# CONSERVED FORAGE (SILAGE AND HAY): PROGRESS AND PRIORITIES

R.E. Muck[1] and K.J. Shinners[2]
[1]U.S. Dairy Forage Research Center
U.S. Department of Agriculture, Agricultural Research Service
[2]Department of Biological Systems Engineering, University of Wisconsin-Madison
Madison, Wisconsin, United States of America

## Abstract

Forage conservation permits a better supply of quality feed when forage production is low. While haymaking and ensiling have been practiced for generations, research is still needed to 1) understand the processes affecting quality during harvesting and storage and 2) develop practical means to minimize losses and enhance quality.

Several trends in harvesting forages for silage are notable. Kernel processing of maize, once confined to Europe, has become popular in North America. Self-propelled forage harvesters have a larger share of the market due to more contract harvesting and larger farms. Larger harvesters, rakes and mergers help improve productivity and forage quality. Finally, farmers are increasing cutting length to meet the fiber needs of high-producing dairy cattle. These latter two trends make good silo management more critical.

The number of silo types has continued to increase. Pressed bag and wrapped bale silages are important recent developments. These newer types have made it easier to segregate silages by quality and allow small farms to make high quality silage. However, disposal of the larger quantities of plastic is a growing issue. Alternatives such as edible or biodegradable films would be welcome for all silo types, reducing labor and environmental concerns. With wrapped bales, spoilage and listeria contamination are more common because of the large surface to volume ratio. Enhanced methods to control spoilage and pathogen development are needed.

With most crops considerable breakdown of true protein occurs during ensiling, subsequently decreasing nitrogen utilization efficiency in ruminants. The polyphenol oxidases in red clover and the tannins in some legumes reduce protein loss during ensiling. These mechanisms may be useful in developing new silage additives or plant varieties.

Additives can enhance silage quality. Inoculants are the most common. Improved inoculants aimed at increasing aerobic stability are beginning to be marketed, but their overall success is uncertain. Enzymes to degrade plant cell walls, providing sugar for fermentation and making the silage more digestible, have not fulfilled their promise but do have potential. Acids and sugars have been declining in use but still are important in certain ensiling situations.

Three types of balers are used to package dry hay: small square (SSB), large round (LRB) and large square balers (LSB). The SSB is declining importance in developed countries because of labor constraints but remains viable in developing countries where farm labor is still plentiful. The LRB is the dominant baler worldwide because of its productivity and low ownership and operating costs. High productivity and a package ideally suited for shipping has promoted the continuing growth of the LSB.

Hay producers struggle with getting crops dry enough (< 20% moisture) to prevent excess storage losses due to biological activity. This is especially important as bale density increases. Typical bale densities are about 130, 190 and 240 kg/m$^3$ for SSB, LRB and LSB, respectively. In

humid climates, forage researchers and producers are investigating intensive conditioning systems to improve field drying rates, utilizing preservatives like propionic acid, and developing bale ventilation and drying systems all in the attempt to improve dry hay quality. In arid regions, producers only bale after dew accumulation has softened brittle plant tissue to reduce leaf loss. Systems are under development that will soften plant tissue at the baler by applying a fine water mist. Larger livestock farms and increased development of markets for commercial hay will push demand for greater productivity and better bale quality.

## Introduction

In most parts of the world, forage conservation is a key element for productive and efficient ruminant livestock farms. Forage conservation permits a better supply of quality feed when forage production is low or dormant. Forage conservation also provides farmers with a means of preserving forage when production is faster than can be adequately utilized by grazing animals. This prevents lush growth from becoming too mature. Consequently, forage conservation provides a more uniform level of high quality forage for ruminant livestock throughout the year.

Forage is preserved as either hay or silage. In hay production, the crop is dried so that it is essentially biologically inactive both with respect to plant enzyme activity and microbial spoilage. The low moisture content also permits easier transportation by reducing the weight per unit of dry matter (DM). Haymaking is dominant in those areas of the world where good drying conditions prevail. However, it may also be used in humid climates where ensiling has been considered too difficult because of forage characteristics, high temperatures or tradition.

In ensiling, the crop is fermented anaerobically by lactic acid bacteria present on the crop. Preservation depends on 1) a low pH to inhibit clostridia and other detrimental anaerobic microorganisms and 2) anaerobic conditions to prevent the growth of aerobic spoilage microorganisms such as yeasts and molds. Ensiling has been practiced primarily in the humid temperate portions of the world, where DM and quality losses in making hay may be excessive.

Typical losses for alfalfa during harvesting and storage in the humid, temperate portion of the United States are presented in Fig. 1. Harvest losses increase with DM content (Rotz and Muck, 1994). The drier crop and the increased drying time increase respiration losses and the chances for losses from rain during wilting. Mechanical losses also increase when equipment processes a drier crop. Conversely, storage losses generally decrease with increasing DM content, particularly for hay. Storage losses for silage are generally higher than for hay but are more dependent on the type of silo and silo management than on DM content.

Overall, Fig. 1 indicates rather substantial DM losses (15 to 30%) between mowing and feeding under good management. Also notable is that the losses represent an even higher percentage of the value of the forage. Consequently, research is still needed to 1) understand the processes affecting quality during harvest and storage and 2) develop practical means to reduce losses and enhance quality. In this paper, we hope to briefly summarize progress to improve the preservation of forage and to highlight areas of research that we believe are most important.

## Harvesting Silage Crops

### *Wilting vs. Direct Cut*

A key decision in making silage is the DM content at which to harvest the crop. The DM content at ensiling determines the potential ensiling problems that may be encountered. On the wet side (<30% DM typically), silage effluent and clostridial fermentation losses may be significant. In dry forage (particularly >50% DM), losses may increase during wilting from precipitation and mechanical losses and later during storage from heat damage and spoilage. Thus ensiling in the 30 to 50% DM range would seem best, wetter (30 to 40% DM) with horizontal silo types and drier (40 to 50% DM) with tower silos. Such a range minimizes the potential for clostridial fermentation and silage effluent as well as provides a low porosity to minimize spoilage losses during storage and feed out. However, such a simplistic answer does not account for interactions of harvest with weather and other issues.

How does the farmer determine the appropriate DM content? All too often it is based on traditional practice rather than what might be the optimum for the conditions. To accomplish the latter a farmer needs a means of accurately and rapidly measuring DM content, an accurate weather forecast and a means of evaluating various options on a given day. Certainly the optimum depends on a wide variety of factors: type of forage (grass, legume, etc.), target animals to be fed, specific weather conditions, harvesting equipment and labor available to the farmer, silo type, silage additives available, means of handling effluent, and specific losses associated with weather, equipment, and silo type and management.

Estimating DM content is easiest. Farmers in many countries have a number of options: electronic moisture meters, Koster testers and microwave ovens. The electronic moisture meters, based on conductance or capacitance of the crop, have been the least accurate whereas Koster testers and microwave ovens rapidly dry samples and can provide estimates similar to normal oven measurements (Pitt, 1993).

While rapid moisture measurement is possible, assistance in weighing the options of when to chop the crop is not yet available for farmers. A guide or software program to assist farmers will require knowledge about the losses and changes in quality that occur during wilting, harvest and storage. Considerable knowledge is available about DM losses and the factors affecting those losses during wilting and harvest from plant respiration, precipitation and various machinery operations regarding both grasses and legumes (McGechan, 1989; Rotz, 1995). Changes in nutritive value from these processes are more limited but perhaps at a sufficient level for decision making at the farm level.

In the silo, the two most significant problems with harvesting and ensiling direct-cut or minimally wilted forage are effluent losses and clostridial fermentation. Effluent losses are primarily a function of DM content and silo type (or density) (Bastiman, 1976; Pitt and Parlange, 1987; Davies and Nicholson, 1999). Effluent increases quadratically as DM content decreases below a critical DM content. The minimum DM content with no effluent in wrapped bale silage is approximately 22 to 25% DM (Davies and Nicholson, 1999); for bunker silos 28 to 30% DM (Bastiman, 1976); and for tower silos 30 to 45% DM, increasing with taller and wider silos (Pitt and Parlange, 1987). Effluent is high in soluble compounds: soluble N, sugars, fermentation products and minerals (Rotz and Muck, 1994). As a consequence, effluent losses can result in a disproportionate loss of digestible nutrients as well as represent a potential environmental hazard if not handled properly.

Clostridial fermentation results in both increased DM losses as well as less palatable feeds. In more severe cases, clostridial silage can cause animal health problems. The key to preventing clostridial fermentation is to drop the pH of the silage sufficiently to inhibit clostridial growth. The critical pH to stop clostridial growth varies with the type of crop and its DM content at ensiling (Fig. 2). Typically with temperate grass and legume silages, clostridial fermentations are infrequent if the crop is wilted to 25 and 35% DM, respectively. However, this can vary substantially, dependent on growing conditions (temperature, moisture and solar radiation) and rainfall during wilting. While Fig. 2 indicates the approximate pH needed to prevent a clostridial silage, it does not indicate the potential for a given crop to reach that pH in the silo. The primary crop characteristics that will affect this are the sugar content and buffering capacity (a measure of the resistance to pH decline in the crop). Weissbach et al. (1974) found the sugar to buffering capacity ratio at ensiling was inversely proportional to the minimum DM content needed to prevent a clostridial fermentation. The further below this minimum the greater are the chances for clostridial activity. To take advantage of this relationship, a farmer would need to evaluate sugar content and buffering capacity during wilting. Refractometers have been used to estimate sugar content in forage juices at mowing, but procedures would need to be developed to process and evaluate drier forages in a consistent fashion. Buffering capacity as done now by titration is unlikely to be performed in a farm setting. A system for farm use that could predict minimum DM content would be useful particularly in northern Europe where direct-cut silage is common as well as in other parts of the world for high moisture alfalfa and tropical grass silages where sugar contents may be marginal for anaerobically stable silage.

Where weather conditions make wilting difficult, means of speeding the wilting process could increase the opportunity to make silage without the use of additives. Improvements in drying rate through chemical and mechanical means have been investigated primarily for making hay and are discussed later in this paper. In general, these approaches work best when drying conditions are good to excellent but do not provide much benefit under cool, damp conditions where a boost in drying rate would be most welcome.

If weather conditions dictate ensiling direct-cut or minimally wilted forage, then provisions must be made to handle effluent and insure a sufficiently low pH to inhibit clostridial growth. A wide variety of plans are available to capture effluent. Treating effluent as a waste, however, adds to the cost of producing silage. An alternative is to feed the effluent. Well-fermented (nonclostridial) effluent is readily consumed by cattle plus is of nutritional value to them (O'Kiely, 1989). Systems to easily feed effluent to cattle may be able to reduce the overall cost of silage production in those regions of the world where effluent production is a normal part of silage production. One possibility is the use of edible absorbents at the bottom of the silo.

*Trends in Forage Harvesters*

In many countries, farm sizes are increasing. Also because of the high cost of farm machinery, contracted operations are becoming more common, particularly in Europe. As a consequence, there is a trend toward larger and self-propelled forage harvesters. Self-propelled forage harvesters have three to four times the capacity of a pull-type harvester so the shift to self-propelled machines has dramatically reduced the total unit sales of harvesters. Worldwide sales of pull-type harvesters have diminished from about 7,000 to 4,000 to 3,500 in 1990, 1995 and 2000, respectively, whereas sales of self-propelled harvesters have increased from about 1,800 to 2,200 to 2,500 over the same period. The worldwide volume of new retail sales of forage harvesters is about 600 million U.S. dollars comprised of 100 and 500 million dollars from the pull-type and self-propelled harvester markets, respectively. This does not include all the ancillary silage equipment such as forage blowers, self-unloading wagons, baggers, etc. On the positive side, larger equipment helps to harvest forage in a more timely fashion, providing forage of a more uniform and higher quality. On the other hand, equipment at the silo must be sized to adequately handle the increased rate of forage received. This is especially critical in bunker or clamp silos where high densities are dependent on good packing practices. Increasing the rate of forage coming to the bunker silo without change packing practices will decrease packing time per unit crop and thus reduce density (Muck and Holmes, 1999). Unfortunately little research has been done on factors influencing density of bunker silos. General recommendations have been available, but they are too vague to allow a farmer to determine the best way to improve his or her particular situation.

Kernel or crop processing has been a common feature on forage harvesters in Europe for making maize silage. It is now becoming popular in North America. It is most commonly performed by passing the chopped crop between two counter-rotating rolls set 1 to 5 mm apart and operating at differential speeds. The purpose is to break open kernels and abrade or shred the cob into small pieces to improve kernel and starch digestion. In addition, there is some reduction in average particle length of approximately 15 to 30% (Schurig and Rodel, 1993; Roberge et al., 1996; Shinners et al., 2000a) and an increase (7 to15%) in specific energy (Roberge et al., 1996; Straub et al., 1996; Shinners et al., 2000a) to harvest the crop at a given theoretical length of cut (TLC). In practice, farmers are being advised to increase the TLC so that machine throughput and power requirements are not adversely affected while the actual length of cut of the final product is similar or longer than traditionally chopped maize.

Effects on animal performance are modest but sufficient to be profitable. Milk production may be increased by 2 kg/cow/d but is more likely to be 1 kg/cow/d or less (Harrison et al., 1997; Shinners et al., 2000a). Effects are more pronounced in more mature corn (1/2 milkline to black layer). Improvements of 6% in feed efficiency have been reported in feedlot cattle (Bolsen et al., 1999).

More research is needed to determine the animal benefits among the interacting factors of TLC, processor setting (and how to measure its actual effect), and crop maturity. Additionally, there is interest in whether crop processing may be of value in the chopping of grasses and legumes. The shearing action of the differential rolls may permit better fiber digestion as suggested by unpublished research of Hunt (1996) reported by Harrison et al (1997). Wilted alfalfa processed through crop processing rolls did show evidence of improved *in situ* fiber digestion, but dairy milk production was unaffected (Shinners et al., 2000b). Additionally, concerns were raised regarding the tight roll clearances needed for processing, damage to the rolls from rocks and greatly increased power requirements (Shinners et al., 2000b). Although crop processors may create more digestible silages in all crops, more research is needed to improve processing performance in wilted crops and insure improved animal production.

A third area of change in forage harvesting equipment is in the area of monitoring yield and quality. The first step in developing forage yield monitors is to develop sensor systems to measure crop mass flow on-the-go. The most promising techniques being applied to the forage harvester include measuring feed roll displacement with potentiometers and determining the magnitude of crop impact from the cutterhead or blower (Shinners and Barnett, 1998; Savoie et al., 2000). Measuring forage moisture on-the-go is quite challenging because of the speed at which the crop moves through the harvester, typically in excess of 50 m/s. Techniques that have been used include capacitance and near-infrared reflectance (NIR) sensors (Shinners and Barnett, 1998; Snell et al., 2000). Measurement of forage quality constituents using NIR techniques could be possible, but no research has been reported. Considerable research is required to improve the accuracy and robustness of the sensor systems for both mass flow and moisture.

The goal for much of this monitoring work is to bring forage harvesting up to a similar level of sophistication as grain harvesting and is aimed mainly at precision management of fields. However with forages, monitors could play a significant role in ensiling management. Forages could be more accurately separated at harvest by quality and placed in different silos so that high quality forage, for example, could be reserved for high producing dairy cattle. Alternatively, means of measuring sugar, buffering capacity, moisture, lactic acid bacterial levels, etc. could allow farmers to apply additives only when necessary, reducing additive use. Finally, yield monitors would also permit more accurate application of additives at the harvester, further improving additive profitability and efficacy. Overall, the development of good monitors for the harvester could greatly improve ensiling management and leave much less to chance.

*Theoretical Length of Cut*

How finely should a forage be chopped for ensiling? The answer varies depending upon who you ask. Animal nutritionists prefer long fiber, particularly for high producing dairy cows that may have limited forage in their rations. On the other extreme, short particles are easier to pack as well as remove from a silo. A wide range of TLCs (6 to 100 mm) is possible from the various types of forage harvesters. Over this range, silage fermentation does not appear to be appreciably affected by TLC in farm-scale silos (Marsh, 1978). However, reduced density in bunker silos has been observed: 14% in alfalfa when particle size increased from 9 to 25 mm (Shinners et al, 1994) and 20% in a survey of grass silage studies for particle size increasing from 20 to 100 mm (McGechan, 1990). Lower density should lead to higher spoilage losses as suggested in the alfalfa study (Shinners et al., 1994). Finally, increasing TLC can reduce machine wear and specific harvesting energy requirements. Overall though, one would most likely favor chopping only as long as needed to meet the long fiber needs of the livestock being fed. Additional length of cut issues will also be considered relative to specific silo types.

## Silo Types

Farmers have a wide variety of silo types from which to choose: piles (clamps), walled horizontal silos (bunkers, trench), tower silos (concrete stave, poured concrete, oxygen-limiting), pressed bags, wrapped bales (large round and square bales; individual vs. multiple bale configurations). While silage can be made successfully in all, each type has specific management issues needing investigation.

*Piles and walled horizontal silos*

The most common silos around the world are horizontal piles with or without walls. Losses during storage and the quality of silage removed from these types of silos are highly dependent on silo management, perhaps more so than other types. The large surface-to-volume ratio makes these silos among the most susceptible to respiration losses during filling so that rapid filling is important. Density depends on primarily on the quality of the job of packing by the filling crew. The large open surface at the end of filling should be promptly and securely covered with plastic to minimize losses. Holes in plastic can result in substantial damage if not repaired promptly. Finally, unloading losses can be substantial if feed out rates are low.

For many of these issues, we tell farmers that they should do the best job possible. However, for some areas we have surprisingly few data to tell them what the tradeoffs are so they can make informed management decisions as to the most profitable actions. Only one area is well known, the value of a good cover. Some farmers feel that spoilage on top of an uncovered silo is not a significant cost. However, a survey of covered and uncovered bunkers on farms found a difference in losses of 140 g/kg DM ensiled in the top 50 cm (Bolsen et al., 1993). Also an analysis of the return on the investment in plastic and labor to cover a bunker was calculated to be 8:1, a very profitable exercise (Rotz and Muck, 1993).

In contrast, we tell farmers to get the silage as dense as possible to minimize spoilage losses. However, for the farmer striving to be profitable and possibly limited by equipment and/or labor, what density is best and how can he achieve it under his circumstances? A recent survey of bunker silo densities on commercial farms did find a correlation between density and factors such as layer thickness, packing tractor weight, packing time per unit of wet forage, silage height and crop DM content (Muck and Holmes, 1999). This study developed an equation between these factors and density. This equation allows farmers to look at the tradeoffs for improving density such as spreading the crop thinner vs. using multiple packing tractors, but more research is needed to verify that relationship.

Finally, what is the true cost of one feed out rate vs. another? Modeling research indicated that low feed out rates could result in rather substantial DM losses at typical bunker densities (Fig. 3). However, some verification is needed. Recently Honig et al. (1999) published a table of energy losses as a function of feed out rate, the stability of the silage, and air penetration that indicates that substantial losses during unloading can occur (Table 1). Certainly more research of this type is needed with various crops and climates.

*Tower silos*

Tower silos are much less common and are primarily found in the northern U.S. and Canada. While these silos are excellent for preserving a crop, they have fallen in usage. First, they are the most expensive as far as capital cost so that economically stressed farmers are less likely to purchase them. However, the cheapest type of tower silo (concrete stave) is competitive with bunker silos on an annual cost basis that considers all costs associated with storage (Rotz and Muck, 1993). Second, larger farms have found the lower filling and unloading rates for tower silos compared to horizontal silos to be less attractive for timely harvest as well as feeding of cattle. A recent development to enhance filling and unloading is the Big Jim Quantum→ system[1]. The unloader is used in the filling process to both pack the crop in the silo as well as create a 60-cm diameter hole in the center of the silo. The hole is then used in unloading to drop silage from the top into a feed elevator at the bottom or directly into a feed wagon positioned below the hole. This increases unloading rates up to five times of conventional tower silo unloaders according to sales literature, but research is needed particularly to evaluate the effect of the hole on DM losses. If the effect is small, this new unloading system may make tower silos more viable on larger farms. However, the compatibility of the self-propelled harvester and the tower silo filling rate may still be a major hurdle.

*Pressed bag silos*

A newer ensiling technique is the pressed bag. Crops are pressed into polyethylene tubes that typically range in diameter from 1.8 to 3.6 m and lengths of 30, 60 and 90 m. This silo type appears to be growing rapidly due to low cost, ability to segregate forages by quality, and flexibility of storage capacity. However, little research has been reported on the performance of these silos. Losses will depend on the quality of the plastic, which has been reported to vary significantly by supplier (Robinson et al., 1988). Losses will also be affected by density and feed

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[1] Mention of trade names is for the benefit of the reader and does not imply endorsement by USDA or the University of Wisconsin.

out rate. Presumably DM densities are in the range of 150 and 200 kg/m$^3$, but there is little information on actual densities and the factors that influence them such as particle size, DM content, and bagger model. The packing mechanism varies from one manufacturer to another which likely affects density (both average and variation across the face), and bagger operators indicate that models vary with regard to ease of attaining a smoothly filled bag. Experienced bagger operators also have found that larger particle sizes can cause problems in filling, resulting in lumpy bags, and that some bagger models are more sensitive to larger particles than others. If densities are in the range of 150 to 200 kg DM/m$^3$, then feed out rate could be a major factor in determining storage losses. Typical recommendations are a minimum of 150 to 300 mm/d, but these rates may be low particularly if the bag is lumpy permitting air to move easily throughout the length of the bag. Overall DM losses could be low (5%) as product literature indicates if the bags are filled smoothly, remain well sealed until opening, and are fed out at high rates. However, substantial losses have been reported on occasion (e.g., Kennedy, 1987). Research on densities and DM losses in these silos and the factors that affect both is needed.

*Wrapped bales*

Another newer method of making silage is the wrapped bale. It is principally popular on smaller farms and provides the farmer with considerable flexibility in terms of harvesting and feeding. Several wrapping systems are available: stretch wrap plastic on individual round and rectangular bales or large round bales arranged end to end and either placed in a plastic tube or wrapped with stretch wrap. These latter alternatives reduce the plastic used, greatly increase the wrapping productivity and reduce the storage space compared to individually wrapped bales. However, tubeline wrapping can reduce feeding flexibility compared to individual wrapping.

Two concerns with wrapped bales are storage losses and poor fermentation. The large surface area to volume ratio with individually wrapped bales suggests that storage losses might be rather high and that failure to routinely monitor for and repair holes in plastic could lead potentially to disastrous losses. Rather surprisingly research data typically show rather low losses (<10% of DM) (Huhnke et al., 1997). Such low losses do not account for bales completely lost due to plastic failure, may not accurately account for spoiled forage that should not be fed, and could also be due to the shorter storage periods used in research studies. Storage beyond six months is rare in any silage study. A positive side of individually wrapped bales is that bales are fed immediately on opening, reducing feed out loss. Certainly more research is needed to evaluate losses particularly under longer storage conditions. Also losses with the bales stored in tubes or wrapped in a line are largely unknown at this time.

Bale silage does not ferment as well as chopped silage (Huhnke et al., 1997). This makes it more susceptible at a given DM content to undergo a clostridial fermentation. It appears that bale silage needs to be approximately 5 to 10 percentage points higher in DM content than chopped silage to avoid clostridial fermentation. Bale silage or rather the outer layers of bale silage where pH is high are more prone to contain pathogenic organisms such as *Listeria monocytogenes* than chopped silage (Fenlon and Wilson, 1991). Certainly spoiled, moldy areas of wrapped bale silage should be discarded. Because the outer layers in bales represent a large proportion of the volume, means of reducing spoilage is very important. Recent work under Irish conditions with a 9-month storage period (Forristal et al., 1999) suggests that plastic color is not important, but the number of layers of plastic was. The average area of visible mold declined from 21.5% to 1.7% to 0.7% with 2, 4 and 6 layers respectively. Similar research under different climates would be useful. Some large round balers permit the coarse chopping (40 to 100 mm) of forage that will be ensiled, but little is known regarding its effect on ensiling.

*Plastic alternatives*

Polyethylene is commonly used on all but oxygen-limiting tower silos. The amount of plastic used to make silage has been increasing because of the popularity of bag and bale silage which use 2 to 6 or more times as much plastic as silage made bunker or pile silos. Recycling of the waste plastic would minimize the amount being placed in landfills or burned. However, the low-density polyethylene used for silo covering is not as valuable as other plastics for recycling, and the contamination of the polyethylene with silage, moisture and soil further reduces its value (Negra and Rogers, 1997).

Various alternatives to polyethylene have been investigated for horizontal silos. Minson and Lancaster (1965) compared ground limestone, sawdust, and soil to plastic and found losses with the alternatives to be at least double that of plastic. A newer approach has been a commercially available, edible film which is sprayed on the crop, but results here too have not been encouraging (Brusewitz et al., 1991). More recently, a different plastic film formulation, which is one-fourth the thickness of traditional polyethylene but of high oxygen impermeability, appears promising (Degano, 1999). Certainly, there is farmer interest for a product that could be sprayed on the crop and be edible, minimizing the labor and costs of handling a cover.

## Changes in Crop Quality during Ensiling

*Plant enzyme activity*

The crop changes in the silo due to plant enzyme activity, microbial respiration and fermentation. Respiration, whether by plant or microbial activity, removes the most digestible components of the crop and is the cause of much of the DM loss during silo storage. It, however, is controllable by the farmer by minimizing the amount of oxygen entering the silo.

The second most important plant enzyme activity relative to animal productivity is proteolysis, the breakdown of true protein to soluble nonprotein nitrogen (NPN). This is an area that many farmers are relatively unaware of but is important for feeding high-producing dairy cattle and altering the fate of nitrogen from animal manures. The high value of the losses in wilted silages shown in Fig. 1 is due primarily to proteolysis in alfalfa during ensiling and resultant need to add less degradable nitrogen to dairy cattle rations. If silages high in NPN are not balanced with rapidly degradable energy sources in the ration, then much of the NPN will be converted in the cow's rumen to ammonia, which will be absorbed into the blood and end up as urea in the urine.

The amount of proteolysis during ensiling across many legumes and C-3 and C-4 grasses is reasonably explained by the total N and DM contents of the crop, increasing with total N and decreasing with increasing DM content (Muck et al., 1996). The exceptions are forages that contain compounds that inhibit proteolysis (Fig. 4). Tannin-containing legumes are the forages most commonly associated with reduced proteolysis, but red clover silage also has less NPN than alfalfa silage at similar levels of total N (Albrecht and Muck, 1991). Efforts have been made to genetically alter alfalfa to produce tannins, which has proven difficult. Research is also pursuing the understanding of protein protection in red clover, which is related to their soluble polyphenol oxidases. These mechanisms could be valuable in developing methods to protect protein in other forage silages.

Various alternate approaches are possible. Lowering pH with formic acid to 4.0 substantially reduces proteolysis and leads to improved N efficiency in dairy cattle (Nagel and Broderick, 1992). Formaldehyde is capable of protecting protein as well although there may be concern about its safe use. Finally, a modified atmosphere (containing low levels of oxygen to maintain plant cell integrity and high levels of carbon dioxide to inhibit spoilage microorganisms) has recently been investigated (Makoni et al., 1997). Success for these mechanisms will depend on cost-effective and safe means of implementing them.

*Microbial activity*

The preservation of a crop in the silo normally depends upon lactic acid bacteria (LAB) overwhelming competitors and fermenting sugars to lactic acid and other products. This occurs on an extremely consistent basis considering that lactic acid bacteria usually represent a tiny fraction (<0.1%) of the natural population of microorganisms on the crop at ensiling. This is further compounded by the fact that the majority of the LAB on the crop at ensiling frequently do not appear to be very effective in the silo, and other strains of LAB end up dominating fermentation (e.g., Pahlow, 1985). We know that LAB in general have many characteristics that help promote them in the silo such as tolerance to a wide range of osmotic pressures, oxygen levels, and temperatures. They tend to grow rapidly and may produce bacteriocins to inhibit competitors. However, we know little about why certain species prevail in one instance and not in others. Is this random chance or is there a pattern that we currently do not understand? New techniques such as DNA profiling allow us to follow not only species but strains within a species (Wortman et al., 1999). While this may be useful to address such questions, we must also be able to look more carefully at differences in crops from one harvest to the next to determine if some characteristic of the crop may also be influencing the LAB strains that develop and consequently the pattern of fermentation. Silages from different varieties of alfalfa have been found to rank similarly by final pH across various harvests (Muck and Hintz, 1996; Dennis et al., 1999), but average pHs and fermentation products across varieties have varied substantially by cutting. Are these differences merely differences in gross sugar content and buffering capacity or are there differences in concentrations of specific sugars, amino acids, organic acids, vitamins, etc. that are favoring one species or strain over another? Having this latter knowledge, could we use it to provide a more consistent fermentation through improved crop varieties, silage additives, etc.?

Beyond promoting LAB, we want to inhibit a wide range of microorganisms in the silo. Traditionally, the list has included clostridia, enterobacteria, yeasts, molds, and bacilli. With clostridia and enterobacteria, poor fermentation is the concern, resulting in higher DM losses and silages that are less palatable. Control of clostridia is assured by reducing pH rapidly and sufficiently as discussed earlier. Enterobacteria are inhibited generally below pH 4.5 (Lindgren, 1991). However, with both groups it is most likely the concentration of undissociated fermentation acids, particularly lactic, that is important. Lindgren (1991) reported that 10 mM and 6 mM concentrations of undissociated lactic acid inhibited *Enterobacter* sp. and *Clostridium tyrobutyricum*, respectively, over a range of silage pHs. However, further work would be useful to see how the minimum inhibitory concentrations vary with osmotic potential or DM content.

With yeasts, molds and bacilli, the primary concern is aerobic respiration and the accompanying DM losses and heating of the silage. In addition, acetic acid bacteria have been found to be important in whole-crop maize silage (Spoelstra et al., 1988). Typically yeasts and acetic acid bacteria are the initiators of aerobic deterioration of silages during unloading and can reasonably predict the initiation of deterioration (Courtin and Spoelstra, 1990). Molds and bacilli are less likely to initiate aerobic deterioration due to slow growth rates in molds and inhibition of growth in bacilli at low silage pHs (Muck et al., 1991; Lindgren, 1991). So the most likely pattern of aerobic deterioration is initiation by yeasts or acetic acid bacteria, followed by bacilli and later by molds.

If we want to effectively inhibit aerobic deterioration, we need an understanding of the factors that lead to the development of yeasts and acetic acid bacteria in silage. With acetic acid bacteria, exposure of the silage to oxygen is very important. These bacteria are frequently below detectable level in well-sealed laboratory-scale maize silages (e.g., Muck et al, 1992) whereas they are commonly found in silages from farm silos. Yeasts in contrast vary substantially, perhaps due to gas composition, sugar content or other plant factors (Muck et al., 1992). Alfalfa silages apparently contain a compound that can inhibit yeast growth (O'Kiely and Muck, 1992), which if identified may be useful in making other crops more aerobically stable.

A growing area of concern is the presence of pathogens and microbial toxins in silage and the potential impact on the animal as well as the human food products coming from those animals. *Listeria monocytogenes* is both a human and animal pathogen, causing listeriosis. It is present in soil and on crops at ensiling. Generally listeria are not considered a problem in well-fermented silages. A pH below 4.5 to 5.0 normally inhibits growth (Fenlon and Wilson, 1991) and low levels of undissociated lactic acid also are inhibitory ( stling and Lindgren, 1993). However, there appears to be a growing incidence of listeria problems associated with the increase in wrapped bale silage (Fenlon and Wilson, 1991). The higher surface area to volume ratio in wrapped bales and the poorer fermentation probably both contribute to a higher proportion of the silage being exposed to oxygen and having elevated pHs, conditions favoring the development of these bacteria. The trend for small farms to make wrapped bale silage suggests research is needed to investigate the best ways to prevent listeria growth in such silages.

*Escherichia coli* is another bacterial species of concern, particularly strain 0157:H7 which is a human pathogen. While it is a member of the enterobacteria, little is known regarding whether *E. coli* survives ensiling, what role silage may play in its transmission on the farm, and what conditions in the silo are needed to kill *E. coli* on the incoming crop.

Many microorganisms produce toxins. Various strains of LAB produce bacteriocins, which typically inhibit other bacteria and give LAB a competitive advantage. This could possibly be used to select LAB that inhibit listeria (Fenlon et al, 1993), clostridia or other microorganisms. Of greater concern are the bacterial endotoxins and fungal mycotoxins that have an adverse effect on livestock. Little is known about endotoxins and their effects. In contrast, a wide variety of mycotoxins have been identified in silages and fermented high moisture grains. The most common fungi that produce mycotoxins in forages and grains are *Fusarium*, *Penicillium* and *Aspergillus* species (Gotlieb, 1997). These fungi need above freezing temperatures, moisture contents above 20% and oxygen to grow. However mycotoxin production generally does not occur over the full range of environmental conditions at which growth occurs. For example, aflatoxin from *Aspergillus* is produced under warm (>30°C) and wet conditions whereas mycotoxins from *Fusarium* are more likely produced under cooler conditions (7 to 24°C) (Gotlieb, 1997). Mycotoxin production in the silo should be minimal if the silo is well sealed, but there still are concerns about mycotoxin production when and where oxygen may be present in the silo. Certainly more research is needed to more accurately define those conditions in which mycotoxins are produced. Also research is needed to develop 1) crop varieties that are resistant to fungal growth and 2) means of reducing mycotoxins in contaminated silages.

## Silage Additives

### *Inoculants*

Lactic acid bacteria are one of the most common silage additives. Their primary aim is to guarantee a fast and efficient fermentation in the silo. Less frequently, animal performance (milk production or gain) is improved (Muck and Kung, 1997; Kung and Muck, 1997). However, the level of improvement in animal performance is often greater than one would expect from shifts in fermentation and reduced proteolysis. In some cases, animal performance has been enhanced without improvement in fermentation (Weinberg and Muck, 1996). These results suggest inoculants may be affecting animal performance directly or indirectly in unexpected ways, ways if known that could further improve animal performance.

Inoculants have been less effective in regard to aerobic stability. Stability is improved some cases and made worse in others, particularly in whole-crop maize and small grain silages (Muck and Kung, 1997). Inoculant manufacturers are currently developing new products to address this. While the most common approach has been to look for improved homofermentative strains, a heterofermentative strain, *Lactobacillus buchneri*, has shown promise (Driehuis et al., 1999). Certainly this is an area where products will be expected to improve in the next few years.

Inoculants do not always work. This may be due to a number of causes, but the most likely is competition from the natural LAB population. If the natural population is sufficiently larger than the number applied, then it is difficult for the inoculant bacteria to overwhelm the fermentation (Muck, 1989). Relationships to predict the natural population have been developed for alfalfa (Pitt and Muck, 1995). These equations can aid farmers in predicting when an inoculant will be most effective. Similar efforts have not been successful in temperate grasses. Hopefully with advancing techniques, farmers will someday be able to quickly assess the microbial status of the crop to determine if an inoculant will be beneficial.

### *Acids*

Acids, particularly formic, have been used for decades to prevent clostridial fermentation. Typically acids have been used in direct-cut silage, and application rates lower pH to approximately 4.7. Lactic acid bacterial fermentation is depended upon to further reduce pH to a stable point (generally 3.9 to 4.0).

Acids could have an additional benefit even in wilted crops. As indicated earlier, rapidly dropping pH to 4.0 in alfalfa significantly reduced proteolysis, improving milk production and nitrogen efficiency in dairy cattle (Nagel and Broderick, 1992). Further research is needed to determine the effects and economics of varying levels of addition.

### *Enzymes*

Enzymes additives, primarily cell-wall degrading enzymes, serve two aims: provide extra sugar for fermentation and partially break down plant cell walls so that animal performance on the silage would be more like one harvested at a more immature stage. These products have been successful, largely in grasses, in breaking down cell walls but much less successful in terms of animal performance (Muck and Kung, 1997; Kung and Muck, 1997). It appears that the crude fungal extracts are breaking cell wall linkages that are readily attacked by rumen microorganisms and leaving cell wall that is less digestible.

These products still could hold promise if they acted on chemical linkages in plant cell walls that limit the activity of fiber-degrading rumen microorganisms. This requires a better knowledge of the barriers to rumen microbial activity. Consequently there is reason to hope that enzymes may be a route to improve (not just preserve) the quality of the crop in the silo.

## Packaging Dry Hay

*Baler Types*

Dry hay is packaged in one of four forms: bales, stacks, cubes and pellets. Bales typically have three configurations: small square, large round and large square. Typical bale size, weight and density are listed in Table 2. Small square bales are categorized by those that can be easily moved by hand (2-tie) and those that are so heavy that they are typically picked up and stacked by machine (3-tie). Large round bales are formed in fixed chamber or variable chamber balers. Fixed chamber balers were originally designed for baling silage bales while variable chamber balers were intended for dry hay. Design improvements on both baler types now allow them to be used under a wide variety of moisture conditions. The cross sectional size of large square bales is often dictated by local trucking restrictions and by the physical constraints of feeding these bales in older, smaller livestock facilities. The smaller cross sections are widely used in Europe and eastern North America. Commercial hay producers in the arid regions of the western United States and in Australia use the largest bale cross section.

*Baler Market Trends*

The major markets for balers are North America, Europe, Australia and Latin America, in rough order of market size. The North American and European markets for balers are about equal and these two markets comprise about 90% of total baler sales. Worldwide sales of small square balers have diminished from about 18,000 to 7,200 to 5,800 in 1990, 1995 and 2000, respectively. Sales have particularly fallen in Europe during this period. Worldwide sales of large round balers have diminished from about 36,000 to 33,000 to 26,000 in 1990, 1995 and 2000, respectively. In Europe, sales of fixed chamber balers dominated the market in the early 1990's. This market is now roughly split evenly between fixed and variable chamber balers. Sales of variable chamber balers have always dominated the North American market and will continue to do so. Worldwide sales of large square balers have increased from about 2,000 to 2,800 to 3,400 in 1990, 1995 and 2000, respectively. Although sales of these balers are small compared to round balers, these machines have tremendous capacity and cost almost three times that of a round baler. The worldwide volume of new retail sales of balers is about 790 million U.S. dollars comprised of 80, 520 and 190 million dollars from the small square, large round and large square baler markets, respectively.

Sales trends of balers indicate that hay producers are striving for greater productivity and reduced cost. Small square balers have low productivity and require considerable hand labor. Although mechanized systems exist to pick up, stack and store small square bales, these machines add considerably to the cost of the baling operation and are prohibitive for most small producers. A major advantage of small square bales is that they can be baled at higher moistures than other packages (see below). In many locations, large round bales are used to form bales of dry hay that will be stored outdoors. This is a low cost system for producing forage for beef animals, but storage losses incurred can be substantial. Other forage producers use the large round baler to produce silage bales. Silage baling eliminates much of the required field curing and, because the bales must be wrapped in plastic to promote fermentation, outdoor storage losses can be quite low if plastic integrity is maintained. The major motivation for the adoption of the large square baler is productivity and the formation of a hay package of suitable dimensions for shipping. There is a worldwide trend for small livestock producers to have their forage harvested by contract harvesters. Many other livestock producers are abandoning forage production altogether and are purchasing all of their herds' forage needs. In either case, the large square baler fills the need for high productivity and shipping efficiency.

*Research and Development on New Baler Designs*

The last major product innovation in balers occurred in the late 1970's with the introduction of the large square baler. In the 1980's, a new design for small square balers was introduced, the in-line design in which the bale chamber was located along the centerline of the machine and was fed from below. This design, although not a radical departure from conventional designs, did lead to slightly lower pick-up and chamber losses (Shinners et al., 1992). Large round baler innovations during the last two decades have included the development of net wrapping systems (Anstey and Ardueser, 1991; Dodds, 1991), improved and automated systems for controlling twine or net wrapping (Busse, 1984) and bale cutting systems (Matthies and Meier, 1992). These innovations were developed to improve productivity, enhance outdoor storage characteristics and increase silage bale density. Another innovation designed to increase productivity is the combining of the baling and stretch wrapping processes on large round balers (Neunaber, 1998). These combination machines are found primarily in northern Europe where bale silage is common. Innovations in large square baler designs include cutting systems and design enhancements, such as roller chutes, to allow bale silage. Whereas it is common for early cutting systems on large round or square balers to offer a TLC of 75 to 100 mm, current cutting systems can be configured with TLC in the range of 40 to 50 mm. Shorter TLC has been demanded by bale silage producers to achieve greater bale density and improved feeding characteristics. Almost all balers offered for sale are pull-type. A German manufacturer has offered a large square baler in a self-propelled configuration. This machine had a 8.5-m windrow pick-up, 80 x 120 cm bale cross–section, 170 kW engine and video camera with in-cab monitor to view a four bale accumulator at the rear. The machine was not a commercial success at the time but does give an indication of the potential scale of machines that will package forage in the future.

Two major disadvantages of the large round baler are that they do not offer a continuous baling process and the round bale shape does not lend itself to efficient shipping. Numerous attempts have been made by manufacturers and hay producers alike to develop a non-stop round baler. The compact roller baler is one intriguing attempt at non-stop round baling (Matthies, 1991; Matthies et al., 1992). This machine used a series of rollers on a skewed axis to extrude a continuous rope of forage out the longitudinal axis of the bale chamber. When the desired width of bale had been reached, a reciprocating knife was used to slice through the bale. The bale was continuously net wrapped to maintain the bale shape. The original design for this baler featured a 30 cm bale diameter and could produce bale density in grass of 400 kg/m$^3$ (Matthies et al., 1992). Efforts to scale-up this technology have not thus far been successful (Neunaber, 1996). When bale diameter was increased to a more reasonable 1 m, high-density bales were not achieved. The machine also had difficulty making bales with crop residue such as straw.

Machine developers have attempted to create a less expensive large square baler by eliminating the expense of a plunger head and associated drive (Urich and Meyer, 1991; Sibley and Sibley, 1995; 1996). These balers used an auger rather than a reciprocating plunger head to force crop into a bale chamber. One design featured a set of conical compacting rollers that was situated at the end of the auger to flatten the crop as it was compacted into a square bale chamber (Sibley and Sibley, 1995; 1996). Challenges faced with these designs included filling a square bale chamber with an auger, separating the continuous "rope" of forage leaving the chamber into bales of discrete lengths, and development of a system for restraining or wrapping the finished bale. Although it is not clear whether these ideas will be successfully commercialized, they give testimony to the engineering development efforts to improve the productivity and economics of packaging dry hay.

## Baling in Humid Climates

### *Required Bale Moisture for Proper Preservation*

No matter what type of bale package is used, the most daunting task for hay producers in humid climates is to ensure that the hay is dry enough to be stable during the storage period. The required minimum moisture for proper storage declines as bale density and volume increase (Table 2). Moisture requirements are the least rigorous with small square bales because they have the lowest density. Large square bales have the greatest density, and so hay placed in these bales must be particularly dry. In some humid climates in North America and Europe, achieving the required low moisture for large square bales is almost impossible.

Environmental factors that have the greatest impact on forage drying rate are intensity of solar radiation, ambient temperature, relative humidity and soil moisture (Rotz and Chen, 1985). Mechanical factors affecting the rate of moisture loss from forage include level of conditioning, swath density and uniformity of the swath (Rotz and Chen, 1985; Shinners et al., 1991). Forages are often harvested with a mower-conditioner, a machine that combines the cutting, conditioning and swath formation operations. Conditioning involves crushing, breaking or abrading the stem to create a path for moisture escape. Mechanical conditioning increased alfalfa drying rate by up to 80% (Rotz et al., 1987). Conditioners can be broadly classified as roll-type or impeller-type. Roll conditioners typically use intermeshing rubber or steel rolls which causes multiple cracks along the stem as the crop passes through the rolls. Impeller conditioners typically consist of a rotor with free-swinging fingers of steel or plastic and an adjustable conditioning hood. The impeller conditions by abrading the stem as the fingers drag the crop across an adjustable hood. Roll conditioners are typically used with leafy legume crops and impeller conditioners with grasses. Wide swaths dry faster than narrow windrows. Alfalfa dried in a windrow dried between 20 to 34% slower than that dried in a swath (Rotz and Sprott, 1984; Shinners et al., 1991). Aggressive conditioning can improve forage drying rate, but losses of valuable plant tissue, mainly leaves, will increase (Shinners et al., 1991).

Machine treatments such as tedding, raking or swath inversion can be used on forages to speed the field drying process. Tedders use rotating tines to stir, spread and fluff the crop to enhance crop drying. Swath inversion involves lifting and inverting the swath and then depositing the new swath on dry ground. Raking is typically performed to narrow the swath to a windrow width compatible with the baler pick-up or to merge two or more swaths into one windrow to satisfy baler capacity. The raking process also rolls the swath so lower moister layers are exposed to wind and sunlight. These field manipulations to enhance forage drying must be carried out at the proper crop moisture or excess loss of valuable plant tissue will occur (Savioe, 1988; Buckmaster, 1993).

Chemical treatments can be used to speed forage drying rates by improving the moisture transfer from the interior of the stem through the waxy cutin layer at the stem's surface (Harris and Tulberg, 1980). Aqueous solutions of potassium carbonate and sodium carbonate are the most common active ingredients in chemical drying agents. Chemical treatments are most effective in improving drying rates during summer harvests when drying conditions are most favorable (Rotz et al., 1987). Unfortunately, the benefits experienced were not economically justified (Rotz et al., 1989). Additionally, the added burden of mixing chemical and hauling water make this an unattractive procedure during cutting when time is at a premium, so chemical conditioning is not widely practiced.

*Chemical and Biological Preservatives*

Chemical and biological preservatives offer the hay producer in humid climates several advantages. First, preservatives allow forage to be baled at higher moistures which reduces the burden of trying to get hay dry and reduces the chances of rain damage. Reviewing the literature, Rotz and Muck (1994) concluded that baling hay at 25% moisture reduced field-curing time by about one day. Second, hay baled at higher moistures will reduce mechanical separation losses during baling (Shinners et al., 1996, Friesen, 1978). Chemicals used for preservation include propionic acid, organic acid mixtures and anhydrous ammonia (Rotz and Muck, 1994). An organic acid mixture of which propionic acid is the major component is the most common hay preservative. This hay preservative has been shown to reduce mold growth (Rotz et al., 1991b), reduce adverse heating in the bale (Rotz et al., 1991b; Shinners, 2000) and reduce short term dry matter loss (Rotz et al., 1991). However, dry matter loss over a longer storage period (> 4 months) was not reduced in either small square bales (Rotz et al., 1991b) or large square bales (Shinners, 2000). High moisture hay treated with an organic acid preservative maintained higher moisture content during storage (Rotz et al., 1991b; Shinners, 2000). The higher moisture during the storage period supports microbial growth albeit at a suppressed rate because of the presence of the preservative. Typical applications rates of propionic based preservatives are 0.5 to 1% per mass of hay, although applications as high as 2% by mass have been reported. Economic benefit from applying organic acid preservatives at the typical rates is only justified when it is used to avoid damage from rain (Rotz et al., 1992).

Anhydrous ammonia is an effective hay preservative (Koegel et al., 1985; Rotz et al., 1986). Ammonia applied at the rate of 1% by mass reduced the incidence of visible mold growth, maintained hay color, and reduced the level of heating in small square and large round bales (Koegel et al., 1985; Rotz et al., 1986). Dry matter loss was reduced especially when the treated bales were wrapped in plastic. The addition of ammonia to baled forage can increase the crude protein concentration by adding nonprotein nitrogen. Increases in *in vitro* fiber digestion have been reported (Rotz and Muck, 1994). Anhydrous ammonia was modeled to be the most economic hay preservation system because of these benefits and its relatively low cost (Rotz et al., 1992). However, anhydrous ammonia is not widely used as a forage preservative, mainly because of animal and human safety concerns. Ammonia can be toxic to ruminant animals when it is applied to high quality legume forages at greater than 3% by mass (Rotz et al., 1986). Anhydrous ammonia can cause burns, blindness and even death when humans are directly exposed. To date, research conducted on preservation with anhydrous ammonia has been done with either small square or large round bales. High quality forage for dairy or equestrian markets is typically packaged in small or large square bales. Small square bales treated with ammonia are very difficult to handle because of the objectionable ammonia odor. Large round bales are not good targets for ammonia preservation because they are typically used for lower quality forage aimed at the beef market. Large square bales would seem ideal candidates for preservation with ammonia because these bales are so large that machine handling is required and therefore objectionable odors will be less of a concern. Also, the high value of the forage placed in these bales will enhance the economic justification for using anhydrous ammonia.

Microbial inoculants are being marketed for making hay as well as silage. Most of these products contain similar strains of LAB as found in silage inoculants. However one commercial product contains *Bacillus pumilus*. They are marketed as permitting hay to be baled in the range of 20 to 25% moisture, reducing mold and heating in storage. This is a moisture range where bacteria are unlikely to grow, and not surprisingly research on these products generally have found little or no benefit (e.g., Rotz and Muck, 1994; Duchaine et al., 1995).

### *Artificial Drying*

For years, hay producers have dreamed of eliminating the field curing process altogether by drying forage with heated air either in the field or stationary at a processing plant. In the 1970's when energy costs were much less expensive than today, there was a small but thriving dehydration business in Europe and North America. Although some of these facilities still exist today, energy costs have caused great consolidation of this segment. The dream of reducing weather risk by artificially drying forage has not died yet. The approach taken now by machine developers involves field drying as much as possible and then finish drying using either heated air (Fingerson and Eickhoff, 1992; 2000) or microwave energy (Herron, 1991). Even this approach has its challenges as drying from 80 to 20% moisture (w.b.) requires U.S. $140/tonne (Koegel, 1995). Besides energy costs, developers of in-field hay dryers face the additional hurdle of matching dryer capacity to baler capacity. For instance, to dry hay from 35 to 15% (w.b.) at the typical mass-feed rate of a large square baler would require approximately 13 $m^3$ per hour of water be removed by the drying system, obviously an enormous capacity.

## Baling in Arid Climates

### *Cutting and Field Curing*

An increasing proportion of the world's forage production is moving to arid climates in the western United States and Australia (Shinners, 1997). Producers in these areas have fewer weather related challenges because of the low annual rainfall and relative humidity. Much of the forage production in these areas is irrigated. Given the high daily temperatures and low relative humidities in these regions, short field curing times would be expected. However, typical field drying times are four to six days (Orloff, 1990). Long field drying periods occur because producers place their forage in narrow windrows that retard drying but reduce the amount of forage bleaching on the top of the windrow from the high level of incident solar radiation (Shinners et al., 1991; Orloff, 1990). Bleaching is a chemical change in the forage pigments that causes it to lose its green color. Although there is no evidence that bleached forage has significantly different nutritional quality than "green" hay, customer acceptance of bleached hay is low, particularly in the dairy, equine or export markets where much of the forage produced in these arid regions is sold.

*Baling Issues*

When leaves are very dry, they become brittle and are easily segregated from the stem by mechanical action at the baler pick-up, pre-compression chamber and bale chamber. If these leaves are lost from the baler, not only is dry matter lost, but the quality of the hay suffers because leaves have a greater concentration of important nutrients than stem material. In arid regions, the large square baler is the dominant baler type. This baler is configured with the bale chamber and plunger directly above the pre-compression chamber and pick-up. When leaves are separated from the stem by the impact of the feeder forks in the pre-compression chamber or plunger in the chamber, leaves often fall into the incoming stream of hay and are not lost from the baler (Shinners et al., 1996). Not only are losses from large square balers less than experienced with either large round or small square balers, but losses from large square balers are less sensitive to changes on crop moisture (Shinners et al., 1996). However, when hay is baled very dry (<13% w.b.), as often would be the case in arid climates, leaves are not only separated from the stem, but become so fine that it becomes very difficult to transport this leaf tissue to the ruminant animal at feeding. This loss at the dairy or feedlot is unacceptable to the hay customer. Therefore, it is common practice in arid climates to bale when the forage has been slightly re-hydrated by dew, typically between 11:00 PM and 4:00 AM.

Although re-hydrating hay with dew is widely practiced and does reduce leaf separation, the practice is not without problems. In some locations, baling may be delayed several days after the hay is dry before an evening with sufficient dew occurs. Or dew may be so heavy that baling is not possible without fear of heating and spoilage in storage. Often baling starts before the level of re-hydration is sufficient and then proceeds through a period when the crop is too wet for proper preservation. Finally, baling in the middle of the night is arduous and finding and scheduling labor for baling can be difficult. When baling is delayed because of lack of dew, the chances of rain damage are greater, and irrigation and regrowth are delayed.

Producers have tried various schemes to re-hydrate their hay without dew. One scheme involves spraying water from a typical agricultural sprayer on the windrow prior to baling. Another involves lightly spraying the field with the irrigation system. Neither scheme has proved successful. Spraying water with either system does not produce droplets small enough to achieve uniform coverage. Also, water cannot be readily applied to crop on the bottom of the windrow. For best results the water should be absorbed into the crop, but it is more likely to evaporate because there is little energy to drive it into the plant tissue. Finally, the absorption time is highly variable based on such factors as crop type, maturity, conditioning level and ambient conditions so matching the time between water application and baling is difficult.

A system of re-hydration has been proposed that uses steam applied at the baler pick-up (Maher, 1986; Maher et al., 1989; Staheli, 1998). With these systems, another machine resides between the tractor and baler, which consists of a diesel-powered boiler, controls and plumbing. Low-pressure steam is injected into the hay as it is picked up, both from above and below. Potential advantages of these systems are that the steam has very small droplets and offers good coverage throughout the windrow. The energy in the steam drives the water vapor into the plant tissue, softening it quickly. The inventors claim leaf loss is less than when baling with dew. Also, the inventors claim that because the steam softens the stem, the plunger more easily flattens the stem, and greater bale density can be achieved. Should this process prove economically justified, producers will be able to bale at any time the crop is sufficiently dry for safe storage.

## Processing Hay for Export

Forage is not commonly exported because of low relative value and bulkiness compared to grain crops. The main market for forage exports is the Pacific Rim, specifically Japan, Korea and Taiwan. Since forage is destined as feed for ruminant animals, it follows that those countries where forage is imported must have both a population of ruminant animals and a climate and geography that does not support homegrown forage production. Obviously, Japan's economy is fully developed so the consumption of products from ruminant animals (dairy products and beef) is high compared to its developing neighbors: Taiwan, Korea and China. As the economies of these new "Asian Tigers" grow and develop, it can be expected that the diets of these countries will begin to include more beef and dairy products and that forage imports will grow.

Forage is imported into the Pacific Rim primarily from North America and Australia, although other forage exporters include Mexico, Chile and China (Sokhansanj and Streeton, 2000). These countries have the climate and infrastructure for producing the dry hay that is required for forage export. Forage imports into the Pacific Rim have increased from 1.9 to 3.0 million tonnes between 1990 and 1997, respectively (Ford, 1998). About two-thirds of the imports are shipped from the United States (Ford, 1998). Forages for export are usually in form of bales, cubes or pellets with almost two-thirds of the exports in the form of re-compressed bales. Although baled hay requires more handling than cubes or pellets, the market is slowly shifting from cubes to baled hay. Customers are moving toward baled hay because they can be more certain of quality, have less dust problems and are able to market bales more easily to small livestock producers.

To improve the shipping efficiency of forage, hay bales are typically re-compressed after baling and a period of moisture stabilization in storage. Bales that are used for re-compression include 2-tie, 3-tie and large square bales. Large square bales would be sliced into quarters prior to re-compression. Bale density is increased by 1.5 to 2 times compared to initial bale density (Sokhansanj and Streeton, 2000). Re-compressed bales are restrained and packaged in a variety of ways including plastic or wire bands, plastic sleeves or plastic bags. Exported forage is usually shipped in sealed shipping containers. Although the containers are sealed and not vented to the moist oceanic environment, moisture in the hay can evaporate and eventually condense on the container walls and ceiling. About 95% of the container volume is occupied by hay. A cover is placed over the bales to prevent condensate from collecting on the top layer of bales. Obviously, ensuring the hay is dry when it is re-compressed can reduce the problem with condensate. The target moisture for re-compressed forage is 12 to 14% (w.b.). Hay at lower moisture than this range will cause problems with excess stem breakage and leaf separation while hay at higher moisture may spoil during transport.

Other challenges that forage exporters face include developing machinery, infrastructure and standards for processing baled hay, maintaining a consistent quality product and fending off competition from grain exports. Despite these challenges, there will be an export market for high quality forages in the future.

## Future of Forage Conservation

- Monitors of various types will be developed for forage harvesters and balers. These will help farmers to segregate forages by quality and apply additives only when needed at accurate rates.

- The trend toward larger forage harvesters will continue and as a consequence force changes in how forages are handled at the silo in order to get adequate preservation.
- In spite of the volume of plastic used, pressed bag and bale silage will continue to grow relative to other silo types because of low costs, reduced weather risks, and the flexibility in harvesting and feeding they offer the farmer. Wrapping on the baler will offer greater productivity while wrapping bales in tubes will present a lower cost, higher productivity wrapping system.
- Improved silage inoculants that offer more consistent benefits in animal performance and aerobic stability will be developed. Enzymes that consistently improve silage digestibility are also likely.
- Products or systems that reduce/eliminate plastic usage in making silage or permit easy recycling of plastic should be expected.
- Concern about pathogen transmission on the farm through silage and hay will grow and bring about rapid systems for detection and means of controlling their development. Similarly rapid detection and control of microbial toxins in forages will be important.
- The large round bale will continue to be the dominant hay package for the foreseeable future because it offers high productivity at low cost. Large square bales will become increasingly popular because they offer very high productivity, high density and shipping efficiency. Small square bales will be of less importance, but will remain a niche package for small livestock producers, equestrian owners and exporters.
- An increasing proportion of the world's hay supply will be grown in arid climates because producers in these areas have greater control of the forage growing, drying and harvesting processes and have less risk of weather damage. New systems that allow hay to be re-hydrated at baling will produce an expanded harvesting window and greater control of the baling process.
- No matter where forage is grown, producers struggle with slow forage drying and excess crop moisture at baling. Systems that speed forage drying or help preserve baled forages will need to be developed.
- Forage exports can be expected to grow as emerging economies in the Pacific Rim improve their diets with meat and dairy products from ruminant animals. The export of forage will be helped by consistent product quality and improved infrastructure and standards for re-packaging hay into high-density packages for improved shipping efficiency.
- Systems that artificially dry forage before the baler will suffer from low capacity, high capital cost and high fuel cost. Unless forage value changes dramatically, these system will not be practical.

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**Table 1 -** Temperature rise, reduction of net energy concentration and net energy losses at different storage and unloading conditions in horizontal silos (Honig et al., 1999)

| Weekly progres-sion in silo (m) | Air pene-tration depth (m) | Temperature rise above ambience at unloading (°C) | | | Reduction of net energy of lactation (MJ/kg DM) | | | Losses of net energy of lactation (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Stability of silage under air influence, d | | | | | | | | |
| | | 1 | 3 | 7 | 1 | 3 | 7 | 1 | 3 | 7 |
| 1 | 1 | 23 | 16 | 0 | 0.40 | 0.16 | 0.0 | 16 | 8 | 0 |
| | 2 | 27 | 27 | 27 | 1.00 | 0.90 | 0.5 | 38 | 34 | 21 |
| 2 | 1 | 11 | 4 | 0 | 0.07 | 0.00 | 0.0 | 4 | 1 | 0 |
| | 2 | 23 | 16 | 0 | 0.35 | 0.16 | 0.0 | 16 | 8 | 0 |
| 3 | 1 | 4 | 0 | 0 | 0.00 | 0.00 | 0.0 | 1 | 0 | 0 |
| | 2 | 14 | 5 | 0 | 0.13 | 0.05 | 0.0 | 7 | 2 | 0 |

**Table 2 -** Typical bale cross-section, density and moisture range

| Machine type | Typical dimensions (h x w or w x ϕ), cm | Density range, kg/m$^3$ | Typical baling moisture, % w.b. |
|---|---|---|---|
| Small square baler | | | |
| 2 – tie | 35 x 46 | 100 - 150 | 19 to 21 |
| 3 – tie | 41 x 56 | 125 - 200 | “ |
| Large square baler | | | |
| | 80 x 80 | 200 - 250 | 17 to 19 |
| | 80 x 120 | “ | “ |
| | 120 x 120 | “ | “ |
| Large round baler | | | |
| Class I (< 1.55 m$^3$) | 120 x 120ϕ | 160 - 225 | 15 to 17 |
| Class II (1.55 - 2.55 m$^3$) | 120 x 150ϕ | “ | “ |
| | 150 x 120ϕ | | |
| Class III (2.55 - 3.54 m$^3$) | 150 x 150ϕ | “ | “ |
| | 120 x 180ϕ | | |
| Class IV (>3.54 m$^3$) | 150 x 180ϕ | “ | “ |

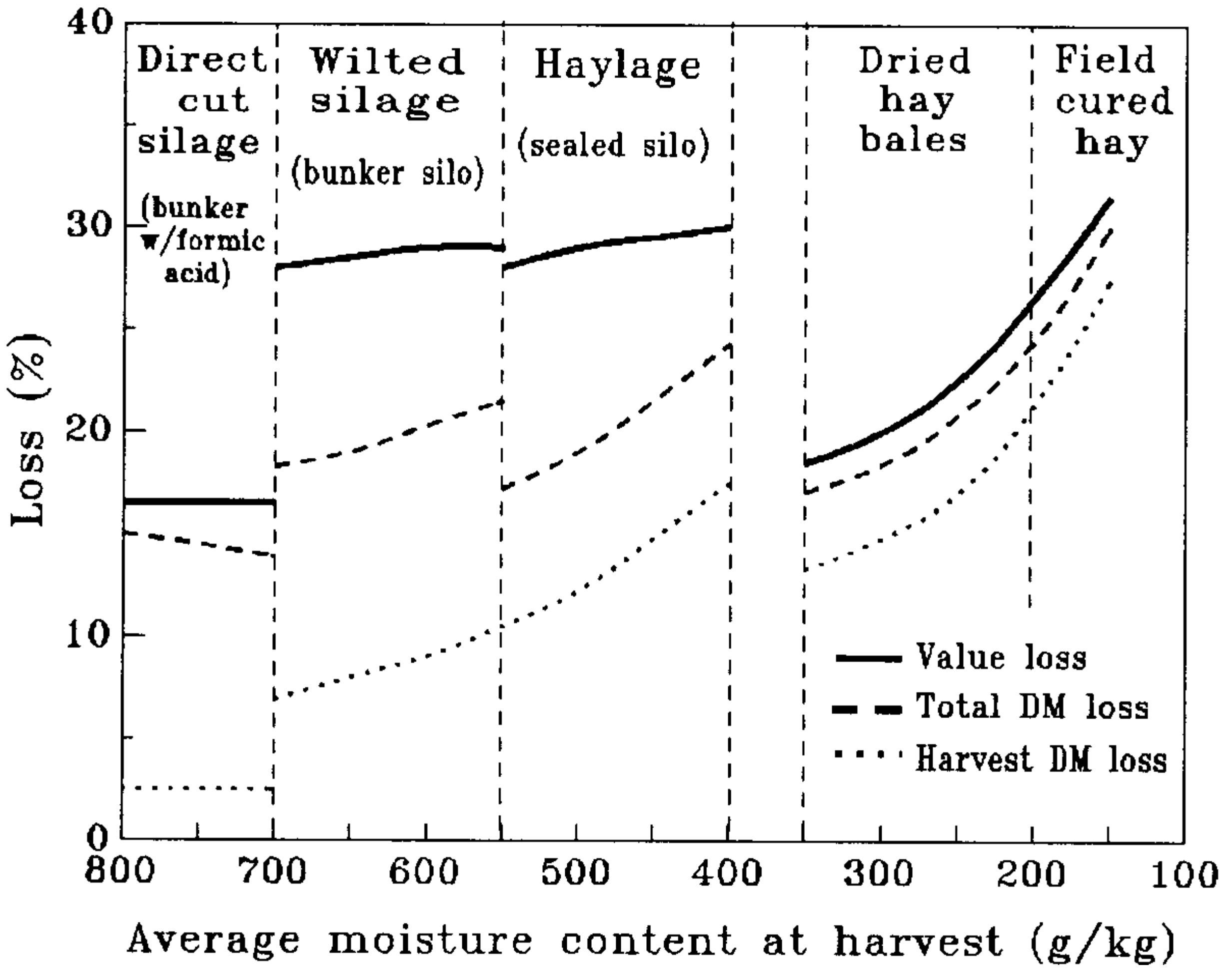


**Figure 1 -** Typical harvest and storage DM losses and total value loss for various alfalfa production systems used in Michigan, USA (Rotz et al., 1991a)

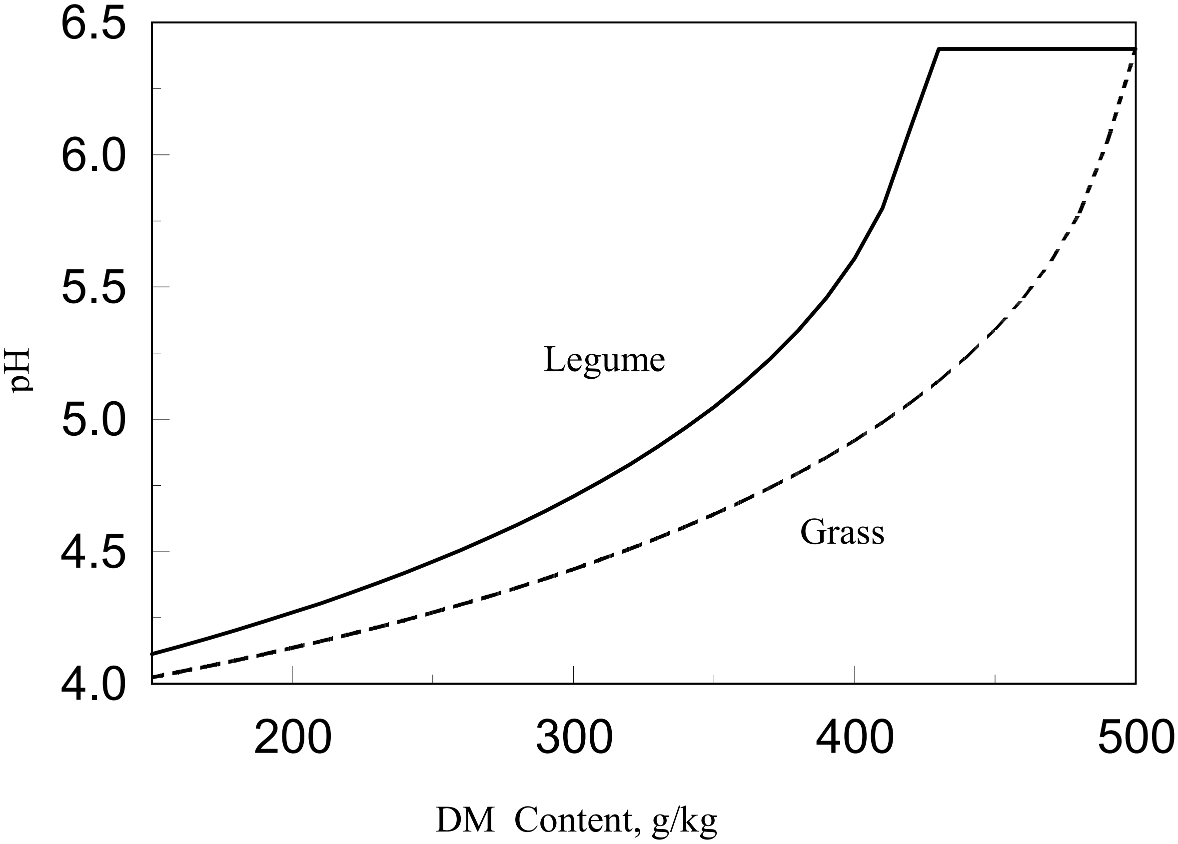


**Figure 2 -** The pH below which the growth of Clostridium tyrobutyricum ceases as a function of the DM content of the crop (Based on equations from Leibensperger and Pitt, 1987).

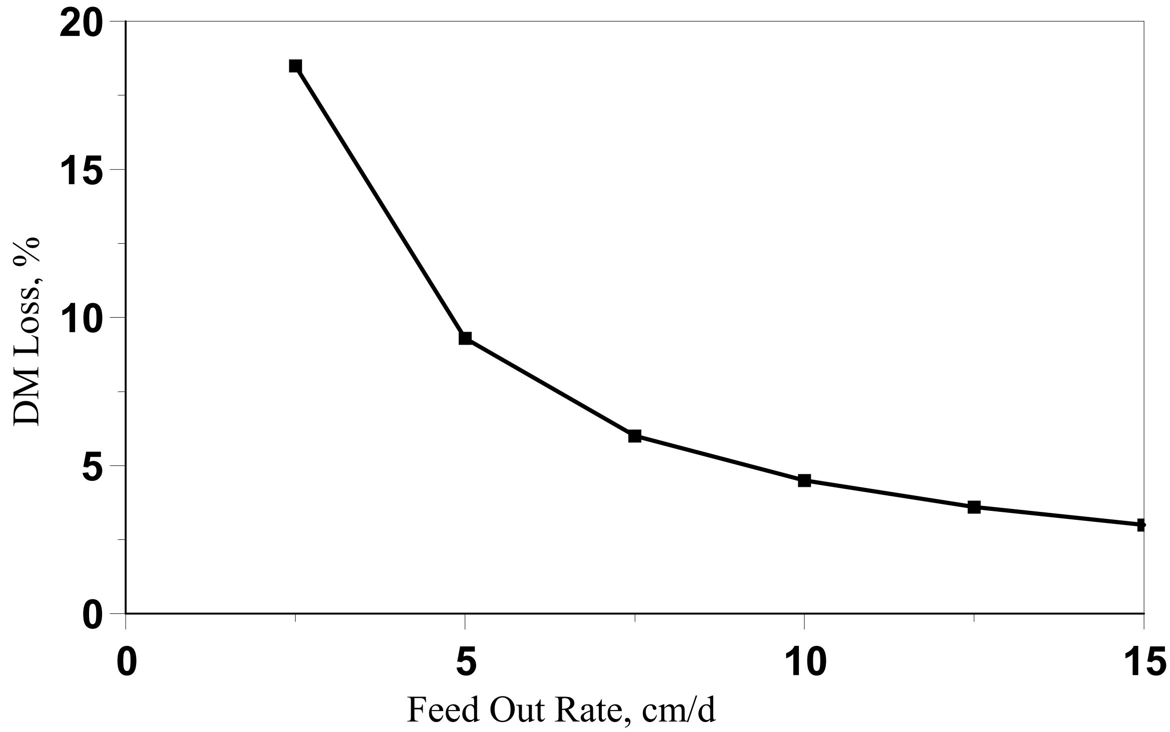


**Figure 3 -** Predicted dry matter losses during bunker silo unloading as affected by feed out rate for 35% DM corn silage at a density of 640 $kg/m^3$ (Pitt and Muck, 1993).

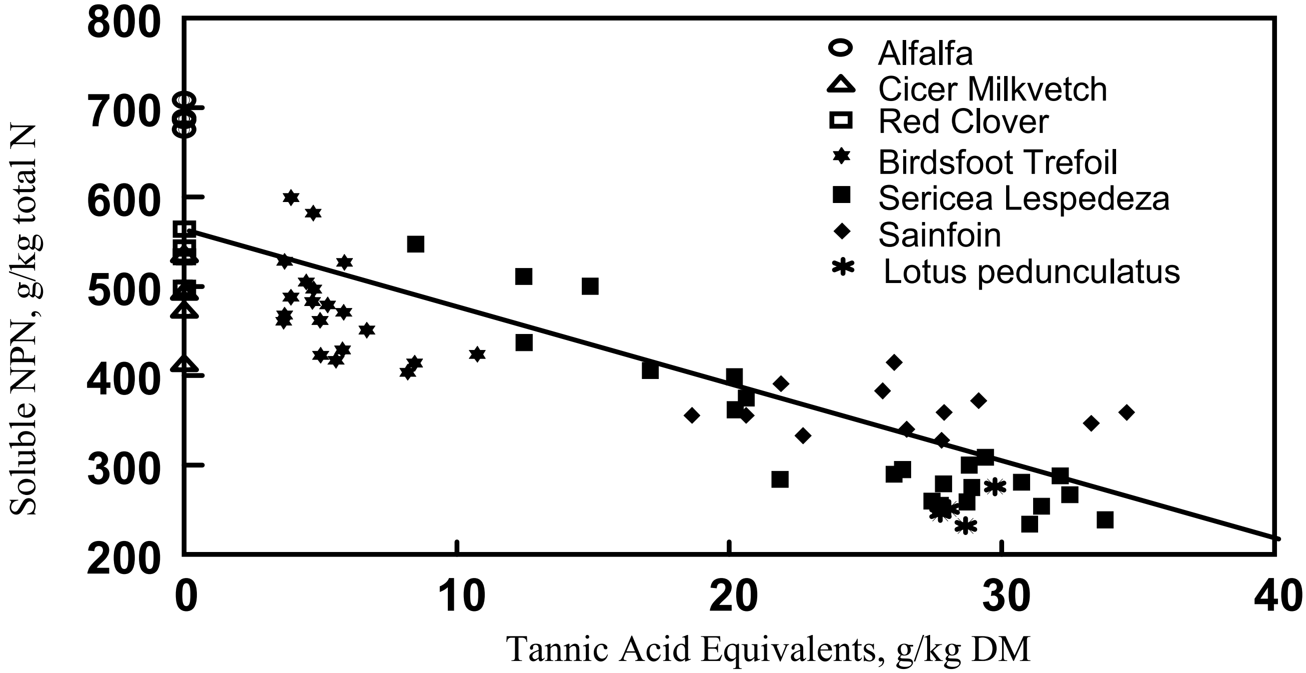


**Figure 4 -** Soluble nonprotein nitrogen in various legume silages as related to the tannic acid content of the silage (Albrecht and Muck, 1991).