Haying Systems In North America….. A Review

Duane McCartney
Agriculture AgriFood Canada Research Center, Lacombe, Alberta

Hay production and storage as a means of conserving forages can be traced back to over 2000 years ago (Robertson 1983). Since the time when hay was harvested by hand, mechanized systems have been developed to harvest, store and feed forage crops without direct handling by people. In 1840, the first reciprocating hay mower was developed in North America. By the late 1890's the cutting and harvesting of loose hay by horse and tractor with the aid of a mechanical hay loader, buck rakes and stacking equipment was prevalent. Around 1908 the first patent was issued for the invention of the round baler, but it was not developed until the late 1940's. This round baler produced small round bales approximately 50cm in diameter and 100cm long. The baler had to stop in the field while the twine was wrapped around the bales. These bales were able to shed water and could be left in the field for a limited amount of time. The bales could then be elevated onto a hay wagon with a specialized bale loader and transported to the hay storage shed. The small round baler was used in North America in the 1950's, but to a lesser extent than the small square baler. The square baler was available in various forms prior to the Second World War. These balers required manual tying of the twine or wire. However it wasn't until 1939 when a farmer in Pennsylvania invented the modern tying mechanism for the square baler that this method of haying became popular As there was a labour shortage on North American farms, a major effort was made around 1939 in the United States to produce this new type of square baler with the automatic tying device. Steel for these new square balers was mainly supplied by diverting materials from the war efforts.

The square baler remained the dominant hay harvesting system until the early

1970’s when the large round balers and various types of loose hay mechanical stacking machines were developed. During these years there was a lot of development and evaluation research occurring in North America and Europe on hay harvesting systems. However, with all this advancement, research shows that losses in quantity and quality still occur between harvest and feeding. These losses can be excessive and are often a result of wet weather or mechanical damage to the forage.

In most parts of the world, forage conservation is a key element for productive and efficient ruminant livestock farms (Muck 2001). Forage conservation permits a better supply of quality feed when forage production is low or dormant. Forage harvesting and storage also provides farmers with a means of preserving forage when production is faster than can be adequately utilized by grazing animals. As a result, harvesting forage prevents lush growth from becoming too mature. Thus, forage harvesting provides a more uniform level of high quality feed for ruminant livestock throughout the year.

In hay production, the crop is dried so that it is essentially biologically inactive both with respect to plant enzyme activity and microbial spoilage (Muck 2001). The low moisture content also permits easier transportation by reducing the weight per unit of dry matter (DM). Hay production is dominant in those areas of the world where good drying conditions prevail.

Harvesting, storage and feeding losses continue to be the largest problem in hay production. It has been estimated that at least 25% of the forage crop can be lost between harvesting and feeding (Rasmussen 1969). These losses occur both in the field and during storage. Field loss is dependent on weather conditions during the drying period and on the moisture content of the forage at time of baling (Thorlacius 1984). Research in North America and Australia has estimated that leaf loss can be as high as 62% and dry matter loss as high as 37% in rain damaged field-cured alfalfa hay. Other research has estimated losses ranging from 4% per day to as high as 80% per day for harvesting hay under poor drying conditions (Thorlacius 1984). Storage losses caused from spoilage and heating increase at moisture levels above 20 to 25%. This reduced animal gain, but did not affect dry matter intake (Miller et. al. (1967).

Harvesting Systems

There are many options available to farmers around the world for harvesting and storing forage crops. In some parts of the world cattle are able to graze year round. This is a low cost operation as the cost of harvesting, storing and feeding the forage crop is not incurred. In other parts of the world mechanical harvesting and storage is required due to cold temperatures and low rainfall preventing year round forage production or grazing. The type of forage harvesting system is dependent upon the climate of the region and the end use of the forage crop. If the forage is to be transported any distance then the method of packaging must be considered. This has lead to the increased use of the big round and square bales. Personal preference of the hay packaging system is also important. Horse owners like to individually feed their horses a single small square bale and in some parts of eastern Asia imported hay is purchased at a market and transported home on the back of a bicycle. Weather is still the major influence on determining the type of forage harvesting system. In areas where it is difficult to have sufficient drying time for hay harvesting, silage is the preferred method.

Many different systems or combinations of machines and processes can be used to produce dry hay. Several authors have reviewed hay harvesting systems throughout the world. Rotz (2001) has presented a review of the various options in forage harvesting equipment in North America. The Teagasc Research Centre (1997) has reviewed forage systems in Ireland, McLennan and Bullen (1998) have reviewed Australian haying systems and Augsburger and Methol (1993) have summarized haying systems technology in Uraguay. There are many forage harvesting equipment manufactures around the world and as a result computer forage programs have been developed to assist the forage producer in their choice of equipment (Rotz 2001). The Prairie Agriculture Machinery Institute in Western Canada has tested the efficiency and performance of most North American and European hay harvesting equipment. This organization is the only center in North America that tests farm equipment (PAMI 2001).

The major mowing options are a cutter bar or sickle bar mower, or a rotary disk mower. The cutter bar mower uses reciprocating knives, while the rotary disk mower has knives rotating at high speed. The cutter bar mower has been used world wide for many years. It is a very reliable, low cost method of mowing. It can be pulled by animal power or a low horse power tractor. The major disadvantage is limited mowing capacity as field speed is limited by the cutting capacity of the reciprocating knives. These knives are more likely to plug in heavy, wet or lodged forage. This limited capacity has led to the development and wide spread use of rotary mowers (Rotz 2001, Savoie 1990). With this equipment, forage is cut with knives attached to disks on a horizontal plane (disk, drum) or on a vertical plane (flail) rotating at a relatively high speed. This type of mowing offers virtually unlimited cutting capacity, as field speed is often limited only by the operator's ability to control the machine. The purchase cost is about 30% more per unit of cutting width, and repair costs may be greater, particularly as the machine ages. Disk mowers require about four times as much power to operate compared to a cutter bar mower (Rotz and Muhtar, 1991). Thus a larger tractor is required and more fuel is consumed per hour of use. With faster field speeds, less labor and tractor time is required (Rotz 2001). Rotary mowers exert a certain amount of suction because of their high rotational speed. This can bring small amounts of dust or soil in to the forage. The flail mower coarsely chops the forage stems in several pieces where as the disk and drum mowers cut the stems at a single point at the base of the plant. Flail chopping increases the field drying rate and field losses as the short pieces are lost in the subsequent handling operations (Savoie 1990).

Time of Cutting

In the Western United States, Fisher and Mayland (2002) have shown that shifting hay mowing from early in the day to late in the day was effective in increasing forage preference by sheep, goats, and cattle. Plants accumulate sugars during the day and then use them at night. This causes a diurnal cycling of forage sugars and overall quality. By cutting forages during the late afternoon, extra sugar is captured thus increasing the feeding value of the forage. Fisher and Mayland have also observed this advantage in preference feeding trials and grazing trials in England and Australia. Orr et al. (1997) also observed that grazing animals consumed more grass and clover in the afternoon than in the morning. However, hay producers must evaluate the need for extra drying time from late morning to late afternoon against the need for the higher quality forage.

Drying the forage crop

Successful storage of hay requires drying to a moisture content of approximately 20% (Robertson 1983 Agriculture and Agri Food Canada Melfort Sask.). The drying process is usually done in the field. The rate of drying is dependent on weather conditions, temperature, humidity, soil moisture, solar radiation and wind speed. The drying behavior of the forage is affected by plant species, stage of growth, leaf-to-stem ratio and the structure and volume of the swath or windrow. The rate of moisture loss follows an exponential pattern so that a drop in moisture from 80% at cutting to 30%, may take as much time as dropping from 30% to 20% (Wilkinson 1981). Plant respiration continues after cutting until moisture levels of 30 to 40% are reached and can result in dry matter loss of non-structured carbohydrates, ranging from 2 to 16%. The loss of nitrogen due to respiration is approximately 2.5% of the initial level. Proteolysis proceeds rapidly from the time of cutting until terminated by either the attainment of a high dry matter content or a low pH value (Robertson 1983). Some studies have found field losses due to poor drying conditions can range as high as 4% per day.

Most mowing devices used in forage production today include mechanical conditioning to help speed field drying of the crop. Conditioning modifies the plant structure to improve drying rate without causing leaf loss. This process eliminates the need for raking to turn the hay windrow over for drying. These mower conditioners also have deflecting baffles to adjust the swath widths. It is advantageous to leave as wide of a swath as possible to increase drying rates (Savoie 1990). A wide variety of conditioning devices are being used, but the major options use either crimpers, crushing rollers, plastic brushes or flails. Some designs are more aggressive at damaging the crop, which speeds drying, but this aggressiveness also increases field loss by disassociating leaves and other small forage particles high in nutritive content. The recommended device for conditioning alfalfa is an intermeshing rubber or plastic roll. Among the common roll devices used and with proper adjustment, little difference has been found in drying rates (Shinners et al. 1991, Rotz and Sprott 1984).

Flail mower conditioners use rotating steel or plastic tines to abrade and break forage stems. These machines were developed in Europe for use in grass forage crops. When used on alfalfa and other legumes, this type of mower conditioner can lead to inferior drying and to a greater leafy loss dependent upon machine adjustment. In general, roll conditioning devices are recommended for alfalfa and legumes and flail mower conditioners are recommended for grass-based forage (Rotz 2001).

Losses with mower-conditioners can vary between 1 and 5% of dry matter (DM) yield with similar losses for the two major types of mowers (Rotz 2001). Roller design does not have much effect on loss. Adjustment of roll pressure and clearance has more effect than the pattern or material used in the rolls. The difference in loss between a well-adjusted mower-conditioner and a similar mower without a conditioner is 1 to 2% of crop yield. Mowing and conditioning loss is mostly leaves causing a small decrease in the nutritive content of the remaining forage.

Robertson (1983) found that the mower conditioner produced the fastest drying time, but this faster drying treatment usually rewetted more readily so that dew or rain eliminated any advantage. However, the advantage of the mower conditioner could mean the difference between baling in the evening and exposing the hay to the risk of remaining in the field until the following morning. When this hay was fed to lambs, the cutting methods that decreased raking and conditioning the hay, increased dry matter digestibility and intake of digestible dry matter.

Very little can be done, to prevent dry or partly cured hay from damage. Once the plant cell has died, rainwater can dissolve its contents and leach them from the hay, the most digestible going first. In the case of light rain the loss of nutrients may be minor but heavy rain leaches nutrients heavily and also compact the windrows.

The top of the forage swath dries more rapidly than the bottom. Turning the swath can speed the drying process by moving the wetter material to the upper surface where it dries more quickly. Spreading exposes more of the crop to the radiant solar energy and drying air. There are three methods used to move hay swaths: tedding, swath inversion, and raking.

Hay tedders use long rotating fingers to stir, spread and fluff the swath. The tedder increases the area over which solar radiation reaches the swath. It also improves aeration and drying time by fluffing the windrow. Tedding can improve the drying rate by 28 to 58% on the day it is applied. However, there can be mechanical loss of the leaves due to the high speed fingers fluffing the crop. Savoie (1990) found field losses of 4 to

8% when he tedded alfalfa (*Medicago sativa L.*) and losses of less than 2% with timothy (*Phleum pratense L*.). In a maritime climate, Savoie found that swaths cut with a mower conditioner required 36 hours to dry to 20% moisture under favorable weather conditions. This was equivalent to 3 to 4 days assuming 10 to 12 hours of drying per day. Tedding twice reduced the drying time by 11 hours or a full day. If the producer only uses the tedder once, then Savoie recommends doing it on the first day right after mowing. Losses in grass varied between 2 and 3% due to tedding and subsequent raking. In alfalfa, the losses ranged between 11% and 15%. Alfalfa can have a very high leaf loss and is not suited for handling by the tedder.

Tedding can cause greater leaf and stem loss. In alfalfa, the loss caused by tedding is often greater than the average rain loss avoided by faster drying (Rotz and Savoie 1991). The decision to use tedding should be made by comparing the probable loss from more time lying in the field to the known loss and cost of tedding. The increased machinery, fuel, and labour costs may only justify routine use of tedding on grass crops in wet climates (Rotz 2001).

Windrow inverting machines gently lift the swath and turn it over and drop it back onto the stubble. The dry layer is moved to the bottom and the original bottom wet layer is moved to the top. The windrow inverter is not as effective in reducing drying time as the tedder but losses in alfalfa or grass hay were much lower after inversion than with the tedder (Savoie 1990). The inverter did not reduce drying time as much as the tedder. In alfalfa haying systems it would be a more suitable machine to manipulate alfalfa swaths. In grass hay, tedding losses were 3% or less and this would not justify changing to an inverter. Rotz and Savoie (1991), recommend minimal use of the tedder or the inverter in alfalfa. The added labor, fuel, and machinery costs of the operation are likely greater than the benefit received (Rotz and Savoie 1991).

Raking is used to turn or roll together the windrows for easier pickup by the baler and to speed drying. Raking hay in the morning of the day of baling can reduce the field curing time by a few hours thus allowing for an earlier start at baling. Raking, particularly at moisture levels of less than 40%, can result in losses of 10 to 25% (Friesen 1980). These losses are primarily alfalfa leaves. In a light crop, which is spread over the field surface, raking loss can be more than double when narrower swaths are used.

Greater loss can be found with a rotary windrower compared to the more standard side-delivery rake. The rotary windrower uses rotating tines to sweep hay into a windrow. These sweeping arms allow more forage material to become entangled with the stubble and lost. Side delivery rakes provide a rolling and wrapping action that reduces entanglement with the stubble but increases entanglement among the plants in the swath (Rotz 2001).

Conventional hay harvesting requires about 2 to 4 days under good climatic conditions. Super conditioning or maceration equipment has been developed to aid in this drying process (Krutz et al.1979; Savoie 1990). The freshly mowed hay is crushed through a series of serrated rollers and compressed into a thin mat. The stems are split longitudinally and this process greatly reduced the drying time. The plant also becomes more exposed to oxidation, evaporation during harvest and storage and eventual microbial activity in the rumen. Super conditioned forages dry very quickly since the intracellular water is freed after the grinding process. Evaporation is faster and more efficient than after conventional roller conditioning. Studies in Canada have shown that intensive maceration of forage can improve both the intake and efficiency of forage fed to dairy cows in early lactation (Savoie 1990). This might be caused by the macerated forage having a greater proportion of ruptured surface area compared to the conventional hay and the rumen microbes being able to have faster access to the cell nutrients (Savoie 1996).

Maceration or mechanical conditioning of forage can be done at various intensities. The animal response is variable and sometimes is maximized at an intermediate level of maceration. Too intense a maceration or conditioning will result in a large proportion of fine particles broken off during the conditioning and these particles would then be lost in the baling process. The maceration conditioning machines are now available in Canada (PAMI 2001).

A large proportion of the world's forage production is moving to arid climates in the Western United States and Australia (Shinners 1997). Here hay producers have fewer weather related problems because of the low annual rainfall and relative humidity. Much of the forage production in these areas requires the use of irrigation. With the high daily temperatures and low relative humidity, 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 the hay producers use narrow windrows that slow drying but reduce the amount of forage bleaching on the top of the windrow from the suns' radiation (Shinners et al., 1991; Orloff 1990). Bleaching causes the forage pigments to lose the green colour. There is no evidence that bleached forage has significantly different nutritional quality than "green" hay, but customers want green hay particularly in the dairy, equine or export markets.

Dry Matter Content

Farmers need a means of accurately and rapidly measuring dry matter content of the hay at harvest time. In addition they also need an accurate weather forecast and a means of evaluating various haying options on a given day. Farmers in many countries have a number of options for measuring dry matter 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 (Muck 2001, Pitt 1993, PAMI 2001). If a farmer doesn't have the access to a commercial dry matter meter, the microwave system is an alternative. A forage sample of 100 gm is cut into small pieces and placed in the microwave unit for 3 to 4 minutes. The sample is then weighed and returned to the microwave unit for an additional minute. The process is repeated until the sample weight loss is less than 1 gram. This will then give an estimate of the dry matter of the forage. There could be danger of fire during the later stages of drying the sample in the microwave. To eliminate the hot spot, a small glass of water can be placed in the microwave during the last few minutes of drying.

Hay Balers

Hay balers are used to compress and package hay for easier handling. Hay balers are capable of producing bales of many sizes and shapes. Small rectangular bales have been most popular over the past fifty years, but now large round and large rectangular bales are becoming the predominate hay packages. Hay harvesting equipment has also been developed to produce low-density stacks, but these constitute a relatively small portion of the hay produced.

The traditional plunger-type small baler makes a rectangular bale about 36 by 46 cm in cross-section with lengths up to 130 cm. The bale weighs from 15kg to 35 kg and can be manually handled in stacking and feeding. The disadvantage of the small square bale is the high amount of labour required from harvest to feeding. A relatively small tractor of 26 to 45 kW is sufficient to power small rectangular balers. The baler pickup normally extends from the right side of the machine, so the tractor pulling the baler is driven on the left side of the windrow. In a newer design, referred to as the centerline baler, the pickup device is centered behind the tractor with the compression chamber located above the center of the pickup. The centerline design is promoted for better maneuverability and less loss during baling, but less loss has not been found (Muck 2001).

Over the years several modifications and devices have been developed to reduce the manual labour in bale handling. Traditionally, a wagon was pulled behind the square baler and a person would carry each bale and stack it on the hay wagon. Another method uses a stooking sled, pulled behind the baler. A person would place each bale on its' edge in a pyramid configuration 9 bales at a time. The stooking sled would then release the bales in a pyramid form and leave them in the field in small stacks for further drying. Later a front end loader tractor with wide pickup tines would load the bale stooks onto a hay wagon for transport to the storage shed. This was very labour intensive. Today, a popular option is a bale thrower mounted at the exit of the baler. This device throws the bales into a trailing hay wagon, reducing the need for handling and stacking on the wagon. At the storage site, bales then have to be handled usually using a bale elevator in order to stack them in storage. Automatic self-propelled bale wagons are also used in large square baling operations. These wagons mechanically lift bales dropped on the field and stack them automatically on the bale wagon. The operator can then haul the completed stack and place it in the storage area.

Long hay mechanical stacking wagons were introduced in the late 1960's in North America as a another labour saving haying system (Coates 1978). Models with a capacity ranging from 1 to 10 tonnes were available in two types, compaction type and the non-compaction model. The compaction model partially shredded or chopped the forage crop and blew it into the container, which shaped the stack. Settling then occurred from the force of the material being blown into the container and by the vibration of the wagon as it traveled over the fields. The compaction wagons used a mechanical force to the lower the roof to compress the entire stack. The quality of the hay following storage was consistently higher for the compaction type stacks as compared to the non-compaction stacks. These types of hay harvesting equipment have now been replaced by the round and large square baling systems.

Large round balers were introduced in the early 1970's. They produce bales 90 to 180 cm in diameter and 120 to 160 cm in length with a mass of 200 to 900 kg. The European round baler produced a narrower bale as compared to the North American bales. Completed bales are transported to the storage site with a tractor mounted loader or a wagon. Other machines have been developed to pick up the round bales in the field and transport them to the storage site. Large round balers require more power than small square balers and the recommended minimum tractor sizes vary with baler size from 35 to *55* kW. The power requirement is dependent on the baler design (Rotz and Muhtar 1991, PAMI 2001). Round balers use either twine or plastic net wrapping to tie the bales. The baler must stop forward motion as the bale is rotated with the twine. Depending upon the number of wraps this can take one to two minutes. The net wraps only require one to two rotations and greatly reduce the time required to about 30 sec. per bale (Beacom 1991). The net wrap is much more expensive than twine, but this is balanced out when considering the hourly cost of running the baler and the reduced time required to wrap or tie the bale. The plastic net wrap does not shed the rain, but some research has shown improved forage quality compared to the twine wrapped bales.

There are two types of large round balers (Beacom 1991 Agriculture and Agri. Food Canada Melfort Sask.). The hard-core baler has a spring-loaded adjustable bale chamber that rolls the hay under continuous pressure from start to finish. The soft-core baler has a fixed bale chamber and the hay does not roll until it fills the chamber and exerts pressure on the rollers. The incoming hay is continually wrapped around the hay mass, which folds the center into a "star" shape. The center is less dense than the perimeter, thus providing better aeration after baling. The soft-core baler requires twice as much fuel and a much larger tractor than the hard core baler. High moisture, soft core bales harvested at 23% moisture and stored outside were superior to hard core bales at the same moisture level for field loss and live weight gain per hectare when fed to steers. When baled at this higher moisture level, losses were significantly greater with the hard core baler than with the soft-core baler. However there were no significant differences in losses due to the type of baler when the hay was baled at the lower moisture level (Beacom 1991).

Dry matter losses during hay baling are considerably higher with the large round baler compared to the traditional small square baler. These losses can be as high as 11% for the pickup losses and 17% for the bale chamber losses (Robertson 1983). Pickup losses are high when the machine is pulled at a faster speed than the rotating speed of the pickup device. Chamber loss is largely influenced by crop moisture content with greater loss in drier material. When hay is baled at night with dew on the forage, leaf moisture is higher, similar to stem moisture, and chamber loss can be cut in half. Chamber loss is mostly high quality leaf material; so excessive chamber loss reduces the nutritive content of the remaining forage. These chamber losses can be minimized by conditioning the forage crop, maintaining the fastest ground speed possible while bailing and by increasing the width of cut and reducing the power take-off speed in light crops. Excessive loss occurs at low feeding rates of hay into the baler and the bale is rolled in the chamber too many times per unit of hay baled (Robertson 1983, Rotz 2001).

During the 1990's the large rectangular, high-density bales become more popular, particularly for hay transported long distances (Muck 2001). These bales have a height and width of 60 to 130 cm, a length of 120 to 250 cm and a mass of 200 to 1000 kg. Special heavy duty equipment is needed for lifting, transporting and feeding these large bales. Balers producing these large packages offer greater baling capacity; they are capable of harvesting twice the amount of hay per hour as the small package balers. These balers are centerline design and more power is required with a minimum tractor size of 90 kW recommended for the largest balers. The big market for these types of balers are in the large hay or alfalfa growing areas where the forage is transported on tractor trailer truck over very large distances. It is much easier to transport a large square bale than the smaller square or round bales.

Hay Storage

The safe storage of hay requires that the moisture content of the harvested forage be below 20%. Microbial activity, heating and molding will occur in hay with a moisture content of over 20%. Hay will heat more when the moisture range is between 30 to 40% and if oxygen is present, the wet hay can reach a temperature where spontaneous combustion can occur and cause major hay barn fires. In many parts of the world it is extremely difficult to dry hay in the field to below 20% due to possible rainfall or high humidity. In these cases silage or hay additives or auxiliary hay drying systems become an option.

Excess moisture from small square bales can be removed by placing the bales on a perforated floor that has air circulation via air fan. The ambient air or heated air is blown through the bales until the moisture level is lowered to below 20%. There must be ample outlets for rapid evacuation of the humid air. The wet bales must be stacked so that the drying air goes through all the bales and the top bales do not retain humidity too long. The problem with this system is the low capacity, high labour requirements and the local cost of electricity (Elsasser 1990 and Jan et al. 1980).

In the past there has been a lot of effort spent in designing systems that would dry forage with ambient air or heated air either in the field or at a processing plant. In the 1970’s when energy costs were much less expensive than today, this drying method was used in Europe and North America. Alfalfa dehydration plants around the world use this process but the energy costs are very high today. Some hay equipment manufactures have developed systems where the forage was field dried as much as possible and then finished drying using either heated air or microwave energy (Rotz 2001). Besides the high energy costs, developers of in-field hay dryers face the additional hurdle of matching dryer capacity to baler capacity. A large square baler could require approximately 13 m^3 per hour of water to be removed by the drying system. Thus, the system would have to have an enormous capacity and a high operating cost.

In the early 1970's, the Schwarting hay drying tower was available to farmers in Germany. At that time a modified version of the system was developed and evaluated in Western Canada at the Agriculture and Agri. Food Canada Research Farm at Melfort Sask. Jan et al. (1980). The hay tower system incorporated a huge, hollow cylindrical and vertical stack. Drying was accomplished by blowing unheated air into the hollow center and through the stack. A movable cover prevented the air from exiting the cylindrical hole at the top of the stack. The hay tower was filled with chopped hay using a typical silage blower and levelled with a silo silage unloader. Unloading was accomplished by reversing the direction of the silo leveller and dropping the hay down the center hole to a conveyor below. Later, the Schwarting hay tower was evaluated in Canada. It employed a central shaft drive for both levelling and unloading the chopped hay. Smooth brome (*Bromus inermis Leyss*.) alfalfa hay was field dried to 40%, chopped and blown into the hay tower where the drying was completed. The hay was later fed to steer calves in a feeding trial and compared to smooth brome alfalfa silage, small square bales and large round bales. The daily gains and feed efficiency was highest for both the silage and the artificially dried hay from the tower followed by the hay baled as small square bales and then the large round bales. Gain per hectare was best for silage and the artificially dried hay, followed by the small square bales and large round bales. The high capital cost and limited capacity of the hay drying tower system prevented further acceptance of this system in North America. (Jan et al. (1980).

Microbial Activity in Haying Systems

Storage losses are directly proportional to microbial growth and heating. Heating depends on the moisture of the hay, the bale size and density, the drying rate of the hay and the microbial population in the hay. If baling is done at 20 to 30% moisture as a means of preventing leaf loss, microbial activity can still exist in the forage after baling. Hay does not become static until the bales reach a moisture content of about 12% and the humidity is below 65%. In these conditions most fungi will not grow (Mahanna 1997).

Fungal growth in hay production can occur on the standing plant, the wilting crop and during storage. The type of fungal growth is strongly influenced by the micro environment in the field, in the swath or bale. A major problem associated with the control of fungal growth is lack of uniform conditions during harvest and storage of hay. Thus, forage must be dried to less than 15 to 18% moisture for safe storage, with the assumption that field losses are a lesser risk than storage losses. Physical or chemical conditioning treatments applied at the time of cutting, are a means of reducing field wilting time and creating a more uniform environment within the swath or the bale. This improves the micro environment within the bale and minimizes the adverse fungal growth during storage.

Wittenberg (1997) at the University of Manitoba has provided and excellent overview of the roll of microbial activity in changing the nutritive values in hay production systems. Wittenberg observed that the bulk of moisture loss from hay stored at 24 to 35% moisture occurred between days 4 to 14 of storage, a period when stack temperatures were the highest. In the initial stages of storage, however, the temperature rise associated with aerobic respiration was important for the initiation of storage micro organism growth. Forage acid detergent fiber (ADE) and neutral detergent fiber (NDF) concentrations increase as a result of the enzymatic, microbial and chemical processes occurring during hay harvest and storage.

Preservation of forage as hay is recognized to be superior to preservation as silage with respect to protein quality for the high producing ruminant animal (Petit and Tremblay 1992). Forage protein value is assessed as the amount of amino acid available for absorption in the animal's small intestine. These amino acids may be derived directly from the dietary protein being offered or may be derived from microbial protein synthesized in the rumen. Forage harvest and storage systems that increase the proportion of forage protein that is undegradable in the rumen without increasing the unavailable protein will result in greater concentrations of dietary protein available for absorption in the small intestine (Wittenberg 1997).

A study in Western Canada (von Keyserlingk et al. 1996) showed that the soluble nitrogen (N) concentrations of alfalfa and grass hays range from 25 to 63% of total N. The fractional rate of crude protein degradation for the degradable N in the hays can range from 3.6 to 17.1% per hour. Thus, hay could be a source of escaped protein in ruminant animals. Hay harvested and stored at moisture levels that result in heating will also affect the protein quality at feeding.

Forage analysis for glucosamine, a constituent of chitin found in cell walls of spores and mycelium of fungi, has been used as a means to estimate the total fungal biomass in forage (Wittenberg et al. 1989, Roberts et al. 1987). It was found that 1 g per kg dry matter of glucosamine can be equated to 10 to 15 g fungal biomass per kg forage dry matter. Fungal biomass concentrations measured in stored forage represents the total fungal biomass accumulated from the time the plant is growing, to the time spent in storage. Studies at the University of Manitoba, Canada show that glucosamine values can be as low as 0.9 g per kg DM under ideal growing, harvest and storage conditions, with levels as high as 10 g per kg DM for severely molded hay (Wittenberg 1994).

Generally, the highest accumulation of fungal biomass is associated with fungal growth on cut forage lying in the field. Further characterization of this biomass has not been conducted. However, it should be assumed that the biomass contributes to the N and carbohydrate fractions of hays. Availability of these fungal fractions to be used as protein and energy sources for ruminants is not known.

Fungal growth

Many environmental factors are involved in the extent of fungal growth and species succession in hay following cutting, including water and nutrient availability, temperature, pH, gaseous composition and interactions with other microorganisms. Variation in the amount of moisture that microorganisms can use for growth becomes critical. This is dependent on the moisture content of the forage in the windrows and in storage.

The availability of substrate and its effects on fungal growth are not as clearly defined. Although leaves have a higher nutrient density than stems, alfalfa and grass stems had a greater spoilage potential than leaves, with fungal growth initiating at breaks or internodes along the stem (Wittenberg 1997).

Fungal growth can occur at a wide range of temperatures. Most fungi found in stored plant products thrive at a range of 10 to 40°C with a range of 25 to 35 °C being optimal. Hay produced under conditions where temperatures do not exceed this optimal range will have adverse range of fungal species. If the temperatures are in excess of 40°C, the species that are not thermo tolerant will disappear. Stack temperatures can readily reach 40°C when forage moisture content at stacking is in the range of 18 to 25%. High ambient temperatures and humidity, and restricted air movement due to bale density or stacking design will contribute to an increase in peak temperature.

The pH remains near neutral in hay that has undergone molding (Wittenberg 1997), unless storage moisture content exceeds 40 % when the pH value may rise to 7.0 or more. Most fungi grow well over a wide pH range, but will compete poorly with bacteria at pH 7.0 or above when there is available moisture.

Wittenberg (1997) found very little research to determine oxygen levels in stored hay. It is likely that poor air exchange could result in lowered O_2 and elevated CO_2 levels when plant or microbial respiration occurs. Although the fungi causing spoilage in hay are considered obligate aerobes, many are capable of growth at low concentrations of O_2.

The criteria most important to the subsequent development of a microorganism in a stored product are, the minimum condition permitting germination and growth. Any decrease in the rate of growth can influence the ability of one organism to compete with another.

Fungal activity in hay harvesting and storage

The process of cutting and conditioning the cut plants, results in the introduction of soil and air borne microbes to the plant material. Microbial populations present at time of cutting, plant physiological stage, temperature and moisture are the main factors determining the predominant fungal species and their relative level of activity during field wilting. Breton and Zwaenepoel (1991) and other European studies with grasses have identified the following soil borne species to be present on forage during wilting and baling: *Alternaria, Ascochyta, Cladosporium, Colletotrichum, Epicoccum, Fusarium, Phaeoseptoria* and *Phoma*. Other Canadian studies with alfalfa have identified the same genera as well as *Aspergillus glaucus*. Wilting trials have indicated that precipitation events can result in 10 to 100 fold increases in the forage bacterial populations during forage wilting, with little change in the fungal counts, although fungal biomass yield has increased (Wittenberg 1995).

Extent of fungal growth is often difficult to assess visually. A single event such as heavy dew or precipitation can double the fungal biomass accumulation on forage during field wilting. Fungal species that become dominant during storage of hay that has under gone heating thrive at low available moisture and higher temperatures. European and Canadian studies have identified these fungi to belong to the genera *Aspergillus, Emericella, Eurotium, Humicola, Paecilomyces, Penicilliun,* and *Rhizopus* (Breton and Zwaenepoel, 1991; Kaspersson et al. 1984; Wittenberg 1997). These studies also suggest that factors influencing the second temperature peak during storage will be a determining factor in the proliferation of a particular dominant species (Wittenberg 1997).

Wittenberg (1997) and others have tried to quantify the adverse effects of fungal biomass in hay by studying its' effects on hay palatability, intake and digestion. Presence of fungal biomass in hays having similar nutrient profiles did reduce palatability of the hay (Undi & Wittenberg 1996) in young heifers, but did not adversely affect intake in growing steers (Bossuyt et al. 1996) when fed as the sole dietary energy source. The fiber fraction of hay with elevated levels of fungal biomass also appeared to be more digestible compared to less moldy hay of a similar nutrient profile, possibly due to the action of mycelia penetrating the plant cuticle and causing splits or fractures in the xylem and lignified vascular bundles.

Many of the field and storage fungi identified are potential mycotoxin producers. Wittenberg (1997) found very few field trials in the literature that included assessment for mycotoxins in forage dried and stored as hay. Mycotoxin screening of alfalfa and grass forages baled and stored at moisture ranging from 15 to 30% in various trials in Western Canada have been negative. Clear description of the storage conditions associated with many of the incidences in which mycotoxin production have been evident were lacking. Most observations have been associated with material exposed to repeated wetting or material stored at moisture levels well in excess of those normally associated with hay production. Some fungi demonstrate very low or no toxin production at a low available moisture even though active growth is still occurring (Corry 1977). If hay could be preserved at moisture levels significantly higher than 20%, both field and storage losses could be reduced (Thorlacius 1984).

Chemical and biological preservatives

Chemical and biological preservatives offer the hay producer several options in humid climates. Preservatives allow forage to be baled at a higher moisture content, thus, reducing field drying time and the chances of rain damage. Baling hay at 25% moisture reduced field curing time by about a day (Rotz & Muck 1994). Hay baled at higher moisture will reduce mechanical separation losses during baling (Shinners et al. 1996, Mir et al 1995 Friesen 1978). There have been a lot of efforts directed towards the development of hay preservatives designed to inhibit microbial activity that may adversely affect quality of hay during storage. Wittenberg (1997) has also reviewed these alternatives.

Alkaline solutions, prepared by adding monovalent alkaline metal ions to a carbonate solution, cause a dissociation of the carboxyl groups in the cutin matrix of the plant cuticle. As a result, the plant is unable to prevent water movement from its interior to exterior. Solutions made with potassium carbonate (K_2CO_3) have received the greatest amount of attention in field trials. Alkaline solutions (0.18 M or higher) are effective for legumes but not for grasses. The ability of K_2CO_3 to improve drying rates with grass-legume mixtures is directly proportional to the forage mix. The recommended application rate will vary with field condition and method of application. Most commonly K_2CO_3 solution is applied at 2 to 3% of forage weight with the location of the spray nozzles and push-bars ahead of the cutters such that the majority of the solution is directed toward plant stems.

Combining mechanical conditioners and K_2CO_3 has an additive effect on drying rates. Crump (1985) found that a combination of mechanical and chemical conditioning was more effective than mechanical conditioning alone in four of six trials, or chemical conditioning alone in three of six trials.

Potassium carbonate has been combined with sodium carbonate to reduce costs without sacrificing effectiveness, however, current recommendations suggest that the ratio should not be less than 1:1 (Wittenberg 1997). Potassium carbonate also has been combined with methyl esters and emulsifying agents in an effort to further improve forage drying rates, however, response to these additions is varied. Other forms in which the alkaline metals have been tested include potassium hydroxide or sodium silicate. Chemical drying agents or desiccants that cause disruption of the plant cuticle can cause increased plant susceptibility to fungal invasion during storage (Kraynyk and Wittenberg 1989) and microbial attack in the rumen (Hong et al. 1983).

Organic phosphates have demonstrated an ability to increase forage drying rates and reduce cell respiration rates but have not been tested under field conditions and could present toxicity problems for livestock. Compounds in this category include tri-n-butyl phosphate and a diphosphate ester.

Two other types of preservatives commonly used in hay production include fungicides, which kill fungi; and fungistats, which inhibit growth of fungi. Categories of hay preservatives, described on the basis of mode of action, include direct acidifiers, specific antimicrobial agents, bacterial inoculants and nutrients. Most preservatives are applied at the time of baling as either a granular or liquid product, however, some products such as anhydrous ammonia and cold-flo ammonia may be applied shortly after stacking. Desirable criteria of hay preservatives include the ability to prevent fungal invasion in hay baled and stored above defined safe moisture levels. The preservative needs to inhibit the production of fungal end products (spores and mycotoxins) that have direct adverse effects on hay handlers and livestock. The product requires easy application and safe handling procedures, a lack of adverse response by animals consuming treated hay, no residue in animal products and sufficient cost recovery (Wittenberg 1997).

Organic acids are effective in preventing fungal invasion of moist hay during storage when adequate levels are applied. Propionic, acetic, isobutyric and formic acids, at levels of 0.5 to 2.5% of wet forage weight significantly reduced dry matter losses and on average increased crude protein, however, most commercial acid based preservatives contain propionic acid or a propionic-acetic acid mixture. This hay preservative has been shown to reduce mold growth, heating in the bale and short term dry matter loss (Rotz 2001). However, dry matter loss over a longer storage period greater than 4 months was not reduced in either small square bales or large square bales. High moisture hay treated with an organic acid preservative maintained higher moisture content during storage. However, during storage the moisture supported microbial growth but at a lower rate because of the presence of the preservative. Typical applications rates of propionic based preservatives are 0.5 to 1% of the weight of the wet hay (Rotz 2001), although applications as high as 2.5% by weight have been reported (Robertson 1983). These additives significantly reduced dry matter losses and on average increased crude protein available at feeding by more than 100 kg per hectare (Robertson 1983). Economic benefit from applying organic acid preservatives at the typical rates is only justified when it is used to avoid damage from rain (Rotz 2001).

The corrosive nature and the high vaporization losses of the original acid products caused application problems. A dilute acid product, which was less corrosive and required a high application rate, was developed. A second approach was to neutralize the acids. Neutralized propionates include ammonium, calcium or sodium salts of propionic acid or use a buffer, thus, making the product less corrosive and less volatile. Laboratory results indicate that neutralized acids are less effective in preventing fungal invasion of moist hay, however, because they do not volatilize during field application, the recommended application rates are similar to that of the acid that is not neutralized (Wittenberg 1997).

Anhydrous Ammonia

Anhydrous ammonia is an effective hay preservative (Koegel et al. 1985, Mir 1991, Rotz et al. 1986, Robertson 1983, Thorlacius 1984). Ammonia preservatives, including anhydrous ammoina, cold-flo ammonia and urea, are fungistats. Anhydrous ammonia is the most commonly used of these products and requires that hay be covered in plastic at the time of and after application. Application rates of ammonia depend on hay moisture content, and are recommended to be approximately 2% of forage weight for hay that is 25 to 30% moisture (Thorlacius & Robertson 1984). Cold-flo ammonia is applied by converting the gas to a liquid and vapour mixture that is metered into a plastic covered stack at similar application rates. Ammonia will inhibit most yeast and mold growth in baled hay, however, the fact that some bacteria and heat resistant fungi will proliferate in this preservation system can present problems. Hay spoilage is frequently observed in the bale or stack when the ammoniated forage is exposed to condensation or moisture infiltration from rain and snow. Also, the chemical reaction associated with ammoniation can generate enough heat to cause an undesirable browning of the forage. Mir et al. (1991) found that ammoniation raised the crude protein content of large round baled brome alfalfa and alfalfa hay harvested at less than 20% and at 30% moisture, compared to non-ammoniated field cured hay at less than 20% moisture. The ammoniated hay was free of mold even after 14 weeks of storage. No significant improvement in animal performance was found due to the hay type, moisture content or ammoniation. It was concluded that ammoniation was effective in preserving the quality of the high moisture hay which would have spoiled otherwise.

Baron (1990) at Lacombe Alberta, found that baling large round bales above 25% moisture with or with out a preservative in excellent or poor weather conditions resulted in less nutrients for feeding than baling between 18 and 21% moisture due to the loss of DM and nutrients in storage. Baling at less than 18% under rain free conditions or after rainfall resulted in a decrease in yield of nutrients. Baron recommended that hay be baled at moisture levels slightly above those considered safe for storage if rain is imminent. Neutralized propionate applied at a rate of 1.25 to 1.50% wet weight basis improved the nutrient yield, but was not an economical option unless the hay could not be harvested at all due to wet weather.

Originally anhydrous ammonia was a very economical method of hay preservation. Today however, anhydrous ammonia is not widely used as a forage preservative because of the high cost and volatile and caustic nature in relation to animal and human safety issues. A cost benefit analysis of adding anhydrous ammonia limits application. Unless the anhydrous is applied to low quality forages or crop residues in years of forage shortages, it is not economical. Ammonia can be toxic to ruminant animals when it is applied to high quality legume hay at rates greater than 3% on a wet weight basis (Rotz 2001). Ammoniated hay on rare occasions has been associated with the development of a nervous disorder in livestock consuming high quantities of the treated forage, especially alfalfa hay. The factors contributing to this condition, commonly referred to as crazy cow syndrome or bovine bonkers are not known (Mir et al. 1991). On the other hand, urea can be applied as a granular product at the time of baling or at the time of stacking, at a rate of 40 kg per tonne to reduce mold and browning in hay (Mahanna 1997). Caution should be exercised in feeding the 4% urea treated hay by diluting it with 50% of the total forage intake coming from untreated hay.

Bacterial Inoculants

Bacterial inoculants are a widely accepted tool in forage ensiling systems because they meet all the criteria of a desirable preservative agent. The potential use of inoculants in hay systems is a relatively recent advancement in forage preservation. Many of the early studies focused on lactic acid anaerobes commonly used in silage preservation, including the genera *Lactobacilli, Pediococci*, and *Streptococci.* A wider range of organisms, which includes the genera *Bacilli,* are being investigated, based on their ability to survive in the early stages of storage within the bale micro environment and on their ability to inhibit or modify fungal activity (Wittenberg 1997). Most microbial hay inoculants marketed today were initially developed to aid in the fermentation of silage. The effectiveness of these bacteria to work in baled hay is questionable, as they are facultative anaerobes that prefer anaerobic and moist conditions. Mir et al. (1995) did not find any advantage of using *Lactobacillus plantarum* on alfalfa round bale forage at 18% moisture content. Baron (1988) found that live bacterial culture, *Bacillus subtilis* or 12% lactic acid extract, were not effective at any moisture level for use in hay harvesting and storage. In the late 1980's aerobic bacterial hay inoculants specifically designed for alfalfa hay were introduced into the market place. These products used selected strains of *Bacillus pumulus* and have been shown to be effective on alfalfa hay baled in small square bales at up to 25% moisture, large round bales at 20% moisture and large square bales up to 18% moisture (Mahanna 1997). The current use of bacterial inoculants is relatively small compared to the use in silage production systems.

The micro environments within the bale are not understood. The large round or square bales can result in much lower oxygen potentials due to respiration, by either the plant or the indigenous bacterial populations. This makes the moisture escape, a byproduct of heat generation, more difficult. These pockets of available moisture in the presence of high temperatures are optimal for microbial growth even though the average moisture content of the bale would not indicate this. Advancement in our ability to use bacterial inoculants as effective hay preservatives depends upon a better understanding of the creation of these micro environments and the microbial activity supported by them (Wittenberg 1997).

Other types of hay additives include sugars, protein, other nutrient supplements and crude enzyme preparations designed to liberate nutrients from forage material for the purpose of enhanced desirable microbial activity. Antioxidants such as butylated hydroxy anisole, ascorbic acid, propyl gallate and butylated hydroxy toluene are sometimes included in hay additives to maintain the green coloration of hay and to enhance the effect of organic acids (Wittenberg 1997). The use of salt (NaCl) has been used on wet hay in the past. In sufficient concentrations, NaCl will absorb free water on the surface of the hay, thus, inhibiting microbial growth. There are however few controlled research studies to evaluate rates, concentrations and palatability problems of adding NaCl to hay (Lacefield 1987).

Hay Storage Losses

Ideally all forms of hay should be stored under cover to prevent rain damage. This is especially true for small square bales. Martins (1980) found that when hay is stored inside at normal moisture levels below 20% there can still be a 5 to 10% dry matter loss. Other studies have found that hay stored inside can loose as much as 1% of dry matter for each percentage unit of moisture loss. Hay baled at 20% moisture will likely lose 5 to 8% of its dry weight by the time it dries to 12% moisture (Mahanna 1997).

Losses in round bales stored outside on the ground are about three times greater than bales stored inside. These losses can be even greater, especially in high rainfall areas of the world. Mahanna (1997) reviewed studies that found 40% storage and feeding losses for large round alfalfa bales stored outside with no cover. Thus, the potential storage losses will justify storing round bale hay under cover in high rainfall areas. However, storing the large round bales under cover might not be cost effective in all cases. In these situations round bales should be stored end to end on well drained ground (Beacom 1991). Much of the weather damage is caused from bales being in contact with the moist ground. This loss can be greatly reduced by storing the bales on crushed rock, raised tires or wooden rails, which provided a small air space underneath the bales. The bales should be placed in long rows with an air space of at least 3 to 4 cm between the bales. There needs to be enough space between the bales to permit good air movement. If the bales touch each other then spoilage caused from rain will occur at those points. When the round bale loading wagons or trucks pick up a number of round bales in the field and haul them to the storage yard, the bales are automatically unloaded and the butt ends of the bales will be touching, thus causing potential spoilage. If space is limited, bales can be placed in piles of three similar to a mushroom shape, two bales vertical and the top one horizontal. Thus, the top bale sheds the rain off the two bottom bales. For short term storage, round bales can be stacked in a pyramid style in rows of 4:3:2:1. However rain can still penetrate this configuration. When high moisture round bale silage or hay is produced the bales must be covered in air tight plastic sheets, wraps or silage tubes to prevent spoilage.

There appears to be reluctance for hay producers to adapt the existing technology that can significantly reduce storage losses in hay. The Teagasc Research Centre in Ireland (1997) survey showed that few producers cover their hay. It seems redundant to grow, cut, harvest high quality hay and not store it under proper conditions. The inability to recycle plastic hay and silage wrap is an environmental concern. Currently there are some edible alternatives to plastic wrap being evaluated for covering silage and large bales. Other products designed to form a tough membrane that protects the hay from rain damage are being developed. With the higher valued hay crops, the economic returns from reduced storage losses can justify some type of coverage system.

Other Hay Harvesting Systems

Dehydrated Alfalfa Pellets

Canada, France, Spain and Italy are the main exporters of dehydrated alfalfa pellets. Commonly referred to as *"dehy",* dehydrated alfalfa pellets are processed from alfalfa cut in the late bud to early flowering stage. The alfalfa forage is only partly field dried to minimize the effects of weathering and to ensure minimal harvesting losses of nutrients and plant material.

Forage harvesters pick up and chop the green, wet material and deliver it to the dehydration processing plant. The green chop is then dehydrated in natural gas dryers at an air temperature of 110 to 120 ^{0}C. The rapid heating and drying process preserves the nutrients in the alfalfa and reduces the solubility of the protein. This heating process changes approximately 60% of the protein into the bypass form, which leads to more efficient use and digestion of the protein, allowing dehy to support higher levels of milk production.

The chopped, dried alfalfa is then ground into a meal prior to pelleting. The texture of the meal determines the size of the pellet produced. With longer fiber, a 9 mm pellet is processed from a coarse meal, whereas a small 6 mm pellet is made from a finer ground alfalfa meal. Following grinding, an antioxidant is added to preserve the beta carotene and other vitamins. The pellets are cooled and transferred to large storage bins to await shipment. As with all processed alfalfa products, the storage conditions are monitored to maintain product quality. Dehydrated alfalfa pellets usually contain 18% crude protein or more on a dry matter basis.

Suncured Alfalfa Pellets

Suncured alfalfa pellets are available in 6 mm and 7 mm sizes produced from alfalfa that has been naturally dried in the field at the late bud to early bloom stage. After field drying, it is moved to the plant for final drying and pelleting. As a suncured alfalfa product, it is dried at a lower temperature. It contains less bypass protein and is more applicable in situations where bypass protein is of less importance. Suncured alfalfa pellets usually contain 17% crude protein or more on a dry matter basis.

Alfalfa Hay Cubes

The United States and Canada are the two main exporters of alfalfa cubes. Regular alfalfa hay cubes are 33 mm on each side and 50 to 100 mm long. The alfalfa in suncured pellets is finely ground, where as it is coarsely ground in cubes. Since cubes retain a longer fibre length and a larger particle size, it can be used as the only forage source for dairy cows.

The smaller cubes are usually 22 mm on each side. They contain either sundried alfalfa or a mixture of sundried and dehydrated alfalfa forage. Alfalfa cubes, which include dehydrated alfalfa contain more bypass protein than a conventional suncured product.

Due to their size and compressed form, alfalfa cubes have an advantage over traditional roughages. In the long form, cubes are easier to handle, they blend with the ration without further processing and are in a reduced volume for economical transport and storage. Feeding cubes increases forage intake and there is less feed wastage and spoilage. The product is also uniform in quality and has a high nutrient content.

Since cubes are a compressed form of alfalfa hay, they offer labour savings in handling. The bulk density of alfalfa cubes is 400 to 500 kg/m3 compared to 200 kg/m3 for baled alfalfa hay. The majority of hay cubes are suncured and processed in stationary cubing facilities. This allows the plants to process suncured hay by using some drying at low temperatures to develop a uniform moisture content and to ensure good keeping quality. Alfalfa cubes usually contain 17% crude protein or more on a dry matter basis.

Despite the shipping advantages of alfalfa pellets and cubes to markets in Japan, Taiwan and Korea, densified or double compressed long hay is now the product of choice. Asian cattle producers are now buying the densified long hay as their sole fibre source.

Densified Hay

With the increasing demand for fiber for livestock feeding in Japan, Korea, Taiwan, United Kingdom and some Middle Eastern countries, a large densified hay market has developed. The United States, Canada and Australia are the main exporters of the product. As the hay is transported in large containers via rail and ship, the bales are double compressed to increase density and reduce volume in the container. The double compressed hay industry started in the late 1970's and early 1980's. For top grade or price, the hay must not be rained on. Thus, longer maturing varieties are grown and harvested (single harvest) on dry land production systems while the earlier maturing varieties will be grown on irrigation where two or more cuts will be taken. The process starts with baling hay in the small square bales at 12% moisture or less. This hay must be bright green and free of weeds.

The hay must also be free of *Agropyron* grasses in order to prevent the spread of the Hessian fly. The Hessian fly will cause great damage to the rice crop and currently these countries are free of this type of fly. Thus, the hay must be free of the Hessian fly or its' eggs for export into the rice growing countries of Japan, Korea and Taiwan. Since the Hessian fly lives in *Agropyron* grass species, these types of grasses along with any damp hay must be hand separated and discarded from the hay before it is rebaled as densified or double compressed bales. The Canadian bales are compressed to 5000 psi bales are about 5.5 cm x 6.5 cm x 1m in size and weigh 42 kg, while the American bales is larger and weigh about 60 kg. Timothy is the main forage exported as double compressed or densified hay from Canada while, Australia specializes in oat hay. The United States exports various fiber based hay or straw products to these countries.

Twenty six tonnes of double compressed bales can be packed into the shipping container. Before this process was developed only thirteen tonnes of hay could be shipped in the same container, doubling the shipping cost. Small farmers in some countries purchase individual double compressed bales and haul them to their farm on their bicycles. Larger operators use this hay as the main source of fiber in their cattle diets.

Utilizing Harvested Forage Crops

Considerable research has been done on the feeding value of harvested forage crops. Beacom (1991) has summarized 35 years of Canadian research from the Agriculture and Agrifood Canada Research Station at Melfort Saskatchewan. The main emphasis of this research program was to maximize the use of harvested forages in beef cattle production and have a consistent production of high quality beef carcasses.

The stage of maturity of the forage is the most important factor in influencing feeding value of the crop. Quality decreases as the plant matures while dry matter yield will increase to the early bloom stage in grasses and legumes. The relative importance of quality and yield will depend on the kind of livestock operation involved and the availability of other feeds. It has been shown that harvesting of grasses and legumes should be done much earlier than is normally practiced, ie. early heading to early bloom stage for optimum yield of digestible nutrients. The application of nitrogen fertilizer will also increase the protein content and yield per hectare of the forage crops. (McCartney 2002).

The moisture content at harvesting and the amount of raking and turning will affect leaf loss in the field, spoilage, storage loss and nutrient loss. Some studies have shown that the loss from fine material lost in the harvesting process can lower the feeding value by 5%.

The degree to which harvested forages can meet the animal's nutrient requirements will depend on the amount of forage that the animal can consume. The maximum amount of forage voluntarily consumed by an animal will depend on the nutritional quality of the forage, the physical form of the forage or its bulkiness, the palatability of the feed and the freedom from spoilage or weeds. Growing and finishing beef cattle can consume between 2.5 and 3% of their body weight in high quality forage but only about 1% low quality forage such as straw. Nursing beef cows can utilize 2.5% to 3% of their body weight in high quality forage and only 1.6% to 1.8% as poor quality forage or straw (NRC 1996).

Large farming operations have used large scale tub grinders for grinding hay, but most are operated using a large screen size of 51 mm as their capacity was greatly reduced with the smaller screens. Economics and labour determines the use of this hay

Beacom (1991) has estimated that growing steers weighing 227 kg, can consume 7.5 kg per day of good quality hay at (>14%) crude protein in the long form and 8.5 to 8.8 kg per day in the pelleted or ground form. While the same steers could only eat 4.8 kg of long form poor quality hay at 8 – 10% crude protein. When the same product was ground they could consume 7.0 kg per day and 8.0 kg per day in the pelleted form.

The degree to which harvested forages can meet the animal's nutrient requirements will depend on the amount of forage which the animal can consume. This depends on the quality or nutrient content and the bulkiness of the forage. Beacom (1991) has shown that steer calves weighing between 250 kg, (ie. a growing steer), or a 450 kg finishing steer, could not consume enough good quality hay in the long form at 12% crude protein to have a daily gain of 1.1 – 1.4 kg. These same animals could consume enough ground hay through a 1.27 cm screen to meet their energy requirements. This eliminated the need for high energy supplements such as grain. In practice Beacom (1991) recommended that feedlot cattle be started on ground high quality forages full-fed from the beginning and gradually increase the grain component of the ration, as required, to achieve the rate of finishing desired. The relative price of grain and hay and the animal's ability to gain and finish on high quality forage ration, and the trends in the slaughter cattle market prices will all influence the timing and extent of replacing hay with grain. In general, it will be advantageous to feed a relatively high grain ration during the final few weeks before slaughter in order to increase the dressing percentage and grade fat cover for finishing to the North American market requirements. This also depends on the type of cattle being finished for slaughter. Farmers are cautioned against increasing the grain level of cattle being fed the ground high quality hay, especially alfalfa, as the risk of bloat is increased once the grain level exceeds 30% and is especially critical at the 50% level. The risk of bloat is reduced and better overall performance is achieved when the quality of the hay is reduced as the level of hay in the ration is reduced with the increase in grain content.

Effects of Grinding Forages

Grinding hay through progressively smaller screens in a hammer mill or farm type tub grinder mixer will increase the density of the product and results in higher intake by the ruminant. There are several manufacturers of tub grinders for processing forages and these machines have been tested for performance by PAMI (2001). On average, grinding through a 13mm screen increased the density of the hay by 23% compared to processing through a 25mm screen. The greatest increase of 35% occurred with the lower quality forages. Intake and rate of gain was increased, by reducing the bulk by grinding. The processing of poor quality hay had a much more beneficial effect that processing a high quality hay. Grinding changed the low quality hay from an unproductive feed to one that would support a higher rate of gain than the unprocessed good quality hay. Using a grinding screen finer than a 55mm screen reduced the digestibility of the forage. This was probably due to the increased rate of passage of the finer particles through the rumen. Processing forages through the 13mm screen gave optimal results for feeding processed hay. There was no benefit to grinding more finely than through a 13mm screen.

Acidulated fatty acids, a byproduct from the canola oil industry, has been used as an energy supplement and as a means of reducing dust in the ground hay rations. When used at the 4% level it improved rates of gain in the high forage ration by 16%, and feed efficiency by 10%. It also improved the financial returns on the cattle (Beacom 1991).

Steers and heifers of large frame exotic breeds tend to produce under finished carcasses according to North American standards on good quality ground forage based rations, and additional grain feeding was required. Cattle also required about two weeks longer to finish than their grain fed counterparts. Although cattle could successfully be finished to some slaughter market specifications, by self feeding ground forages, the labour and energy costs of grinding these forages made this process questionable (Beacom 1991).

Feeding Round Bale Hay

Most large round bales are fed in a metal feeder that allows 12 to 18 cows access to the forage. Many round bales are also rolled out and fed directly on the ground. These methods of winter-feeding are widely practiced due to low labour and machinery inputs. There has been lots of research on storage losses of round baled hay but there has been little work done to evaluate the feeding losses according to the feeding method even though some studies suggest that feeding losses may reach 20 to 30%. A study has been conducted at Michigan State University, USA to assess the feeding losses of several designs of round bale feeders. Waste ranged from 3.5 to 14.6% of the dry matter with the cone and ring type feeders, where cows were able to keep their heads inside the perimeter of the feeder while eating, were the most effective (Buskirk 1998).

In many parts of the western United States and Canada, cattle are wintered outside and fed round bale hay on the ground. These bales are rolled out using several different types or designs of machines manufactured by various equipment manufacturers. Bale shredders are also manufactured for chopping or shredding round bale hay and distributing it for feeding (PAMI 2001). These machines work well for spreading round bale hay onto the ground. If fed in proper amounts, there is very little wastage.

What about the future?

The methodology and physiology of harvesting and storing hay is in most cases universal around the world. Research findings in general as reviewed in this paper can be used in any hay producing area. Similarly, hay harvesting equipment that is manufactured by most companies can be used domestically as well as exported to different countries. Major advancements in equipment design and harvesting research have been accomplished in the past 30 years. However this trend has slowed down and at present there is very little research on haying systems occurring in any of the major hay growing countries due to the lack of research funds. The major question that still hasn't been answered involves drying the crop faster by shortening the time between cutting and baling in order to reduce or eliminate the effects of weather. Hay producers around the world are still faced with this issue. Hay quality is still the biggest issue for the farmer compared to productivity. With the increased need for high quality dairy hay as a fiber source, increased efforts in research and management are still required to reduce these quality losses.

In the future, more accurate weather forecasting data will be required at hay harvest time. In part of North America, a daily drying index is available for producers to use in order to decide when hay should be cut and baled. This system needs to be expanded and the information could be used to develop computer simulation models to help hay producers in determining hay harvesting options as a means of reducing losses. In the future this process must include information on possible dry matter and nutritional losses during wilting and harvesting from plant respiration, precipitation and include the various machinery and storage losses. This would aid the large scale hay producer in purchasing equipment (Rotz 2001) and identifying the critical points that need to be addressed to reduce the nutritional losses.

Rapid moisture determination is possible through the use of electronic metering systems, but multiple samples must be tested in order to get more accurate moisture readings throughout the field (PAMI 2001). Many hay equipment manufacturing companies are in the process of developing on the move moisture metering and yield monitoring systems. These units will be hooked into the GPS (Satellite Global Positioning System) and GIS (Global Information System) for on farm use. The baler operator will then be able to monitor hay yield and the moisture content as each bale is being made. If the moisture content is too high in a certain spot in the field then he can leave it for another time or he can add a metered amount of hay preservative to the individual bale.

Across North America farms are consolidating and become larger. Most hay harvesting equipment manufacturers are observing a marketing trend towards the bigger and more efficient equipment. The large round bale will continue to be the main haying system in the future because high productivity at low cost. Large square bales will become increasingly popular because they offer very high productivity, density and shipping efficiency. Small square bales will be of less importance due to high labour costs but will remain as a specialty packaging system for small livestock producers, equestrian owners and exporters.

Haying machinery in general has not been developed for regions with short daily drying times combined with frequent showers. Evidently, this makes the present windrow to bale type system perform very poorly on a quality basis as most hay becomes weathered before baling. Alternatives which would allow for more sun drying with gentler raking systems are also required as a means of obtaining better quality hay. Further engineering research is required to enhance the total hay harvesting systems

Although the round baler is still the most economical it still requires the operator to stop to tie the bale. This is a major productivity disadvantage and equipment manufactures need to address this issue in order to speed the harvesting process.

There are still handling problems with all forms of hay baling. Farmers need to automate the system for feeding hay, as silage feeding systems are much easier to automate. This is one of the main reasons that hay production will decrease. If forage needs to be transported over long distances, because of its high dry matter content, hay is the product of choice. In large scale operations and for transport markets, because of the high capital cost of large baling equipment, there is becoming an increased dependency on large scale custom operators owning/operating the expensive equipment.

Long fiber forage exports will grow as countries in the Pacific Rim increase their diets with meat and dairy products from ruminant animals. This market will require consistent high quality products. Improved systems and quality standards for the high-density bales, which are used to improve shipping efficiency, will need to be developed. Presently the technology is available to produce the double compacted bale. However, the hand sorting of the unwanted plant material could be enhanced with the development of visual electronic scanners for identification and removal of damp or unwanted material prior to compaction. There is also a need to develop a baling system for producing high density bales (i.e. 300 kg/m^3) in the field.

If high quality hay is to be produced on a consistent basis, improvements on hay inoculants and other types of hay preservatives will be required to provide more consistent and beneficial effect in animal performance. These products must be cost effective, environmentally friendly and safe, and easy to apply. The present adoption of hay inoculants is relatively small due to cost and lack of consistent results.

In many parts of the world there is concern about pathogen, microbial toxins and insect transmission through hay. In addition there is the concern of respiratory problems in humans caused by hay dust. Research is needed to develop rapid systems for detection and means of controlling their development in a safe and economical way.

An increasing proportion of the world's hay supply will be grown in arid climates under irrigation as producers in these areas will have a greater control of growing, drying and harvesting forage with less risk of weather damage. In some cases re hydration at baling will be required to lengthen the harvesting opportunity and enhance the baling process by reducing stem and leaf loss due to breakage. In other areas there is still concern about bleaching or discoloration of hay. The market place wants green hay and as a result producers tend to leave hay drying in large swaths for a long time to reduce the bleaching and this can lead to possible rain damage. There is very little scientific evidence that bleaching from the sun reduces nutritional quality. This question still needs to be addressed in these specific regions.

It is doubtful that systems for artificially dried forage before or after baling will develop as they have low capacity, high capital cost and high fuel cost. Forage value must increase substantially before these systems will be adapted.

In conclusion the hay harvesting industry is still looking for ways of reducing forage quality and quantity losses. Methods must be developed to shorten the time between cutting and baling, and reduce weathering losses. Improved bale handling and feeding systems will be required to reduce additional forage losses. Silage systems will become the way of the future in many regions of the world. Hay harvesting systems will continue to provide a long fiber forage product to meet specialized needs in the world livestock industry of the future.

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