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EFFECT OF POTASSIUM CARBONATE ON FORAGE DRYING

by

SUSAN VIRGINIA CRUMP

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled EFFECT OF POTASSIUM CARBONATE ON FORAGE DRYING submitted by SUSAN VIRGINIA CRUMP in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in AGRONOMY.

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Supervisor

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Date.........Mar 13/86.........

Abstract

Field drying of hay after application of potassium carbonate was compared to a control receiving no mechanical conditioning, mechanical conditioning alone, and a combination of potassium carbonate and mechanical conditioning. Six field tests were run in 1982 and 1983 in central Alberta on brome/alfalfa, alfalfa and red clover hay.

The moisture content (wet basis) of individual samples averaged across all sampling times was highly correlated with the weight of dry matter in the sample in 1982. When average sample moisture contents were adjusted for weight of dry matter, the potassium carbonate treatment dried faster than the control in two of the four experiments in 1982 and the combined treatment dried faster than the mechanically conditioned treatment in three of the four experiments.

In 1983, no significant differences were found between treatments. This was likely due to the high windrow resistances created by high yields and a change in the sampling technique which precluded the adjustment of treatment means for weight of dry matter in the sample.

Controlled environment studies tested the influence of potassium carbonate on the time to reach 20% moisture content (wet basis) of single stems of five different species of legume. Potassium carbonate significantly decreased drying time of all species. The chemical was slightly less effective on red clover and alsike clover than

on alfalfa, sweetclover or sainfoin.

The effect of potassium carbonate on the single stem drying of field grown 'Beaver' alfalfa was tested over a range of temperatures and relative humidities in controlled conditions. Results showed a slight decrease in the effectiveness of the chemical at lower temperatures (12°C) and lower relative humidities (45% RH).

Recommendation for the use of the chemical will be subject to crop and environmental conditions. The procedure is not recommended for fall cut hay. Strong stemmed species and mixtures which form a loose, open windrow will realize the greatest effect from potassium carbonate or mechanical conditioning treatment. Crops over 4 tonnes/ha should be managed to increase drying rates. This could be accomplished by leaving the crop in a swath or wide windrow after cutting or by raking or fluffing the crop during drying.

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1. INTRODUCTION

Tame hay was produced on 1.5 million hectares in 1983 in Alberta. At a five year average yield of 4.0 tonnes/hectare and value of $60 per tonne the total value of Alberta's hay was $360 million in 1983. This compares favorably with that derived from 3.1 million hectares of wheat grown in Alberta in 1983 and indicates the relative importance of hay in the agricultural industry of Alberta.

Hay quality is dependent on a number of factors. These include forage species, crop maturity, severity of handling losses, and duration of the curing period. Field losses of hay are directly related to the duration of drying (Shepherd et al. 1954). Continued respiration and the increased probability of rain damage are the primary causes of the relationship between drying time and loss severity.

Considerable research effort has sought out new methods to accelerate field drying of hay and thereby reduce losses. Various types of mechanical conditioning, thermal and chemical treatments and manipulation of the swath or windrow have all been tested in either the field or the laboratory. The result is that farmers have a number of options at their disposal. However, effects of drying treatments have been variable. Results depend on environmental conditions (particularly evaporative demand), post-cutting treatments (raking) and the structure of the windrow or swath. One of the methods used to accelerate hay drying is the application of a potassium carbonate solution at the time of cutting.

This method has been used commercially in Australia and the United States.

The overall objective of this study was to test mechanical and chemical conditioning procedures under field conditions in central Alberta. A further objective of the project was to relate the drying of forage to species and environmental conditions using controlled environment chambers.

2. LITERATURE REVIEW

2.1 Hay Drying Principles

Field losses of hay are directly related to the duration of drying (Shepherd et al. 1954). Therefore, efficient forage conservation depends largely on the speed with which water can be removed from the cut crop. This in turn depends on a number of interacting factors. These factors include:

1. Climatic limits to drying - evaporative demand and addition of moisture after cutting (rain or dew) will both affect this variable.
2. Plant limits to drying - the inherent ease or difficulty of removing water from a plant. This is affected by moisture content of the plant, number and size of stomata, thickness and type of cuticle and epicuticular waxes, leaf to stem ratio (l/s), and the diameter of the stem.
3. Limits imposed by the structure of the drying environment (swath or windrow). Stubble height, density of the drying crop, and strength of the plant components all influence this factor (Jones and Harris 1979).

The success of any drying enhancement procedure which influences only one factor will thus depend on the interaction of the other factors in allowing the increased water loss to diffuse into the atmosphere. It is important to our understanding of any treatment effect to understand each of these factors.

2.1.1 Climatic limits to water loss

Moisture loss in all phases of drying is ultimately dependent on a vapour pressure deficit gradient between the drying material and the air. Solar radiation increases the temperature of the drying material thereby increasing this gradient. Wind acts to reduce the size of the boundary layer (the layer of still air surrounding a structure where water moves by diffusion alone) around the windrow and around individual stems thereby increasing water loss by convection and increasing the gradient of vapor pressure near the cut plants.

Good drying conditions (high temperatures and low relative humidities) are important throughout the drying process to achieve the fastest drying rates. An important consideration at low moisture contents is that plants are beginning to reach equilibrium humidity. At a water content of .25 (dry basis) the equilibrium humidity for perennial ryegrass is 65% relative humidity (Green and Jagger 1977). Therefore ambient relative humidity and more importantly relative humidity within the swath must be at 65% or below to successfully dry the crop to safe storage moisture levels.

At the begining of drying when large amounts of moisture are available to be lost from the crop, good drying conditions are less important. Moisture will still be lost from the crop even at relatively high humidities.

Rewetting by rain or dew is an important consideration during the drying of hay and is often overlooked in the literature. The advantage of windrowing hay is to reduce the surface area exposed to a light rain or overnight dew. Rewetting by dew can be particularly important when the non-drying period is longer than the daytime drying period. This prolonged rewetting period is a feature of most fall cuts (September or October) in central Alberta. The low temperatures, reduced solar radiation, and extensive rewetting extend the duration of drying in the fall.

The interaction of treatments designed to accelerate drying with the effects of rain has not been extensively researched. A drier forage will take up more moisture at night or after a rainfall (Tullberg and Minson 1978). However, there is no evidence that subsequent daytime drying rates will be diminished after rewetting. Alfalfa hay treated with a commercial dessicant (containing potassium carbonate) continued to dry faster after receiving significant rainfall (Vough 1983). In Saskatchewan, it was found that wetting cycles, whether due to overnight dew or rain, tended to reduce differences between treatments by rewetting drier treatments faster than the wetter treatments. This factor meant that few differences due to treatments could be detected (Feldman and Lievers 1973).

2.1.2 Plant limits to water loss

Studies to characterize water loss in cut plants have typically been carried out on isolated plant parts or a thin layer of crop fully exposed to a known and constant environment. This avoids the complications of a variable swath micro-climate and changing weather conditions (Jones and Harris 1979).

A typical drying curve for a thin layer of alfalfa is given in Figure 2.1. When the plant is cut, water content begins to fall and this results in stomatal closure. Estimates of the time of stomatal closure vary among researchers and species. Stomata in perennial ryegrass are fully closed thirty to forty minutes after excision (Clark et al. 1977). Alfalfa stomata closed within two hours after cutting (Jones and Palmer 1932).

The low light intensity within the swath (or windrow) also induces stomatal closure (Harris and Tullberg 1980).

After stomatal closure, resistance to water loss increases. At this point it is the epidermis and specifically the waxy cuticle which limits water loss by the cut plants (Jones and Harris 1979). It is generally thought that water loss through the cuticle is by diffusion and the rate of water loss depends not only on the thickness of the cuticle but on its structure and composition as well as the composition of the epicuticular waxes (Price 1982).

Though little research effort has been devoted to relating cuticular structure to drying rate it is known that

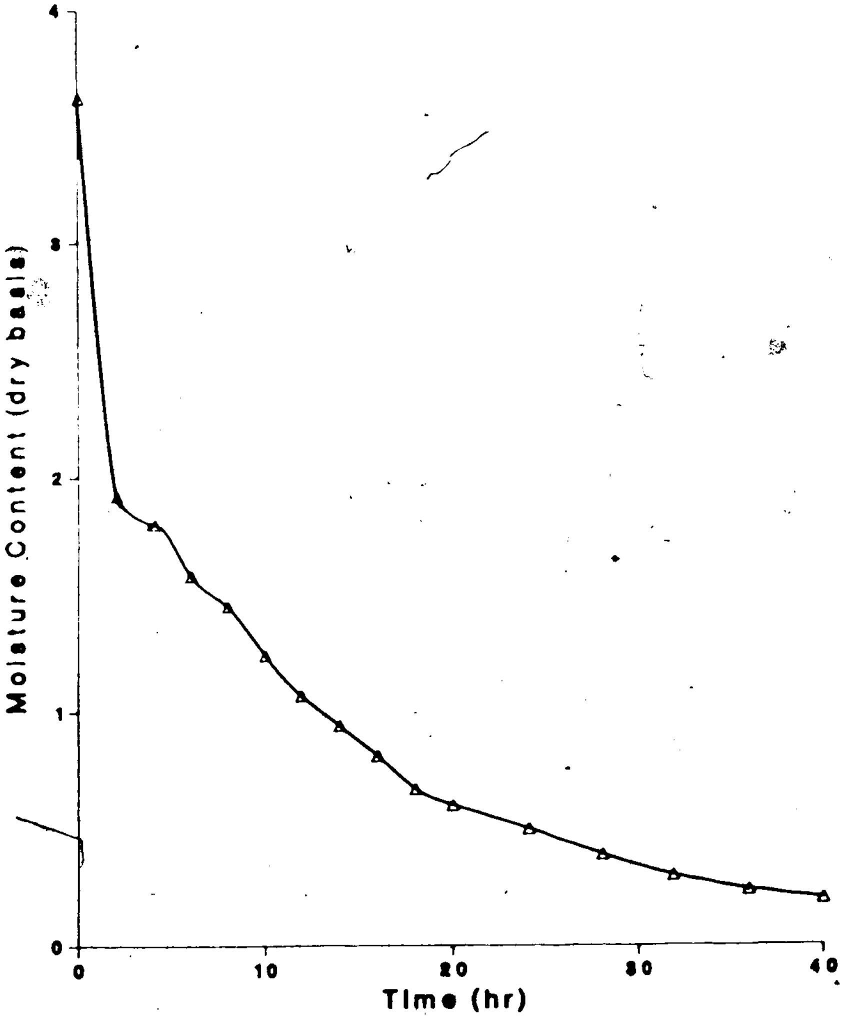

Fig 2.1 Pattern of water loss for 'Beaver' alfalfa dried as a single layer at 18°C, 45%rh, and 450uEm⁻² sec⁻¹.

the cuticles of young leaves are thinner and more permeable than those of mature leaves (Leon and Bukovac 1978). This may also be the case with stems.

Environmental conditions may also affect the amount of cuticular and epicuticular waxes found on stems and leaves (Price 1982). Greenhouse grown plants have been shown to have a much thinner cuticle than field grown plants (Hull 1958).

Temperature also affects cuticle structure. Changes in the crystal structure of the cutin and cutin waxes have been correlated to changes in temperature of 16.3,38,41,and 45°C (Eckl and Gruler 1980).

Measurements on leaves of white clover indicate that cuticular resistance is about 45 times that of stomatal resistance (Shepherd 1964). In general leaf diffusion resistance is increased by 10 to 50 times with the closure of stomata (Larcher 1980). Treatment of orchardgrass with hot vapour of petroleum ether (to remove cuticular and epicuticular waxes) increased drying rate by 10 times (Jones and Harris 1979).

The rate of water diffusion in an alfalfa stem is 10 times greater in the axial direction than radially. Axial diffusion of water is 10^4 times that of diffusion through the epidermis (Bagnall et al. 1970). Removal of the epidermis speeds drying (eight times that of the control) but the cortex then becomes a barrier to water removal. By removing both epidermis and cortex drying rate is 30 times that of the control.

The results of Bagnall et al. (1970) indicated a tenfold difference between the axial and radial diffusivity in alfalfa stem segments. This is consistent with the concept that the normal movement of water in the growing plant from stem to leaf can continue after the plant has been cut (Harris and Tullberg 1980).

Stem to leaf transfer of water appears to depend on species and the moisture content of both leaf and stem. In white clover (Shepherd 1964), alfalfa (Tullberg 1975), and ryegrass (Jones and Harris 1979, Green and Jagger 1977) leaves dry faster than stems. More stomata, a larger surface area, lower cuticular resistance, and decreased distance between the evaporating surfaces all contribute to the higher rates of water loss from leaves (Jones and Harris 1979). A maximum of 24% of total petiole water was lost via the leaf in white clover dried in controlled conditions (Shepherd 1964). This amount was greater than the initial amount of water within the petiole xylem. Transfer ceased when the water content of the petiole was between 71 and 81% of the total petiole weight.

Tests on alfalfa determined initial drying rate of detached leaves was approximately 1.5 times that of intact leaves and the initial drying rate of stems of intact plants was 6 times greater than that of detached stems. The only mechanism to explain these differences was stem to leaf transfer in intact plants. At least 35% of water in the stem was lost via this pathway, which remained active until stem water content approached 60% of total stem weight and the whole plant contained approximately 40% water (Tullberg 1975).

As drying proceeds other factors begin to affect water loss. Two such factors are reduced permeability of the protoplast and increased osmotic concentration of the cell sap (Jones and Harris 1979). In later stages of drying the matric suction in cells and cellulosic material increases making further extraction of water more difficult (Firth and Leshem 1976).

2.1.3 Swath and windrow limits to water loss

Much less is known about the limits to water loss imposed by the swath or windrow. For the purposes of this discussion a swath is defined as a loose arrangement of cut forage material which is nearly the width of the cutter bar while a windrow is a more dense structure formed by concentrating the material by baffles attached to the mower or by raking a swath after cutting.

Conditions inside the swath are less conducive to rapid drying than conditions at the swath surface. Green and Jagger (1977) studied swaths of perennial ryegrass and found the following conditions.

1. The swath surface reflects approximately 20% of incident solar radiation and the remainder is rapidly attenuated at the surface of the swath. Radiation 2 cm below the

surface was approximately one half that at the surface. Only 10% of the amount received at the surface reaches the base of the swath.

2. The mean air temperature at the surface of the swath may be up to 6°C above ambient, but air temperature in the center of the swath only exceeds ambient by 2°C.
3. The air movement inside the swath is severely restricted; even on windy days airflow rarely exceeds .2 m/s.
4. During the early stages of drying the very high crop water content and low ventilation inside the swath lead to humidity values which rarely fall below 80% RH during the day.

As drying proceeds, stem and leaf tissues shrink but the structure of the swath or windrow is maintained allowing for greater penetration of solar radiation and a faster airflow through the swath. This, in turn, increases the sensible heat in the swath, reduces plant boundary resistance, and reduces humidity within the swath (Jones and Harris 1979). At this point the water vapor gradient between the site of evaporation and the ambient air is increased, allowing for a greater (potential) water loss. However this stage corresponds to a period when the drying rate of the individual plant is slowing due to low water content and increasing plant resistances (Jones and Harris 1979). Consequently, plant factors become limiting to water loss and drying rates are further reduced.

Three other factors that influence swath or windrow drying in the field as opposed to single stem drying in controlled conditions are:

1. The drying gradient found within the swath or windrow.
2. The diurnal pattern of water loss
3. The effect of species transfer of water in a mixed crop.

Water is lost most rapidly from the surface layers of the swath. As drying proceeds plant limits to water loss develop more rapidly in surface material than in the center of the swath. The rate of water loss from surface material is less than it would be from wetter material in the center of the swath. Eventually drying in these layers is also affected by plant limits (Jones and Harris 1979).

Clark and McDonald (1977) followed the diurnal pattern of drying in swaths of ryegrass mixtures in England for the first two days of drying (swaths had reached 62% moisture). They found limited evaporation between sunrise and 0900 because of low vapour pressure deficit. Between 0900 and 1200 available energy increased to a maximum, resistance (includes both swath and plant resistances) to evaporation was still fairly low and rapid evaporation resulted. Between 1200 and 1800, available energy decreased and the resistance to evaporation within the swath increased resulting in a lower evaporation rate. Between 1800 hours and sunset high resistance to evaporation within the swath and declining energy made for very low evaporation rates. Resistance to evaporation within the swath increased throughout the day and throughout the drying period (Clark and McDonald 1977).

Although considerable work has been done on stem to leaf moisture transfer, no one has investigated the effect of moisture transfer within the swath between species. Practically however, farmers know that a grass mixed with a legume will speed drying. This may be a result of moisture transfer; or simply a result of the reduced swath density and lower initial moisture of the crop.

2.2 Treatments to Accelerate Drying

Treatments to accelerate drying have two major objectives. One is to better understand the drying process, the other is to speed field drying. Investigations aimed at understanding the drying process are usually done in the laboratory on single stems or on thin layers of plant material. Studies aimed at speeding field drying have involved both laboratory and field work. The major types of treatments are: 1) thermal, 2) chemical 3) mechanical conditioning, 4) swath or windrow manipulation.

2.2.1 Thermal treatments

Thermal treatments to accelerate drying have rarely been used in the field because of the expense. Both dry and steam heat have been tested on grasses and legumes. Steaming increased drying rates of Italian ryegrass leaves by twofold and produced a fivefold increase in the drying rates of stem internodes (Harris and Thaine 1975). From scanning electron micrographs it could be seen that the steam treatment caused the epicuticular wax platelets to fall into disarray and largely disappear (Harris et al. 1974). Even larger differences were found when steaming was applied together with mechanically splitting the stem.

Steaming also increased the drying rate of alfalfa (Byers and Routely 1966). The authors felt that this could be the result of action of the stomata in inhibiting metabolic activity, of reduction of cuticular resistance to viscous flow, and of saturation of the epidermis prior to drying. Steaming may also induce chemical changes in the protoplasm of the plant thereby affecting rate of internal moisture movement. Steamed alfalfa contained only half the alcohol soluble nitrogen of the unsteamed samples. This protein breakdown may lower the capacity of the plant to hold water (Byers and Routely 1966).

2.2.2 Chemical treatments

Chemicals tested to inhibit stomatal closure include sodium azide, fusicoccin, and kinetin. Tullberg (1972) found that dipping alfalfa into a solution of sodium azide increased the initial rate of water loss but the rate declined rapidly and the overall increase in drying rate which resulted in the treatment was small. Similarly Turner (1970) and Morris (1972) found the initial effect of fusicoccin on increased drying rate to be offset by a considerably slower rate in later stages of drying. This was particularly noticeable in the field where treatments rarely increased the overall drying rate of the hay.

Most other chemical treatments are aimed at reducing resistance to water loss through the cuticle. Vapour of petroleum ether treatment resulted in increased drying rates over control samples (Harris et al. 1974). Similarly, spraying leaves of perennial ryegrass with tri-n-butyl phosphate, a constituent of cotton defoliants, increased their drying rate when measured in controlled conditions (Harris and May-Brown 1976). Other phosphates have also been found to be effective drying agents when tested on single stems in controlled conditions (Harris 1978).

Numerous herbicides have been tested for accelerating drying of hay under both field and laboratory conditions. Kennedy et al. (1954) applied translocated and contact herbicides to various legumes cut for hay. Dinoseb and endothal showed the most promise but the advantage obtained in the field was considered to be too small to justify the expense of the spraying operation. Diquat and paraquat have also received attention as these have been used to aid in the dessication of crops grown for seed. Again some advantage in drying time has been realized with these chemicals but rarely enough to justify the expense (Shepherd 1959a, Craven et al. 1963). There is also some question as to the quality of hay produced using herbicides. In one study it was found that the use of paraquat prior to mowing produced hays which had a lower percentage of water soluble carbohydrate and a higher percentage of cell wall material. This decreased in-vivo digestibility of the hay (Arnold and Barrett 1978).

The use of potassium carbonate in an oil emulsion to speed the drying of grapes has been known and used for centuries. Columella (c.a. AD 60) recommended the use of a lye made from the ash of cane vines with a little olive oil to increase the drying rate of grapes. This preparation is still used in Greece and Dudmen (1962) has described and discussed similar present-day methods used in Australian sultana production.

The mechanism of action of potassium carbonate is not precisely understood but it is known that it acts on the cuticular and epicuticular waxes on the outer surface of the fruit. The chemical does not remove significant amounts of wax from the grapes (Chambers and Possingham 1963). Rather it has been suggested that the solution forms a continuous film over the surface wax platelets and extends down the cavities between them to join liquid phase moisture within the parenchyma, pectin, and cuticular membrane. This enables the moisture to be transferred in the liquid phase through the wax layer by capillary forces (Possingham 1972).

Potassium carbonate was first tested on forages in Australia. Initial tests were performed on separated leaves and stems of alfalfa dried in controlled conditions. Results indicated a considerable improvement in drying rate of both leaves and stems following potassium carbonate application

(Tullberg and Angus 1972). Aqueous solutions were as effective as an oil emulsion and rapid dipping as effective as several minutes immersion. Drying rate increased with increasing concentrations of potassium carbonate up to a value of .2M (Tullberg and Angus 1972).

Further studies revealed that the drying rate of potassium carbonate treated alfalfa was greater than that of the control over a wide range of temperatures and relative humidities (25,30,35,and 40° C at 45 and 75% RH) (Tullberg and Angus 1978). The drying advantage of the chemical was also maintained over a range of moisture contents. Variations in 1/s had a smaller effect on the drying rate of chemically treated samples than on control samples. The authors hypothesized that potassium carbonate increased the drying rate of stems more than that of leaves (Tullberg and Angus 1978).

In an effort to understand the process by which potassium carbonate enhances the drying of alfalfa, Tullberg (1975) measured both diffusive and viscous flow resistance of potassium carbonate treated and control samples. Diffusive resistance measures the inhibition of mass transfer of water vapor through the leaf. Viscous flow resistance is a measure of the inhibition of mass transfer of air through the leaf. The chemically treated samples showed a decrease in diffusive resistance in darkness compared to the control samples and an increase in viscous flow resistance. This increase in viscous flow resistance is in contrast to sodium azide - a known stomatal closure inhibitor - which actually decreases viscous flow resistance (Tullberg 1975). If potassium carbonate affects the cuticle by rearranging the cuticular wax platelets so they are appressed to the surface and hydrophilic (as found in grapes by Possingham, 1972) drying can occur by liquid phase transfer rather than vapor phase transfer. This mechanism may explain the observed difference in the action of sodium azide and potassium carbonate.

Mixtures of potassium carbonate and methyl esters of fatty acids were tested on single stems of alfalfa in laboratory trials (Weighart et al. 1978). They confirmed the findings of Tullberg and Angus (1972) that concentrations of the chemical over .18 M produced no increases in drying rate and that method of application (spraying or dipping) made little difference in drying rates (Weighart et al. 1978). The methyl ester mixture TE1618 and CE1618 was found to give the fastest drying rates (Wieghart et al. 1980). The addition of methyl esters (ME) and X-77 (a surfactant) decreased moisture content at 24 hours compared to potassium carbonate alone (Weighart et al. 1980). The addition of potassium carbonate to ME and X-77 showed no advantage in moisture content at 24 hours compared to the ME and X-77 mixture alone (Weighart et al. 1978) but it did significantly reduce time to reach 75% dry matter (Weighart et al. 1980). Weighart and her coworkers concluded that the fastest rate of desication of alfalfa was achieved with a mixture of 2% ME and 1% X-77 in .2 M potassium carbonate applied at a 5% solution rate.

Potassium carbonate has also been tested in full scale field trials in a number of areas in North America and Australia. In Australia, potassium carbonate treated hay (applied at a rate of 74.5 kilograms/hectare) dried faster than both mechanically conditioned and untreated hay (Tullberg and Minson 1978b). Hay was left in a swath after mowing. Application rates of 4,7, and 17 kilograms/hectare did not result in significantly different drying rates.

In Alberta, alfalfa hay sprayed with potassium carbonate reached suitable moisture for baling (20%-wet basis) approximately 28 hours after cutting while the control was at approximately 32% and would have required at least one more day to reach suitable storage moisture (Redshaw and Lopetinsky 1981). Rates of application were 5.6 kilograms in 224.6 liters/hectare of water and all hay was windrowed immediately following cutting. A similar experiment on red clover showed no drying advantage for the potassium carbonate treated hay over the control hay.

Initial studies in Michigan on alfalfa measured percent dry matter at the end of the day and found that the addition of potassium carbonate to a 2% solution of methyl esters and X-77 increased dry matter percent relative to control. It did not affect dry matter percentage when applied with a 10% solution of methyl esters (Weighart et al. 1979). Another study (Weighart et al. 1983) found no difference between control and potassium carbonate alone, but potassium carbonate with methyl esters or a grape dipping solution significantly increased rates of drying. Grass did not respond to potassium carbonate + methyl ester treatment but 1/5 bloom or mature alfalfa were affected equally (Thomas et al. 1981). Alfalfa sprayed with potassium carbonate, potassium carbonate+ME+X-77, potassium carbonate+sodium carbonate+triglycerides, or sodium carbonate+sodium silicate all dried at statistically similar rates (Rotz and Thomas 1983). Application rates of 150, 300, or 450 liters/hectare of water were tested with both high and low concentrations of potassium carbonate+ME+X-77. The fastest drying occured at the highest rate of water application but the concentration of the chemical made little difference in drying rates.

2.2.3 Mechanical conditioning

Many of the principles of drying enhancement found with chemical conditioning also pertain to mechanical conditioning.

Mechanical conditioning of a hay crop can be performed by a number of different machines. The three commercially exploited forms of mechanical conditioning are; crushing and crimping (both by pressure rollers), and laceration by flails. Crushing rollers generally crush the material between smooth steel or hard rubber rolls causing longitudinal splitting and localized bruising, whereas crimping rollers are generally corrugated and produce intermittent splits and breaks in the stem (Klinner and Shepperson 1975). Laceration by flails has a random effect producing both longitudinal and intermittent splitting and is the most severe.

Mechanical conditioning increases drying rates largely due to cracking the epidermis and exposing more cells to the air. Few cells are actually broken. As soon as the exposed cells dry, the drying rate reverts to that of the untreated plant (Byers and Routely 1966).

As with any post-cutting treatment, hastening drying by mechanical conditioning will depend on the further treatment of the hay. Before con~~ditioners~~, the traditional means of drying hay was by cutting with a sickle bar mower and raking or tedding the crop. The raking could be performed one or many times to speed drying. Conditioners can leave the crop in either a swath (close to the full width of the cut) or a windrow (1/3 to 1/2 the width of the cut). The general practice in Alberta is to place the hay directly into a windrow at cutting. This can be advantageous at night (or with a light rain) because rewetting occurs primarily on the surface and the reduced surface area of the windrow results in less rewetting. However, during the day this reduces the amount of surface area exposed to radiant energy and increases the relative humidity around the majority of the stems thereby reducing drying rates.

Consequently the results of drying studies testing mechanical conditioning depend largely on other postcutting treatments and the type of windrow or swath in which the hay dries.

Tests at Melfort, Saskatchewan, compared a sickle mower with no conditioner (which left the crop in a swath), a mower conditioner which was operated both in a swath and a windrow mode, a self propelled windrower with conditioner, and a rotary drum mower without conditioner which left the crop in a swath. Generally the mower conditioner in the swath mode produced hay which was approximately 5 percentage points drier during the first day than hay produced with the other treatments but this gradually decreased as drying proceeded. Overall few significant differences in drying rates were found between treatments (Feldman and Lievers 1973).

Studies done in Texas on alfalfa show that mechanical conditioning (crushing) decreased the time to reach 25% moisture (wet basis) by approximately 25% when drying in a windrow and by 38% when drying in a swath. Conditioned alfalfa dried in a windrow required approximately the same number of hours to reach 25% moisture (37.9 hours) as alfalfa which was not conditioned but dried in a swath (39.5 hours) (Sorenson and Person 1967). However, under poor drying conditions, when hay takes several days or even a week to dry, the advantage of a windrow (reduced surface area and rewetting) may be considerable (Jones and Palmer

1932).

The advantages of flail conditioning in speeding drying are debatable. Flailed alfalfa/brome dried considerably faster than crushed or unconditioned material in one test but much the same as crushed in a second test (Hall 1964). A flail type machine could be operated to produce a drying rate comparable to roll type crushers but such operation results in much higher potential field losses (Barrington and Bruhn 1970).

Klinner (1976) has done considerable work on developing a mower conditioner for 'difficult climates'. It consists of a crop conditioning rotor which can be attached to either a drum or sickle bar mower and uses brushes to damage the cuticle of the stem. It has generally produced drying rates and losses similar to a normal mower conditioner.

2.2.4 Combined treatments - Chemical and mechanical conditioning

Treatment with potassium carbonate combined with mechanical conditioning allowed alfalfa hay to reach storable moisture (20%-wet basis) approximately 20 hours sooner (in 30 hours) than the mechanical conditioning treatment alone in New South Wales, Australia (Crocker and Lodge 1981). Trials in Maryland found that alfalfa hay treated with a commercial product containing potassium carbonate, ME's, and X-77 combined with mechanical conditioning was ready to bale the day after cutting while the mechanical conditioning treatment was not ready until two days after cutting (Vough 1983).

In Alberta the combined treatment of chemical and mechanical conditioning reached 20% moisture (wet basis) four hours earlier (approximately 24 hours after cutting) than either treatment alone on alfalfa hay. This same treatment on red clover hay produced hay at safe storeable moisture within 24 hours after cutting compared to 28 hours for mechanical conditioning alone and 30 hours for potassium carbonate alone (Redshaw and Lopetinsky 1981).

Comparisons of potassium carbonate+ME+X-77 applied with mechanical conditioning using a number of different machines indicated that a cutter bar with roll conditioner provided a greater increase in drying constant than flail, disk or drum mower (Rotz et al. 1984). This may have been due to better coverage and a thinner swath produced by this machine. Point of application of the chemical (in front of the machine or ahead of the conditioner rolls) had no effect on drying rate (Rotz et al. 1984).

The structure in which the hay is laid after cutting has been found to affect drying rates. Comparisons of drying after spraying potassium carbonate+ME+X-77 with mechanical conditioning indicated an increased drying rate of 79% when hay was placed in a swath compared to 39% when placed in a windrow (Rotz et al. 1984). An economic analysis of the combined treatment in Michigan found the cost was justified for later cuttings of hay but not for haylage or first cut hay and that the cost effectiveness was dependent on swath structure (Rotz 1983).

Trials in California using a commercial preparation of the chemical demonstrate a 38-63% decrease in drying time of the combined treatment over mechanical conditioning alone (Schoner et al. 1984).

2.2.5 Dry matter losses

Four major losses occur during field drying; respiration, shatter, leaching, and microbial decomposition. Under good drying conditions, losses of dry matter are due to respiration and shattering. After the plant is cut it continues to respire, oxidizing organic matter. Shatter loss is caused by the action of machinery on the plant tissues (mainly leaves) during cutting, swath or windrow manipulation, and baling. When material is rained on, leaching and microbial decomposition contribute to dry matter losses.

Respiration continues until low plant moisture results in cell death. Estimates of the plant moisture content that causes cell death vary widely. Mitchell and Shepperson (1955) state that losses continue down to a moisture content of about 67% (dry basis) while Greenhill (1959) gives 35% moisture (dry basis) as the point at which no further changes in dry weight occur. The respiration rate of cut herbage declines with decreasing moisture content and with increasing age (later stage of development) of the material

(Pizzaro and James 1972). The loss of dry matter by respiration varies inversely as the rate of drying, and at any one drying rate, it increases with increase in temperature (Greenhill 1959). At 15, 20, and 25°C, Wood (1982) estimated losses of 4.9, 6.9, and 9.7%, respectively, of total dry matter on cut grass. Greenhill (1959) estimated losses of dry matter from a crop of alfalfa at 4 to 12% depending on temperature and saturation deficit.

Shatter losses from mechanical action depend largely on the moisture content at which the crop is treated. The loss of dry matter as a result of raking the swath can vary from about 0.5% per treatment with crops of 70 to 80% moisture content to 2.5% per treatment with crops of 20% moisture content (Wilkinson 1981). Honig (1980) found that mechanical losses resulting from turning a drying grass crop increased from 0.1 tonnes/hectare to 1.2 tonnes/hectare dry matter for each treatment in the moisture content range from 75 to 20%.

Shatter losses can be particularly severe when forage is cut with a flail conditioner. Shatter losses of approximately 3% of initial dry matter were found after alfalfa was cut by a cutterbar with roll conditioner compared to 6.2% when cutting was done with a mower with flail conditioner (Rotz and Sprott 1984). Baling losses can range from 4.4 to 11.1% (Honig 1980). These losses will also depend on the moisture at which the hay is baled, as well as the type of baler and operator competance.

Some forages are more susceptible to mechanical damage (Shepherd 1959b). In trials on alfalfa and white clover, Shepherd found significantly higher shatter losses in late season, overmature, and fast curing materials. He also found increased losses in crushed and rewetted material as well as plants which had suffered drought or flood conditions.

The effects of rain on forage dry matter losses have not been extensively researched. In addition to leaching losses, rain exacerbates losses due to shattering and microbial decomposition. Estimates of losses incurred after rainfall range from 2 to almost 30%. The greater the moisture content, the greater the dry matter loss for an equal amount of rain (Rucker and Knabe 1977). Losses increase with increased rainfall over the range of 6 to 25 millimeters (Kormos and Chestnutt 1968). Laceration also increased dry matter losses following rainfall (Kormos and Chestnutt 1968).

In Alberta, decreases in dry matter digestibility of 0 to 8% occurred after rain. Raking following rain damage decreased digestibility by 13 to 16%. This decrease was attributed to shatter loss (Milligan et al. 1981).

Wilkinson (1981) estimated total dry matter losses of field dried grass (6 days, no rain) at 22%. He attributed 8% of this loss to respiration and 14% to mechanical losses.

3. METHODOLOGY

3.1 Field Studies

A total of six trials were performed on different species/mixes and locations over two years. Four trials were done on brome/alfalfa, henceforth called B/A-1-82, B/A-2-82, B/A 3-82 in 1982 and B/A-1-83 in 1983. One test was run on red clover (RC-1-82) in 1982 and one on alfalfa (A-1-83) in 1983. A randomized complete block design with two replications of four treatments was used for all trials.

3.1.1 Brome/alfalfa 1,1982 (B/A-1-82)

This trial was performed 5.5 miles North of Spruce Grove, Alberta (N lat 53°22',E 113°37') in TP 53 R 27 E of 5. The land was owned by Mr. Alan Shenfield. The soil series was a mixture of Ponoka Light Loam and Codner Loam. The Ponoka Light Loam is classified as an Eluviated Black to Orthic Black Chernozem and the Codner Loam is of the Gleysolic soil order. The soil rating is fair to fairly good arable.

The field was seeded in 1980 with Canada No.1 seed at a rate to produce a 60% alfalfa (Medicago sativa L.) and 40% smooth brome (Bromus inermis Leyss.) stand. Samples (10 per plot) removed to determine species composition after cutting indicated dry weight percentage of brome as 81.6.

The field measured approximately 32 hectares. An area of approximately 12 hectares was selected in the field for our studies. Selection criteria were uniformity of crop and distance from windbreaks.

The experimental area of the field measured 132 by 68 meters. This area was divided into eight plots (two replicates of four treatments), each measuring 15 by 68 meters. Six meters was left on either end for machinery access. Each plot contained five 68 meter long windrows. Forage material from a 3 meter cut was concentrated into a 1 meter wide windrow. Samples were removed from two of these windrows to follow the pattern of drying. The other three windrows were included to assure enough material to bale each of the treatments separately. These bales were subsequently used in another study.

The material was cut on July 9, 1982. Though cutting was planned to coincide with the 1/10 bloom stage of the alfalfa (recommended time for maximum of quantity and quality) it was delayed due to rain. Consequently the alfalfa was in full bloom.

3.1.2 Brome/alfalfa 2,1982 (B/A-2-82)

This material was cut from the same field as B/A-1-82. The experimental area and plots were of a similar size as that used in B/A-1-82 and directly adjacent to it. Samples removed to determine species composition after cutting indicated dry weight percentage of brome as 83.1. The material was cut on July 13, 1982 and the alfalfa was in full bloom.

3.1.3 Brome/alfalfa 3,1982 (B/A-3-82)

This trial utilized regrowth material from B/A-1-82. The plots were of similar dimensions and samples removed to determine species composition after cutting indicated dry weight percentage of brome as 87.6. Cutting took place on September 8,1982 and the alfalfa was at the 50% bloom stage.

3.1.4 Brome/alfalfa 1,1983 (B/A-1-83)

This trial was located in a 32.7 hectare leased site near Fawcett, Alberta. The field was located approximately 170 kilometers NW of Edmonton (N lat 54°30',E 114°13') in the NE quarter of section 27,TP 63 R 2 W of 5. The soil is a Leith Codner and Codessa series. The Leith is classified as a dark grey wooded. The Codner is classified as a degraded Eutric Brunisol and/or Orthic Grey Wooded. The Codner is classified as an Orthic Humic. The soil rating is fair to fairly good arable.

The field was seeded in June,1982 at the recommended rate of 7 and 5 kilograms/hectare respectively of 'Beaver' alfalfa and 'Carlton' brome.

The experimental area of the field consisted of two, nonadjacent replications, each measuring approximately 14 by 270 meters.

This area was divided into four plots. Each plot consisted of one windrow measuring approximately one meter wide (width of cut was 3 meters) by 270 meters long.

Frequent rains delayed cutting until August 4. The alfalfa was in the post bloom stage.

3.1.5 Alfalfa 1,1983 (A-1-83)

This test was also located at the site near Fawcett. The field was seeded in June,1982 to 'Beaver alfalfa' at the recommended rate of 9 kilograms/hectare.

Two nonadjacent 1.2 hectare replications were available for the test. Treatment areas and plot sizes were similar to those of B/A-1-83. The plots were cut simultaneously with B/A-1-83 (August 4) and the alfalfa was in the post bloom stage.

3.1.6 Red clover 1,1982 (RC-1-82)

This field was located 1.7 kilometers east of Morinville, Alberta (N lat 53° 48', E 113° 35') in TP 56 R 25 E of 5. The land was leased by Mr. John Keiser. The soil series was a Navarre Silt Loam and classified as an Orthic Black Chernozem. The soil rating was fairly good to good arable.

The field was underseeded to red clover (<u>Trifolium pratense</u> L.)(cv. Altaswede - a single cut cultivar) in 1981. The exact seeding rate was not available but the crop was quite dense yielding approximately 3.56 tonnes/hectare of dry matter.

The field was approximately 64 hectares and an area of 68 by 60 meters was selected for the trials. Two adjacent replications of 30 by 68 meters were used. Plots consisted of two windrows for each treatment. Plot size was approximately 3 meters by 68 meters. In this instance treatments were not baled separately so only two windrows per treatment/replication were required.

Cutting took place on July 26 when the clover was at the 80% bloom stage.

3.1.7 Treatments

The following treatments were used in all field trials:

1. Control - hay cut with a mower conditioner with the conditioning rolls open as far as possible (25 millimeters apart).
2. Conditioned - hay cut as above with conditioning rolls at normal distance apart for moderate conditioning (6 millimeters apart).
3. Potassium Carbonate - Potassium carbonate sprayed at a rate of 10 kilograms/hectare in 400 liters of water on the crop as it was cut. Mower conditioner set as in control.
4. Combined - Combination of treatments 2 and potassium carbonate as in 3.

All treatments were windrowed at time of cutting and no further manipulations were performed until baling.

Treatments were performed on adjacent windrows which were cut to a length to accomodate the appropriate number of samples. Treatments were contained in two adjacent blocks in

1982. In 1983, treatment blocks were separated by other plots seeded to other species.

3.1.8 Mechanics of application

Potassium carbonate application (10 kilograms/hectare in 400 liters water) was at the high range of recommended rates used in Australia (Crocker and Lodge 1981). Commercial products have been used for some tests in the United States but these products are not licensed in Canada.

Modifications to a John Deere mower conditioner to accomodate spraying included:

1. attachment of a spray boom 60 centimeters ahead of the cutter bar and 60 centimeters above the ground. Tee Jet nozzles were spaced 45 centimeters apart and pointed 45° forward of vertical.
2. attachment of an adjustable push bar approximately 12 centimeters ahead of the spray boom and adjusted to the height of the crop. This bar bent over the stems to more directly expose them to the spray.
3. a tractor mounted pump and agitator.
4. a 160 gallon tractor mounted tank to hold the spray solution.

The mower conditioner had a measured cut of 3.0 meters with full width rubber conditioning rolls set at 6 millimeters spacing for the conditioning treatments. This produced stems with breaks about every 10 centimeters. Metal baffles at the rear of the machine laid the cut forage in a windrow which measured one meter wide. The chemical was applied to the forage immediately before cutting.

3.1.9 Sampling procedures

Two different sampling methods were employed in the two years of the study. In all cases ten samples per plot were collected for each sampling time.

In 1982, nondestructive samples were used to follow the pattern of drying. Immediately following cutting, ten sampling areas (each 10 meters long) were measured off in the windrow. Within each area three 1 meter sections (each separated by two linear meters of undisturbed windrow) were cut from the windrow. The first of these was bagged, weighed, dried and reweighed to determine initial moisture content. The second (nondestructive) sample was weighed immediately after cutting and at subsequent intervals until harvest to follow the pattern of drying. The third sample in each area was collected at harvest, weighed, dried and reweighed to determine final moisture content. After a number of trials showed no appreciable loss due to lifting and weighing the second sample, the final moisture content was determined from this sample and only two samples were used in subsequent experiments in 1982.

Nondestructive sample weighing was done with a specially designed metal lifting platform suspended from a scale attached to a portable tripod.

The lifting platform consisted of ten parallel, 1 meter long steel rods spaced 10 centimeters apart. The rods were free at one end (the open side of the lifting platform), allowing the platform to slide under the windrow sample without disturbing the stubble beneath the windrow. The rods that formed the lifting platform were held in place by a frame constructed from hollow steel tubing. During weighing, the lifting frame was suspended from a 'Hanson' dairy scale that was, in turn, suspended from a portable tripod. The tripod was constructed from two 1.8 meter and one 2.8 meter lengths of 3.4 by 3.4 centimeter lumber. The top ends of the shorter legs pivoted on a bolt that passed through the long leg about 75 centimeters from it's upper end. A pointed steel pin affixed to the lower end of the longer leg and pushed into the soil held the tripod securely in position. The dairy scale was suspended from a steel hook in the extreme upper end of the long leg.

Samples were cut from the windrow with 'Black and Decker' electric hedge shears powered by a portable generator.

Destructive sampling was used in 1983 to avoid some of the problems encountered the previous year. Although a much larger number of samples had to be processed with destructive sampling the time required to collect samples in the field was reduced. This assured greater similarity between sampling times for each treatment. More accurate electronic balances (set up in a tent to shield them from wind) could also be used for weighing in the field rather than the dairy scales. The dairy scales had been particularly troublesome, especially on windy days in the previous year.

Destructive samples in 1983 measured 10 centimeters in length bythe width of the windrow. A clamp was placed on a section of windrow and samples were then collected by cutting along the edges of the clamp with a pair of manually operated hedge shears. The clamp consisted of a 105 centimeter length of 3.4 by 8.8 centimeter lumber (placed under the windrow) and an 8 by 70 centimeter piece of 125 millimeter plywood. The plywood was attached to the lumber by 31 millimeter cable, and it was tightened on the windrow with a binder. Samples were placed in labeled bags and weighed (to .1 gram) immediately on a 'Mettler' electronic balance in the field. Empty bags were also weighed at each time interval so net content weights could be determined at a later date.

Sampling times were at least once every day (at the end of the day) in 1982. Sampling was more frequent near the end of drying in an effort to determine the exact time the forage reached 20% moisture content. Samples were not taken if the forage was still wet from rain at the end of the day. On two occasions it rained during sampling. In these cases samples were not collected from all treatments.

Sampling times in 1983 were twice a day (morning and evening) for the alfalfa and brome/alfalfa and once a day for the red clover. Morning sampling was planned to catch the samples before dew had begun to evaporate from the hay (highest moisture content of the day) and evening sampling before samples had become wet with dew (lowest moisture content of the day).

Small grab samples were collected for determination of species composition and l/s determinations. Measurements (length, width, and height) were taken of the freshly cut one meter sections of windrow for B/A-3-82 and RC-1-82. Yield estimates were determined by calculating the average sample dry matter of measured sample areas in the plots.

3.1.10 Weather monitoring

A Campbell Scientific weather station was available in 1982 and was on site for all cutting times. The station was fitted with a pyranometer (Li-Cor LI 200S) to measure net incoming radiation, a thermistor (Fenwall UUT-S1J1) to measure ambient temperature, a temperature-compensated relative humidity sensor (Phy-Chemical Research Model PCRC-11), a rain bucket, and an anemometer. Readings were automatically taken every minute and fed into the computer attached to the weather station. Hourly averages were recorded on a cassette tape. The tape was then read directly into a computer file using an interface developed by Campbell Scientific.

In 1983 the weather station was set up at a site 50 kilometers east of the experimental site and weather data for that year was collected both from this site and from weather records from the Environment Canada weather station at Slave Lake.

3.1.11 Statistical analysis

The results of forage drying studies can be expressed in a variety of ways. No single method of expression dominates the literature on forage drying. Hence, comparisons between studies is difficult.

There are a number of factors that make expression of results in hay drying difficult. The first concern is whether results are expressed as 'wet' or 'dry' basis moisture content. Producers generally determine moisture content on a 'wet' basis (the amount of water in a sample divided by the fresh weight of the sample multiplied by 100) while many authors express moisture content on a 'dry' basis (the amount of water in a sample divided by the dry weight of the sample). Tullberg (1975) argues that the dry basis moisture content has a linear relationship with the weight of water present and thus is the preferred method. However, because drying is not linear; water is lost at a faster rate at the beginning of drying than at the end; a difference in initial moisture of two samples will be less important in determining final drying time than an equivalent difference at the end of drying. Table 3.1 illustrates a 5% difference in initial and final moisture on a 'wet' basis compared to the same difference on a 'dry' basis.

Table 3.1. Example of water loss on a 'wet' versus 'dry' basis moisture content.

	Wet basis		Dry basis	
	Moisture content (g water/g total)	Difference	Moisture content (g water/g DM)	Difference
beginning of drying	.80	.05	4.00	1.00
	.75		3.00	
end of drying	.25	.05	.33	.08
	.20		.25	

The 'dry' basis moisture content places heavy emphasis on differences at the beginning of drying (which has little effect on overall drying time) and little emphasis on the end of drying where differences are very important in determining 'safe' storage moisture content. In a field situation this may mask treatment effects on overall drying, particularly in comparisons across experiments or species where differences in initial moisture may be substantial. Consequently, in this study 'wet' basis moisture content was used in all field comparisons.

Either 'wet' or 'dry' basis moisture content can then be used in a number of different ways before final analysis of treatments. Analysis can be performed on:

1. hours to reach a particular moisture content
2. moisture content at a particular time or averaged across all sampling intervals
3. daily or overall drying rates (change in moisture content over time)

Practically, the best method of measuring treatment differences in drying in the field would be to compare the exact time at which each reached a predetermined 'safe storage moisture content'. Unfortunately this is very difficult to do in the field situation. The exact moisture of the samples cannot be calculated until after oven drying. Estimates of moisture content of nondestructive samples or of small samples dried in a microwave are rarely accurate enough. Just the time required to collect the final samples will make it very difficult to catch all samples at the correct moisture content. In addition, it is quite difficult to extrapolate to these values because of variable environmental conditions and overnight nondrying periods.

In the field studies the original intent was to measure total time to reach 20% moisture. For the reasons outlined above, this was not possible. Therefore the basis for comparison of treatments is the mean of the moisture content values (wet basis) at all time intervals until the first treatment reached 20% moisture. Twenty percent moisture is the generally accepted 'safe' storage moisture content for baling in Alberta. There are problems with this method as well. One of the drawbacks of this method is that it incorporates all values. It includes morning values where differential wetting has occurred. Because drier treatments usually absorb more moisture overnight, this underestimates treatment effect.

Secondly, because different experiments had different numbers of sampling times, differences in drying between experiments can not be compared. Differences in sampling technique, yields, species, and environmental conditions, also prohibit this comparison. However, this method accurately represents the moisture status of each treatment over time and is the most appropriate comparison for evaluating treatment effect.

For each experiment, moisture contents (wet basis) for each sampling time were compared using standard analysis of variance procedures. Plot values were calculated as a mean of 10 samples. Moisture content means for treatments across all sampling intervals were also tested for significance using analysis of variance, and treatment means were compared using the Duncan's New Multiple Range test (Steel and Torrie 1980). Standard regressions were run to determine correlation coefficients between moisture content mean and initial weight of dry matter for all samples.

Due to the highly significant correlation coefficients found between mean moisture content values and weight of initial sample dry matter, sample dry matter was used as a covariate in the analysis. Mean moisture contents for treatments were adjusted for initial sample dry matter weight using a covariance program (Desmat and Lsqanova) which incorportes adjustment for missing values.

Preliminary analysis determined that covariate/factor coefficients for the four treatments were not significantly different for B/A-1-82 and B/A-3-82 so moisture content means were adjusted for a single covariate coefficient. In B/A-2-82 and RC-2-82 covariate/factor coefficients were significantly different for treatments. Consequently these means were adjusted with a covariate coefficient for each treatment.

Dry matter losses for the four experiments in 1982 were calculated by multiplying the initial fresh weight of the nondestructive sample by the initial dry matter percentage (found from the destructive sample taken at cutting). This gave the dry matter (in grams) for the sample at cutting. The final dry matter was determined from the collected samples at final harvest (after oven drying). The difference between these two is the dry matter loss occurring in the field due to respiration, leaching and shattering. It does not include any losses due to raking or baling. This dry matter loss is expressed as a percentage of the initial dry matter.

Analysis of the relationship between sample dry matter and mean moisture content was not possible in 1983. In 1982, the pattern of drying was followed throughout drying on each sample, and dry weight was recorded for each sample. In 1983, a new sample was harvested at each sampling interval and the pattern of drying was reconstructed from these samples. Therefore, the mean moisture content of these samples was not closely related to their mean dry matter weight.

3.2 Controlled Environment Studies

3.2.1 Species comparisons

The effect of potassium carbonate on drying times of various legumes dried as a single layer of plants was examined under controlled conditions. The legumes tested were two cultivars of alfalfa (Beaver and Anchor), alsike clover (Trifolium hybridum L.), sweetclover (Melilotus alba Desr.), red clover, and sainfoin (Onobrychis viciaefolia

Scop.). All material was grown in a greenhouse. The species selected are the legumes most typically grown for hay in Alberta. 'Beaver' alfalfa is a widely grown winter hardy variety; 'Anchor' is somewhat less winter hardy.

The test procedure consisted of clipping off the apical 20 centimeters of stem and dipping the cut end in paraffin to seal it. Calipers were used to measure the diameter of the cut end of the stems. The sample was then immersed in either distilled water or .18 M (aqueous solution) potassium carbonate for five seconds. Excess water was shaken from the stems in a routine manner. Each replicate consisted of five stems placed in a 25 centimeter^2 wire mesh tray. Two replications of each of the species - treatment combinations were placed randomly in a growth chamber (Conviron E15) and dried at 45% relative humidity and 18°C under full continuous illumination (550 $uEm^{-2}sec^{-1}$). This procedure was then repeated giving a total of four replications. Hourly measurements of tray weights were recorded for the first 24 hours. Thereafter measurements were taken every four hours until the samples reached equilibrium moisture. Stems were then removed from the trays, separated into leaf and stem fractions and dried in a forced air oven at 60°C for 48 hours. Samples were reweighed to determine dry matter and the moisture content was calculated.

A repeat of this experiment was run at a later date at slightly different environmental conditions (20°C, 450 $uEm^{-2}sec^{-1}$, and 45% rH) on four ('Beaver' alfalfa, 'Anchor' alfalfa, sweetclover, and red clover) of the six species. Results were quite similar to the above so results are only presented for the first run.

3.2.2 Environment comparisons

Field and greenhouse grown 'Beaver' alfalfa were tested under two photosynthetic photon flux densities (PPFD) (350 and 700 uEm^{2}sec^{-1}), two relative humidities (45 and 70%) and three temperatures (12, 20 and 30°C). Test procedure was the same as in the species comparisons but used field grown and greenhouse grown alfalfa. Material was treated, weighed, and placed in growth chambers as quickly as possible. Unfortunately field material was not cut until post bloom stage. Consequently it had somewhat lower moisture contents than would be expected of material cut at the recommended 1/10 bloom stage. Greenhouse grown material was cut in the 1/10 to 1/2 bloom stage.

Three chambers were available for the project and were set continuously at 12, 20 or 30°C. Temperature (dry bulb) was recorded on a chart recorder and remained within +/- 1°C of the desired temperature. Illumination was altered by raising or lowering the shelf inside the chamber and was checked with a LiCor (Li 188) photometer set to measure PPFD. Relative humidity was monitored by a wet bulb in conjunction with the dry bulb. This was also recorded on the chart recorder. Relative humidity was accurate only to +/- 3% on average. Accuracy was greater at the higher temperatures and less at lower temperatures.

The chambers were vented and air movement inside the chambers was quite high. Measurements indicated an air speed of .265 m sec^{-1}. This is below the critical airspeed of .4 m sec^{-1} recommended for 'completely exposed' conditions of drying between 4.0 and 2.5 moisture content (dry basis) (Shepherd 1964).

Each treatment replicate (dipped in chemical or water) consisted of ten stems placed on a wire mesh tray. Three replicates of each treatment were tested in each of ten environments. Because of a problem with the lighting in the 12° chamber the higher illumination (700 uEm^{-2}sec^{-1}) was not possible.

Measurements of tray weights were recorded every two hours from 0800 to 2400 and every four hours from 2400 to 0800. Measurements were continued until the samples appeared to reach equilibrium moisture. Stems were then removed from the trays, separated into leaf and stem fractions, and dried in a forced air oven at 60°C for 48 hours. Samples were reweighed to determine dry matter and the moisture content was calculated. All field material was run through all environments first. Greenhouse material was done after all field material had been tested.

3.2.3 Statistical analysis

Two different ways of reporting results are presented for the controlled environment studies. Results are reported in the form of 'hours to reach 20% moisture' for practical purposes as this comparison will be the most important in the field. Occasionally, exact times to reach 20% moisture were not available. If drying appeared to be continuing (equilibrium moisture had not been reached) then the time to reach 20% was determined by extrapolation from the last recorded moisture content using a regression derived drying rate. These are indicated with a (ˆ) in Table 3.17.

The need to run material through the chambers rather quickly to avoid differences in growth stage of the material required the termination of some experiments in the poorer drying environments before all treatments had reached 20% moisture. It has been suggested in the literature that data from the drying of single stems in controlled conditions fit the equation:

$$Y = e^{-bt}$$

where Y=moisture content(dry basis)
b=drying rate constant
t=time from treatment

Data from these experiments generally fit this equation well after the data from the initial drying period was removed. The initial period usually lasted only two hours and likely corresponded to water loss through open stomata.

Solving the equation for the drying rate constant (b) results in:

$$\ln Y/t = -b$$

Regression analysis (Steel and Torrie 1980) was performed on each data set (rep - species - treatment combination) to determine drying rate constants (b). In all cases, the natural log of the moisture content (dry basis) from two hours until .25 moisture content (or equilibrium moisture) was regressed against time in hours. Coefficients of determination (r^2) were generally above .9 (Appendices 1 - 3).

In the species comparisons, a randomized complete block design was used with two runs (replications) of two treatments-six species combinations. Within each run, two replications of each treatment-species combination were performed and the mean values of the two replications were used in the analysis. Total time to reach 20% moisture and drying rates (b) were analyzed using standard analysis of variance procedures and means were compared with a Duncan's New Multiple Range test (Steel and Torrie 1980).

In the environmental comparisons, the experimental design was a randomized complete block with three replications of two treatments completely randomized within each of ten environments. Data analysis was similar to the species comparisons experiment.

Correlation coefficients relating time to dry and drying rates to stem diameter, l/s, and initial moisture were determined from a SPSS regression program.

4. RESULTS AND DISCUSSION

4.1 Field Studies

4.1.1 B/A-1-82

Moisture content differed significantly among drying treatments at each time interval (50 hours was not included because of missing data) (Table 4.1). At 70 hours (approximately 3 days after cutting) the combined treatment was drier than all other treatments and the mechanically conditioned and potassium carbonate treatments were drier than the control. Mechanically conditioned and potassium carbonate treatments were not significantly different.

Slightly different results were obtained when mean (across all sampling intervals) moisture contents of treatments were compared (Table 4.2). The combined treatment produced hay with the lowest moisture content, followed by the potassium carbonate treatment, mechanically conditioned treatment, and the control.

Mean moisture content was highly correlated (p=.01) with initial weight of sample dry matter across all treatments (Table 4.3). Within individual treatments, significant correlations were obtained in mechanically conditioned and combined treatments. These data indicate that drying and treatment effectiveness is related to the dry matter weight in a sample.

Table 4.1. Percent moisture content (wet basis) in B-A-1-82 [illegible]

Treatment	Time after cutting (hours) 0	19	28	44	50	[illegible]	[illegible]
Control	66.8 b	65.7 a	38.4 a	54.5 a	30.3	31.4 a	[illegible]
Conditioned	67.1 b	61.8 b	36.8 a	44.7 b	*	[illegible] b	
Pot. Carb.**	69.4 a	56.1 c	31.0 b	45.9 b	18.2	18.7 b	
Combined	66.3 b	57.0 c	27.3 c	41.8 c	20.3	14.0 c	
SEM	.39	.40	.52	.43		.54	

* Data missing due to rainfall
** - Potassium carbonate treatment
a-d - Means within a column followed by the same letter are not significantly different (P=.05) according to Duncan's New Multiple Range test

Table 4.2. Mean moisture content (wet basis) for four treatments in six experiments in 1982 and 1983.

Experiments	Treatments Control	 Conditioned	 Potassium Carbonate	 Combined
B/A-1-82	51.45 a	46.09 b	44.23 c	41.31 d
B/A-2-82	62.73 a	54.58 b	61.13 a	52.38 b
B/A-3-82	56.02 a	51.25 a	52.76 a	49.57 a
RC-1-82	67.55 a	62.08 a	69.97 a	49.44 a
B/A-1-83	48.60 a	46.07 b	47.86 a	45.22 b
A-1-83	46.57 a	44.78 a	43.71 a	42.45 a

a-d - Means within a row followed by the same letter are not significantly different (at p=.05) according to Duncan's New Multiple Range test.

Table 4.3. Correlation (r) between mean moisture content and weight of initial sample dry matter for four treatments in four experiments in 1982.

	Treatments				
Exp'ts	Control	Conditioned	Potassium Carbonate	Combined	Overall
B/A-1-82	.36 ns	.72 **	.35 ns	.76 **	.46 **
B/A-2-82	.65 **	.78 **	.71 **	.67 **	.46 **
B/A-3-82	.15 ns	.06 ns	.52 *	.64 **	.05 ns
RC-1-82	.84 **	.93 **	.76 **	.89 **	.75 **
Overall	.56 **	.69 **	.77 **	.72 **	.62 **

ns - non significant correlation
* - significant correlation at p=.05
** - significant correlation at p=.01
n=20 for individual treatments within experiments
n=80 for overall treatments and experiments

When adjusted to weight of dry matter in sample mean moisture contents were compared, treatment differences changed slightly (Table 4.4). The combined treatment dried significantly faster than all other treatments. The potassium carbonate and mechanically conditioned treatments dried significantly faster than the control but did not differ from each other. Addition of sample dry matter as a covariate in the model reduced sample variability (expressed by the error mean square) by 36% (Table 4.5).

Drying conditions during this cut were excellent (Table 4.6). A small amount of rain fell on the second night. This rain prevented sample collection for some treatments but had little effect on drying. Mature material resulted in low initial moisture values. The yield was also fairly low compared to other cuts and to the provincial average (Table 4.7).

4.1.2 B/A-2-82

Significant treatment differences were found only at 48,72 and 100 hours after cutting (Table 4.8). At 100 hours moisture contents for all treatments were significantly different. The combined treatment had the lowest moisture content, followed by the mechanically conditioned, potassium carbonate, and control treatments.

A comparison of mean moisture contents over all intervals yielded slightly different results (Table 4.2). The combined and mechanically conditioned treatments had

Table 4.4. Adjusted+ mean moisture contents (wet basis) for four treatments in four experiments in 1982.

	Treatments			
Experiments	Control	Conditioned	Potassium Carbonate	Combined
B/A-1-82	51.16 a	45.45 b	44.76 b	41.76 c
B/A-2-82	62.91 a	55.72 c	59.45 b	52.50 d
B/A-3-82	57.16 a	50.80 a	52.67 a	49.04 a
RC-1-82	68.04 a	60.74 b	68.64 a	54.59 c

+ - Treatment means adjusted for initial weight of sample dry matter by covariate analysis

a-d - Means within a row followed by the same letter are not significantly different (p=.05) according to Duncan's New Multiple Range test.

Table 4.5. Sample variability of mean moisture content (as measured by error mean square) with and without sample dry matter as covariate for six field experiments in 1982 and 1983.

Experiments	Year	Error Mean Square (without covariate)	Error Mean Square (with covariate)
B/A-1	1982	6.284	4.013
B/A-2	1982	6.007	3.538
B/A-3	1982	6.657	5.528
RC-1	1982	[illegible].322	15.543
B/A-1	1983	7.005	
A-1	1983	8.947	

Table 4.6. Environmental parameters for six field experiments in 1982 and 1983.

Experiments	Net Radiation[1] (KJ m^{-2})	Daytime[2] Temperature (°C)	Daytime RH (%)	Rain (mm)
B/A-1-82	2544	20.07 (17)[3]	66.78	5.0
B/A-2-82	2004	17.03 (16)	79.72	29.0
B/A-3-82	1399	12.31 (13)	67.71	1.0
RC-1-82	2422	21.55 (16)	72.15	1.0
B/A-1-83	2095	19.87 (17)		0.0
A-1-83	2095	19.87 (17)		

[1] Average of the daytime totals for the drying period.

[2] Averaged over daytime periods only

[3] Number of hours with positive net radiation values.

Table 4.7. Dry matter yields for six experiments in 1982 and 1983.

Experiments	Year	Dry matter(tonnes ha^{-1})
B/A-1	1982	2.37
B/A-2	1982	2.75
B/A-3	1982	2.92
RC-1	1982	3.56
B/A-1	1983	5.04
A-1	1983	6.05
Alberta average	1983	3.17

Table 4.8. Percent moisture content (wet basis) in B-A-2-82 - cut July [illegible]

Treatments	Time after-cutting (hours)							
	0	44*	48	68*	72	92	[illegible]	[illegible]
Control	67.9	76.4	69.1 a	72.3	63.8 a	47.3	[illegible] a	43.2
Conditioned	68.8	74.2	62.0 c	63.6	49.7 c	40.3	24.[illegible] c	
Pot. Carb.**	70.5	74.6	65.8 b	70.5	58.9 b	52.8	38.6 b	39.8
Combined	70.2	72.6	60.3 c	65.4	47.3 c	32.5	18.4 d	
SEM	.19	.17	.35	.27	.43	.39	.46	

* - significant rainfall (greater than 1mm) occured between this time interval and the preceeding one
** - Potassium carbonate treatment
a-d - Means within a column followed by the same letter are not significantly different (p=.05) according to Duncan's New Multiple Range test

lower moisture contents than the potassium carbonate and control treatments.

Mean moisture content was highly correlated with weight of sample dry matter across all treatments (Table 4.3). Correlation coefficients for all treatments were also highly significant (p=.01).

Adjustment of mean moisture contents by the sample dry matter covariate resulted in significant differences between all treatments (Table 4.4). The addition of sample dry matter in the model decreased sample variability by almost 50% (Table 4.5).

Frequent and substantial rainfall occurred during the drying period of this cut. A total of 29 millimeters fell over the five day period (Table 4.6). Radiation and temperature values were somewhat lower than in B/A-1-82. The yield was slightly higher (Table 4.7).

4.1.3 B/A-3-82

Significant differences were found between treatments at 99,122 and 170 hours after cutting (Table 4.9). At 99 hours after cutting, the combined, mechanically conditioned and potassium carbonate treatment produced drier hay than the control. At 122 hours after cutting, the combined and mechanically conditioned treatments produced drier hay than the potassium carbonate or control treatments. At 170 hours, the combined treatment was below 20% moisture content so no samples were removed for this treatment. A comparison of the

Table 4.9. Percent moisture content (wet basis) in B/A-3-82 - cut September 8

Treatments	Time after cutting (hours)								
	0	3	24	75	99	122	149	172	195
Control	72.3	67.9	60.7	53.3	55.5 a	47.3 a	34.4	35.5 a	24.2
Conditioned	74.6	65.0	58.8	47.1	47.9 b	36.9 b	29.1	25.8	18.6
Pot. Carb.*	73.7	68.2	57.6	48.6	48.5 b	41.7 a	31.1	29.3 b	25.7
Combined	74.2	67.4	59.1	45.8	46.0 b	36.2 b	19.5		
SEM	.20	.45	51	46	36	33	48	53	47

* - Potassium carbonate treatment
a-d - Means within a column followed by the same letter are not significantly different (p=.05) according to Duncan's New Multiple Range test.

other three treatments showed the mechanically conditioned treatment had the lowest moisture content, followed by the potassium carbonate treatment and the control.

A comparison of mean moisture contents over all intervals failed to reveal significant treatment differences (Table 4.2).

Though the combined and potassium carbonate treatments showed significant correlation between mean moisture content and weight of dry matter in the sample, the overall correlation proved nonsignificant (Table 4.3).

Adjustment of mean moisture contents to sample dry matter still produced no significant treatment differences. (Table 4.4). This is consistent with the absence of a significant correlation between mean moisture content and sample dry matter in this cut. Sample variability was only reduced slightly with the addition of the covariate (Table 4.5).

Drying conditions were poor in this cut but fairly typical of conditions found in the second (fall) cut in central Alberta. Average radiation and temperature values were only 55 and 61%, respectively, of those measured in B/A-1-82 (Table 4.6).

The average yield was slightly higher than the first two cuts, close to the provincial average for 1983 (Table 4.7).

4.1.4 RC-1-82

No significant differences existed between moisture contents at any sampling interval (Table 4.10). Though the average moisture content for the combined treatment was considerably lower than the other treatments at 52 hours, the pronounced variability between replications and within samples (Table 4.5) overshadowed treatment differences.

A comparison of mean moisture contents across all sampling intervals failed to reveal significant treatment differences (Table 4.2). Mean moisture content was highly correlated with weight of sample dry matter in all treatments (Table 4.3).

Treatment differences became significant when means were adjusted by sample weight (Table 4.4). The combined treatment had the lowest mean moisture content followed by the mechanically conditioned treatment. The potassium carbonate and control treatments had the highest mean moisture content and were not significantly different from each other.

Variability within samples was very high (Table 4.5) The addition of the covariate reduced it considerably.

Drying conditions were similar to the first cut of brome/alfalfa (Table 4.6) except that the daylengths were slightly shorter. The yield was fairly high (Table 4.7); greater than provincial average.

Table 4.10 Percent moisture content (wet basis) in RC-1-82 [illegible]

Treatments	Time after cutting (hours)					
	0	26	52	70	75	[illegible]
Control	81.0	69.6	52.0	49.9	43.5	30.6
Conditioned	83.1	62.3	42.4	39.9	37.1	
Pot. Carb.*	81.6	69.9	56.5	57.2	42.4	
Combined	79.7	48.2	21.0			
SEM	.15	.65	1.03	1.02	1.19	

* - Potassium carbonate treatment
No significant difference between treatment means at p=.05

4.1.5 B/A-1-83

Treatment differences were significant at 47,63,72 and 87 hours after cutting (Table 4.11). At 72 hours, the combined treatment had reached 20% moisture and was drier than the control or potassium carbonate treatment. No significant difference was found between combined and mechanically conditioned or potassium carbonate treated and control.

The same results were obtained when mean moisture content (all intervals) for treatments were compared (Table 4.2[illegible]

Weather conditions were quite good for this cut. Radiation values were somewhat lower than the brome/alfalfa of the previous year because of the delay in cutting (Table 4.6). Temperature values were quite similar to B/A-1-82 and no rain fell on the hay. The yield was very high; (Table 4.7) more than twice that of B/A-1-82.

4.1.6 A-1-83

Moisture contents for treatments were significantly different at 41,49,65 and 74 hours after cutting (Table 4.12). At 49 hours after cutting the combined treatment produced drier hay than any of the other treatments. At the end of the following day (74 hours after cutting) all treatments were below 20% moisture. At this time the hay from the combined treatment was significantly drier than the hay from the control treatment but was similar to hay

Table 4.11. Percent moisture content (wet basis) in B-A-1-83 cut August 4

Treatments	Time after cutting (hours)									
	0	16	26	39	47	63	72	8[illegible]	[illegible]	95
Control	73.0	69.1	51.1	50.4	36.4 a	33.9 a	26.3 a	29.5 [illegible]	23.4	19.[illegible]
Conditioned	71.0	68.2	48.2	48.0	32.5 b	31.1 a	21.3 b	24.9 [illegible]	18.8	
Pot. Carb.*	72.0	68.6	51.4	48.3	35.1 ab	33.9 a	25.8 a	28.[illegible]	21.8	19.[illegible]
Combined	71.4	66.4	47.7	50.6	31.6 b	32.[illegible] b	18.8 b			
SEM	.32	.28	.74	.56	.64	.5[illegible]	[illegible]	.28	.42	

* - Potassium carbonate treatment
a-d - Means within a column followed by the same letter are not significantly different at p≤.05 according to Duncan's New Multiple Range test

Table 4.12 Percent moisture content (wet basis) in A [illegible]

Treatments	Time after cutting (hours)						
	0	17	27	41	49	[illegible]	[illegible]
Control	73.3	66.9	47.6	51.4 a*	34.2 a	[illegible]	[illegible]
Conditioned	73.9	65.3	46.0	48.0 b	3[illegible].6 ab	[illegible]	[illegible]
Pot. Carb.*	73.3	65.5	44.0	47.4 b	[illegible] a	[illegible]	[illegible]
Combined	73.8	[illegible]	43.5	46.9 b*	25.6 b	[illegible]	[illegible]
SEM	26	48	65	58	79	[illegible]	[illegible]

* - Potassium carbonate treatment

a-d - Means within a column followed by the same letter are [illegible] Duncan's New Multiple Range test produced by the mechanically conditioned and potassium carbonate treatments.

No significant differences were found between mean moisture contents for treatments (Table 4.2).

The crop was cut simultaneously with B/A-1-83 so it dried under similar conditions (Table 4.6). The yield was almost twice that of the crops cut in 1982 (Table 4.7). Windrows were quite dense due to the high yield and the absence of a grass in the mixture.

4.1.7 Losses of dry matter

Accurate measurement of losses was not an objective of this study. However, data on this variable was easily obtained from samples taken in 1982, and comparison among the four experiments in that year are quite interesting. It is important to remember that these figures represent losses due to respiration, leaching and shattering by rain. They do not include any raking or baling losses.

Table 4.13 gives mean treatment and overall losses for experiments in 1982. No consistent differences between treatments were found. This may be partly due to different treatments remaining in the field longer than others. Also all treatments could not be collected exactly when they reached 20% moisture.

Differences between cuts were substantial. The highest losses occurred in B/A-2-82. This hay dried under high radiation values and relatively high temperatures but with a

Table 4.13. Dry matter losses (as % of original) and durat[illegible]
1982

Experiments	Treatments									
	Control		Conditioned		Potassium Carbonate		[illegible]		Mean	
	loss (%)	drying (days)	loss (%)	drying (days)	loss (%)	drying (days)	[illegible]	[illegible]	[illegible]	[illegible]
B/A-1-82	8.8	3.0	10.2	3.0	5.4	3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B/A-2-82	20.5	12.0	13.4	[illegible]	17.2	13.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B/A-3-82	-1.2	9.4	2.0	8.[illegible]	1.4	9.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RC-1-82	2.0	5.2	7.4	3.6	8.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mean	7.5	7.5	8.3	3.9	8.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

No significant differences between treatment means (losses [illegible]
a-c - Means within a column followed by the the same letter [illegible]
Duncan's New Multiple Range test

considerable amount of rainfall (Table 4.6). Leaching and leaf losses caused by the rain as well as high respiration values during sunny periods accounted for high losses. Hay stayed in the field for a long period of time (up to 13 days for some treatments) and this also contributed to the high losses.

B/A-1-82 and RC-1-82 had moderate losses. Both dried under good conditions (high respiration) with little rainfall. These figures are probably typical of first cut hay in Alberta.

B/A-3-82 had the lowest losses (mean=0.5%) even though the hay was in the field for over eight days. This is a result of the cool drying conditions with a consequent reduction in respiration values.

4.1.8 Discussion

An examination of unadjusted mean moisture content for treatments (Table 4.2) indicates an advantage of the potassium carbonate treatment over the control and the combined treatment over the mechanically conditioned treatment in only one of the six experiments. Mechanical conditioning produced drier hay than the control in three of the six experiments.

Adjusted (for sample dry matter) moisture content means indicated that the potassium carbonate treatment dried significantly faster than the control in two of the four experiments in 1982 and the combined treatment dried significantly faster than the mechanically conditioned treatment in three of the four experiments in that year (Table 4.4).

The increased effectiveness of the combined treatment over either chemical or mechanical conditioning treatments alone in three of the four experiments in 1982 agrees with the results of Rotz et al. (1984) and Redshaw and Lopetinsky (1981). Mechanical conditioning increases drying rates by cracking the stem and exposing internal cells directly to the air. Potassium carbonate is proposed to speed drying by reducing cuticular resistance. It appears that the combined treatment can speed drying more than either treatment alone. The mechanism for the increased drying rates is not clear but it is reasonable to assume that the reduction in cuticular resistance provided by potassium carbonate enhances drying rates even in cracked stems. Increased drying of the combined treatment may also be related to greater coverage of the chemical on the plant material as it is run through the conditioning rollers.

Results indicating no advantage of the conditioned treatment over the control in some cuts was surprising. In Alberta, it is generally assumed that conditioning always speeds drying.

However, Feldman and Lievers (1973) found that conditioning did not always speed drying, particularly when hay was immediately windrowed after cutting. In New Zealand, Clothier and Taylor (1980) found no statistical difference in drying rates of alfalfa produced by a disc mower with conditioner compared to the unconditioned control.

The importance of crop yield and windrow density to drying and drying enhancement treatments is shown in the high correlation coefficients between mean moisture content and weight of sample dry matter. Using sample dry matter as a covariate produced significant treatment differences in mean moisture content in several instances when original analysis showed no treatment differences. Rotz et al. (1984) found that potassium carbonate increased drying rates by 39% over that of the control when hay was dried in a windrow compared to 79% over that of control when dried in a swath. This stresses various management factors, such as leaving hay in wide windrows or swaths, and raking into loosc fluffy windrows.

B/A-3-82 showed no treatment advantage even after means were adjusted to weight of sample dry matter. Drying conditions in this cut were particularly poor and material remained in the field for a prolonged period. Treatment effectiveness may be reduced slightly by poor drying conditions. In addition, the prolonged duration of the drying period increased the effects of differential overnight rewetting. This effect is particularly important when night time periods are quite long compared to daytime drying periods. Since drier treatments take up more moisture overnight, prolonged drying under such conditions reduces treatment effect. Measurements of dry matter losses (respiration and leaching) indicate very low losses for this cut despite the lengthy drying period. Consequently, chemical drying enhancement may not be economical in the fall cut.

The poor performance of the chemical in 1983 was probably related to the very high yields experienced in these cuts. No attempt was made to create an environment to favor chemical effectiveness. High yields, such as those experienced in these cuts, would probably prompt a producer to reduce windrow density. This could be done by increasing the width of the windrow, or raking at some point after cutting. A higher rate of application may also have produced greater treatment effectiveness.

4.2 Controlled environment studies

4.2.1 Species comparisons

An analysis of 'hours to reach 20% moisture' indicated that species and treatments effects were significant at p=.05 (Table 4.14). An analysis of drying rates yielded similar results but the species-treatment interaction also proved significant (Table 4.15). A comparison of species means for 'hours to reach 20% moisture' indicated that drying was similar for 'Beaver' alfalfa, 'Anchor' alfalfa, and sainfoin (Table 4.16). Alsike clover and sweetclover dried slower than the alfalfa varieties, and red clover dried significantly slower than all other species/varieties. A

Table 4.14. Analysis of the effect of species and treatments on the time to reach 20% moisture content for six greenhouse grown legumes.

Source	df	SS	MS	F	
Reps(R)	1	90	90	3.17	ns
Species(S)	5	3347	669	23.58	**
Treatments(T)	1	4974	4974	175.19	**
ST	5	419	84	2.95	ns
Error	11	312	28		
Total	23	9142	397		

ns - not significant
** indicates that F values calculated from the mean squares are significant at the 0.01 level.

Table 4.15. Analysis of the effect of species and treatments on drying rates (b) of six greenhouse grown legumes.

Source	df	SS	MS	F	
Reps(R)	1	.00003	.00003	0.61	ns
Species(S)	5	.00424	.00085	18.24	**
Treatments(T)	1	.01392	.01392	299.75	**
ST	5	.00264	.00053	11.38	**
Error	11	.00051	.00005		
Total	23	.02134	.00093		

ns - not significant
** indicates that F values calculated from the mean squares are significant at the 0.01 level.

Table 4.16. Hours to reach 20% moisture content for six legumes dried at 18°C, 400uEm ^{2}sec ^{1}, and 45% rh.

	Treatments			
Species	Control (hours)	Potassium Carbonate (hours)	Mean (hours)	TER† (untreated)/(treated)
'Beaver' alfalfa	44.2 *	24.5	34.4 a[1]	1.80
'Anchor' alfalfa	49.8 *	22.2	36.0 a	2.24
sainfoin	52.2 *	26.2	39.2 a	1.99
alsike clover	57.5 *	37.5	47.5 b	1.53
sweetclover	72.0 *	30.0	51.0 b	2.40
red clover	87.7[2]*	50.2	69.0 c	1.75

† - ratio of untreated to treated drying times

* - Means for control and potassium carbonate treatments significantly different (p=.05) according to a t-test.

[1] Means within a column followed by the the same letter are not significantly different (p=.05) according to Duncan's New Multiple Range test.

[2] Three reps only, all other species were replicated four times.

separate analysis (t test) on each species showed that 'time to reach 20% moisture' for chemically treated material was significantly less (faster drying) than that of the control in <u>all</u> species.

A similar analysis for drying rates indicated that drying was fastest for 'Anchor' alfalfa, sainfoin, and 'Beaver' alfalfa (Table 4.17). Sweetclover and alsike clover dried slower than 'Anchor' alfalfa and sainfoin but the same as 'Beaver' alfalfa. Red clover dried slower than all other species. Drying rates for chemically treated material were significantly greater than those of the control in all species.

The treatment effectiveness ratio (TER) is a measure of the relative effectiveness of the chemical in speeding drying (drying time for untreated/drying time for treated). Examination of TER's for 'time to reach 20% moisture' for each species showed a range of effectiveness from 1.53 for alsike clover to 2.40 for sweetclover (Table 4.16). TER's for drying rates were quite similar to those for 'time to reach 20% moisture'. They ranged from 1.66 for alsike clover to 2.98 for sweetclover (Table 4.17).

Differences in species drying rates and in the TER's may be related to differences in plant morphology. Some of the factors that may affect drying rate and treatment effectiveness are cuticle type and thickness, presence of hairs, number and size of stomata, surface area to volume ratio of leaves and stem, location of water within the

Table 4.17. Drying rates(b)† after first two hours for six legumes dried at 18°C, 400uEm^{-2}sec^{-1}, and 45% rh.

	Treatments			
Species	Control (b)	Potassium Carbonate (b)	Mean (b)	TER[1] (treated)/(untreated)
'Beaver' alfalfa	-.056 *	-.096	-.076 ab[2]	1.71
'Anchor' alfalfa	-.049 *	-.112	-.081 a	2.29
sainfoin	-.043 *	-.128	-.086 a	2.98
alsike clover	-.050 *	-.083	-.066 b	1.66
sweetclover	-.042 *	-.089	-.066 b	2.12
red clover	-.034[3]*	-.055	-.045 c	1.62

† - Drying rates expressed as (Δ ln moisture content(g moisture/g dry matter) • hr^{-1})

* - Means for control and potassium carbonate treatments significantly different (p=.05) according to a t-test.

[1] - ratio of treated to untreated drying times

[2] Means within a column followed by the the same letter are not significantly different (p=.05) according to Duncan's New Multiple Range test.

[3] Three reps only, all other species were replicated four times.

plant, l/s, stem diameter, and initial moisture. The last three parameters were measured in this experiment and mean values are presented in Table 4.18.

Stem diameter and initial moisture of chemically treated and control material were similar in all instances. L/s values for the chemically treated stems were higher than control values in all species except sainfoin (Table 4.18). L/s determinations were made after drying was completed. Since treatment and control material was obtained from the same plots, there is no reason to suspect that the material was different before it was treated. The observed difference between treatment and control material probably results from overdrying and consequent loss of leaves through the holes in the wire mesh trays. This observation is consistant with the hypothesis that potassium carbonate has a greater effect on the stems than the leaves (Tullberg 1975). Sainfoin leaves may not have been affected because they were larger and thicker than the other species and remained whole throughout drying and separation. Tullberg (1975) also found that the mean l/s for control and potassium carbonate treated material were significantly different for alfalfa.

Because leaves dry faster than stems a higher l/s is associated with a lower resistance to water loss (Green and Jagger 1977).

Smaller stem diameter is also associated with faster drying, because the distance between evaporating surfaces is reduced. A high initial moisture will also result in slower

Table 4.18. Mean values for drying parameters of chemically treated and control stems of six legumes dried at 18°C, 400uEm^{-2}sec^{-1}, and 45% rh.

Species	Trt	Time to reach 20% (hrs)	Leaf/ Stem (g/g)	Stem Diameter (cm)	Initial Moisture (g/g DM)*
'Beaver' alfalfa	Cont	44.2	0.97	0.15	4.30
	Chem	24.5	1.10	0.14	4.00
'Anchor' alfalfa	Cont	49.8	0.99	0.16	4.16
	Chem	22.3	1.08	0.16	3.74
sainfoin	Cont	52.2	1.86	0.14	4.18
	Chem	26.2	1.75	0.12	3.84
sweetclover	Cont	72.0	1.17	0.23	4.85
	Chem	30.0	1.38	0.22	4.64
alsike clover	Cont	57.5	0.70	0.30	6.06
	Chem	37.5	0.72	0.28	6.08
red clover	Cont	87.7	0.66	0.35	5.89
	Chem	50.2	0.76	0.33	5.92

* - gram moisture per gram dry matter

drying.

The relationship between these parameters and overall drying for the species tested is clearly defined. The fastest drying species; the two alfalfa cultivars and sainfoin; had medium to high l/s, small stem diameters, and comparatively low initial moisture contents. Sweetclover, which dried somewhat slower, also had a high l/s, but larger stem diameter and higher initial moisture. Both alsike and red clover had very low l/s, large stem diameters, and high initial moisture contents which contributed to their slow overall drying.

4.2.2 Environment comparisons

Analysis of variance of the time to reach 20% moisture indicated significant treatment effect as well as a significant environment - treatment interaction (Table 4.19). Environmental differences in drying could not be tested as there was no replication of this variable. Individual t-tests within each environment showed that the time to reach 20% for chemical treatments was significantly less than the control in all environments (Table 4.20).

A similar analysis of drying rates also indicated significant differences between treatments and the environment-treatment interaction (Table 4.21). Individual t-tests within each environment showed that drying rates for chemical treatments were significantly higher than control in all environments (Table 4.22).

Table 4.9. Analysis of the effect of environments and treatments on the time to reach 20% moisture content for field grown 'Beaver' alfalfa.

Source	df	SS	MS	F	
Environments(E)	9	12583	1398		
Treatments(T)	1	15472	15472	1080.4	**
ET	9	3582	398	27.80	**
Error	40	572	14		
Total	59	3211			

** indicates that F values calculated from the mean squares are significant at the 0.01 level.

Table 4.20. Hours to reach 20% moisture content for field grown 'Beaver' alfalfa.

Temperature			12°C	20°C	30°C
Treatment	RH (%)	Irradiance (uEm^{-2}sec^{-1})	Time (hrs)	Time (hrs)	Time (hrs)
Control	45	450	69.0 *	34.6 *	14.7 *
Chemical			21.2	9.9	3.5
TER†			3.2	3.5	4.2
Control	45	700	71.0 *	35.6 *	15.2 *
Chemical			21.2	8.3	3.0
TER			3.4	4.3	5.1
Control	70	450		75.0 *	30.0 *
Chemical				16.4	4.9
TER				4.6	6.1
Control	70	700		59.0 *	24.6 *
Chemical				18.8	4.5
TER				3.1	5.5

† - ratio of untreated to treated drying times
* - Means for control and potassium carbonate treatments significantly different (p=.05) according to a t-test.

Table 4.21. Analysis of the effect of environments and treatments on drying rates(b) for field grown 'Beaver' alfalfa.

Source	df	SS	MS	F
Environments(E)	9	1.14	0.13	45.9[illegible]
Treatments(T)	1	0.89	0.89	322.40 **
ET	9	0.53	0.06	21.56 **
Error	40	0.11	0.003	
Total	59	2.67	0.04	

** Indicates that F values calculated from the mean squares are significant at the 0.01 level.

Table 4.22. Drying rates(b)† after first two hours for field grown 'Beaver' alfalfa.

Temperature			12°C	20°C	30°C
Treatment	RH (%)	Irradiance ($uEm^{-2}sec^{-1}$)	Time (b)	Time (b)	Time (b)
Control	45	450	-.028 *	-.058 *	-.156 *
Chemical			-.101	-.221	-.672
TER'			3.61	3.81	4.31
Control	45	700	-.029 *	-.062 *	-.144 *
Chemical			-.101	-.268	-.764
TER			3.48	4.32	5.31
Control	70	450		-.029 *	-.072 *
Chemical				-.130	-.385
TER				4.48	5.35
Control	70	700		-.036 *	-.093 *
Chemical				-.111	-.451
TER				3.08	4.85

† - drying rates expressed as (Δ ln moisture content(g moisture/g dry matter) · hr^{-1})
* - treatment means within each environment. significantly different (p=.05) according to a t-test.
'-ratio of treated to untreated drying rates.

An increase in temperature of 8-10°C approximately halved the drying time for both control and treated material (Table 4.20). Drying rates generally increased 2 to 3 times with an increase of 8-10°C. Changing irradiation levels from 450 to 700 $uEm^{-2}sec^{-1}$ decreased drying times and increased drying rates only slightly. Under constant temperatures, higher irradiation levels would raise the temperature of the plant tissue above the cabinet temperature. Increasing relative humidity from 45 to 70% increased the drying times approximately twofold for both treatments.

Increasing temperatures resulted in increasing treatment effectiveness. The mean TER's for 'time to reach 20% moisture' for all relative humidities and irradiance levels were 3.30, 3.87, and 5.22 for 12,20, and 30°C respectively. The mean TER's for drying rates were 3.54, 3.92, and 4.96 for the three temperatures. Increasing levels of irradiance increased TER's at the lower level of humidity but depressed them at the higher level. Increased treatment effectiveness was associated with higher humidity levels in all but one case (20°C and $700uEm^{-2}sec^{-1}$).

There was no relationship between 'time to reach 20% moisture' or drying rate and l/s, stem diameter, or initial moisture as expressed by the simple correlation coefficient. This contradicts findings by Tullberg (1975) that l/s was correlated with drying in untreated stems and potassium carbonate treated stems. This contradiction probably derives from the difference between the range of l/s tested. In the data reported, a range of 1.63 to 4.49 for l/s were tested by Tullberg. Values in this study for l/s ranged from 1.19 to 1.84, stem diameter from .16 to .23 centimeters and initial moisture from 1.93 to 2.67. Field grown material had passed 100% maturity so little change would be expected in l/s, stem diameter, or initial moisture over time. The effort made to test material quickly to avoid differences due to maturity also contributed to the restricted range of the measured parameters.

Results from the greenhouse grown material were considerably more variable than those for the field grown material (Table 4.23). Prolonged drying times of control material prevented accurate determination of the 'time to reach 20%' in many of the environments. In addition some material appeared to reach equilibrium moisture above 20%. Consequently, a comparison of drying times between greenhouse and field grown material or between treatments in greenhouse material is not appropriate. The reason for the variability in this data was not apparent but may have resulted from poor relative humidity control in some of the chambers. All of the greenhouse grown material was run after the field grown material and an undetected problem may have developed in some of the chambers.

A more complete set of data is presented for drying rates (Table 4.24). Coefficients of determination (r^2) for drying rates for the greenhouse grown material were not as high as those for the field grown material and in three

Table 4.23. Hours to reach 20% moisture content for greenhouse grown 'Beaver' alfalfa.

Temperature			12°C	20°C	30°C
Treatment	RH (%)	Irradiance ($\mathrm{uEm^{-2}sec^{-1}}$)	Time (hrs)	Time (hrs)	Time (hrs)
Control	45	450	101.0	50.7	23.7
Chemical			43.9	22.4[1]	17.4
TER[2]			2.3	2.3	1.4
Control	45	700		27.1	17.2
Chemical				8.8[1]	9.7
TER				3.1	1.8
Control	70	450	*	*	18.0
Chemical			*	22.0	8.0
TER					2.2
Control	70	700		48.5	22.0
Chemical				21.5	17.0
TER				2.3	1.3

[1] - 2 reps only
[2] - ratio of untreated to treated drying times
* - reached equilibrium moisture above 20%

Table 4.24. Drying rates(b)† after first two hours for greenhouse grown 'Beaver' alfalfa.

Temperature			12°C	20°C	30°C
Treatment	RH (%)	Irradiance ($uEm^{-2}sec^{-1}$)	Time (b)	Time (b)	Time (b)
Control	45	450	-.025	-.038[1]	-.096 *
Chemical			-.048	-.050	-.165
TER[2]			1.96	1.32	1.72
Control	45	700		-.062	-.105 *
Chemical				-.229	-.395
TER				3.69	3.76
Control	70	450	-.029[1]	-.050	-.111 *
Chemical			-.028	-.093	-.278[1]
TER			0.97	1.86	2.50
Control	70	700		-.042	-.084 *
Chemical				-.095	-.169
TER				2.26	2.01

† - drying rates expressed as (Δ ln moisture content(g moisture/g dry matter) • hr^{-1})

[1] 2 reps only

[2] ratio of treated to untreated drying rates

* - treatment means within each environment significantly different (p=.05) according to a t-test

cases regressions were not significant (Appendix 3). An analysis of variance of this data indicates significant treatment effect but no significant environment-treatment interaction (Table 4.25). However, significant differences between treatments were found only at 30°C (Table 4.24).

Though specific comparisons are not appropriate, TER's for the greenhouse material were generally lower than for the field grown material. Differences in drying rates and TER's for field and greenhouse material may be related to differences in the measured parameters of the two types of material (Table 4.26). Greenhouse grown material had lower leaf/stem, smaller stem diameters, and higher initial moistures. However, correlations between drying rates and these measured parameters were not significant.

Differences between the two types of material may also relate to differences in unmeasured parameters. Greenhouse grown plants have been found to have a much thinner cuticle than field grown plants (Hull 1958). This may be due to differences in light quality in greenhouse conditions. Material with a thinner cuticle might be expected to respond less to a chemical which decreases cuticular resistance. The lower TER's for greenhouse grown material indicate that this may have been the case in this experiment.

Table 4.25. Analysis of the effect of environments and treatments on drying rates (b) for greenhouse grown 'Beaver' alfalfa.

Source	df	SS	MS	F
Environments(E)	9	0.335	0.037	8.97
Treatments(T)	1	0.051	0.051	12.28 **
ET	9	0.028	0.003	0.73 ns
Error	39	0.162	0.004	
Total	58	0.645	0.011	

** indicates that F values calculated from the mean squares are significant at the 0.01 level.
ns - not significant

Table 4.26. Means (and standard deviations) for drying parameters of chemically treated and control stems of field and greenhouse grown 'beaver' alfalfa dried in ten environments.

Treatment	Parameters	Field	Greenhouse
Control	Drying rate	-0.07(.05)	-0.06(.03)
	L/S	1.49(.18)	0.82(.25)
	Stem diameter	0.19(.02)	0.14(.02)
	Initial moisture(db)	2.38(.18)	3.92(.51)
Chemical	Drying rate	-0.32(.24)	-0.16(.12)
	L/S	1.49(.22)	0.84(.20)
	Stem diameter	0.19(.02)	0.14(.02)
	Initial moisture(db)	2.28(.17)	3.73(.63)

5. SUMMARY AND CONCLUSION

In field studies in 1982, the potassium carbonate treatment dried significantly faster than the control in two of the four experiments whereas mechanically conditioned and combined treatments dried faster than the control in three of the four experiments after treatment means were adjusted for initial weight of sample dry matter. In three of the four cases, the combined treatment dried faster than either treatment alone.

Yields in 1983 were very high (5 to 6 tonnes/ha). In this year, no significant differences were found between treatments. The absence of significant treatment effect in 1983 probably resulted from very high windrow resistance but differences in sample dry matter may also have masked significant treatment effects. A change in the sampling technique precluded the use of dry matter as a covariate in 1983.

Mean moisture content was highly correlated with weight of dry matter in samples in all experiments in 1982 except B/A-3-82. This, combined with the significant treatment differences found in the two cuts with the lowest yields (B/A-1-82 and B/A-2-82), indicates a significant treatment interaction with yield and windrow density. Decreasing windrow density by laying the crop in as wide a windrow as possible or by mowing and then windrowing in a later operation would increase the effectiveness of chemical treatment.

The results of B/A-3-82 (no significant treatment effect) indicate that spraying with potassium carbonate is not useful in the fall cut in Alberta. Slightly decreased treatment effectiveness found at 12 and 20°C in the controlled environment studies may account for some of this ineffectiveness. Prolonged rewetting periods may also partially explain the ineffectiveness of the chemical during this cut. If the very low values for dry matter losses calculated for this experiment are typical of losses at this time, drying enhancement would save the producer little in any case.

Potassium carbonate will speed drying of a number of different legumes (greenhouse grown) dried as single stems in a single controlled environment. All species tested showed a decrease in drying time of at least 36% with the application of potassium carbonate. The greatest drying advantage was found in sweetclover and the least in alsike and red clover.

Treatment of field grown 'Beaver' alfalfa with potassium carbonate decreased drying time by 68 to 84% across a wide range of controlled environments. A similar experiment on greenhouse grown 'Beaver' alfalfa suggested possible differences in the effect of potassium carbonate on field grown versus greenhouse grown material.

In single stem drying, the chemical is consistently effective on a variety of legumes grown for hay in Alberta and under levels of temperature and relative humidity typical of conditions here. Differences in the consistency and magnitude of the effect of potassium carbonate on these legumes dried as single stems under varied environmental conditions and under field conditions indicate considerable interaction with crop yield, windrow structure, and other environmental variables associated with field conditions. Recommendations for the use of the chemical in field drying will be subject to crop and environmental conditions.

The chemical should not be recommended for fall cut (September and October) hay. The slight decrease in effectiveness of the chemical at lower temperatures (12°C) found in the controlled environment studies may affect treatment effectiveness in the field in this cut. Of greater importance in the field would be the effect of rewetting. Because drier treatments take up more moisture overnight, the relative number of drying to nondrying hours in a day will be important in determining eventual treatment effectiveness. In central Alberta, this would tend to favor chemical conditioning in summer cut hay (June, July, and August) over fall cut hay (September and October).

The structure of the windrow will be determined by crop yield and the type of machine used for cutting and postcutting treatments. Structural strength of the forage species will also be important in determining windrow or swath structure. Slight species differences in the effect of potassium carbonate on the drying of single stems of the five legumes tested would largely be overshadowed in the field by differences in the type of windrow or swath formed by each species. Species with fairly strong stems, such as alfalfa or sweetclover form a less dense windrow than species with weak stems (red or alsike clover). This loose, open type of windrow will favor the use of drying enhancement procedures. The addition of a strong stemmed grass, such as smooth brome, timothy (<u>Phleum pratence</u> L.), or reed canarygrass (<u>Phalaris arundinaceae</u> L.) will also help to form a loose windrow, thereby increasing the effect of drying enhancement techniques.

Crop yield, as it affects the density of the swath or windrow, will also determine the magnitude of drying enhancement of a particular treatment. The data from this study indicate that drying enhancement will be successful for a crop up to 4 tonnes/hectare using the traditional system of a mower conditioner. This system would include leaving the crop in a relatively narrow windrow (1 meter wide from a 3 meter cut) with no other postcutting procedures. In a crop over 4 tonnes/hectare, some type of management to increase drying rates and treatment drying enhancement should be incorporated. Preferably, the crop should be left in a swath or wide windrow for initial drying and then raked to form windrows when the crop reaches about 50 to 55% moisture. Raking or fluffing the windrow or swath in the early stages of drying would also be beneficial.

These recommendations are based on the significant differences in mean moisture content which were found between treatments in certain experiments. However, statistically significant differences do not imply an economic advantage. A number of factors will be important in determining the acceptance of the procedure by a producer. Foremost among these will be the cost (in money and labor), the benefits in terms of increased quality and quantity of crop harvested, and the feeding system for which the hay is intended.

A full economic analysis of the possible benefits of the chemical in increasing quality and quantity of hay involves a multitude of factors. These would include the probability of rain during the curing period, losses associated with the type of machinery used, respiration losses associated with differences in weather conditions during drying and a host of other factors. Milligan et al. (1981) estimate an average loss of 4-10% of digestible energy intake of hay following a rainfall of over 30 millimeters and a loss of 27-35% of digestible energy intake following raking after 30 millimeters of rain. The range of losses reported by Milligan et al. (1981) would translate into a loss of \$10 to \$24/hectare for an average 4 tonnes/hectare crop (at \$60/tonne) after rain and \$63 to \$84/hectare after the hay was raked following rain. At an estimated cost of \$18/hectare (\$14/hectare for the chemical and \$4/hectare associated with the cost of application) for potassium carbonate application, benefits could accrue if the treatment could speed drying enough to avoid the rain damage.

The economics of the procedure will also depend on the type of feeding system for which the hay is intended. Chemical treatment will be more attractive to operations which require high quality hay (e.g. dairy operations or other operations where maximum forage intake is essential). The procedure would not be attractive for producers involved primarily in maintenance feeding (e.g. cow/calf operations).

Further research in this field should be aimed at determining exactly how much field time could be saved using potassium carbonate under intensive management. Estimates of quality and quantity of forage harvested in comparison with normal practice would be useful to producers. Further controlled environment studies should focus on comparing field and greenhouse grown material.

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Appendices

Appendix 1. Drying rates(b), standard errors(se), and coefficients of determination(r^2) for six legumes dried as single stems in a single controlled environment.

Treatment		Control			Chemical		
Species	Rep	(b)	(se)	(r^2)	(b)	(se)	(r^2)
'Beaver' alfalfa	1	-.038	.0007	.984	-.089	.0006	999
	2	-.045	.0006	.992	-.083	.0007	998
	3	-.039	.0009	.987	-.098	.0010	997
	4	-.046	.0050	.792	-.088	.0007	999
'Anchor' alfalfa	1	-.047	.0008	.987	-.078	.0020	.982
	2	-.054	.0010	.982	-.074	.0010	.989
	3	-.052	.0020	.950	-.084	.0020	988
	4	-.049	.0030	.943	-.097	.0030	988
Sainfoin	1	-.049	.0010	.985	-.149	.0080	957
	2	-.039	.0008	.983	-.116	.0040	975
	3	-.041	.0008	.992	-.055	.0030	933
	4	-.045	.0006	.996	-.069	.0030	969
Sweetclover	1	-.038	.0007	.984	-.089	.0006	999
	2	-.045	.0006	.992	-.083	.0007	998
	3	-.039	.0009	.987	-.098	.0010	997
	4	-.046	.0009	.792	-.088	.0007	999
Alsike clover	1	-.047	.0008	.987	-.078	.0020	982
	2	-.054	.0010	.982	-.074	.0010	989
	3	-.052	.0020	.950	-.084	.0020	988
	4	-.049	.0030	.943	-.097	.0030	988
Red clover	1	-.035	.0007	.980	-.068	.0010	991
	2	-.032	.0005	.986	-.051	.0010	979
	3	-.035	.0020	.899	-.050	.0020	956

Appendix 2. Drying rates(b), standard errors(se), and coefficients of determination(r^2) for field grown Beaver alfalfa dried in ten environments

Temperature				12°C			20°C			30°C		
Treatment	Rep	RH (%)	Irradiance ($uEm^{-2}sec^{-1}$)	(b)	(se)	(r^2)	(b)	(se)	(r^2)	(b)	(se)	(r^2)
Control	1	45	450	-.032	.0007	.992	-.057	.0029	.963	-.185	.0156	.966
	2			-.029	.0006	.993	-.062	.0022	.982	-.153	.0099	.979
	3			-.024	.0006	.988	-.056	.0018	.984	-.131	.0079	.979
Chemical	1			-.106	.0041	.988	-.222	.0139	.985	-.712	.0621	.992
	2			-.109	.0049	.986	-.228	.0164	.980	-.625	[illegible]	.999
	3			-.088	.0025	.993	-.213	.0207	.964	-.680	.0172	.999
Control	1	45	700	-.027	.0006	.994	-.061	.0013	.985	-.141	.0058	.990
	2			-.029	.0007	.993	-.067	.0026	.967	-.146	.0092	.976
	3			-.030	.0008	.992	-.058	.0010	.991	-.144	.0047	.994
Chemical	1			-.102	.0078	.950	-.328	.0045	.999	-.722	.0272	.999
	2			-.124	.0102	.949	-.219	.0152	.976	-.740	.0577	.994
	3			-.078	.0084	.897	-.257	.0122	.991	-.830	.0693	.993
Control	1	70	450				-.026	.0003	.996	-.067	.0022	.986
	2						-.031	.0008	.986	-.088	.0027	.991
	3						-.030	.0007	.991	-.062	.0021	.985
Chemical	1						-.129	.0142	.933	-.422	.0823	.930
	2						-.131	.0068	.984	-.294	.0675	.864
	3						-.131	.0085	.976	-.440	.0627	.960
Control	1	70	700				-.033	.0005	.996	-.104	.0023	.996
	2						-.040	.0020	.961	-.083	.0017	.996
	3						-.035	.0008	.990	-.084	.0018	.995
Chemical	1						-.094	.0167	.818	-.302	.0887	.853
	2						-.135	.0031	.997	-.595		.000
	3						-.105	.0174	.839	-.457	.0266	.997

Appendix 3. Drying rates(b), standard errors(se), and coefficients of determination(r^2) for greenhouse grown 'Beaver' alfalfa dried in ten environments

Temperature				12°C			22°C			35°C		
Treatment	Rep	RH (%)	Irradiance ($uEm^{-2}sec^{-1}$)	(b)	(se)	(r^2)	(b)	(se)	(r^2)	(b)	(se)	(r^2)
Control	1	45	450	-.027	.0019	.940	ns			-.118	.1863	.968
	2			-.026	.0018	.943	-.038	.0941	.957	-.129	.2141	.958
	3			-.021	.0007	.997	-.038	.0863	.978	-.041	.3477	.870
Chemical	1			-.052	.1802	.932	-.036	.1807	.828	-.175	.5308	.783
	2			-.044	.1055	.966	-.060	.2371	.801	-.097	.4189	.802
	3			-.048	.0725	.992	-.055	.1988	.925	-.223	.3182	.942
Control	1	45	700				-.056	.0039	.976	-.128	.0147	.949
	2						-.056	.0037	.985	-.096	.0014	.983
	3						-.073	.0038	.992	-.091	.0044	.998
Chemical	1						-.328	.1457	.988	-.609	.0962	.998
	2						-.142	.5001	.745	[illegible]	[illegible]	.818
	3						-.218	.3744	.894	-.276	.3632	.904
Control	1	70	450	-.034	.0168	.994	-.053	.0037	.960	-.108	.0054	.985
	2			-.024	.0430	.963	-.047	.0017	.983	-.104	.0047	.991
	3			ns			-.050	.0029	.977	-.120	.0049	.992
Chemical	1			-.029	.1069	.774	-.100	.1878	.933	-.168	.4251	.839
	2			-.026	.0339	.980	-.104	.1456	.962	ns		
	3			-.028	.0323	.986	-.074	.1369	[illegible]	-.391	.6133	.803
Control	1	70	700				-.029	.0012	[illegible]	-.086	[illegible]	.975
	2						-.032	.0015	.966	-.087	.0118	.989
	3						-.066	.0024	[illegible]	-.078	.2292	.887
Chemical	1						-.093	[illegible]	[illegible]	[illegible]	[illegible]	.733
	2						[illegible]	[illegible]	[illegible]	-.112	[illegible]	.869
	3						-.112	[illegible]	[illegible]	-.214	[illegible]	.827