AN EVALUATION OF HAY DRYING AND HARVESTING SYSTEMS

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Abstract: The drying rate of alfalfa is highly related to weather and crop conditions. The major factor that influences drying rate is the level of solar radiation. Other factors include the vapor pressure deficit (temperature and humidity) of the ambient air, the soil moisture content and the density or thickness of the swath. A mower-conditioner with gentle but effective conditioning (rubber rolls) can speed drying when crop and environmental conditions are favorable. Chemical conditioning (use of a drying agent) can also speed drying under these conditions, but neither process can compensate for poor drying weather. When making hay, alfalfa should be laid in relatively wide swaths for more rapid drying and raked prior to baling. Swath manipulation with a tedder or inverter can speed drying, but increased costs and losses caused by the operation may be greater than the average benefit received. Hay preservatives such as propionic acid can be used to bale moist hay and thus reduce field curing time. The treatment cost is high though, and preservation is inferior to that in dry hay. There is little evidence that the use of bale ventilation (creating a hole through the center of the bale) or the use of bacteria and enzyme inoculants can improve hay preservation. A low-cost drying system can provide better preservation and greater economic return than the use of preservatives. A new mat drying process is being developed for future hay making. By shredding the alfalfa and pressing it into a mat, the field curing time for hay production can be reduced to 1 day. The quality of the forage produced is exceptionally high, perhaps superior to that produced by any other method.

Keywords Hay, Drying, Harvest, Preservation, Losses, Costs

INTRODUCTION

The awareness of hay harvesting losses and their effect on animal performance has improved considerably in the past 50 years. As a result, the desire to speed the curing process has grown in an effort to reduce losses. Hay harvest losses are often categorized as: 1) respiration loss, 2) leaching or rain loss and 3) mechanical or shatter loss. These losses are relatively small when the crop is dried quickly under good drying conditions. When dried slowly, the plant has more time to respire as a living organism, and respiration loss can be as high as 10% of the crop dry matter. When rain damage occurs, the leaching loss can be as much as 30% of the crop dry matter, and of course, at times the whole crop is lost. Mechanical losses increase as more machinery operations are used. For example, a typical raking operation can reduce the crop yield 5 to 10%. All of these losses, but especially respiration and leaching losses, reduce the content of digestible nutrients and increase the fiber content of the hay. These quality changes can have a major impact on the performance of the animal consuming the hay.

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Hay growers are presented with a variety of products and strategies promoted to reduce losses and/or improve hay quality. New products are introduced each year with much promise, yet few survive for the long term. The many choices tend to create confusion. Given the technology available today, what is the best way to make hay? Which products and strategies provide economic return and which do not? These are the questions to be addressed. Many of the available techniques will be discussed, but first, let's look at the factors which affect the speed at which alfalfa dries.

FACTORS THAT AFFECT DRYING

The field drying rate of forage is limited by characteristics of the forage plants, the swath and the surrounding environment. All three of these constraints have some effect on limiting drying; however, the predominant constraint varies from one set of conditions to another. When the environmental conditions are not conducive to good drying, little can be done to the plant or swath to improve drying. More specifically, if the humidity is high, solar radiation is low, and air temperature is low, then the vapor pressure gradient is low. With a small difference in vapor pressure between the plant surface and ambient air, little moisture movement occurs. Crushing the plant, spreading the swath or any other treatment to the plant or swath has little effect on drying because the environment is the predominant constraint.

When forage is laid in a thick, dense swath, the resistance created by the swath can become the principal constraint to drying. Alteration of the plant has little effect on drying since the moisture cannot readily move out of the swath. Even when the environment is ideal for drying, the drying rate may be relatively low due to the constraint of the swath. When forage is dried in a thin open swath under good environmental drying conditions, the plant becomes the predominant constraint to moisture movement. Crimping, crushing or other alteration of the plant provides the greatest increase in drying rate under this scenario.

Field curing occurs with each of these constraints placing some control on drying. The relative impact each of the major constraints has on drying varies throughout the day. Early and late in the day, the environment normally provides the greatest constraint. During much of a sunny day, the drying rate is limited more by swath and plant constraints. The effect each has on drying changes continuously throughout the curing process as characteristics of the plant, swath and environment change. We have collected drying data from thousands of alfalfa samples throughout Michigan as well as the more arid region of central California (Rotz and Chen, 1985; Carlson et al., 1989). The results are very consistent in pointing out the factors which have the greatest effect on drying.

Factors with the greatest influence on drying are weather parameters, and the parameter with greatest influence is solar radiation (Table 1). The primary driving force for moisture evaporation from curing hay is the radiant energy falling on the crop. Under very low levels of solar radiation, i.e., a very overcast day, over 60 hours of drying or up to 6 days are required to make hay. Under very sunny conditions, hay can dry in as quickly as a day and a half. Actual drying times will vary considerably due to other crop and weather conditions; these numbers are given only to illustrate how sensitive the drying time is to solar radiation.

Table 1. Long-term average influence of environmental and crop variables upon alfalfa drying rate and field curing time in Michigan (Rotz and Chen, 1985).

Environmental or crop variable	Units	Range in value		Drying rate[†] (h^{-1})		Max. effect on field curing time[‡] (h)
		Min.	Max.	Min.	Max.	
Solar radiation	langley/h	8.5	82	0.046	0.232	48.0
Vapor pressure deficit	lb/in^2	0	0.65	0.154	0.197	3.9
Air temperature	°F	50	100	0.153	0.186	3.2
Swath density	lb DM/ft^2	0.03	0.30	0.199	0.128	7.8
Soil moisture content	% db	10	25	0.196	0.160	3.2
First day of curing		0	1	0.156	0.178	2.3

[†] Drying rate expressed as portion of available moisture lost each hour.
[‡] Difference in field curing time (drying hours with rewetting and night periods excluded) between the minimum and maximum expected value of the crop or environmental variable.

Vapor pressure deficit is another important weather parameter. Vapor pressure deficit is a combined measure of air temperature and humidity. A high value of vapor pressure deficit implies a warm, dry air which promotes faster drying. Comparing relatively poor drying air to very good drying air only shows a difference in drying time of about 4 h (Table 1). This indicates that drying is less sensitive to vapor pressure deficit than to solar radiation. Although this is true, the difference between the effects of these two parameters is not as great as this data implies. Vapor pressure deficit, as well as many other weather variables, is highly correlated to solar radiation, i.e., a day with bright sunshine normally has a high vapor pressure deficit. Our data, therefore, may be attributing more drying benefit to solar radiation than it deserves and less to vapor pressure deficit because of the difficulty in separating the effects of these parameters through field measurement. Nevertheless, these two parameters both influence drying, and solar radiation is the predominant factor.

Wind is often thought to be important in hay drying, but our measurements do not show any relationship between wind velocity and drying. These measurements were all made on alfalfa drying in a swath, i.e., in a relatively thin layer on the field surface. Wind has more benefit when hay is rolled from the field surface into a windrow.

Another factor which greatly affects drying is the density of the plant material laying in the swath. When the crop is piled into a relatively narrow swath, it dries slower than when it is spread over the field surface. Our data indicate that a thick, narrow swath requires about 8 more hours of drying (1 day) than a thin swath spread over much of the field surface (Table 1). When the crop is in a thin swath, it is better exposed to the radiant solar energy, and moisture movement is not inhibited by the swath.

Soil moisture also influences drying, particularly when the crop is spread over the soil surface in a thin swath. The wet soil inhibits the drying of the swath bottom, and it may prevent the hay from drying completely. Unless the soil is very wet, this factor's influence is relatively small. When soil moisture is inhibiting drying, the crop should be raked into a windrow to reduce contact with the soil.

Another factor we have found to influence drying is the time from mowing. Hay dries faster on the day in which it is mowed than on subsequent days. Immediately following mowing, the crop moisture is uniformly spread throughout the swath. Moisture near the surface of the swath can readily evaporate into the surrounding air. As the swath dries, the moisture must migrate toward the surface from within the swath which slows drying. This factor becomes more important as the thickness of the swath is increased.

Crop maturity was not found to effect the drying rate of alfalfa, but it can affect the drying time. As the crop matures, the moisture content of the standing crop decreases. Although the drying rate is the same, less time is required to dry the hay because less moisture must be removed. This effect is of minor importance in alfalfa harvest where the normal goal is to harvest an immature crop for optimum quality.

Remaining factors which influence alfalfa drying are the mechanical or chemical treatments used to increase the rate of drying or to reduce the field drying time. With this background on drying, let's look at how various mechanical and chemical treatments can be used to improve hay making. Major factors considered are field curing time, losses and production costs.

HARVEST OPTIONS

Mowing

Reciprocating cutterbars have been used for many years in mowing. Their major disadvantage is limited capacity or field speed. The rotary disk mower is a viable option for increasing mowing capacity. In fact, field speed is often limited only by the operator's ability to control the machine. Mowing loss is similar to that of a cutterbar mower. The disadvantage is higher operating costs. For a given width of cut, disk mowers cost 30% more. Repair and maintenance costs are low initially, but as the machine ages the many gears and other moving parts may lead to higher repair costs. Disk mowers require about four times more power to operate. Therefore, a larger tractor is required and more fuel is used per hour. With faster field speeds, less labor and less tractor time are required. All things considered, neither type of mower has a strong economic advantage. If mowing capacity is limiting harvest capacity, a disk mower can show good economic return; otherwise, the increased costs may be a little greater than the return received.

Other types of mowers which have more serious disadvantages are the rotary drum and flail mowers. These require much more power. Drum mowers also tend to leave a less uniform swath which may cause uneven drying. Flail mowers provide faster drying but also cause higher field losses. With dull knives or improper adjustment, flail mowers (and sometimes rotary mowers) cause a ragged cut or damaged crown which retards regrowth and reduces stand persistence.

Conditioning

Mechanical conditioning and mowing are normally combined in the same machine. Many types of conditioning devices are used; these devices can be categorized as either roll or flail conditioners. Rolls are used to smash and/or break the plant stems, and flails abrade the waxy surface of the plant and break the stems. Both processes can improve drying, but for alfalfa, roll devices are more effective.

The intermeshing, rubber roll is the most common type of conditioner. In Michigan, we found this type of conditioning to be very effective on first cutting alfalfa, but less effective on later cuttings (Rotz et al., 1987). For first cutting alfalfa, the stem is normally relatively thick, but the stem size decreases in the regrowth of second and later cuttings. Since thick stems are more difficult to dry, the smashing and breaking action has more potential for improving drying. The finer stems of later cuttings also tend to flow through the rolls with less damage.

Many different roll designs are used in today's mower-conditioners. Some designs are promoted as providing faster drying, but this is not supported by research. Field and laboratory drying studies consistently show little or no difference in the drying of alfalfa or grasses treated with commonly-used crushing roll designs (Shinners et al., 1991). Factors such as roll pressure, roll clearance and feed rate have more effect on drying than the type of roll. More pressure causes more rupturing of plant tissue and thus faster drying. The feed rate of crop between the rolls can affect the amount of conditioning received. Feed rate is controlled by the peripheral roll speed and the length of the rolls relative to the machine's mowing width. When the rolls are rotated faster than the ground speed of the machine, the crop is drawn into a thinner mat passing through the rolls. Likewise when the rolls run the full width of the machine, a thinner mat is created for more effective conditioning. The effect of feed rate is small and difficult to detect in field drying studies.

Flail conditioners, developed in Europe for grass crops, use rotating brushes or tines to scratch or abrade the plant surface. Since the stems are not broken or ruptured, they remain more stiff creating a less dense swath or windrow. This type of conditioner provides a greater throughput capacity when harvesting very high yielding or entangled crops that are difficult to handle with roll type mower-conditioners. Flail conditioning is less effective on alfalfa and it can cause greater loss (Rotz and Sprott, 1984). Although not recommended for use on alfalfa, flail conditioning can be effective on grass crops.

In addition to drying improvement, dry matter losses and the associated nutrient changes caused or promoted by conditioning must also be considered. In general, losses increase with the severity of conditioning. Although heavy conditioning can provide the fastest field curing, the forage is more susceptible to high harvest losses. The loss is minimal for a well-designed, properly-adjusted conditioner (1-2% of yield).

Mechanical conditioning is normally economical in alfalfa hay production. When compared to a cutterbar mower, use of a mower-conditioner increases production costs due to the higher initial cost and slightly higher power requirement. In the midwest, the benefits of faster drying and reduced losses return up to four times the amount spent on increased costs. With the drier weather and heavier swaths commonly encountered in California, the economic value may be less, but it is still likely to be beneficial for most situations.

Chemical conditioning is a newer process for increasing the drying rate of alfalfa. A chemical, referred to as a conditioner or drying agent, is sprayed on the crop at the time of mowing (Rotz and Thomas, 1986a). The chemical affects the waxy surface of the plant to allow easier moisture removal from the plant. Several chemicals are known to speed drying, but potassium and sodium carbonates are the most commonly used. Chemical conditioning is effective on all cuttings, but it is most effective on cuttings harvested in the summer months. The treatment provides the greatest drying improvement when used under good drying conditions, and the best improvement is obtained when alfalfa is dried in a relatively thin swath.

Chemical conditioning can be economically used by the hay producer, but the return is often small. When the chemical is purchased for $0.60/lb and applied to all alfalfa at an appropriate rate, the average cost of the treatment is about $5/ton of hay produced. In the midwest, the long-term average gain in feed value is about the same. More selective use of the treatment may improve the economic return, but a greater chemical price makes the process less economical. The economic value is not documented for dry climates. The primary advantage in these areas is earlier application of irrigation water when curing time is reduced. Regrowth is stimulated earlier providing greater yields on later cuttings. An annual 5% increase in harvested yield can recover the cost of the treatment.

Swath manipulation

As alfalfa dries in the field, the top of the swath dries more rapidly than the bottom. Manipulation of the swath can speed the drying process by moving the wetter material to the upper surface where it dries more quickly. Swath manipulation can also improve drying by spreading the hay over more of the field surface. Spreading the swath (reducing swath density) can increase the drying rate by increasing the exposure of hay to the radiant solar energy and drying air.

There are three operations used in haymaking which manipulate the swath: tedding, swath inversion and raking. Interest in tedding has grown in recent years following the introduction of the European style tedder. This device uses rotating tines to stir, spread and fluff the swath. This operation can be used anytime during field curing, but it is best to do so before the crop is too dry (above 40% moisture content). Faster drying is the primary benefit of tedding. The stirring or fluffing aspect of tedding typically reduces field curing time up to half a day. Tedders are sometimes used to spread a narrow swath formed by the mower-conditioner over the entire field surface. When done soon after mowing, the average field curing time in the midwest is reduced up to 2 days compared to drying in a narrow swath. Under California conditions, the benefit to drying may be even greater. In addition to speeding the drying process, tedding also tends to create more uniform drying, so wet spots in the swath are reduced. A disadvantage though is that spreading the hay may promote bleaching of hay color. Bleaching does not normally affect the nutritive value of hay, but it often affects the market value.

Other disadvantages of the tedding process include increased losses and increased fuel, labor and machinery costs. When tedding is done on a relatively wet crop (above 50% moisture), the resulting loss is about 3%; however, applied late in the drying process, the loss can be more than 10%. Raking loss will also increase. When a light crop (less than 1.5 ton/acre) is spread over the field surface, raking loss can be more than double that when raking narrower swaths. The increased machinery, fuel and labor costs of tedding increase production costs up to $16/acre.

The decision to use tedding must be made by comparing the probable loss from respiration and leaching to the known loss and cost of tedding. The loss caused by tedding is normally greater than the average rain loss avoided by faster drying. With little overall reduction in field loss and the increased costs, the treatment is not economical for routine use even in the midwest (Rotz and Savoie, 1991).

Swath inversion machines are available which gently lift and turn the swath placing it back on the field surface inverted from its original position. Exposing the wet bottom layer of the swath speeds drying enough to reduce the average field curing time a few hours. Swath inversion is not as effective in improving drying rate as tedding, but shatter loss is reduced. In general, the gentler crop handling by the swath inverter causes little loss. The economics of using the swath inversion process are similar to tedding. The added operation in haymaking increases labor, fuel and machinery costs. Although swath inversion causes less loss, it also has less drying benefit and thus less potential to reduce rain damage and respiration losses. Again the cost of the operation is greater than the economic benefit received (Rotz and Savoie, 1991).

Raking is another form of swath manipulation. Raking tends to roll the wetter hay from the bottom of the swath to the outer surface of the windrow which increases drying. Following the initial improvement in drying, the increase in swath density can reduce drying rate, so the moisture content of the crop when raked is important. If the crop is too wet, the wet material rolled into the center of the windrow dries slowly. Raking also causes loss, and the loss is related to crop moisture (2% when wet to 15% in very dry crop). The best moisture content to rake for minimum loss and optimum drying is between 30 and 40%. In the dry climate of California, hay should be raked at night or early morning when leaves are moist and less prone to shatter. Raking at the proper time can reduce field curing time a few hours to allow an earlier start at baling.

Another alternative in hay drying is to use a narrow swath with no manipulation during field curing. Hay dries more slowly requiring up to two more days for field curing. With slower drying, more loss will occur from plant respiration and perhaps rain damage. Eliminating all raking can reduce production costs if baler capacity is not reduced. A substantial economic benefit can often be obtained by rolling a couple swaths together to allow larger balers to operate more efficiently.

Hay Preservation

Field curing time can also be reduced by baling hay before it is dry enough for stable storage. Baling moist hay reduces loss because leaves are not as brittle. Rain damage may also be avoided at times by earlier baling. Moist hay heats and deteriorates rapidly in storage, so the key to success of this strategy is an effective treatment to improve preservation.

A variety of substances have been proposed to preserve moist hay. These include anhydrous ammonia, urea, organic acids, and various inoculants. The most effective hay preservative is anhydrous ammonia, but it creates hazards for human and animal safety.

Urea provides a less hazardous method of applying ammonia, but urea is not as effective. Propionic acid and some other organic acids are effective preservatives of moist hay when properly applied. A recommended application rate for propionic acid is 20 lb/ton for hay with up to 28% moisture (Rotz and Thomas, 1986b). Commercial chemicals available for hay preservation contain between 10 and 100% propionic acid. Research has shown that the effectiveness of the treatment is directly related to the amount of propionate in the chemical mixture. This includes the 'buffered' acid products where propionic acid is mixed with ammonia or other chemicals to reduce its corrosiveness.

Baling of moist hay with an acid treatment is generally not economical when hay is used by the producer. The cost of the treatment is between $15 and $30/ton depending upon the chemical price and application rate. The only time this cost can be justified is when not using the process causes hay to experience heavy loss from rain damage (Rotz et al., 1992). The producer who sells hay primarily by weight, appearance and crude protein content may benefit more from the process. The buyer and seller should be aware that a greater portion of the weight may be coming from water and that other quality constituents of the hay may be more important to the animal than crude protein.

Microbial inoculants are also promoted for use in hay preservation. Most of these products contain lactobacillus bacteria with or without a variety of enzymes. This type of product was originally developed to promote better fermentation in the silo. Lactobacillus is an anaerobic organism which thrives in an environment like the silo where oxygen is depleted, but in a hay stack, they struggle to survive. Scientific studies have not shown these types of products to be effective in improving hay preservation. Another bacterial product is available which uses a different bacteria called bacillus. Bacillus bacteria are aerobic organisms which means they are better suited to the hay environment. Although this type of product shows more potential, there is still little scientific evidence that it can provide substantial improvement in preserving moist hay.

In the past few years, interest has grown in the use of bale ventilation to enhance hay preservation. Bale ventilation is a process that creates a hole through the center of small rectangular bales. This is done by mounting an 8 to 10 inch spear on the center of the face of the baler plunger. As each section of the bale is compressed in the chamber of the baler, the spear creates a hole. The completed bale contains a hole up to 2 inches in diameter through the length of the bale. The hole is hypothesized to promote moisture loss from the center of the bale during storage and thus enhance the preservation of hay at moisture contents up to 25%.

The concept of bale ventilation is not new, but recent development and promotion of new devices for the process has created new interest. Up to fifty years ago, baler manufacturers experimented with the concept of placing one or more spears or prongs on the plunger to create holes in bales. The results found did not encourage commercial manufacture of the equipment. In the past few years, new designs for the spear device were patented. Kits for baler modification are being sold for about $200, and some growers are building their own baler modifications.

Research does not show benefits in hay preservation with the use of bale ventilation. In our work comparing conventional and ventilated bales of hay at a similar moisture, bale ventilation did not result in significant reductions in hay temperature, dry matter loss and moldiness nor improvements in hay quality or color (Rotz et al., 1993). A disadvantage was more difficulty in maintaining proper feeding of hay through the baler for high density bales of high-moisture hay.

An alternative to treatments used to enhance preservation is the use of a low-cost drying system during storage. Hay is stacked on pallets with a plenum under the center of the stack. A fan is used to push ambient air through the stack during the first month of storage. The air movement prevents heating and mold development in the hay and losses are maintained at a level similar to dry hay (Rotz and Muhtar, 1992). A 5 hp fan can dry about 100 tons of hay. The economic value of this low-cost drying system is better than that of chemical preservatives due to the lower storage loss and perhaps a lower treatment cost.

Maceration and mat drying

A new harvest process called maceration and mat drying is under development which can greatly speed drying, reduce losses and enhance hay quality. Maceration shreds the plant stems, fully exposing the internal moisture. Macerated alfalfa can dry to a moisture content suitable for baling in 4 to 6 h of favorable drying conditions. The concept of maceration has been known for some time, but it has not been implemented because the macerated material is very susceptible to field loss. A recent development has combined maceration with a mat forming process. The shredded material is pressed into a mat and laid back on the field surface for rapid curing. The mat system requires several new machines. A mat maker mows, macerates and presses the crop into a mat that is placed back on the field. When dry, the mat can be picked up with a modified baler that rolls up the mat, forming a bale. Modification of the baler is required to handle the mat with minimal loss. More research and development is needed to work out the details of the new system for harvesting, handling and storage. Commercially available equipment is under development with limited availability over the next couple years.

Fast drying is a major advantage of the mat process. The drying rate of alfalfa mats is 2 to 3 times greater than the rate of conventional swaths. With an appropriately designed mat system, hay can be made with one day of field curing. Another potential advantage of the mat process is the quality of the hay produced. With reduced harvest loss, forage quality is improved. In addition, the maceration process increases the digestibility of the forage. Improved digestibility allows the animal to obtain more energy from the crop, and it may increase the animal's feed intake, both of which lead to higher production. The mat process, therefore, may produce a forage that is superior to any currently produced.

A disadvantage of the mat system is expensive equipment. The projected price for the mat maker is over $30,000 for a trailing machine with a 9 ft cutting width and over $80,000 for a self-propelled model. The power requirement for this operation is high, requiring at least 120 hp. The added equipment and fuel cost is high, but the long-term benefits appear to outweigh the cost. The gain in feed value obtained with the mat process could return up to four times the amount spent on the increased costs (Rotz et al., 1990).

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