest, the required work is the quantity of forage that must be harvested for any given harvest, and 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 during 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 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 2 wk. The number of days suitable for harvest within that window depends on the climate. The normal procedure is to use the minimum number of suitable days available in 8 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 in the range of 20 to 40%. The number of hours available on a given day will also vary some with the climate and harvest procedures. Typically about 8 to 10 h d^{-1} are available for silage chopping.

Equipment must be selected to meet the required capacity. The capacity of harvest machines is related to swath width, field speed, field efficiency, maximum throughput of the machine, and available power (Rotz, 2001). Because harvest capacity is very variable, equipment suppliers normally do not provide an estimated capacity for individual machines. Procedures are available to estimate the capacity for a given machine under specific harvest conditions (ASAE, 2000), and this can be used to match available capacity to required capacity.

After the harvester is chosen, a tractor must be selected to match this machine. Often equipment suppliers recommend a maximum tractor size for a given machine, which provides a guide for tractor selection. Generally, a tractor should be within 70 to 100% of the maximum recommended size. Using a larger tractor could lead to damage of the implement, while a smaller tractor will slow the harvest operation and may be overloaded and damaged. Procedures are available for calculating the power requirement of an operation as a function of the implement's throughput capacity, the implement and wagon weights, and field slope (ASAE, 2000). From this power requirement, tractors can be sized allowing for power loss and reserve power for extra difficult conditions (ASAE, 2000). To best meet the needs of the whole farm, each tractor must be selected considering the needs of other farm operations as well.

After the harvest equipment is determined, transport and unloading equipment must be selected to appropriately match the harvest capacity. When transport–unloading operations and harvest are done simultaneously, the transport and unloading capacities should equal or exceed the harvest capacity to prevent idle time for the harvester. For high capacity silage harvest systems, transport and dumping into a bunker silo is a relatively high capacity operation. When large self-propelled harvesters are used, a common problem is that a high rate of silage flow to bunker silos does not allow adequate time for packing. This leads to less dense silage, poor fermentation, greater loss, and more rapid deterioration of the silage during the emptying and feeding processes. To eliminate this problem, more tractors must be used to load and pack the silo.

This machinery selection procedure often provides a number of feasible equipment systems. The best option among feasible options can then be determined using an economic analysis. The total (fixed plus operating) production costs of all feasible systems are compared to find the least cost option. For more accurate selection, the costs of harvest and storage losses, nutritive changes, and timeliness should be included along with the linkages to other farm operations.

Computer software tools can be quite useful in easing the laborious task of calculating and comparing costs of multiple systems (Rotz, 2001). An economic model is the simplest and most common tool used in machinery selection. This tool calculates the total ownership and operating costs of individual machines, machine operations, or machinery systems. A drawback of this approach is that the costs of untimely harvest, forage losses, and nutritive changes specific to the operation normally are not included. A more complete and comprehensive comparison can only be obtained through simulation where the impact of equipment type and size is linked to the whole farm. The best equipment system is selected by comparing long-

Table 11–11. Harvest capacities, labor requirements, and costs of typical silage harvest systems (Rotz, 2001).

Harvest system	Capacity†	Labor‡	Cost§
	t DM yr^{-1}	h t^{-1} DM	\$ t^{-1} 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
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 per tonne 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^{-1} DM of stored silage in wilted and direct-cut silage system costs.

term farm profitability for several options. Profitability integrates production costs with the effects of losses, nutritive changes, timeliness, and the interactions between forage production and other parts of the farm.

Although equipment selection should be specific to the needs of a farm, a general comparison can be made of the most suitable type and size of equipment needed to harvest various amounts of forage. Capacities, labor requirements, and production costs for a variety of silage harvest and handling systems are listed in Table 11–11. Round-bale silage systems are best suited to smaller, low-capacity operations where the same equipment can be used for both dry hay and wilted silage production. Although the labor requirement and production costs are high, this system eliminates silo storage cost, which is typically in the range of \$15 to 20 t^{-1} DM of forage stored. Direct-cut silage systems offer a little higher capacity, lower labor requirement, and lower production cost than wilted silage systems, but direct-cut harvest is only suitable for certain crops or under the most adverse climatic conditions.

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. In this case, one could justify the use of a larger chopper, transport vehicles, and unloading equipment than would be recommended for either crop alone. Thus, as the total forage produced on the farm increases, larger equipment can generally be justified with a lower cost per unit of forage produced.

EVALUATION OF SILAGE SYSTEMS

Computer models have been used to evaluate both the performance and economics of a number of options for silage-based farming systems. Such evaluations have compared silage systems and other forage options such as grazing and dry-hay production, various alternatives in harvest and storage, and various silage crops. These comparisons normally emphasize impacts on feed costs and farm profit, but other comparisons include impacts on animal production, farm performance, labor utilization, and the environment.

Silage and Pasture

Several studies have used models to compare the use of silage and pasture farming systems. Armstrong et al. (1962) used a linear programming technique to determine the most economical forage production methods for relatively small Midwest dairy farms with about 35 milking cows on 40 to 80 ha of land. Rotational grazing was the preferred forage source. For all forage scenarios where grazing was used, family income was improved. Silage was one of the last alternatives considered under Corn Belt conditions. Corn silage was selected on small farms only after the other forage-handling practices were incorporated into the farm organization. Corn silage was always preferred to grass–legume silage.

Pasture was also shown to be the preferred forage for beef production. Ainslie et al. (1992) used the Cornell Cattle Systems III spreadsheet model to compare feed intake, production, and overall return for high silage-, low silage-, and pasture-based forage systems in Holstein steer production. In every scenario considered, pasture-based forage yielded a higher return through reduced feed costs and improved feed efficiency. The economic benefit resulted because pasture was lower in cost than the alternative of using alfalfa silage and dry, shelled corn.

Elbehri and Ford (1995) conducted an extensive analysis of the major forage options for dairy production in Pennsylvania. A stochastic farm level simulation model was used to compare 10 combinations of alfalfa, grass, and corn silage with and without pasture. Under the assumption of equal milk production (8230 L yr^{-1} cow^{-1}), the 7-yr annual average net cash income for farms increased 14 to 25% with intensive grazing compared with those without grazing. This profit increase was largely due to an average decrease of \$0.027 to \$0.032 L^{-1} in the cost of producing milk. Farms that benefited most from grazing were those that grew corn silage and grass hay. Less benefit was found when protein-rich alfalfa was used because smaller changes in grain and protein supplementation were needed to meet milk production goals. If milk yields dropped 4 to 6% with grazing, nongrazing forage crop mixes were preferred.

In another study, grazing of alfalfa was compared with silage-based systems on a representative, 100-cow dairy farm in Michigan (Rotz, 1996a). With the use of rotational grazing and good feeding management for a herd producing 7900 to 8800 L of milk per cow, about 42% less alfalfa hay and silage, 35% less corn silage, 10% less corn grain, and 25% less soybean meal were required. Other benefits of grazing included reductions in fuel, electricity, and labor use and 34% less manure handled. The use of grazing increased annual net return of the farm by \$145 cow^{-1} or \$143 ha^{-1}, but grazing also increased risk. The variation in feed and manure handling costs over 25 weather years was 40% greater for the grazing system than with confined silage feeding.

A decrease in milk production often occurs with the use of grazing, and this can shift the economic benefit toward silage-based systems. At a production level of 8080 L using grazing, the net return on this representative farm was similar to that for an 8800 L herd using confined feeding. Thus, under this specific set of conditions, the dairy producer must accept less than an 8% decrease in milk production to maintain a greater profit than the alternative with confined feeding of silage. The importance of maintaining production varies among farm systems. Low input systems can be used where more animals are maintained at a lower cost with grazing to meet the same total milk production and thus greater profitability than attained with silage-based confinement systems. Therefore, a general conclusion cannot be made on the economic preference between grazing- and silage-based systems. This conclusion is farm specific, and often some combination is desirable.

Silage and Dry Hay

Another common alternative to silage is dry hay production. Several modeling efforts have included farming system level comparisons of silage and dry hay as the primary forage in dairy production. Early work by Armstrong et al. (1962) indicated that silage systems were not economical on dairy farms at that time (about 35 milking animals). Higher farm income was maintained with high quality hay than when silage was produced and fed. Since that time, farm size and the use of silage have increased.

McIsaac and Lovering (1982) found that hay systems are normally more profitable than silage production on dairy farms in Eastern Canada. In the situation where land was a constraint and herd size was increased to consume all available forage, silage systems were more profitable. But when both land area and herd size constrained farm expansion, the hay system was most profitable.

McGechan and Cooper (1995) used their forage system model to compare grass silage and hay making options for climatically different areas of Scotland. Crop growth, harvest timing, losses, and nutrient changes were integrated into the model to predict net forage value to the producer. For most sites simulated, similar net forage values were obtained between silage and hay production. A two-cut harvest system was used with silage, compared to a one cutting hay system, which provided a greater gross value for silage. After the higher production cost of silage was subtracted, however, the net values were similar. In climatic areas with less rainfall, hay systems produced forage with up to 30% greater net value, whereas in wetter climates silage had up to 30% greater net value.

A representative 100-cow dairy farm was modeled where alfalfa was produced as either silage, dry hay in large round bales stored in a shed, or small bales stored in a shed (Rotz, 1996b). A four-cut harvest strategy was used in silage production, but a three-cut strategy was used with hay systems because of the difficulty of fall harvest. This, along with greater harvest losses, led to less production and lower forage quality than obtained with silage. In the large-bale system, hay was chopped, mixed, and fed in a mixed ration. Under this assumption, the potential profit of the farm dropped by about \$11 000 yr^{-1} with the use of hay compared with the all alfalfa silage system. With the small-bale system where hay was hand fed, machinery, fuel, electricity, and storage costs were reduced, while labor costs increased. The overall profit margin for this hay system was similar to that of the all silage system when the same milk production level was maintained.

To summarize the comparison of silage- and hay-based forage systems, neither option is more economical or more practical relative to the other for use in all farm systems. Farms vary considerably in size and other management options. Each farm must be evaluated through comparisons to other feasible options for that farm. As farm size increases, more silage is often fed. This may be due to a small economic advantage, but the more important incentives are convenience, mechanized handling, and easier mixing of animal rations.

Direct-Cut and Wilted Silage

The use of a direct-cut method of perennial forage harvest has been desired since the process of ensiling forage began. Benefits include a reduction in the number of field harvest operations and an elimination of a field-wilting period, which together reduce field losses. But ensiling of forages with moisture concentrations above 750 g kg^{-1} can cause poor fermentation, excessive effluent production, greater storage loss, and less desirable feed characteristics. Several farm-level analyses have been conducted to compare direct-cut with more conventional field-wilting methods of harvesting perennial grass and alfalfa silage.

A comprehensive comparison of harvest methods was conducted for timothy silage production in eastern Canada (McIsaac & Lovering, 1982). Direct-cut harvest was found to be more profitable than the wilted silage system for dairy farms of 40 to 120 milking cows with the greatest benefit on smaller farms. These harvest methods were also compared for alfalfa silage production in Quebec, Canada (Savoie et al., 1986). Direct-cut alfalfa had 9% less field loss, higher nutritive characteristics, and less variation in annual feed costs than wilted alfalfa. However, the average cost of both systems was about the same because of the substantial cost of the formic acid treatment required to improve the preservation of protein in the direct-cut alfalfa silage. Economic differences were small and slightly favorable toward wilted silage.

Direct-cut and field wilting harvest methods were also compared for grass silage production in Scotland (McGechan, 1990b). The net forage value (gross value minus production costs) was always greater for wilted silage. Compared with direct-cut harvest, field wilting to 700 g moisture kg^{-1} DM increased the net value of the forage by about 30%. This study concluded that the economic differences between harvest methods were dependent on the assumptions of the analysis, particularly regarding the effect of silage moisture on animal intake. The large benefit of wilting was so decisive though that it was unlikely that any reasonable set of assumptions could overturn its benefit relative to direct-cut harvest.

A whole-farm comparison of these harvest methods was done for alfalfa in the upper Midwest and Quebec, Canada (Rotz et al., 1993). Twenty-six-year simulations were used to compare the performance and economics of direct-cut (with a formic acid treatment) and wilted harvest. Differences in the quantity and nutrient contents of the forages produced were small. Production costs were greater for the direct-cut system even without considering the chemical, equipment, and labor costs for applying the acid treatment. Higher costs were largely due to greater equipment use for transport and feeding of the higher moisture silage (75% more weight handled per unit of forage DM). With greater costs and similar animal production, the net return was less for the direct-cut system, indicating no economic benefit over wilted silage. If direct-cut harvest was used only when needed to prevent rain damage, 18% of the silage was harvested at moisture concentrations requiring an acid treatment. Slightly higher quality silage was produced with this scenario, but again there was no economic benefit. The producers' risk of crop and financial loss was reduced with direct-cut harvest where the variance in harvested yield was reduced 15%, with a 30% reduction in the variance of silage production costs. When these costs were pooled with other farm costs, the variance in the net return over feed costs was reduced 10%.

A synopsis of the analyses of direct-cut harvest indicates little or no economic benefit over the more traditional field-wilting method for perennial grass and alfalfa forage crops. Since these analyses were done for climatic regions of Europe and North America that were most unfavorable to field wilting, the results should generally apply to most regions. When all effects on the farming system are integrated, field wilting is normally justified for perennial crops.

Alternative Storage Systems

The type of storage used in silage production also interacts with many other components of the farm system. Thus, modeling and whole-farm level analyses have been applied to compare bunker silo, tower silo, bag, wrapped bale, and other storage methods and their impact on farm performance and economics. McIsaac and Lovering (1980) compared 10 storage methods for timothy silage on dairy farms in eastern Canada. The horizontal bunker silo was slightly more economical than the stave tower silo. Bags of compressed silage were economically competitive with bunker and stave silos when more than 200 t DM of silage was produced annually. Oxygen-limiting tower silos and stack silos were the least economical options.

A partial budget analysis prepared by McGilliard et al. (1987) compared systems using concrete bunker, concrete stave tower, oxygen-limiting concrete, and oxygen-limiting steel tower silos. When the oxygen-limiting structures were filled 1.5 times per year, the ratios of cost per unit of silage recovered were 1.0, 1.0, 1.5, and 2.5, respectively, for the four types of structures. Bunker silos were more economical on a cost per silage unit basis as silo capacity increased.

Savoie and Marcoux (1985) compared round-bale silage and stack silo systems with more traditional storage systems through 10-yr simulations under Quebec weather conditions. Round-bale systems were promising because a lower investment was required compared with tower silos, and production costs were more consistent across years. Stack silos were not economically competitive; they could only be economically feasible if the costs of the required formic acid treatment and storage platform were substantially reduced.

Through a whole-farm analysis, silage systems that used stave silos, uncovered bunkers, silage bags, or bale silage were compared on a 100-cow dairy farm in the upper Midwest (Rotz & Gupta, 1996). Storage type affected harvest rate, machinery use, forage losses and nutritive value, animal performance, production costs, and farm profit. Greater DM and nutrient loss in uncovered bunker silos reduced the alfalfa and corn silage available as feed and caused a small drop in milk production. Labor was a little higher for the bunker silo because an extra person is needed to operate the packing tractor. Storage costs were lowest for silage bags and highest for bales wrapped with plastic. Overall, the annual net return of the farm was $13 000 greater using the bag silage system compared with stave silos. Use of uncovered bunker silos reduced the annual net return by $15 000, and the net return using bale silage was $2000 below that of the stave silo system.

The comparison of silage storage systems is highly dependent on many management practices of the farm. Whole-farm level analyses cannot provide consistent ranking in economical preference of storage methods, but general guidelines can be drawn. Well-managed bunker and tower stave silos provide similar economic returns to the producer. As farm size is increased, bunker silos are normally preferred more for convenience than for economic benefit. Compressed silage in bags is very competitive with well-managed bunkers and tower stave systems. Bale silage may be economical on small farms, particularly with production methods that provide efficient use of plastic. New construction of oxygen-limiting silos is difficult to justify in most cases. Stack silos normally should be avoided to prevent excessive silage loss and improve farm profit.

Alternative Silage Crops

Considering the many crops available for silage production, relatively few simulation studies have evaluated or compared alternative crops. A study was conducted to project the consequences of integrating wheat with perennial forage grass production on dairy farms in the UK (Doyle et al., 1990). Comparative costs were examined for growing and feeding whole-crop wheat silage in place of grass silage in dairy production. Use of wheat was found to improve farm profit by up to $250 cow^{-1}. However, the improvement obtained was very sensitive to assumptions about the use of surplus land or silage arising from such a switch. Whole-crop cereals were found to complement grass silage rather than provide a substitute crop.

In the northern USA, a major choice in silage production is between corn and alfalfa. Extensive comparisons of cropping strategies ranging from all alfalfa to all corn silage were made using whole-farm simulations (Borton et al., 1997; Rotz, 1996b). Relatively small economic differences were found when forage produced and used on representative dairy farms consisted of none, one-third, one-half, two-thirds, or all corn silage, with the remainder provided by alfalfa. As more corn silage was used on the farm, less corn grain was required to meet the energy needs of the herd. In addition, more forage DM and energy were produced per unit of land with corn silage. Together these changes increased the sale of excess feed (corn grain) in systems using corn silage. Forage protein production was higher with alfalfa, so the purchase of protein supplements increased with the use of more corn silage.

Production costs varied across the forage systems, but many of these differences offset each other. With all costs and incomes considered across the four systems, the net return or estimated profit was similar among the forage mixes. An all alfalfa system or all corn silage system showed higher profit than the mixed forage systems, but the difference was relatively small. Although there were not large economic differences when using various portions of alfalfa and corn silage, a mix of one-third to one-half corn silage was preferred. This mix reduced economic risk, spread labor requirements more uniformly throughout the production season, and provided the best long-term nutrient balance for the whole farm.

Whole-farm simulation was also used to determine if adding small grain crops to traditional corn and alfalfa rotations could provide long-term environmental and economic benefits (Rotz et al., 2002). Nitrogen leaching loss over the whole farm was reduced by 10 kg ha^{-1} when 40% of the corn was double cropped with a small grain, and soil P accumulation was reduced by 2 to 3 kg ha^{-1}. Annual farm net return or profit increased by up to \$111 cow^{-1} when barley or wheat was harvested as a cash crop or feed grain along with straw bedding. The net return was increased by \$15 cow^{-1} when double-cropped barley was harvested and used as silage and \$36 cow^{-1} for double-cropped rye silage. The economic benefit received through the use of small grain crops was affected by management options such as soil type, herd milk production level, the amount and type of forage fed in animal rations, protein supplements fed, and the need for straw bedding. In most scenarios evaluated, the use of small grains double cropped with corn benefitted dairy farms by reducing N leaching loss, reducing soil P accumulation, and improving farm profit. Use of small grain cropping strategies normally reduced the risk or year-to-year variation in net return by providing more consistent feed production and crop sales.

Alternative Processes in Silage Production

Other silage making processes evaluated through simulation include mechanical dewatering, maceration and mat drying, absorbents, and silage additives. McGuckin et al. (1982) integrated models of alfalfa growth, harvest, and feeding to determine the feasibility of a wet fractionation system. With this experimental technology, alfalfa was mechanically dewatered to avoid field wilting and thus avert the risk of weather damage and delays. Wet forage, harvested by a direct-cut harvester, was macerated and squeezed to extract plant juices leaving forage suitable for ensiling. The protein-rich juice was heat treated to extract a high concentrate protein suitable for human or animal consumption. When all products were used on the farm, the technology was feasible for large dairy farms with at least 125 ha of alfalfa. If, however, the protein coagulum was marketed as a substitute for soybean oil meal, the technology became economically feasible for smaller farms as well.

An experimental process of maceration and mat drying of alfalfa was evaluated using whole-farm simulation (Rotz et al., 1990). With this technology, alfalfa was mowed, macerated, and pressed into a mat that dried in the field up to three times faster than hay mowed with a mower–conditioner. When used in silage making, the novel system was found to provide about the same economic return as a conventional wilted silage system. The benefit was greater in a dry hay system where up to $4 were returned to the farmer for each dollar spent on increased machinery costs.

McGechan et al. (1993) used the Scottish dairy forage model to evaluate the alternative technologies of mat making, dewatering, and absorbents in perennial grass silage production. Ten-year simulations showed that the maceration and mat drying technology improved farm profit by as much as \$3800 yr^{-1} on a 40-ha, 100-cow farm. About $950 of the gain was due to reduced field losses, another $950 was attributed to improved digestibility, and $1900 was due to the replacement of the forage harvester by a lower-cost mat harvester. No benefit was found for the dewatering technology; feeding benefits were less than the cost of the equipment and chemicals required for separating and preserving the juice. Also, the use of absorbents to reduce effluent production proved to be uneconomical. When applied at rates large enough to substantially reduce effluent production, costs were too high to be justified.

Corn silage processing is a technology where the crop is passed through a device on the forage harvester that crushes corn kernels and cobs and shreds the stalk material. Rotz et al. (1999a) assessed the long-term impacts of using this process through whole-farm simulation. Processing improved packing in the silo and increased the digestibility of the silage. When used on farms with 40% of the forage requirement met by corn silage, the treatment provided about a 2% increase in milk production along with a small decrease in supplemental grain feeding. Increased production costs were more than offset by the increase in milk sales, providing a \$50 cow^{-1} improvement in the annual net return or profit of the farm. Without an increase in milk production, the economic benefit dropped to \$5 cow^{-1}. If the amount of corn silage fed was increased to 75% of the total forage requirement, processing provided a 4% increase in milk production, with an annual economic benefit near \$100 cow^{-1}.

The use of silage additives has been of considerable interest in recent years, but relatively little has been done to evaluate their impact on farming systems. The potential value of silage enzyme additives was determined using a model with a mechanistic rumen submodel sensitive to variations in feed carbohydrate fractions (Knowlton et al., 1993). For each of a series of potential effects of enzyme treatment, the treatment value was determined either from a reduction in direct costs or an increase in milk production. When diets were rebalanced as NDF was reduced by the enzyme while maximizing the use of alfalfa and minimizing the use of corn grain, the value of the treatment was less than \$1.10 t^{-1} of silage. When milk production was allowed to increase as a result of an enzyme-induced increase in metabolizable energy, a value of \$3.10 to \$5.30 t^{-1} of silage was obtained. Under the most optimistic assumptions where DM intake was increased to maintain a fixed intake of effective NDF and milk production was increased, values as high as \$44 t^{-1} were obtained. They concluded that an increase in milk production must be obtained to receive substantial economic benefit from enzyme treatment of silage.

The same modeling approach was used to evaluate additives or processes for reducing the solubility of alfalfa silage protein for lactating dairy cows (Knowlton & Pitt, 1992). With a reduction in solubility from 610 to 510 g kg^{-1} CP, the savings ranged from \$2.96 to \$3.26 t^{-1} of silage across animals in all stages of lactation. The value of an acid treatment needed to obtain this reduction exhibited diminishing returns as application rate increased. The treatment was most cost effective when used on high quality alfalfa fed to high-producing cows with application rates <2 kg t^{-1}. Management practices that reduce silage temperature were also predicted to save \$.50 to \$1.50 t^{-1} of silage.

SUMMARY

Proper evaluation and management of silage systems requires a systematic look at the interactions with the whole farm. The technology used in silage production and other management decisions must be made based on their effect on farm production and efficiency. Selection of silage options normally influences the nutritive value of the forage, which affects feed supplementation and animal performance. Machinery and labor used in silage production interact with other farm operations, also affecting production efficiency. If labor is limited or equipment is too small, too much time is spent harvesting silage, leaving less available time for other operations.

The bottom line on production efficiency is its effect on production costs and farm profit. At times, some reduction in production efficiency may be justified if the profitability of the whole farm is improved. The economics of silage production cannot be studied in isolation from other parts of the farm. For example, a small harvest system may provide the least cost method of harvesting silage, but the interference this creates with other farm operations may reduce farm profit. By considering all major farm components and the interaction among these components, the best farm management decisions can be made.

Computer models provide tools that help integrate the many factors involved in silage production and their influence on farm management. By simulating all the major farm components and their interactions, the effects of management decisions can be quickly assessed. Such models provide a means for evaluating and comparing a wide range in silage production technologies and management strategies. Model evaluations have shown silage production to be competitive and sometimes preferred to dry hay and grazing methods, but the relative benefits are heavily dependent on farm size, climate, animal production level, and other farm characteristics. No forage production method is ever best for all circumstances.

Models have also been used to extensively compare silage harvest and storage techniques. Direct-cut silage systems are best for some crops, such as corn silage, but field-wilting methods are much more profitable for perennial grass and alfalfa silages. Innovative harvest methods that macerate or shred the forage crop for rapid field drying show a good potential for economic return, but mechanical dewatering of the macerated forage offers little or no economic benefit.

In general, model analyses show that well-managed bunker and tower stave silos provide similar economic benefits to the producer. As farm size is increased, bunker silos are normally preferred more for convenience than for economic benefit. Compressed silage in bags is very competitive with well-managed bunkers and stave tower silo systems. Bale silage may be economical on small farms, particularly with production methods that provide efficient use of plastic. Oxygen-limiting silos and stack silos are normally more difficult to justify based on whole-farm economic benefits.

More work is needed to compare alternative silage crops. In general, strong economic advantages cannot be shown in comparisons of grass, alfalfa, small grain, and corn silage production systems. Small grain and corn silage production often complements perennial grass- and alfalfa-based forage systems. A combination of silage crops reduces the risk of crop loss and spreads labor and machinery use over more of the cropping season. Also, the use of multiple forages can improve the rationing and utilization of feeds by animals.

Economic and environmental pressures on animal production continue to increase the need for greater efficiency and cost reduction in silage production. The role of model evaluation of silage production in farming systems will continue to develop, providing suitable tools for improving farming efficiency and profitability.

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