INFLUENCE OF EIGHT FACTORS ON THE DRYING RATE OF TIMOTHY HAY

Philippe Savoie and Alain Mailhot

Département de génie rural, Université Laval, Québec G1K 7P4

Contribution no. 280, Sainte-Foy Research Station, Agriculture Canada; received 23 July 1985, accepted 7 January 1986

Savoie, P. and **A. Mailhot.** 1986. Influence of eight factors on the drying rate of timothy hay. Can. Agric. Eng. **28**: 145–148.

Fresh timothy grass was placed in a windrow structure in a drying chamber to measure the effect of eight variables on the drying rate. Seven variables were controlled in the following ranges: air temperature (16.5–30.0°C), vapor pressure deficit (1.08–1.70 kPa), wind speed (0.7–2.5 m/s), radiation (0–975 W/m^2), conditioning (0–80 indentations/m), soil water saturation (0–80%) and forage density (2000–10 000 kg dry matter/ha). An eighth uncontrolled variable was initial moisture content; it ranged between 60 and 85% on a wet basis. Samples were weighed regularly and dried during 22 h in a constant environment. A modified drying model was proposed to reduce a systematic overestimation of early moisture contents. The drying rate was positively correlated with radiation and vapor pressure deficit. It was negatively correlated with forage density (windrow thickness) and initial moisture content. The chamber could be used to obtain a rapid assessment of new hay conditioning treatments.

On a reconstitué au laboratoire des andains de fléole fraîchement coupée afin d'évaluer l'importance de huit facteurs sur le séchage du foin. On a fixé sept variables à l'intérieur des plages suivantes: la température de l'air (16,5 à 30,0°C), le déficit de pression de vapeur (1,08 à 1,70 kPa), le vent (0,7 à 2,5 m/s), le rayonnement (0 à 975 W/m^2), le conditionnement (0 à 80 pliures/m), le degré de saturation du sol en eau (0 à 80%) et la masse surfacique du fourrage (2000 à 10 000 kg de matière sèche/ha). La huitième variable, la teneur en eau initiale du fourrage, n'était pas fixée mais seulement mesurée; elle a varié entre 60 et 85% sur une base humide. Chaque échantillon était pesé régulièrement dans un environnement constant où il a séché pendant 22 heures. On a modifié l'équation de séchage conventionnelle afin de réduire une erreur systématique de surestimation des teneurs en eau en début de séchage. Le taux de séchage était corrélé positivement avec le rayonnement et le déficit de pression de vapeur. Il était corrélé négativement avec la masse surfacique (ou l'épaisseur des andains) et la teneur en eau initiale. Le montage expérimental permet l'évaluation rapide de nouveaux traitement pour conditionner le foin.

INTRODUCTION

The study of forage field drying has three main purposes: (a) to predict drying rates better, (b) to understand drying mechanisms better and (c) possibly to modify the factors that affect drying. Accurate drying models are useful for simulation studies to assess the long-term performance of various harvest systems (Savoie et al. 1985). A better understanding of hay drying might also be helpful in developing new hay conditioning systems, either chemical (Rotz et al. 1984) or mechanical (Krutz et al. 1979).

A number of empirical models have been proposed to predict the field drying of forages at different locations such as Nova Scotia (Hayhoe and Jackson 1974), Ontario and Saskatchewan (Dyer and Brown 1977), Indiana (Dale et al. 1978) and Michigan (Savoie et al. 1982). These models are often limited to a specific region or a single crop; for example, Lovering and McIsaac (1981) had to modify the Dyer-Brown model to use it in Prince Edward Island.

To develop a more general forage drying model, it is necessary to understand better the combined effect of three groups of factors: the environment (air temperature and humidity, wind, rain, solar radiation and soil moisture), the crop itself (species, maturity and yield) and the treatments (chemical or mechanical). Most studies have considered only a limited number of factors at a time. For example, Shepherd (1965) noted a significant effect of wind speed on hay drying when air speed was the main variable. However, Savoie et al. (1982) found that solar radiation and air temperature completely overshadowed the wind effect in a regression analysis based on 2 yr of field observations of alfalfa drying. Rotz and Chen (1985) hypothesized that all weather variables, including wind velocity, follow a diurnal pattern with a maximum normally occurring in early afternoon. Wind effects, therefore, may be masked in the statistical model by solar and vapor pressure deficit effects. Another example is given by Jones (1979) who found that leafy vegetative grasses dried faster than stemmy, mature grasses under controlled conditions in a thin layer. In field conditions, Wilman and Owen (1982) did not find such a drying advantage. Although water seems to evaporate faster from single leaves than from single stems, stemmy material creates naturally a looser, better ventilated and faster drying windrow than leafy material which tends to pack down. It is thus important to take into account the numerous interactions observed in hay drying.

Controlled laboratory experiments can be helpful in understanding and predicting field drying as long as they attempt to simulate as closely as possible the actual windrow structure of hay and the drying environment. Moreover controlled experiments have the advantage of allowing a rapid examination of interactions during drying.

The present study had three objectives. The first was to develop a drying chamber to simulate field conditions for drying forage windrows. The second was to compare simple drying models to predict drying rate of timothy hay over the entire moisture range. The third was to correlate the drying parameters with eight independent factors: air temperature, air humidity, air speed, radiation, soil water content, mechanical conditioning, windrow thickness and initial moisture content.

MATERIALS AND METHODS

Fresh timothy grass (*Phleum pratense* 'Climax') was used to reconstitute a windrow in a controlled environment. Seven of the factors stated earlier were controlled at the levels indicated in Table I. The eighth

TABLE I. SEVEN FACTORS AND THE LEVELS AT WHICH THEY WERE CONTROLLED IN THE TIMOTHY HAY DRYING EXPERIMENT

Symbolic level	Air temperature (°C)	Vapor pressure deficit (kPa)	Wind speed (m/s)	Radiation (cal/(cm²/min))	Conditioning (indentations/metre)	Soil water saturation (%)	Forage density (kg DM/ha)
$-\alpha$	16.5	1.08	0.7	0	0	0	2000
-1	20.9	1.28	1.3	0.45	26	26	4586
0	23.3	1.39	1.6	0.70	40	40	6000
1	25.6	1.50	1.9	0.95	54	54	7414
α	30.0	1.70	2.5	1.40	80	80	10000

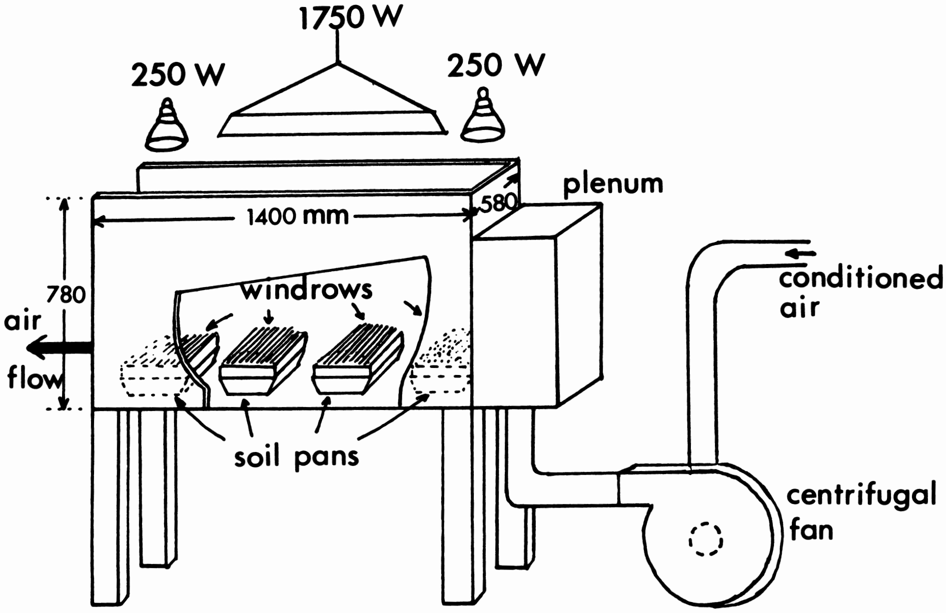

Figure 1. Drying chamber with an inside view of forage windrow trays placed on top of the soil pans.

factor, initial moisture content, could not be controlled but was monitored. To reduce the number of experiments required to cover such a large number of combinations (5^7), a central composite design was used (Box and Hunter 1957). It included a 1/2 factorial at symbolic levels of -1 and $+1$, i.e. 64 (2^{7-1}) combinations, 14 axial experiments where one factor was set either at level $-\alpha$ or level $+\alpha$ ($\alpha = 2.828$) while all other factors were set at symbolic level 0, and 22 central points (all factors set at symbolic level 0).

A drying chamber made of wood was built to carry four trays of forage placed in a windrow pattern (Fig. 1). A side door was equipped to remove each tray for weighing. Weighing schedule was set at 0.0, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 10.0 and 22.0 h after the beginning.

Air was conditioned to specific dry bulb and wet bulb temperatures, equivalent to a desired vapor pressure deficit, by an Aminco-Aire conditioner (American Instrument Co., Silver Spring, Md.). The internal fan of the air conditioner provided an airflow of 0.26 m^3/s, and an average air speed of 0.7 m/s above the windrow. A centrifugal fan with a 2.2-kW variable speed motor was added between the conditioner and the drying chamber to increase airflow above 1.0 m^3/s, at average air speed of 2.5 m/s above the forage. A Chromalox CRL-4017 infrared, 1750 W, quartz tube radiant heater and two General Electric 250 W infrared brooder lamps set at each end of the quartz tube provided the heat required for the experiment. The lamps were set at about 900 mm above the forage. Heat was adjusted by controlling voltage to the lamps between 0 and 240 V. At maximum voltage, a radiative power of 1.4 cal/(cm²/min) (975 W/m²) was measured at the level of the forage; such a radiative power is similar to the maximum solar radiation usually observed on a sunny day at noon in the month of June in Eastern Canada. Radiation was relatively uniform lengthwise in the chamber and decreased widthwise from the center to the sides. By placing the four trays side by side lengthwise, the radiation pattern for each tray was homogeneous. As a point of comparison, the maximum radiation resulted in a pan evaporation rate of 0.90 mm/h at an airspeed of 0.7 m/s, and of 0.82 mm/h at zero airspeed. Without illumination, the ambient air, at 24°C and 35% relative humidity, produced a pan evaporation rate of 0.10 mm/h.

Before placing the wet forage in the drying chamber, the forage was conditioned with a rack and pinion type conditioner. It consisted of a 610-mm-diameter wheel (pinion) around which 50-mm side corner rods were welded over a width of 400 mm. A fixed base (rack) was made of the same corner rods. The wheel, weighing 179 kg, was rolled over the forage to provide a crimping effect. Conditioning was quantified by the number of indentations per unit length, and varied between 0 and 80 indentations/metre. Variation in the number of indentations per unit length was achieved either by rolling the wheel twice or by placing the forage at an angle on the fixed base.

The thickness of the forage windrow was quantified by the dry matter weight per unit area. It was planned to vary between 2000 and 10 000 kg dry matter/ha to reflect actual variations in the field due to differences in yield and shape of the windrow (wide swathes versus narrow or raked windrows). The actual dry matter density was measured at the end of each experiment from the oven-dry weight of the whole sample on each tray dried at 103°C for 24 h.

The seventh factor was soil moisture under the forage windrow. It varied between 0 and 80% of the saturation line of silica sand (particle diameter size approximately 1.2 mm). A 500 × 300-mm aluminum tray, 80 mm deep, was filled with 14 kg of sand. Water was added 24 h before the start of the experiment to the desired degree of saturation. Full saturation (100%) was achieved with 3.9 L of water.

The preparation of an experiment consisted of adjusting the seven factors to the desired level. Radiation was set by adjusting the voltage of the lamps; windspeed was controlled by the variable speed of the centrifugal fan; air temperature and vapor pressure deficit were controlled by the air-conditioner. Radiation and windspeed could be adjusted to within 5% of the desired level. Dry bulb and wet bulb temperature of the incoming air were adjusted to within 0.5°C. An appropriate quantity of forage was conditioned as required. It was put into a 25-mm-mesh wire tray measuring 500 mm long × 300 mm wide × 50 mm high. The tray was set on the wet sand inside the drying chamber.

The forage used for the experiment was

TABLE II. VALUES OF PARAMETERS ESTIMATED FOR THE THREE FORAGE DRYING MODELS BASED ON THE 99 LABORATORY EXPERIMENTS

Model $(M - M_e)/(M_0 - M_e) =$	Values of k			Values of M_e			Values of c		
	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.
$\exp(-kt)$	0.209	0.336	0.122	0.254	0.869	0.000	—	—	—
$\exp(-kt^c)$	0.234	0.338	0.121	0.135	0.355	0.001	0.879	1.019	0.704
$\exp(-kt^{0.879})$	0.235	0.373	0.136	0.149	0.741	0.000	0.879	—	—

TABLE III. COMPARISON OF THE THREE DRYING MODELS ON THE BASIS OF R^2 OBTAINED FROM THE 99 EXPERIMENTS

Drying model	Average R^2	Maximum R^2	Minimum R^2
$\frac{M_0 - M_e}{M_0 - M_e} = \exp(-kt)$	0.995	1.000	0.979
$\frac{M - M_e}{M_0 - M_e} = \exp(-kt^c)$	0.999	1.000	0.996
$\frac{M - M_e}{M_0 - M_e} = \exp(-kt^{0.879})$	0.999	1.000	0.992

TABLE IV. NUMBER OF POSITIVE AND NEGATIVE RESIDUALS (CALCULATED MINUS MEASURED MOISTURE CONTENT) AT THE 10 TIME INTERVALS FOR THE 99 DRYING EXPERIMENTS AND TWO DRYING MODELS

	Time of measurement (h)									
	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	10.0	22.0
Model $\exp(-kt)$										
+ residuals	97	94	96	98	74	9	6	5	10	95
− residuals	2	5	3	1	25	90	93	94	89	4
Model $\exp(-kt^{0.879})$										
+ residuals	59	52	51	40	40	35	41	53	48	51
− residuals	40	47	48	59	59	64	58	46	51	48

TABLE V. LINEAR CORRELATION BETWEEN THE DEPENDENT VARIABLES IN EQ. 3 (c = 0.879) AND THE EIGHT INDEPENDENT VARIABLES

Independent variables	k	M_e
Dry bulb temperature	−0.0892	−0.1623
Vapor pressure deficit	0.3605	0.1464
Wind speed	0.0266	0.2214
Radiation	0.5420	−0.1195
Conditioning	−0.0542	−0.1855
Soil water content	−0.0636	−0.0188
Forage density	−0.4687	−0.0488
Initial moisture content	−0.5723	0.3923

field-grown timothy hay from an established stand at Deschambault, Quebec. It was cut at four different dates: 13 June, 27 June, 11 July and 25 July 1983, during the first growth cycle. Moisture content decreased with maturity from a high of 85% at the first date of cut to a low of 60% at the last date of cut. Forage from each cut was used for approximately one-quarter of the trials determined at random. The freshly mowed forage was stored in sealed plastic bags at 2°C for up to 12 d before being used in the drying chamber. Bags were brought out from the refrigerator 16 h before the onset of a trial so the forage would warm up to ambient temperature.

DRYING MODEL

The decreasing rate drying model suggested by Hall (1957) is still widely used in the literature to predict hay drying rate (see for example Rotz and Sprott (1984)).

$$\frac{dM}{dt} = -k(M - M_e) \qquad (1)$$

where M is the moisture content on a dry basis (g H_2O/g DM), M_e is the equilibrium moisture content, t is time (h) and k is the drying constant (h^{-1}). The solution of Eq. 1 is obtained after defining a boundary condition, namely $M = M_0$ (initial moisture content) at $t = 0$.

$$\frac{M - M_e}{M_0 - M_e} = \exp(-kt) \qquad (2)$$

A limited number of studies (Bakker-Arkema et al. 1962) have attempted to correlate equilibrium moisture content of a thin layer of hay with air temperature and relative humidity. The results are not always consistent, however, with field observations, especially with thick windrows subjected to varying climatic conditions. Rotz and Sprott (1984) for example neglected equilibrium moisture content ($M_e = 0$) when they calculated the drying constant k. The error is minimal for moisture contents above 1 g water/g DM, but becomes important when moisture content approaches the real equilibrium moisture content, as shown by Pitt (1984). In such a case, it is necessary to estimate M_e.

In Eq. 2 there are two parameters to be estimated, k and M_e. A parameter estimation algorithm for nonlinear models (Box procedure in Kuester and Mize (1973)) was used to estimate the parameters by minimizing the sum of the errors (estimated minus observed moisture content) squared from the 10 observations of moisture content versus time for each drying experiment.

RESULTS AND DISCUSSION

The original design required 100 distinct drying experiments. One of these could not be done because the minimum axial temperature (16.5°C) was difficult to control at the central vapor pressure deficit point of 1.39 kPa. All other 99 experiments were carried at the specified levels for the 22-h drying period.

The statistical analyses revealed that Eq. 2 was biased, systematically underestimating early drying rates and overestimating later drying rates. For this reason, the following empirical model was also considered in the analysis:

$$\frac{M - M_e}{M_0 - M_e} = \exp(-kt^c) \qquad (3)$$

Parameters were estimated for Eqs. 2 and 3 and a special case of Eq. 3 with $c = 0.879$. The range of parameters estimated for the 99 trials is given in Tables II and III. The accuracy of prediction is very good in all cases (average $R^2 \geqslant 0.995$). The unknown parameter c in the second model was fixed at the average value in the third model to reduce the number of parameters from three to two. There was practically no reduction in the accuracy of the prediction (average $R^2 = 0.999$).

In Table IV, the analysis of residuals shows that the first model ($\exp(-kt)$) overestimated the moisture content during the first 3 h of drying, underestimated moisture content between 4 and 10 h of drying and overestimated the final moisture content. The other drying model considered ($\exp(-kt^{0.879})$) provided a more balanced set of residuals for all time intervals. The latter was retained to correlate drying parameters with the eight independent factors.

Parameter k was highly and positively correlated with radiation and vapor pressure deficit (Table V). It was highly and negatively correlated with forage density (windrow thickness) and initial moisture content. Since initial moisture content of timothy is negatively correlated with maturity (Savoie et al. 1984), mature timothy had a higher drying rate than immature timothy under the same environment. The four other factors were poorly correlated with k. As expected, wind speed was positively correlated and soil water content was negatively correlated. Unexpectedly dry bulb temperature and conditioning were negatively correlated with k. The effect of air temperature might have been masked by the microclimate created by radiation and heat accumulation within the windrow. The crimper conditioner used was not effective in increasing the drying rate. It might even have had a deleterious effect by compacting the forage and reducing air flow through the windrow.

Generally, equilibrium moisture content is a function only of ambient temperature and humidity, and the physical characteristics of the material. The single most important factor explaining M_e was initial moisture content. As it increased, M_e increased; as timothy became more mature, M_e decreased. Bakker-Arkema et al. (1962) found a similar trend with alfalfa. As expected M_e was negatively correlated with air temperature and vapor pressure deficit. Other correlations were relatively low and sometimes difficult to explain physically.

A regression model was developed between k and the eight independent factors. It explained 88.3% of the sum of squares about the mean of k. When used in Eq. 3, the model predicted very accurately the moisture content over time from the 99 laboratory experiments (R^2 = 0.991). However, when compared with field drying data (Savoie et al. 1984), the model tended to overestimate the drying rate. Faster laboratory drying might partly be explained by the presence of residual energy from the heat source, unmeasured as direct radiation but available for drying in the chamber.

The central composite design (CCD) was efficient to combine several factors at several levels for simultaneous analysis (seven factors at five levels in the present case). It put in perspective the relative importance of each in explaining the drying rate. However, the precision of prediction with the CCD is uniform only in the range of symbolic values of factors between -1 and $+1$ in Table I; it decreases for values up to $-\alpha$ and $+\alpha$. Since actual field drying covers a much wider range of environmental conditions than those between levels -1 and $+1$, the CCD is less efficient than a factorial design to consider extreme conditions.

It will be necessary to reduce the number of factors evaluated in future drying experiments. One useful simplification might be to integrate all the environmental factors (air temperature, vapor pressure deficit, wind speed, solar radiation) into a single factor such as pan evaporation as suggested by Pitt (1984). However, under such an hypothesis, moisture content loss would have to be the same for the same accumulated evaporation, independently of evaporation source and of time. Dimensional analysis could also be used to reduce the number of experimental factors.

The drying chamber proposed in the present study can be used to simulate field drying conditions. It allows the experimenter to assess quickly differences between treatments, species and maturities. Complementary field and laboratory studies are necessary if we are to develop a general forage field drying model, applicable to a wide range of conditions.

CONCLUSIONS

The following conclusions were drawn from this study:

(1) A drying chamber was built to simulate drying of forage windrows in the field. The chamber can be used to assess quickly the efficiency of new conditioning treatments under various climatic conditions.

(2) The conventional drying curve ($\exp(-kt)$) systematically overestimated early moisture contents (during the first 3 h) and underestimated later moisture contents (up to 10 h). A modified drying curve ($\exp(-kt^{0.879})$) provided more balanced residuals.

(3) Radiation and vapor pressure deficit were highly and positively correlated with k of the modified drying curve; windrow thickness and initial moisture content were negatively correlated. Mature timothy dried faster than immature timothy in the same environment.

ACKNOWLEDGMENTS

This research project was supported by the Sainte-Foy Research Station, Agriculture Canada and by an operating grant from the Natural Sciences and Engineering Research Council of Canada. We thank Jean-Pierre Lessard for his valuable contribution in carrying out the experiment.

REFERENCES

BAKKER-ARKEMA, F. W., C. W. HALL, and E. J. BENNE. 1962. Equilibrium moisture content of alfalfa. Mich. Agric. Exp. Sta. Q. Bull. 44: 492−496.

BOX, G. E. P., and J. S. HUNTER. 1957. Multifactor experimental designs for exploring response surfaces. Ann. Math. Stat. 28(1): 195−241.

DALE, J. G., D. A. HOLT, and R. M. PEART. 1978. A model of alfalfa harvest and loss. ASAE paper no. 78-5030. ASAE, St. Joseph, Mich.

DYER, J. A. and D. M. BROWN. 1977. A climatic simulator for field-drying hay. Agric. Meteorol. 18: 37−48.

HALL, C. W. 1957. Drying farm crops. AVI Publishing Co., Westport, Conn.

HAYHOE, H. N. and C. P. JACKSON. 1974. Weather effects on hay drying rates. Can. J. Plant Sci. 54: 479−484.

JONES, L. 1979. The effect of stage of growth on the rate of drying of cut grass at 20°C. Grass Forage Sci. 34: 139−144.

KRUTZ, G. W., D. A. HOLT, and D. MILLER. 1979. For fast field drying of forage crops. Agric. Eng. 60(8): 16−17.

KUESTER, J. L. and J. H. MIZE. 1973. Optimization techniques with Fortran. McGraw Hill Book Co., Toronto, Ont. pp. 368−385.

LOVERING, J. and J. A. McISAAC. 1981. A timothy-beef production model for Atlantic Canada. Agric. Systems 7: 219−233.

PITT, R. E. 1984. Forage drying in relation to pan evaporation. Trans. ASAE (Am. Soc. Agric. Eng.) 27(6): 1933−1937.

ROTZ, C. A. and D. J. SPROTT. 1984. Drying rates, losses and fuel requirements for mowing and conditioning alfalfa. Trans. ASAE (Am. Soc. Agric. Eng.) 27(3): 715−720.

ROTZ, C. A. and Y. CHEN. 1985. Alfalfa drying model for the field environment. ASAE paper no. 85-1025. ASAE, St. Joseph, Mich.

ROTZ, C. A., D. J. SPROTT and J. W. THOMAS. 1984. Interaction of mechanical and chemical conditioning of alfalfa. Trans. ASAE (Am. Soc. Agric. Eng.) 27(4): 1009−1014.

SAVOIE, P., R. C. BROOK, and C. A. ROTZ. 1982. Empirical model for field drying of alfalfa. ASAE paper no. 82-1528. ASAE, St. Joseph, Mich.

SAVOIE, P., E. PATTEY and G. DUPUIS. 1984. Interactions between grass maturity and swath width during hay drying. Trans. ASAE (Am. Soc. Agric. Eng.) 27(6): 1679−1683.

SAVOIE, P., L. D. PARSCH, C. A. ROTZ, R. C. BROOK, and J. R. BLACK. 1985. Simulation of forage systems on dairy farms. Agric. Systems 17: 117−131.

SHEPHERD, W. 1965. Air speed effects during drying of harvested pasture material. Aust. J. Agric. Res. 16: 384−389.

WILMAN, D. and I. G. OWEN. 1982. Effects of stage of maturity, nitrogen application and swath thickness on the field drying of herbage to the hay stage. J. Agric. Sci. (Camb.) 99: 557−586.