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# Effect of mechanical conditioning, windrow handling, and maturity on the drying rate of timothy hay in a wind tunnel

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Savoie, P., Tremblay, Y., Dubreuil, S. and Khelifi, M. 2002. **Effect of mechanical conditioning, windrow handling, and maturity on the drying rate of timothy hay in a wind tunnel.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **44**:2.1-2.8. The time needed to reach a low moisture content of 16%, as required for commercial hay or biomass, was estimated with various conditioning and windrow handling techniques at three maturity stages. Fresh timothy was placed in a drying tunnel simulating alternately sunny conditions (0.42 mm pan water evaporation per hour) for 4 h and overcast conditions (0.05 mm pan water evaporation per hour) for 20 h. The time to reach the target moisture content of 16% after mowing was found to be 59, 43, and 37 h at the boot, early heading, and heading stages, respectively, under similar conditions. Windrows on a dry soil reached the target moisture in 5 to 13 h less time than windrows on a wet sandy soil at 80% water saturation. Intensive mechanical conditioning reduced drying time by 4 to 9 h compared to no conditioning. Spreading the windrow in a wide swath reduced drying time by 4 to 7 h. Windrow inversion after 24 h reduced drying time by 6 h. The field drying time of hay may therefore be reduced by harvesting a more mature crop, conditioning it, inverting the windrow and spreading it over the dryer part of the stubble. **Keywords:** hay, biomass, drying, conditioning, timothy, windrow.

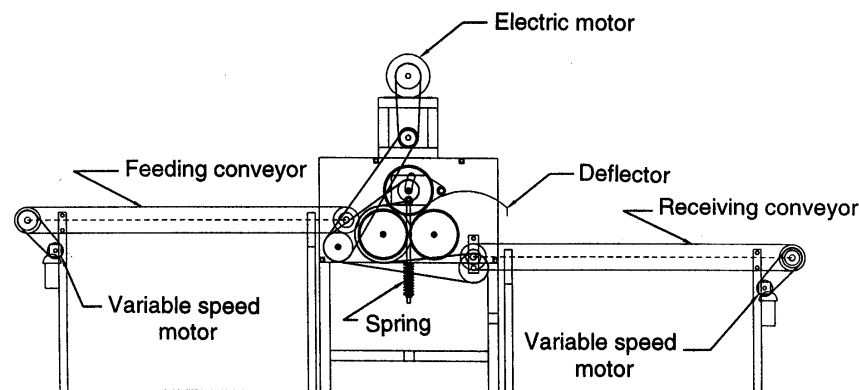
On a estimé le temps nécessaire pour sécher de la fléole des prés jusqu'à une teneur en eau cible de 16%, jugée nécessaire pour la production de foin commercial ou de biomasse énergétique, en fonction du conditionnement et de la manipulation des andains à trois stades de maturité. On a placé de la fléole fraîchement fauchée pendant 4 h par jour dans un tunnel de séchage simulat des conditions ensoleillées (0,42 mm d'évaporation d'eau h<sup>-1</sup>), suivies de 20 h par jour dans des conditions simulat l'ennuage (0,05 mm d'évaporation d'eau h<sup>-1</sup>). Le temps pour atteindre la teneur en eau cible (16%) était de 59, 43 et 37 h aux stades de gonflement, début épiaison et épiaison, respectivement, sous des conditions de séchage similaires. Les andains sur un sable sec atteignaient la teneur en eau cible de 5 à 13 h plus rapidement que des andains déposés sur un sable humide, à 80% de saturation d'eau. Un conditionnement mécanique intense réduisait le temps de séchage de 4 à 9 h par rapport à aucun conditionnement. L'étalement des andains réduisait le temps de séchage de 4 à 7 h. Le retournement des andains effectué après 24 h de fanage réduisait le temps de séchage de 6 h par rapport à aucun retournement. On peut ainsi réduire le temps de séchage du foin en fauchant le fourrage à un stade de maturité avancé, en le conditionnant, en l'étalant, en le tournant et en le déposant sur la portion sèche du chaume. **Mots-clés:** foin, biomasse, séchage, conditionnement, fléole, andain.

## INTRODUCTION

The main objective of forage production on livestock farms is to provide an economical feed for the maintenance and growth of animals. To reach this objective, forage is usually harvested at an early maturity stage when the levels of metabolizable energy and crude protein are high and the fibre content is low (Hopkins 2000). However, when grass is produced for sale outside the farm, objectives may be different. A major market for dry grass is "horse" quality hay, typically mature and green with a high fibre content (CHA 2001). Another potential market for herbaceous crops is the biomass industry which requires a cellulose-rich (i.e. high fibre) crop for conversion into sugars and ethanol (Wyman 1996).

Most of the current haymaking techniques have been developed for handling early maturity forages for livestock farms. Several studies have compared mowing, conditioning, and windrow handling techniques in this context (Borreani et al. 1999; Shinnars et al. 1991; Rotz and Savoie 1991). New mechanical treatments have been proposed for improving the field drying rate and the feed value of forage, mainly for livestock production (Savoie 2001). Little work has been done, however, with respect to handling more mature crops that are preferred for the horse hay and biomass markets.

The objective of this research was to determine the effect of hay handling techniques on the time needed to produce dry hay, especially in the context of grass at varying maturity stages. Factors investigated included controllable factors such as mechanical conditioning, windrow turning, windrow thickness (i.e mass per unit area), and maturity stage at mowing, and other factors that are more difficult to control such as evaporation potential and soil moisture. This investigation was carried out in the laboratory where a drying tunnel simulated field drying conditions with wind and solar radiation. Drying in a wind tunnel removes natural phenomena such as dew and fluctuating air conditions, has the advantage of allowing a well controlled comparison of different factors, and has regularly been used to assess mechanical treatments for hay making (Savoie 2001). The crop used was timothy (*Phleum pratense*) because of its abundance in eastern Canada and its good potential for both the horse hay market (CHA 2001) and the biomass market (Alvo et al. 1996).



**Fig. 1. Schematic view of the three-roll intensive forage conditioning test bench.**

## METHODOLOGY

### Experimental protocols

Fresh timothy mowed on June 12, 20, and 26, 2000 at the Deschambault Experimental Farm, Québec was brought to the laboratory at Université Laval in Sainte-Foy. The dates corresponded to three maturity stages: boot, early heading, and heading. At each mowing date, an experimental protocol was followed to evaluate various factors and their effect on forage windrow drying.

Three factors were compared during the first experiment (mowing on June 12): (1) mechanical conditioning (MC) at two levels (no conditioning and intensive conditioning), (2) soil moisture (SM) at two levels (dry sand and 80% water saturated sand), and (3) windrow inversion (I) at three levels (no inversion, inversion 24 h or 48 h after mowing). In total, twelve treatment combinations were evaluated and replicated three times which required the preparation of 36 forage trays. During the first experiment, a mass of 600 g of fresh forage was placed in a tray of dimensions 300 mm by 450 mm for each treatment and replication. Since the forage had an average initial moisture content of 82.7% (wet basis), this mass represented 0.77 kg dry matter (DM)/m<sup>2</sup>. Such a windrow corresponded to a forage yield of 3.8 t DM/ha that would be narrowed to cover half the surface after mowing.

During the second experiment (mowing on June 20), three factors were evaluated: (1) mechanical conditioning at two

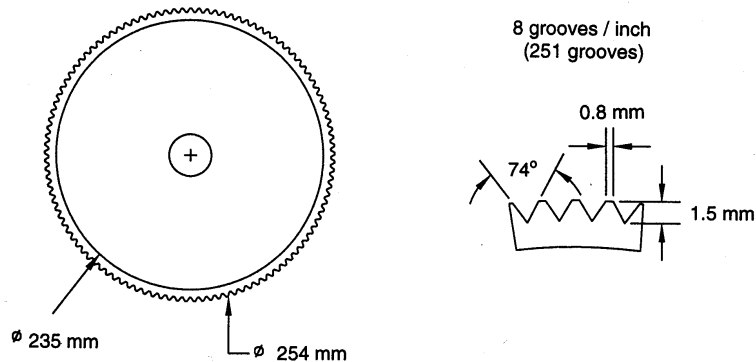
levels (intensive and no conditioning), (2) mass of fresh forage in the windrow at three levels (400, 600, and 800 g per tray), and (3) soil moisture at two levels (dry sand and 80% water saturated sand). The twelve treatment combinations were replicated three times resulting in 36 trays. No inversion was applied. Since the average moisture content was 78.9% (wet basis), the three levels of mass per unit area corresponded to 0.63, 0.94, and 1.25 kg DM/m<sup>2</sup>.

During the third experiment (mowing on June 26), three factors were evaluated: (1) mechanical conditioning at three levels (no conditioning, intensive conditioning once, and intensive conditioning twice), (2) mass of fresh forage in the windrow at two levels (400 and 800 g per tray), and (3) windrow inversion at two levels (no inversion or inversion 48 h after mowing). The experiment was replicated three times on the 12 treatment combinations. All forage windrows were laid on dry soil in this third experiment. Since forage moisture content averaged 81.2% (wet basis), the two levels of windrow thickness corresponded to 0.54 and 1.08 kg DM/m<sup>2</sup>.

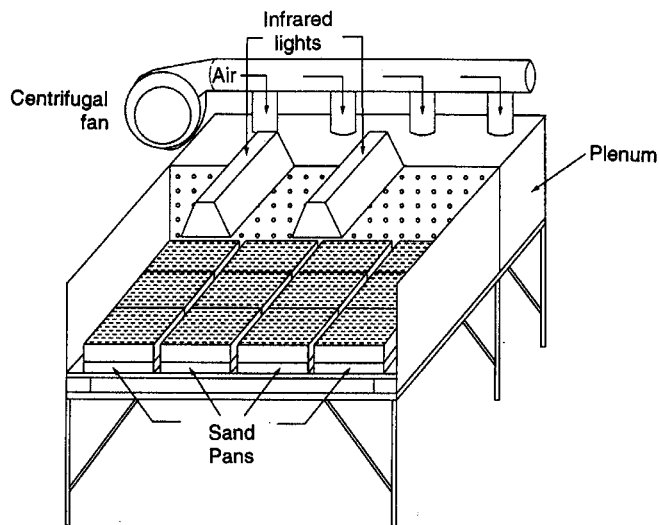
### Forage preparation and treatment

Forage was mowed with a cutterbar, without conditioning, between 8:00 and 9:00 h and brought to the laboratory by 10:00 h in plastic bags to avoid moisture loss. Part of the forage was intensively conditioned with a three-roll test bench illustrated in Fig. 1. Such intensive conditioning is similar to “maceration” which has been observed to increase the field drying rate by 26 to 160% in ten different experiments reviewed by Savoie (2001). Each macerating roll was 600 mm long with a 254 mm outside diameter (Fig. 2); its outer surface was grooved to provide a shearing effect on the forage surface. Roll speeds were 866 rpm for the two bottom rolls and 1732 rpm for the upper roll which was spring loaded to allow vertical displacement as forage passed through the conditioner. Spacing between the rolls was set at 1 mm. This test bench was built to specifications nearly identical to the three-roll field prototype described by Savoie et al. (1999). The intensive mechanical conditioning treatment was applied to the fresh forage before the onset of drying.

A pre-determined mass of fresh forage (400, 600, or 800 g, depending on treatment and experiment) was spread out in a wire-mesh tray (25 mm mesh size with a fine nylon screen at the bottom). Trays had horizontal dimensions of 300 mm by 450 mm and a height of 120 mm. The forage was placed in each tray to simulate a short windrow section. The various initial fresh masses were intended to compare the drying rate between “light”, “medium”, and “heavy” windrows. The initial moisture content of fresh forage was determined by taking a 200-g sample from the same batch of forage used to prepare each tray. Samples were oven dried at 60°C for 72 h (ASAE 2001; standard procedure S358.2).



**Fig. 2. Surface characteristics of the roll.**



**Fig. 3. Wind tunnel with 12 forage trays simulating windrows in a natural drying environment.**

To study the effect of soil moisture on windrow drying, trays containing forage were placed over soil pans of 60 mm height filled with a fine silica sand (mean diameter of 0.14 mm). The sand pan surface area was slightly larger (340 mm by 490 mm) than the forage tray which sat completely on the sand layer. For the dry soil treatment, pans contained dry sand only. For the wet soil treatment, water was added until 80% soil saturation was reached.

The inversion treatment was applied manually. The windrow was turned upside down and placed back into the tray at the designated time (either 24 h after mowing, 48 h after mowing, or not at all).

### Drying procedure

Twelve trays were placed simultaneously in a tunnel that reproduced field drying conditions with wind and radiation (Fig. 3). The tunnel was connected to a centrifugal fan blowing ambient air at a temperature of  $24 \pm 2^\circ\text{C}$ . The velocity of air averaged 1.43 m/s (SD = 1.10 m/s) based on 48 measurements taken horizontally at a height equivalent to the forage upper surface, when no forage tray was in the tunnel. Two infrared lamps of 1600 W each were installed at 1.0 m above the forage trays. The pan water evaporation rate at the forage surface was calibrated to be as homogeneous as possible by adjusting the horizontal lamp position (average evaporation rate of 0.42 mm/h, typical of a mild sunny day, with SD = 0.08 mm/h between the twelve positions). To reduce the effect of evaporation rate differences, all trays were moved every 10 minutes and each tray made a complete rotation (i.e. occupied each position in the tunnel) by the end of a 2-h cycle. During forage tray rotation, each soil pan was also rotated to accompany the same forage tray throughout the drying cycle.

On a mowing day, a first set of 12 trays was placed at 12:00 h in the tunnel and the first drying period in the tunnel was completed by 14:00 h. Trays were placed alternately in the drying tunnel or in the shade during three or four days to complete the entire drying cycle, as described below. When trays were removed from the tunnel, they were left in the shade in the laboratory under ambient air where the pan evaporation

rate averaged 0.05 mm/h. Over a 24-h period, each tray was exposed to about 2.7 mm pan evaporation. Pitt (1984) estimated that 3 mm evaporation was required to remove half the available water in field drying forage.

During each experiment, 3 replications (or blocks) of the 12 treatments were carried out with a short time delay between each replication. A set of 12 forage trays, representing one replication, was dried simultaneously. The first replication had the following sequence over a three day period. On the first day, trays were initially placed (at about 12:00 h) for 2 h in the tunnel, then 4 h in the shade, again 2 h in the tunnel, and finally 12 h in the shade. On the second day, windrows were turned upside down at 8:00 h in cases where the inversion treatment was applicable (24 h after mowing). All forage trays were then placed in the tunnel for 2 h, moved for 4 h in the shade, moved again for 2 h in the tunnel, and finally left 16 h in the shade. On the third day, windrows were turned upside down at 8:00 h in cases where the inversion treatment was applicable (48 h after mowing). The 12 windrows were placed in the tunnel for 6 h, after which replication 1 was terminated. The forage from each tray was then placed in a perforated paper bag for determination of the final moisture content (ASAE 2001; standard procedure S358.2).

The second replication followed the same sequence as the first replication with a 2-h delay during the first and second day, and a 6-h delay during the third day. The third replication followed the same sequence as replication 1 with a 4-h delay during the first and second days. On the third day, the 12 forage trays of the third replication were left in the shade all day and all night until the fourth day (i.e. 40 h in the shade instead of 16 h in the case of replication 1 and 20 h in the case of replication 2 between day two and the last day of drying in the tunnel). The last sequence of 6-h drying in the tunnel for the third replication was therefore postponed to start on the 4th day at 8:00 h. The three replications were analysed as three randomized blocks so that the longer time in the shade for replications 2 and 3 would not affect comparisons between treatments.

The initial and final moisture contents were used to estimate initial and final dry matter in each tray. The arithmetic average dry matter was used to estimate intermediate moisture contents. Trays containing forage were weighed before and after each period in the tunnel to monitor moisture evaporation. Drying coefficients were calculated using the model of Rotz and Chen (1985):

$$M = M_0 \exp(-kt) \quad (1)$$

where:

- M = moisture content on dry basis (kg of water/kg of DM),
- t = drying period (h),
- $M_0$  = initial moisture content at beginning of drying period (kg of water/kg of DM), and
- k = drying coefficient ( $\text{h}^{-1}$ ).

From Eq. 1, the drying coefficient was estimated as:

$$k = \frac{\ln(M_0 / M)}{t} \quad (2)$$

Drying coefficients were estimated for four periods. Coefficient  $k_1$  corresponded to the drying period of day 1 (4 h in tunnel and 4 h in shade) which was between 0 to 8 h after the beginning of drying in the tunnel. Coefficient  $k_2$  corresponded

**Table 1. Drying coefficients (k) and drying time (t) for timothy mowed on June 12, 2000 at the boot stage (experiment 1).**

Parameters	Moist sand															
	Dry sand						Moist sand									
	No conditioning			Conditioning			No conditioning			Conditioning						
	I <sub>0</sub> <sup>a</sup>	I <sub>24</sub>	I <sub>48</sub>	I <sub>0</sub>	I <sub>24</sub>	I <sub>48</sub>	I <sub>0</sub>	I <sub>24</sub>	I <sub>48</sub>	I <sub>0</sub>	I <sub>24</sub>	I <sub>48</sub>	SE <sup>b</sup>	SM <sup>c</sup>	MC	I
k <sub>1</sub> <sup>d</sup> (h <sup>-1</sup> )	0.0832	0.0859	0.0864	0.0897	0.0937	0.0920	0.0771	0.0789	0.0788	0.0808	0.0788	0.0841	0.004	0.001	0.05	NS
k <sub>2</sub> (h <sup>-1</sup> )	0.0853	0.1075	0.0795	0.0789	0.1156	0.0835	0.0664	0.0896	0.0668	0.0695	0.1032	0.0640	0.005	0.001	NS	0.001 <sup>Q</sup>
k <sub>3</sub> (h <sup>-1</sup> )	0.0969	0.0951	0.1019	0.1101	0.1003	0.1430	0.0904	0.0974	0.1191	0.1102	0.1153	0.1605	0.011	NS	0.002	0.05 <sup>L,Q</sup>
k <sub>OF</sub> (h <sup>-1</sup> )	0.0483	0.0527	0.0483	0.0483	0.0540	0.0540	0.0393	0.0433	0.0423	0.0410	0.0453	0.0437	0.002	0.001	0.08	0.05 <sup>L,Q</sup>
t <sub>16%</sub> <sup>e</sup> (h)	58.6	53.3	59.6	56.8	50.5	51.4	73.9	67.4	69.9	70.4	62.4	66.8	3.3	0.001	0.06	0.03 <sup>Q</sup>

<sup>a</sup> Subscripts of I indicate no inversion (0), inversion 24 and 48 h after mowing, respectively.

<sup>b</sup> SE = Standard Error

<sup>c</sup> SM = soil moisture; MC = mechanical conditioning, I = windrow inversion

<sup>d</sup> Subscripts of the drying coefficients k stand for day 1, day 2, day 3, and overall (OF), respectively.

<sup>e</sup> Time to reach a moisture content of 16% (wet basis)

NS = non-significant at the 10% level

L, Q = linear and quadratic effects, respectively

to the drying period of day 2 (4 h in tunnel and 4 h in shade) which was between 20 and 28 h after the beginning of drying in the tunnel for each replication. Coefficient k<sub>3</sub> corresponded to the drying period of day 3 (6 h in tunnel) which was between 44 and 50 h after the beginning of drying in the tunnel for replication 1, between 48 and 54 h for replication 2, and between 64 and 70 h for replication 3. The overall drying coefficient, k<sub>OF</sub>, also was estimated. This corresponded to a drying period of 0 to 50 h for replication 1, 0 to 54 h for replication 2, and 0 to 70 h for replication 3.

Another estimated variable (t<sub>16%</sub>) was the time to reach the desired moisture content of 16% on a wet basis (0.191 kg of water/kg of DM, on a dry basis). Interpolation or extrapolation was used to calculate this variable depending on whether the final moisture content measured experimentally was lower or higher than 0.191 kg/kg. Coefficient k<sub>3</sub> was used in the case of extrapolation.

### Statistical analysis

SAS (1990) software was used to analyse the variance of the variables k<sub>1</sub>, k<sub>2</sub>, k<sub>3</sub>, k<sub>OF</sub>, and t<sub>16%</sub>. Each of the three experiments (mowing on June 12, 20, and 26) was analysed independently. The three replications in each experiment were considered as random blocks. Each replication had the same overall drying period in the tunnel (14 h over 3 or 4 days) but different periods in the shade. Replication 3 was expected to have dried further than the two others since it stayed longer in the shade where some drying could occur. Since replications were considered as random blocks, differences between replications were removed and the comparisons were focused on differences between the 12 treatments in each experiment.

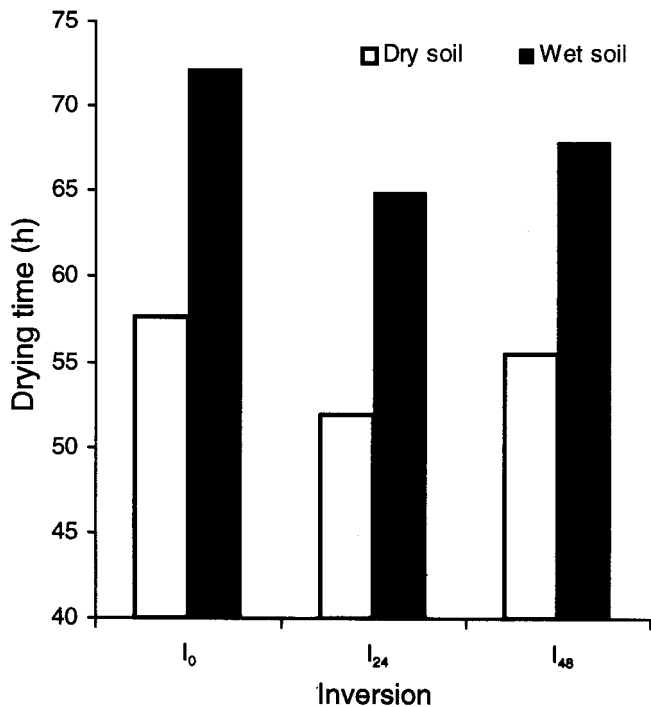
## RESULTS and DISCUSSION

### First experiment

Timothy mowed on June 12 was at the boot stage and had an initial moisture content of 82.7% (SD = 1.6%). Results of this experiment are presented in Table 1. During the first day of drying, soil moisture had a statistically significant effect on drying (p = 0.001); the coefficient k<sub>1</sub> was 0.088 h<sup>-1</sup> for windrows on dry soil and of 0.080 h<sup>-1</sup> for windrows on moist soil. Mechanical conditioning had a significant effect on drying as well (p = 0.05). The coefficient k<sub>1</sub> was 0.087 h<sup>-1</sup> with conditioning and 0.082 h<sup>-1</sup> without conditioning. Inversion could not have an effect on drying during the first day because it was applied only 24 or 48 h after mowing.

During the second day of drying, soil moisture again had a statistically significant effect on drying (p = 0.001); the coefficient k<sub>2</sub> was 0.092 h<sup>-1</sup> for windrows on dry soil and 0.077 h<sup>-1</sup> for windrows on moist soil. Mechanical conditioning did not have a significant effect on drying, but inversion had a significant effect. The coefficient k<sub>2</sub> was 0.104 h<sup>-1</sup> for windrows after inversion and 0.074 h<sup>-1</sup> for windrows without inversion.

During the third day of drying, soil moisture did not have a significant effect on drying whereas mechanical conditioning had an effect; coefficient k<sub>3</sub> was 0.123 h<sup>-1</sup> for conditioned windrows and 0.100 h<sup>-1</sup> for non-conditioned windrows. The higher drying coefficients estimated during the third day compared to the two previous days are due to more favourable drying conditions (6 h in the tunnel and no time in the shade,



**Fig. 4.** Effects of windrow inversion ( $I_0$  = no inversion,  $I_{24}$  = inversion 24 h after mowing,  $I_{48}$  = inversion 48 h after mowing) on drying time of forage to reach the desired moisture content of 16% (wet basis; experiment 1).

compared to 4 h in the tunnel and 4 h in the shade on days 1 and 2 for “t” in the drying model). Mechanical conditioning had a greater effect under good drying conditions (radiation, wind) than under slow drying conditions (in the shade). Inversion 48 h after mowing also had a significant effect on drying during the third day. Coefficient  $k_3$  was  $0.131 \text{ h}^{-1}$  for windrows after inversion and  $0.102 \text{ h}^{-1}$  for windrows without inversion.

The overall drying coefficient over 3 or 4 days ( $k_{OF}$ ) was influenced by soil moisture and inversion ( $p = 0.001$  and  $0.05$ ) and less significantly by mechanical conditioning ( $p = 0.08$ ). The time required to reach the desired moisture content of 16% ( $t_{16\%}$ ) is an indicator of the cumulative effect of the various treatments. Soil moisture had a significant effect ( $p = 0.001$ ); the average  $t_{16\%}$  was 55.0 h on a dry soil and 68.3 h on a wet soil, representing a difference of 13 h. Windrow inversion also had a significant influence ( $p = 0.05$ ) on  $t_{16\%}$  which averaged 64.9, 58.4, and 61.7 h for  $I_0$ ,  $I_{24}$ , and  $I_{48}$ , respectively. It was most beneficial to invert windrows early (i.e. 24 h after mowing), which reduced the drying time by 6 h compared to no inversion. The effect of inversion was consistent at both soil moisture levels, as illustrated in Fig. 4.

Mechanical conditioning had an overall small effect on  $t_{16\%}$  which was reduced by 4 h on average (59.7 h vs 63.7 h without conditioning). Under good drying conditions, as in the laboratory, a combination of dry soil (-13 h), inversion (-6 h) and mechanical conditioning (-4 h) could reduce the field drying time by a full day to reach 16% moisture content. A difference of 23 h was observed in Table 1 between the shortest

time (50.5 h on dry soil, inversion after mowing and conditioning) and the longest time (73.9 h on moist soil, without inversion and without conditioning).

### Second experiment

Timothy was mowed at the early heading stage with an initial average water content of 78.9% (SD = 0.9%). During the first drying day, forage dried on the wet soil as rapidly as on the dry soil (Table 2). With conditioning, coefficient  $k_1$  was 15% higher than without conditioning ( $0.119 \text{ h}^{-1}$  vs  $0.104 \text{ h}^{-1}$ ). As mass per unit area increased, the drying coefficient decreased ( $0.135$ ,  $0.110$ , and  $0.089 \text{ h}^{-1}$  for  $0.63$ ,  $0.94$ , and  $1.25 \text{ kg DM/m}^2$ , respectively). Soil moisture had an effect on drying during the second day but not during the third day. Conditioning had a consistent effect on windrow drying during the second and third days while windrow mass had a continued effect only during the second day.

The overall drying coefficient  $k_{OF}$  was higher for windrows on dry soil than for windrows on wet soil, for windrows with conditioning compared to windrows without conditioning, and for windrows with a lower mass per unit area. Similar significant effects for  $t_{16\%}$  were observed (Table 2). On dry soil, the average drying time to reach the target moisture was 40.5 h compared to 45.6 h on wet soil. The average drying time was 38.4 h for conditioned windrows versus 47.6 h for non-conditioned windrows. The drying times were 39.7, 42.5, and 47.0 h at the three levels of mass per unit area ( $0.63$ ,  $0.94$ , and  $1.25 \text{ kg DM/m}^2$ ), respectively. Drying time could therefore be reduced by 5 h for windrows left over a dry soil, by 9 h with conditioning, and by 7 h for windrows spread out over a wider area, thereby reducing mass per unit area.

### Third experiment

Timothy was mowed at the heading stage with an initial water content of 81.8% (SD = 1.3%). On day one (Table 3), the mass per unit area was highly significant ( $p = 0.001$ ) with respect to the drying coefficient ( $k_1 = 0.161 \text{ h}^{-1}$  for 400 g per tray and  $0.098 \text{ h}^{-1}$  for 800 g per tray). Mass per unit area remained a significant factor during the second day ( $k_1 = 0.190 \text{ h}^{-1}$  for 400 g per tray and  $0.109 \text{ h}^{-1}$  for 800 g per tray) and during the third day ( $k_1 = 0.138 \text{ h}^{-1}$  for 400 g per tray and  $0.199 \text{ h}^{-1}$  for 800 g per tray). There was, however, a reversal between the second and the third day on the way mass per unit area affected the drying coefficient. During the first two days, a low mass per unit area had a higher drying coefficient. During the third day, a low mass actually had a lower drying coefficient. This can be explained because moisture reached a lower level more quickly in the light windrow, so there was less residual water to evaporate on the third day. On the contrary, a heavy windrow lost its moisture more slowly initially so there remained a greater amount of moisture to evaporate on the third day. Overall, the drying coefficient ( $k_{OF}$ ) was higher for a low mass per unit area. The total drying time to reach 16% moisture was shorter with a low mass (32.2 h for  $0.54 \text{ kg DM/m}^2$  vs 36.5 h for  $1.08 \text{ kg DM/m}^2$ ).

Mechanical conditioning was found to be non-significant on the first day of drying, significant on the second day, non-significant again on the third day, and finally non-significant overall. The time  $t_{16\%}$  was somewhat affected by mechanical conditioning ( $p = 0.08$ ). Windrows reached the target moisture after 37.4 h without conditioning, 32.2 h with intensive

**Table 2. Drying coefficients (k) and drying time (t) for timothy mowed on June 20, 2000 at the early heading stage (experiment 2).**

Parameters	Moist sand												Probability				
	Dry sand						No conditioning						Conditioning		SM <sup>c</sup>	MC	M
	No conditioning		Conditioning		No conditioning		Conditioning		No conditioning		Conditioning		SE <sup>b</sup>	SM <sup>c</sup>	MC	M	
$k_1^d$ (h <sup>-1</sup> )	$M_{400}^a$	$M_{600}$	$M_{800}$	$M_{400}$	$M_{600}$	$M_{800}$	$M_{400}$	$M_{600}$	$M_{800}$	$M_{400}$	$M_{600}$	$M_{800}$	0.007	NS	0.001	0.001 <sup>L</sup>	
$k_2$ (h <sup>-1</sup> )	0.1307	0.1016	0.0833	0.1490	0.1206	0.0999	0.1240	0.1003	0.0831	0.1374	0.1174	0.0895	0.01	0.02	0.01	0.001 <sup>L</sup>	
$k_3$ (h <sup>-1</sup> )	0.0969	0.0848	0.0690	0.1354	0.1035	0.0921	0.0886	0.0840	0.0652	0.1158	0.0789	0.0602	0.02	NS	0.001	NS	
$k_{OF}$ (h <sup>-1</sup> )	0.1755	0.1533	0.1579	0.1420	0.2061	0.2305	0.1403	0.1503	0.1555	0.2241	0.2197	0.2339	0.005	0.03	0.01	0.02 <sup>L</sup>	
$t_{16\%}^e$ (h)	0.0664	0.0553	0.0495	0.0692	0.0693	0.0669	0.0552	0.0533	0.0474	0.0642	0.0587	0.0541	3.5	0.03	0.001	0.01 <sup>L</sup>	
	40.0	46.5	51.9	34.7	34.2	35.7	45.5	47.4	54.5	38.6	41.7	45.8					

<sup>a</sup> M is the mass of fresh forage per tray of 0.45 m x 0.30 m area; subscripts indicate mass in grams.

<sup>b</sup> SE = Standard Error

<sup>c</sup> SM = soil moisture; MC = mechanical conditioning, M = mass of forage per unit area

<sup>d</sup> Subscripts of the drying coefficients k stand for day 1, day 2, day 3, and overall (OF), respectively.

<sup>e</sup> Time to reach a moisture content of 16% (wet basis)

NS = non-significant at the 10% level

L = linear effect

**Table 3. Drying coefficients (k) and drying time (t) for timothy mowed on June 26, 2000 at the heading stage (experiment 3).**

Parameters	M <sub>400</sub> <sup>a</sup>												M <sub>800</sub>		Probability				
	I <sub>0</sub> <sup>b</sup>						I <sub>48</sub>						I <sub>0</sub>		I <sub>48</sub>		MC	T	C
	C <sub>0</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>0</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>0</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>0</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>0</sub>	C <sub>1</sub>	C <sub>2</sub>	SE <sup>d</sup>	MC	T	C
$k_1^e$ (h <sup>-1</sup> )	0.1617	0.1650	0.1673	0.1363	0.1733	0.1633	0.1037	0.1037	0.1037	0.1037	0.1037	0.0900	0.0967	0.0997	0.0943	0.007	0.001	NS	NS
$k_2$ (h <sup>-1</sup> )	0.1457	0.2007	0.2393	0.1210	0.2007	0.2317	0.1097	0.1197	0.0973	0.1073	0.1073	0.1130	0.1073	0.1073	0.1130	0.02	0.001	NS	0.01 <sup>L</sup>
$k_3$ (h <sup>-1</sup> )	0.2010	0.0663	0.0923	0.1777	0.1767	0.1157	0.1327	0.2103	0.2347	0.1747	0.2230	0.2160	0.1747	0.2230	0.2160	0.04	0.02	NS	NS
$k_{OF}$ (h <sup>-1</sup> )	0.0853	0.0777	0.0803	0.0730	0.0880	0.0777	0.0653	0.0797	0.0697	0.0673	0.0743	0.0717	0.0697	0.0743	0.0717	0.006	0.02	NS	NS
$t_{16\%}^f$ (h)	29.2	34.9	30.7	38.9	28.0	31.2	42.1	32.1	36.4	39.3	33.6	35.2	33.6	33.6	35.2	3.2	0.03	NS	0.08

<sup>a</sup> M is the mass of fresh forage per tray of 0.45 m x 0.30 m area; subscripts indicate mass in grams.

<sup>b</sup> Subscripts of I indicate no inversion (0) and inversion 48 h after mowing.

<sup>c</sup> Subscripts of C indicate no mechanical conditioning (0), conditioning once through three rolls (1), and conditioning twice through the rolls (2).

<sup>d</sup> SE = Standard Error

<sup>e</sup> Subscripts of the drying coefficients k stand for day 1, day 2, day 3, and overall (OF), respectively.

<sup>f</sup> Time to reach a moisture content of 16% (wet basis)

NS = non-significant at the 10% level

L = linear effect

conditioning (one passage through the rolls), and 33.4 h with more intensive conditioning (two passages through the rolls).

Windrow inversion 48 h after mowing had no significant effect on the drying coefficient or the drying time. Overall, there was no benefit from more intensive conditioning (two passages) but a combination of moderate conditioning (one passage) and lower mass per unit area could save about 10 h of drying time in this relatively mature crop.

#### Effect of forage maturity stage on drying

Results of the three experiments show clearly that the drying time required to reach the target moisture content of 16% decreased with increasing maturity stage of forage (Fig. 5). For example, based on similar conditions (dry soil, no inversion, and no conditioning), forage at the boot stage required on average 58.6 h of drying time (with a mass per unit area of 0.78 kg/m<sup>2</sup>) against 42.5 h at the early heading stage (0.94 kg DM/m<sup>2</sup>) and 36.5 h the heading stage (1.08 kg DM/m<sup>2</sup>). Average drying times ( $t_{16\%}$ ) were 62, 43, and 34 h for experiments 1, 2, and 3 with forage mowed on June 12, 20, and 26, respectively. Hay harvested at a later stage of maturity for a fibrous crop market (horse hay, biomass hay), therefore presents an advantage of shorter drying time when compared to drying time required for an early maturity stage.

### SUMMARY and CONCLUSIONS

Three experiments were carried out to evaluate windrow handling treatments on the drying rate and time to reach a target moisture at three maturity stages of timothy. A number of consistent effects were observed among the treatments.

Compared to a wet soil, a dry soil reduced the drying time by 13 h at the boot stage and by 5 h at the early heading stage. When moving or turning windrows, it is therefore preferable to lay them on the dry stubble previously exposed to direct sunshine rather than to lay them back on the wet, previously covered stubble. Mechanical conditioning using three grooved rolls reduced the drying time consistently but moderately (4, 9, and 5 h for experiments 1, 2, and 3, respectively at three maturity stages). Inversion 24 h after mowing reduced the drying time by 6 h (experiment 1) whereas inversion 48 h after mowing did not result in any significant time saving (3 h for experiment 1 and none for experiment 3). A lower mass per unit area consistently reduced the drying time. In experiment 2, drying time averaged 47 h at 1.25 kg DM/m<sup>2</sup> and was reduced by 3 h at 0.94 kg DM/m<sup>2</sup> or by 7 h at 0.63 kg DM/m<sup>2</sup>. In experiment 3, a forage mass per unit area of 0.54 kg DM/m<sup>2</sup> required 4 h less time to dry than a forage mass per unit area of 1.08 kg DM/m<sup>2</sup> (32 vs 36 h total time).

A combination of several factors can speed up drying in the field and reduce the time during which windrows are exposed to rain, bleaching, and plant respiration. Based on this study, a number of recommendations can be made to reduce the field drying time for the production of marketable hay or herbage biomass. These include: (1) spread the windrows over the widest possible area; (2) invert windrows 24 h after mowing rather than 48 h; and (3) apply some form of mechanical conditioning.

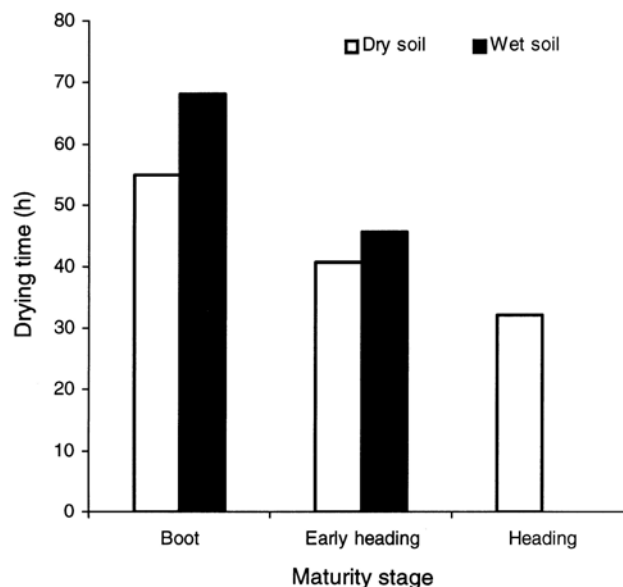


Fig. 5. Effects of maturity stage on drying time of forage to reach the desired moisture content of 16% (wet basis).

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