INNOVATIVE METHODS TO PRESERVE ALFALFA QUALITY

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ABSTRACT

Production of high quality forage is positively impacted by productive and efficient cutting equipment, rapid field drying baling moisture, and timely harvest with minimal losses. Rapid drying to harvest moisture is most effectively accomplished by placing the crop in as wide a swath as possible and by properly conditioning the crop to reduce the physical resistance to moisture leaving the plant. Steam re-hydration at baling is a recent technology that allows baling without dew while also reducing leaf loss and creating denser bales. New uses of alfalfa as a feedstock for production of human food from plant material could enhance the market for alfalfa. Fractional harvest by stripping the protein-rich leaves from the fibrous stems could enhance this new market.

BASICS OF FORAGE DRYING

Forage plants have many built-in mechanisms used to regulate water throughout the growing period. The plant surface provides the first barrier to moisture loss. The stem and leaf have a waxy cuticle (cutin layer) to resist moisture evaporating through the epidermis. Additionally, some plant stems are covered with tiny hairs which slow air movement near the plant surface. This mechanism reduces water loss by creating a stagnant, humid environment near the stem. Finally, plants have millions of tiny pores called stomata that serve as valves that let carbon dioxide in to support photosynthesis and let oxygen and water vapor out. The opening and closing of stomata are regulated by many parameters, but the water turgidity of the plant is an important factor. When the plant becomes water stressed, the stomata close to preserve water. The living plant does a remarkable job of retaining and regulating its water content; however these mechanisms continue their work after cutting, resulting in slow field curing. Harvesting practices like conditioning and wide swathing are used to help overcome the natural barriers to water movement from the plant.

The process of moving water vapor from inside the plant during drying can be thought of as analogous to movement of water through a level pipe (fig. 1). Water moves though a pipe because of a pressure differential between the upstream and downstream sections. In our schematic example, the upstream pressure is the water vapor pressure within the plant and the downstream pressure is the air vapor pressure. Water movement through a pipe in our houses or barns is often resisted by restrictions like valves, elbows, and small orifices. The plant "orifices" resisting flow are the physical and/or chemical barriers within the plant. As the plant wilts, water held in the plant cells is heated by the sun to begin evaporation by building internal vapor pressure but movement of the vaporized water is resisted both physically by the cell wall, cutin layer, and closed stomata and chemically by osmotic forces within the cell. At the end of our pipe model, the external air

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conditions affect the water vapor pressure around the plant. The difference between vapor pressure within the plant and the surrounding air vapor pressure is known as vapor pressure differential. The more stagnant and humid the air, the lower the vapor pressure differential, and the slower the rate of water vapor movement from within the plant. Vapor pressure properties around the drying plant are affected by temperature, humidity, wind speed, and soil moisture. Although many of these forces may seem out of our control, the way we harvest alfalfa can actually have an important impact on the water vapor forces. The parameters which we can use to control these drying forces are swath width, swath openness (i.e. fluffiness and uniformity) and conditioning level.

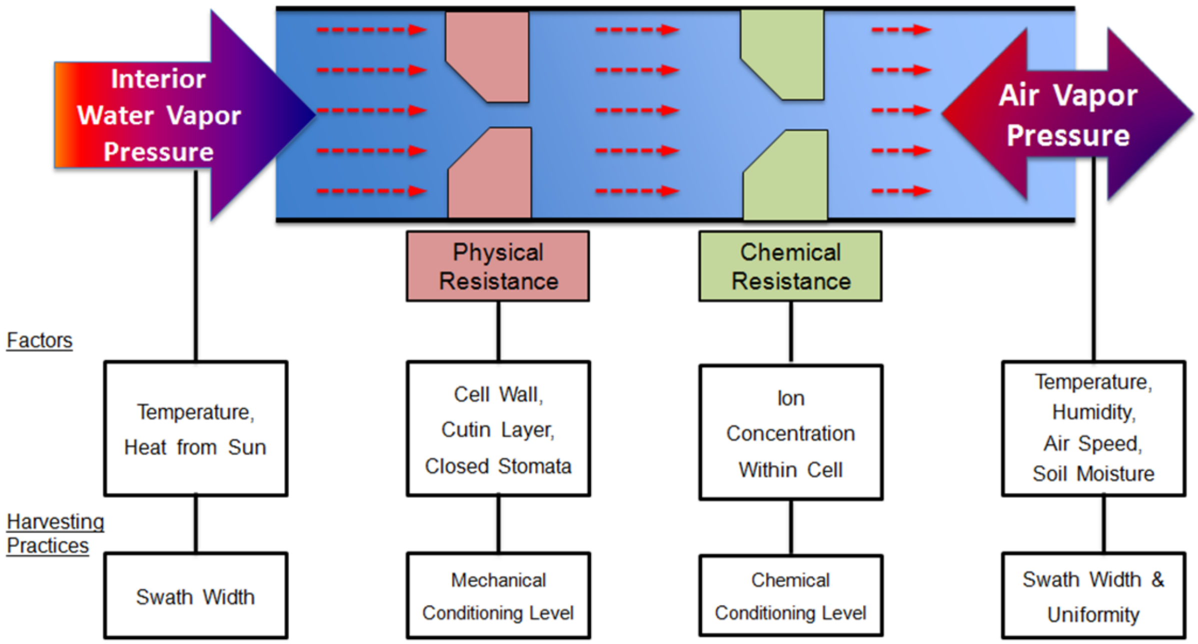


Figure 1. *Diagrammatic representation of water vapor flow from a drying forage plant. If water vapor pressure inside the plant is greater than the air vapor pressure, and can overcome the physical and chemical resistance of the plant, then water vapor will leave the plant and drying occurs. Interior vapor pressure is affected by plant temperature and the heat absorbed by the sun. Plant physical resistance is created by the cell wall, cutin layer on the epidermis, and closed stomata. Chemical resistance is created by osmotic forces from ion concentration in the cell. Air vapor pressure is affected by temperature, humidity, air speed and soil moisture. Swath width and uniformity affect the interior and air vapor pressure. Mechanical conditioning affects the physical resistance to water vapor leaving the plant.*

WIDE-SWATH DRYING

Laying the crop in a wide swath improves forage drying in several ways. First, it allows the drying crop to take advantage of the solar energy that strikes the field. A wide swath allows more of the suns energy to be used to raise the plants temperature to increase the internal water vapor pressure. The sun's energy also increases the air's water holding capacity and reduces the vapor pressure in the micro-environment around the drying plant. Finally, wide, uniform swaths promote more air exchange around the plant, helping to reduce the chances of stagnant, humid air surrounding the drying plant. Considering the schematic shown figure 1, when forage crops are dried in wide, uniform swaths, internal vapor pressure is increased and the external air vapor pressure is reduced, so there is greater vapor pressure differential to move water vapor from the plant.

One of the concerns western hay producers have about wide-swath drying is that this practice exposes more hay to bleaching. Bleaching occurs when hay is exposed to intense sunlight and to evaporation of heavy dew. The conundrum for western hay producers is that drying in narrow windrows reduces sun bleaching, but increases drying time which increases the time the crop is exposed the bleaching effect of sunlight. Customers often use hay color as a quick indication that the hay was dried without rain exposure. Bright green hay is deemed desirable even though color alone should not be used as the sole metric for quality hay. In fact green hay may be of inferior nutritional quality than off-colored hay. Sun bleaching can cause green hay to lose it's color but still be of very good quality. Unfortunately, off-colored hay caused by exposure to rain during curing can be hard to distinguish from sun-bleached hay. This is why lab compositional analysis is so important and as more hay is sold strictly on the basis this analysis and less on “good color”, then wide swath drying may become more widely practiced.

There are two basic means to achieve wide-swath drying – swath it at cutting or post-harvest tedding. The first approach can be challenging when the cutting width is large and the conditioning mechanism is narrow. For instance most windrowers with a 16 ft. cut have conditioning rolls that can produce at best a swath 8 ft. wide – what is known as a 50% swath ratio. This means that at best only 50% of the sun’s energy is being captured by the swath. Recent trends in cutting equipment have shifted some producers to what are referred to as “triple-mowers” – a single front-mounted mower with two “butterfly” rear-mounted mowers. In these machines the conditioning mechanisms are almost as wide as the cut-width, so the swath ratio can be 70% or greater.

Tedding after cutting can produce swath ratios approaching 100% so that most of the incoming solar insolation can be used for drying the crop. Tedding is most commonly practiced with dry hay production. However, some custom harvesters are tedding alfalfa haylage to reduce fielding wilting time and improve timeliness to their next job. Of course tedding requires another field operation and an additional piece of equipment. Some producers prefer to ted quite soon after cutting so that the maximum swath ratio is achieved quickly and to insure that the alfalfa leaves are not overly brittle at tedding. Other producers prefer to ted after a day or two of wilting so that the ground between the windrows can dry out. Our research has shown that the tedding alfalfa at cutting or tedding the next day resulted in about the same time to dry hay moisture (fig. 2) (Shinners and Herzmann, 2006). To eliminate the need for an additional operation, we mounted our tedder to the rear of the windrower, creating near 100% swath ratio in a single operation that combined cutting and tedding. It will be interesting to see if this type of swath manipulation becomes more common on windrowers of the future.

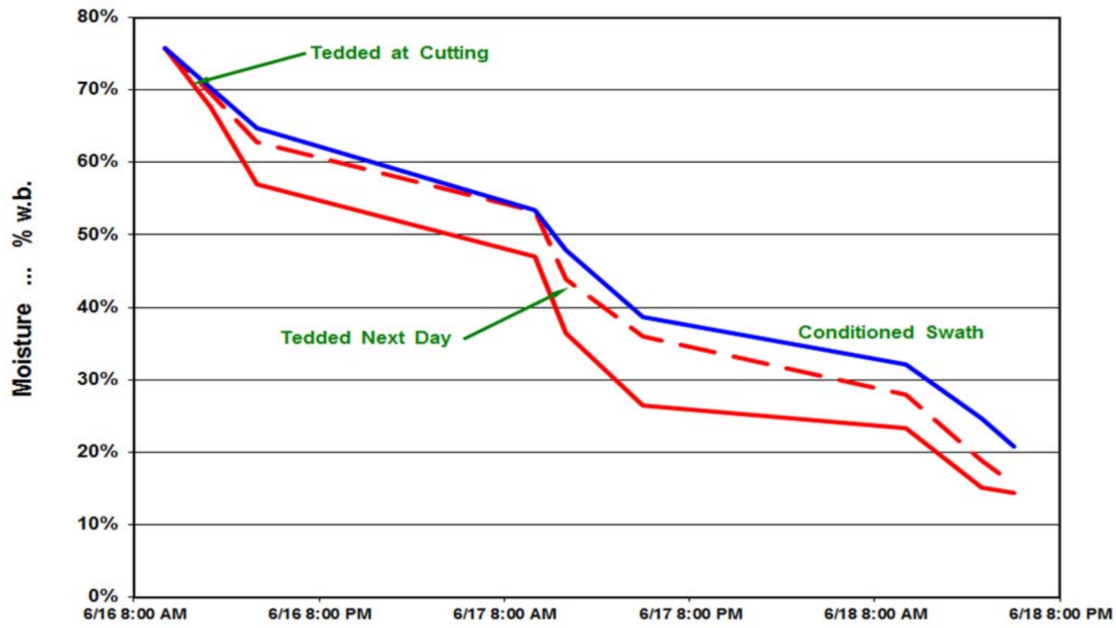


Figure 2. *Drying rate of alfalfa conditioned with urethane rolls with three different treatments – swathed, tedded at cutting or swathed and then tedded the next day (after Shinners and Herzmann, 2006).*

MECHANICAL AND CHEMICAL CONDITIONING

Mechanical conditioning helps to overcome the physical resistance to water moving from the plant. Water movement from the plant is resisted physically by the cell wall, waxy cutin layer, and by the closing stomata. Right after cutting, the stomata are likely to be open, promoting water loss. However, the stomata are "programmed" to close when the plant experiences water loss conditions, which of course is what occurs during field drying. Once the stomata close, the only outlet for water vapor is radially outward through the cell wall and cutin layer. It is not well known how quickly stomata close after cutting. However, research done with Italian ryegrass indicated that water vapor movement from the leaf stomata dropped dramatically within 15 min of cutting and that the physiological closure of stomata occurred by 30-40 min after cutting (Clark et al., 1977). It is well known that it takes many hours to achieve the desired harvest moisture for haylage, so the results of Clark et al. indicate that most of the water vapor that leaves the plant must move radially outward through the cell wall and waxy cutin layer. This is why mechanically conditioning the crop is so important to achieve faster drying rates.

When the plant is crushed or crimped at many locations, and when the cutin layer is abraded or disrupted, the physical resistance to water movement from the plant is reduced. Either rolls or impellers are typically used for conditioning. Rolls condition the stem by crimping or crushing the stem. A crimping device passes the crop between intermeshing, non-contacting rolls, which bend and crack the stem at intervals. A crushing device passes the crop through intermeshing rolls with small clearances, intermittently flattening the stem. In either case, plant moisture evaporates more easily from these breaks in the epidermis. Impeller conditioners use rotating fingers to abrade the plant cuticle and to intermittently crack the stem. Comparisons between impeller and roll designs show roll conditioners produce faster alfalfa drying with slightly faster drying of grasses using impeller conditioning (Rotz and Sprott, 1984; Greenlees et al., 2000; Shinners et al., 2006).

Over the last 6 decades, many researchers have explored the positive impact that conditioning has on a wide variety of forage plants. A careful review of this literature shows the consistent positive influence that conditioning has on improving forage drying rate. When swath width and formation was similar, mechanical conditioning always resulted in faster drying compared to drying without mechanical conditioning (Shinners and Herzmann, 2006; Shinners et al., 2006). This is true whether the intended harvest is haylage or dry hay. Conditioning forage crops always results in shorter field drying time.

There are a variety of different roll conditioning configurations available and we have investigated many of these (Shinners et al., 2006). Below is a summary of our findings with respect to alfalfa drying:

- Laying crop in a narrow windrow can mask the benefits of conditioning (fig. 3). In other words, in some cases the benefits of conditioning are lost when that crop is subsequently placed in a tight windrow. To maximize drying rate, condition well and also place the crop in a wide swath.

- Drying rate was similar between steel crimper and urethane crushing rolls and roll conditioning dried more quickly than impeller/finger conditioning.

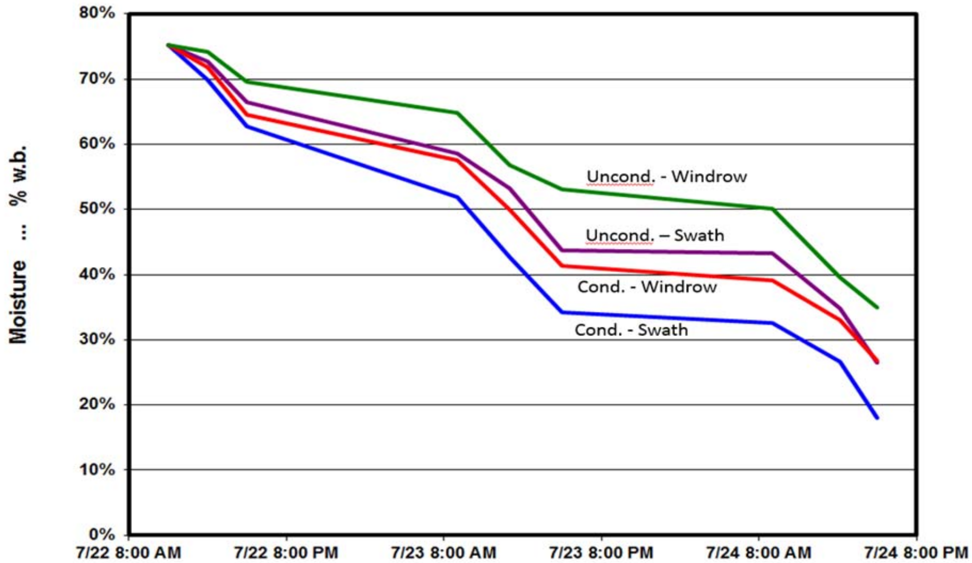
- Conditioning roll clearance was very important. If roll clearance is too wide the stems will not be conditioned, no matter how much pressure is applied to the rolls.

- Manufacturers now offer rolls with high specific crushing area that are carefully fabricated with small radial runout that allows rolls to have tight clearance with less worry of interference. In our research conducted in Wisconsin, Kansas and Utah, we found these rolls provide improved drying rate compared to conventional rolls.

- We speculated that a thicker layer of crop passing through the conditioning rolls might not provide as thorough conditioning as a thin layer. This "mass-flow" through the conditioning rolls is affected by crop yield, cut width, ground speed, and conditioner roll speed. The ratio of cut to conditioner width also affects the thickness of the layer through the rolls. Our research found that with rubber crushing and steel crimping rolls, mass-flow-rate had no effect on drying rate when the crop was placed in similar width swaths. Swath width mattered a lot, but ground speed and conditioner width did not.

- Twin roll conditioning (in our case tire-core rolls followed immediately by crushing rolls) did not provide significantly faster drying than conventional rubber crushing rolls alone.

The last parameter that affects the forage drying rate is the chemical resistance to water movement from the cell (fig.1). The concentration of ions within the cell increases as the plant cell loses water which results in a stronger chemical hold on the water remaining in the cell. So as the plant dries, the chemical hold on the water increases, making it increasingly difficult to remove water. This is one important reason why it can be incredibly frustrating to remove that final few percentage points of moisture needed to safely bale dry hay. Chemical conditioning, the application of solutions of potassium carbonate or sodium carbonate, is used by some producers to enhance forage drying rate. It is widely thought that these chemicals reduce the physical resistance to water movement by disrupting the waxy cutin layer. However, it is possible that these chemicals also affect the ion concentration of the plant, reducing the chemical resistance to water being held in the plant cells (Rotz, 2011).



<u>Figure 3.</u> *Drying rate of alfalfa either conditioned by conventional methods or unconditioned and placed in narrow windrow or wide-swath. (After Herzmann, 2005).*

STEAM REHYDRATION AT BALING

In the arid western regions of the United States, weather conditions are often so dry that alfalfa leaves becomes over-dry and very brittle. When dry alfalfa is baled under low humidity, leaves are not only lost, but many of the captured leaves are crushed into a fine powder which is easily lost during feed preparation and mixing (Orloff and Mueller, 2008; Thomas, 2009). To overcome these problems, hay grown in this climate is typically baled when it has been slightly re-hydrated from the accumulation of dew during nighttime or early morning hours (Orloff et al., 1995). When adequate dew does not occur for several days, harvest is delayed which increases risks of weather-related losses, increases the time between cuttings, delays irrigation and crop re-growth, and can increase traffic damage to alfalfa re-growth at baling. Late night dew formation often makes scheduling labor difficult and the baling season arduous. Producers are too often forced to bale when there is too little or too much dew in an effort to maintain productivity (Orloff et al., 1995).

A recent technology has been developed and marketed as an alternative re-hydration system that uses steam applied at the baler pick-up (Staheli West, 2016). Low-pressure steam is injected into the windrow from above and below as it is picked up and moved into the baler pre-compression chamber. The small droplet size and energy of the steam allows it to be easily absorbed, softening plant tissue quickly. Compared to baling with dew re-hydration, steam re-hydration significantly reduced baler losses by an average of 58% (1.2 to 0.5% of bale dry weight, respectively) for large square balers and 43% (0.7 to 0.4%, respectively) for 3-tie balers (Shinners and Schlesser, 2014). The softened plant tissue and additional leaves help create greater bale density. Compared to bales formed with dew re-hydration, steam re-hydration increased bale density by an average of 20% and 30% for large and 3-tie bales, respectively (Shinners and Schlesser, 2014). Of course the benefits of this system have to weighed against the added fixed and variable costs that the process adds to the hay making process. Producers would benefit from a rigorous techno-economic analysis of the process so that data driven decisions can be made. The combination of wide-swath drying which will get the crop cured more quickly and steam re-hydration which might allow baling at the time the crop gets dry rather than when adequate dew is available, might provide a total system that produces a high-quality crop with acceptable levels of bleaching.

MACERATION

About 30 years ago engineers at the University of Wisconsin began development of new way to make dry hay known as maceration and mat formation (Shinners et al., 1989). Forage maceration is considered the ultimate in conditioning where the plant structure is completely disintegrated. This process was accomplished by passing the crop through a shredding macerator (fig. 4) configured with a series of aggressive toothed rolls operating at small clearance and differential speed to crush and shred the stems into long ribbons. To reduce losses from the disintegrated crop and promote faster drying, the macerated material was subsequently pressed into a thin, continuous mat or carpet. When everything went right with our process, we were able to achieve “dry-hay-in-a-day” with this approach, even in our humid Midwest climate. About 20 years ago, one North American and two European manufacturers spent considerable effort and treasure trying to commercialize this concept (Kraus, 1997). However, development efforts were not able to overcome two major technical hurdles. Mats needed to be thin and very uniform to achieve fast drying. If mats were thick in spots, these thick layers would dry on the top and bottom, and seal-in the wet middle layer, which would then begin to spoil before drying. Mats that were too thick in some spots also meant that mats were too thin in other spots, and there the mat would not hold together and droop to the ground making it difficult to pick-up the mat without high losses. Other challenges included how to package this highly processed crop into a bale and how to handle bales without the bales falling apart. The dream of “dry-hay-in-a-day” is still out there, but engineers have not yet found a cost effective solution.

FRACTIONAL HARVEST OF LEAVES AND STEMS

In the late 1970’s there was considerable research and development on “wet-fractionation” of alfalfa. This process created value-added products along with conventional ruminant animal feed, while also promising a weather independent harvesting system (Koegel and Straub, 1994). With wet fractionation, plant juices are expressed from freshly cut and macerated alfalfa. The juice fraction is about half the crop weight and is processed post-harvest to obtain a high-protein, low-fiber concentrate for animal supplemental feed or other value-added products. The dewatered fiber fraction is ensiled as a ruminant animal feed. This harvest process could be carried out under most weather conditions as long as the soil could support wheel traffic. International Harvester, through their Advanced Harvesting Systems group, attempted to commercialize this process, developing a machine called the “Probine” (Klancher et al., 2015). Unfortunately the economics of this process were not favorable and the attempts at further development withered during the depressed agricultural economy of the 1980’s.

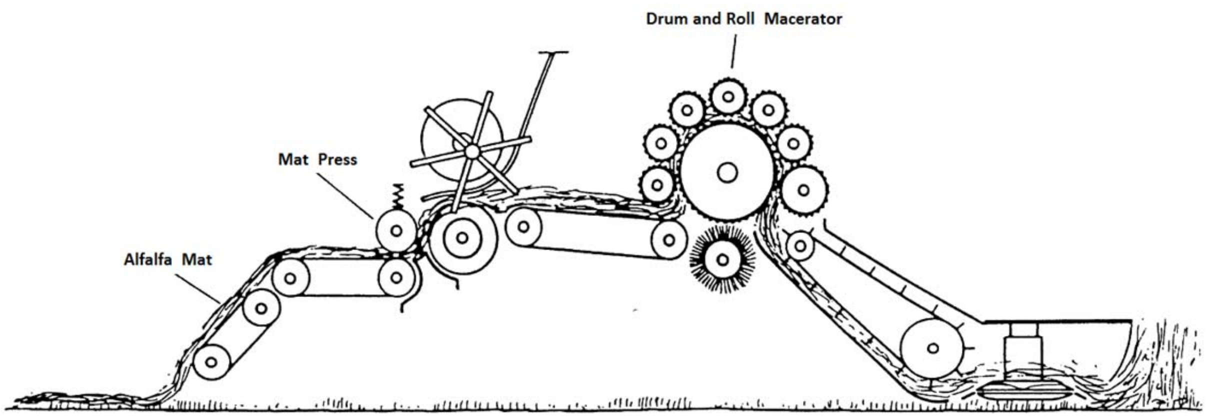


Figure 4. *Maceration and mat forming prototype configured with drum and roll macerator and mat forming press. (After Deutz-Fahr Grasliner Sales Literature, 1990)*

There has been recent uptick in interest in creating human foods from plant sources, specifically creating plant-protein-based foods that mimic the taste and look of foods currently derived from animal proteins (Soller, 2106). Since alfalfa has tremendous protein production per acre, it could become a good feedstock for human foods created from plant-based proteins. Researchers are investigating a new approach to fractional harvest where the protein-rich leaves are harvested separately from the fibrous stems (Shinners et al., 2007). This process involves stripping the leaves from the standing stems with a multi-tine rotor, and then windrowing the remaining stems. With this process, only the protein-rich leaves have to be shipped to the processing facility, resulting in lower transportation and processing costs. Protein can then be extracted from the leaves by maceration and juice expression. The residue press-cake can then be blended back with the stem fraction as a ruminant animal feed. New markets for alfalfa beyond animal feed will result if co-product proteins targeted for production of human foods can be economically developed.

One unexpected result of the alfalfa harvest fractionation work is the rapid drying rate of the stems once the leaves have been removed by stripping (fig. 5). The tines that strip the leaves also severely abrade the waxy cutin layer of the stem, making this process an outstanding conditioning method. If engineers could devise a means to condition the stem in this fashion without also stripping the leaves, we might have the ultimate mechanical conditioning system.

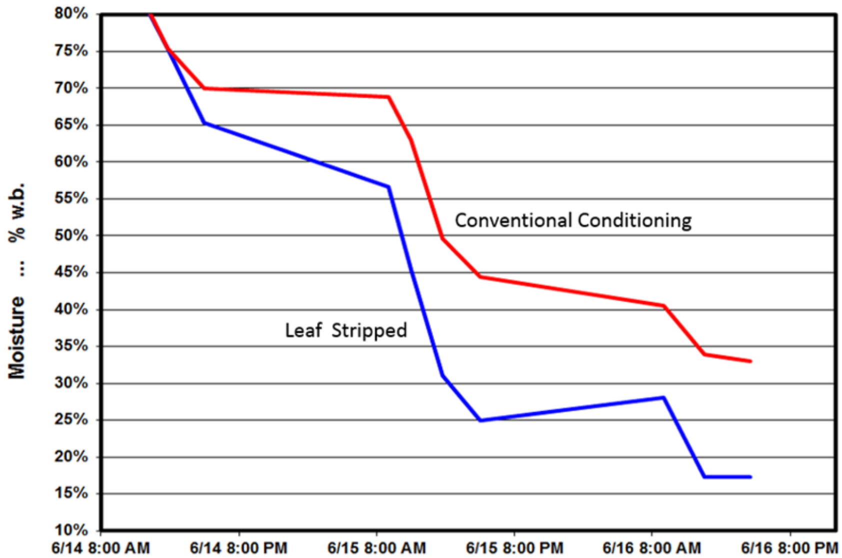


Figure 5. *Drying rate of alfalfa swaths conditioned by conventional methods and by leaf stripping. Both swaths had the same swath density. (After Shinners et al., 2007)*

BEST MANAGEMENT PRACTICES FOR RAPID DRYING TO PRODUCE QUALITY DRY HAY

The mechanics of forage drying clearly show that drying rate will be enhanced if the plant is properly conditioned and placed in a wide, uniform swath. Here are a few best management practices to consider:

- Cut forage at about 3 in. stubble height. This allows the swath to reside slightly above the moist soil and promotes initial air movement through the swath.

- Make sure that the three adjustments available for roll-type conditioners – timing, clearance, and pressure – are set correctly:

    - Intermeshing rolls that are out of time will chatter and vibrate leading to the incorrect conclusion that the roll clearance is set too close, so insure that timing is properly adjusted before adjusting clearance.

    - Next set the clearance uniformly across the width of the rolls. Setting the roll clearance correctly for the expected size of the stems is the most critical adjustment to achieve fast drying. Methods to properly adjust your conditioner clearance can be found at: http://www.uwex.edu/ces/crops/uwforage/AdjustingConditioner.pdf

    - Finally, set the roll pressure to achieve the desired level of stem splitting and leaf damage. Note that if the clearance is too great, adding additional roll force will not help condition the crop.

- To maximize use of available solar insolation, place the crop in a wide, uniform swath. Consider tedding the crop soon after cutting. Placing the crop in a narrow windrow may reduce bleaching exposure, but windrowing definitely slows drying.

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