Potential impact of mowing-maceration on an alfalfa dehydration plant

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Savoie, P., Pouliot, M. and Sokhansanj, S. 1995. **Potential impact of mowing-maceration on an alfalfa dehydration plant**. Can. Agric. Eng. **37**:295-304. A feasibility analysis was done to assess the impact of field maceration on an alfalfa dehydration plant. On the basis of current research knowledge, a hypothetical self-propelled (SP) mower-macerator was assumed to increase the field drying rate by 70% compared to a conventional SP mower-conditioner. It was also assumed to have a purchase price 50% higher and a throughput capacity 17% lower than a conventional machine. The macerator reduced the amount of water to be evaporated artificially by 25 to 33% under a wide range of climates, between 0.2 and 0.5 daily rainfall probability (p_R). Although the macerator operated more slowly than the conventional mower, it operated more hours and harvested more dry matter (DM) per year except in a very dry climate ($p_R < 0.3$). The net benefit in favor of the macerator was \$0.36, \$1.31, \$2.29, and \$3.88/t DM under 0.2, 0.3, 0.4, and 0.5 daily rainfall probabilities, respectively. This represented net annual savings between \$14,000 and \$20,000 per mower unit in the wetter climate (0.4 to 0.5 rain probability). Additional economies of \$2.61 and \$2.12/t DM could be achieved if maceration were able to double the drying rate and if improved design maintained throughput to a level equal to that of current mower-conditioners.

Une analyse de faisabilité a permis d'évaluer l'impact du surconditionnement des fourrages sur une usine de déshydratation de la luzerne. À partir des données de recherche, on a supposé qu'une faucheuse-surconditionneuse automotrice produirait des andains séchant 70% plus vite que des andains conventionnels, qu'elle coûterait 50% plus cher et qu'elle aurait une capacité de récolte diminuée de 17% par rapport à une faucheuse-conditionneuse automotrice conventionnelle. La faucheuse-surconditionneuse a réduit de 25 à 33% la quantité d'eau à évaporer artificiellement à l'usine sous des climats dont la probabilité de pluie quotidienne (p_p) variait entre 0,2 et 0,5. Bien que la surconditionneuse opérait plus lentement que la faucheuse conventionnelle, elle pouvait travailler plus d'heures et permettre de récolter plus de matière sèche (MS) par année excepté sous un climat très sec ($p_p < 0,3$). Le bénéfice net en faveur du surconditionnement était de 0,36, 1,31, 2,29, et 3,88 \$/t MS sous des probabilités de pluie quotidienne p_p de 0,2, 0,3, 0,4, et 0,5, respectivement. Ce bénéfice correspondait à une économie annuelle de 14 000 à 20 000 \$ par année par unité automotrice sous les climats plus humides ($p_p \geq 0,4$). Une amélioration des composantes mécaniques de la faucheuse-surconditionneuse occasionnerait des bénéfices supplémentaires de 2,61 \$/t MS si le taux de séchage était augmenté de 100% au lieu de 70% et de 2,12 \$/t MS si la capacité de fauche n'était pas diminuée par rapport à celle d'une faucheuse-conditionneuse conventionnelle.

INTRODUCTION

The Canadian processed alfalfa industry has expanded considerably in the last 15 years, from a yearly production of 350,000 t in 1978 to over 750,000 t in 1992 (Anon. 1992). Over 70% of the processed alfalfa is dehydrated from fresh or wilted crop and processed into pellets or cubes. The remaining portion of processed alfalfa is made from suncured hay.

The highest quality, the greenest colour, and the lowest field losses are obtained by processing a fresh crop with little or no field wilting. However, the dehydration costs are highest in this case because a lightly wilted crop may contain greater than 70% moisture. Berney (1991) estimated energy costs alone to be US\$30.20/t for 70%-moisture alfalfa compared to US\$4.50/t for 30%-moisture alfalfa (\$ figures are in Canadian funds unless stated otherwise). In addition to this variable cost, a dehydration plant would require larger dryers for wet forage and a capital investment four times larger (US\$826,000) than for low-moisture forage (US\$196,000). To process the same annual volume of 8900 t, the annual fixed cost of the dryer was estimated by Berney (1991) to be US\$10.50/t for 70%-moisture alfalfa and US\$2.50/t for 30%-moisture alfalfa in addition to energy costs.

There is a strong economic incentive to process a drier crop; however, a 30%-moisture crop typically requires a 3-day wilting period. Forage quality, greenness, and value are likely to be affected by prolonged respiration, bleaching, and possible leaching due to rain. Dehydrators must therefore make a compromise between the cost of drying and the quality of the processed forage.

Over the past decade, several research groups have significantly increased the field drying rate of forage with intensive mechanical conditioning, sometimes referred to as maceration, mat making, or superconditioning. In one scheme, maceration is integrated in a mower-conditioner by replacing the conventional conditioning rolls with a series of grooved shredding rolls operating at differential speeds and close clearances. The macerated forage is usually compressed to form a thin mat before deposition on the stubble. Koegel et al. (1988) built the first small-scale (1.2 m wide mower) field prototype which doubled and even tripled the field drying rate. They were able to reduce the drying time to reach a target moisture by half or two thirds and make hay within a day (Shinners et al. 1987). Savoie et al. (1993) built a larger prototype (2.1 m wide mower) and observed drying rates about double those of a conventional mower-conditioner. Research and development are continuing to produce a large size mat-maker with simplified components and high capacity (Shinners et al. 1992; Deutz-Fahr 1993).

Two economic studies have shown that maceration and mat making would effectively reduce drying time, enhance forage quality, and increase milk production on dairy farms. At a cost not exceeding twice that of a conventional pull-type mower-conditioner, a mower-macerator-mat-maker would be very profitable on a dairy farm feeding hay in Michigan (Rotz et al. 1990) and on dairy farms feeding silage in the United Kingdom (McGechan et al. 1993). Maceration should be even more profitable for a dehydration plant because of the large and immediate savings in energy to evaporate water.

Table I: Yield of standing alfalfa, forward speed and throughput with a self-propelled (SP) conventional mower-conditioner and with a SP mower-macerator.

Period[1]	Yield (t DM/ha)	Mower-conditioner Speed (km/h)	Mower-conditioner Throughput (t DM/h)	Mower-macerator Speed (km/h)	Mower-macerator Throughput (t DM/h)
C1-W1	2.4	11.9	9.6	9.9	8.0
C1-W2	3.3	8.7	9.6	7.2	8.0
C1-W3	4.2	6.8	9.6	5.7	8.0
C1-W4	4.8	6.0	9.6	5.0	8.0
C1-W5	5.2	5.5	9.6	4.6	8.0
C1-W6	5.5	5.2	9.6	4.3	8.0
C2	2.4	11.9	9.6	9.9	8.0
C3	1.0	12.0	4.0	10.0	3.4

[1] A period is one week within a growth cycle. C1 ranges between June 8 and July 19. C2 and C3 are averaged over the entire growth cycle between July 20 and August 30 for growth cycle 2 and between August 31 and October 11 for growth cycle 3.

OBJECTIVE

The objective of this study was to assess the impact of maceration on the operation of an alfalfa dehydration plant. This included the effect of maceration on field drying, on moisture content of the crop coming into the dehydration plant, on the artificial dryer capacity, and on the total costs of mowing and dehydration. The economic analysis assumed that the plant owners who would benefit from the likely decrease in energy cost for dehydration were also responsible for the mowing equipment which would be more expensive with maceration.

PROCEDURE

Crop characteristics

The alfalfa crop was assumed to be harvested continuously during the growth season from June 8 to October 12, an 18-week period. Alfalfa was cut during three successive growth cycles, each spanning over a 6-week period. Experimental plot yield data for eastern Canada conditions (Bertrand and Gervais 1979) were used to estimate parameters in a logistical growth model (Savoie and Marcoux 1985). The model predicted weekly yield and a total annual yield of 9.5 t dry matter/ha (t DM/ha). The total annual yield was adjusted to 7.6 t DM/ha, considering an 80% management correction factor compared to the almost ideal experimental conditions. Table I shows weekly yields for the first growth cycle which varied between 2.4 and 5.5 t DM/ha and a single average yield for second and third cuttings. Weekly yields varied between 2.0 and 2.8 t DM/ha during second cutting and between 0.6 and 1.5 t DM/ha during third cutting. Weekly yields of second and third cuttings tended to be higher when the previous cut was taken early. A single average value for second cutting and for third cutting was considered adequate for the subsequent analysis and reduced the number of periods analysed from 18 to 8.

Moisture of the fresh crop was assumed to decrease with maturity. This was modeled as a weekly 2% unit decline in moisture content (wet basis) from 84% to 74% over 6 weeks in first cutting, and average moisture contents for second cutting (78%) and third cutting (82%) that corresponded to typical crop conditions observed in eastern Canada (Savoie et al. 1984).

Mowing equipment

The conventional method of mowing alfalfa for a dehydration plant was assumed to use a self-propelled (SP) unit with a mower 4.2 m wide equipped with conditioning rolls. The machine could travel up to 12 km/h and handle an instantaneous throughput as high as 12 t DM/h. When throughput was non-limiting (i.e. at low yields), speed was the limiting factor and maximum theoretical capacity was 5.04 ha/h. A mower field efficiency of 80% was assumed. The maximum field capacity was therefore 4 ha/h. In straight operation without turning, the mower could move up to 12 km/h and have an instantaneous capacity of 5.04 ha/h. At this speed, a yield above 2.38 t DM/ha became the limiting factor. Table I shows the maximum forward speed and actual throughput of a self-propelled mower-conditioner for the typical yields estimated throughout the growth season.

There was no commercially available self-propelled mower-macerator-mat-maker at the time of the study. A hypothetical machine would include a series of macerating rolls and a compression system integrated onto a self-propelled mower. This would certainly require additional power; it might also result in a slight reduction in forward speed and throughput compared to a conventional self-propelled mower-conditioner. In Table I, we assumed that maximum forward speed was 10 km/h and maximum throughput 10 t DM/h for a self-propelled mower-macerator of 4.2 m mowing width. Considering an 80% field efficiency, throughput was the limiting factor for all cuttings except for the low yield third cutting where speed became the limiting factor.

Field drying rate

Field drying is often modelled by a simple exponential curve (Rotz and Chen 1985):

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

where:

M = final moisture concentration on a dry basis (kg water/kg DM),
M_o = initial moisture concentration (kg/kg),
k = drying coefficient (h^{-1}), and
t = day-time drying time (h).

There is a wide range of drying data on maceration and mat making, from Wisconsin (Shinners et al. 1987), Germany (Bischoff et al. 1989), Sweden (Sundberg and Lundvall 1991), and Canada (Savoie et al. 1993). In general, drying rate increased about two-fold in field conditions and as much as five-fold in laboratory conditions. Rotz et al. (1990) developed a general relationship between drying rate of macerated forage (k_m) and conventionally conditioned forage (k_c) based on field data from Michigan and Wisconsin. The ratio k_m/k_c ranged between 1.7 and 2.3 for a large range of yields and swath widths. Savoie et al. (1993) observed a similar variation, with drying rate gains ranging between 61% and 137% (ratios of 1.61 to 2.37), the higher values being associated with alfalfa and the lower values associated with grass. Good mechanical implementation of maceration on a self-propelled mower should provide similar gains in drying rate. A conservative value of 1.7 was assumed for the ratio k_m/k_c, unless stated otherwise. A typical drying coefficient on a non-rainy day in eastern Canada was considered as $k_c = 0.10\ h^{-1}$ (Savoie et al. 1993).

Field drying time

Mowing and field drying were restricted to days without rain. The time during which forage was assumed to dry in the field was part of 1, 2, or 3 days depending on expected weather of days following mowing. Therefore, the main variable in the analysis was the final moisture content of forage at harvest, estimated by Eq. 1 with $k_c = 0.10\ h^{-1}$ or $k_m = 0.17\ h^{-1}$ as stated above. The diurnal times assumed for field drying are in Table II; the rationale for these values is explained below.

A constraint on total available time for mowing was set at 14 hours daily. When only one day in a row without rain was expected, the cut material was assumed to be collected the same day after a limited period of drying, averaged at about half the day-light hours: 7, 6, and 5 h for first, second, and third growing cycles, respectively. When the weather forecast was favourable for several days, it was assumed that forage would lay for a longer period of time in the field before harvesting. The average daytime drying was assumed to be 14 h for two consecutive non-rainy days and 21 h for three consecutive non-rainy days during the first growth cycle. The amount of time was adjusted proportionately in second and third growth cycles according to the shorter day-light hours.

Rainfall probability

As stated above, mowing took place only on non-rainy days. It was therefore possible to estimate the probability associated with various sequences of harvest days. The total probability can be expressed as:

$$p_T = p_R + p_{1DNR} + p_{2DNR} + p_{3DNR} \quad (2)$$

where:

p_T = total probability, equal to 1,
p_R = daily rainfall probability,
p_{1DNR} = probability of only 1 day without rain, followed by a rainy day,
p_{2DNR} = probability of 2 consecutive days without rain followed by a rainy day, and
p_{3DNR} = probability of 3 or more consecutive days without rain.

Sequential rainfall events were considered independent, i.e. p_R was assumed to be constant from day to day although, in some areas, rainy days tend to come in clusters rather than to come as independent events. This assumption allowed to estimate the intermediate probabilities as:

$$p_{1DNR} = (1 - p_R)\, p_R \quad (3)$$

$$p_{2DNR} = (1 - p_R)^2\, p_R \quad (4)$$

The last term in Eq. 2, p_{3DNR}, was the residual probability, calculated by substraction.

Table III shows a list of probability levels of each sequence as a function of rainfall probability. A rainfall probability of 0.4 is typical in eastern Canada during alfalfa growth season and is considered in subsequent analysis unless stated otherwise.

Table II: Average day-time hours assumed for field drying prior to harvesting

Growth cycle	Diurnal field drying time (h): 1 day w/o rain	2 days w/o rain	3 days w/o rain
First (8 June-19 July)	7	14	21
Second (20 July-30 August)	6	12	18
Third (31 August-11 October)	5	10	15

Table III: Probability of various harvest conditions as a function of rainfall probability

Rainfall probability	Independent field working probability: p_{1DNR} (1 day w/o rain)	p_{2DNR} (2 days w/o rain)	p_{3DNR} (3 or more days w/o rain)
0.20	0.16	0.13	0.51
0.30	0.21	0.15	0.34
0.40	0.24	0.14	0.22
0.50	0.25	0.13	0.12

Water to be evaporated artificially

Alfalfa pellets and cubes are usually processed at a final moisture content of 10 to 12% (wet basis). The alfalfa is often overdried to 7% in the dehydrator and rewetted during cube or pellet formation to improve product cohesion and durability. A final value of 0.08 kg/kg (M_{DEHY} on a dry basis) was assumed for moisture of alfalfa coming out of the dehydrator.

The water to be removed in the dehydrator was the difference between the incoming moisture and the final moisture. The quantity of water to be evaporated was calculated on the basis of one hour of field mowing operation.

$$W = C\,(M - M_{DEHY}) \tag{5}$$

where:

W = quantity of water needed to be evaporated artificially per hour of mowing operation (t water/h),

C = actual mowing field capacity or throughput (t DM/h),

M = final moisture in the field (kg/kg), and

M_{DEHY} = final moisture out of the dehydrator (kg/kg).

Matching the mower and the dehydrator

On the one hand, the mowers were seen to have limitations with respect to speed and throughput (Table I). On the other hand, dryers also have a limitation on the daily amount of water which can be evaporated. In practice, all the forage harvested daily must be dehydrated within 24 h, otherwise it will heat and mold rapidly. The maximum daily evaporation capacity in the dryer can be expressed as:

$$E_d = 24\,E_h \tag{6}$$

where:

E_d = daily evaporation capacity (t water), and

E_h = hourly capacity (t water/h).

The evaporation capacity had to be matched with the amount of water to be evaporated artificially:

$$n\,W \leq E_d \tag{7}$$

where n = number of hours of mowing per day.

The value of n was corrected as n_a, the smaller value between the one calculated from Eq. 7 and 14 h, this latter being the maximum time assumed to be available for mowing each day.

The actual dry matter harvested and dried in a day was therefore:

$$Q_d = n_a\,C \tag{8}$$

where:

Q_d = amount of dry matter harvested daily (t DM), and

n_a = the actual number of hours of mowing considering the dryer's limits and the maximum number of hours available for mowing daily.

The actual dryer capacity considered was 4000 kg water/h (Berney 1991). This capacity corresponded to a maximum evaporation of 96 t of water daily or 12,000 t for the harvest season under continuous operation, which never happened because of rain and because of yield and harvest limitations.

Weekly and seasonal capacity

For the conventional mower-conditioner, daily mowing rates were estimated under three conditions: 1 day without rain, 2 consecutive days without rain, and 3 or more consecutive days without rain. Under each condition, the forage was harvested at a different moisture content. The harvest capacity for each of the three conditions was associated with a probability given in Table III.

Therefore the weekly probable harvest was:

$$Q_w = 7 \sum_{i=0}^{m} (Q_d\,p)_i \tag{9}$$

where:

Q_w = weekly dry matter harvested and dried (t DM),

m = number of harvest conditions considered, and

p = probability level associated with the specific harvest condition of Q_d taken from Table III.

The number of harvest conditions considered (variable m) was 3 in the case of the conventional mower-conditioner and 2 in the case of the mower-macerator (see below).

The weekly dry matter harvested and the associated water evaporated were summed over the whole season of 18 weeks. Weekly values were obtained for the first growth cycle. For the second and third growth cycles, the average values for the growth cycle were multiplied by 6 weeks.

In the case of the self-propelled mower-macerator, field wilting was considerably faster than for the conventional mower-conditioner. For this reason, only two harvest conditions were considered with the macerator: 1 day without rain and 2 or more consecutive days without rain. Values of p_{2DNR} and p_{3DNR} in Table III were combined and m equalled 2 in Eq. 9.

Economic analysis

Maceration may have an impact on processed forage quality. However because there was no information on quality at the time of the study, the economic analysis considered only the most obvious differences between maceration and conventional mowing-conditioning: mowing costs and artificial drying costs. The self-propelled (SP) mower-conditioner was assumed to have a purchase price of \$60,000. The SP macerator was assumed to have a purchase price of \$90,000 considering the precision-machined macerating rolls, the mat compression device, and the extra power required from the tractor engine. Fixed annual machinery costs, including depreciation, interest on capital, and other fixed costs, were assumed to be 15% of purchase price: \$9,000/y for the SP mower-conditioner and \$13,500/y for the SP mower-macerator. A fixed annual cost of 15% of purchase price is equivalent to a 10-year depreciation schedule at an 8% interest rate with no salvage value.

Variable machine costs included repair and maintenance (R&M), fuel, and labour. ASAE (1993) indicated that the life-time R&M costs of a SP windrower are 55% of its purchase price over a 3000 h expected life. R&M costs were averaged at 2% of purchase price per 100 h of use: \$12/h for the SP mower-conditioner and \$18/h for the SP macerator. Extra power for maceration on a 2.8 m wide mower has been estimated as 8 to 10 kW (Asselin et al. 1994). It was therefore estimated that 15 kW more power would be sufficient for a 4.2 m wide SP mower. A conventional SP mower-conditioner typically uses 45 kW, so a 60 kW engine was assumed for the SP macerator. With regards to fuel efficiency, a value of 3 kWh/L which is typical for agricultural tractors was used (ASAE 1993). Fuel consumption was therefore 15 L/h ($6/h) for the mower-conditioner and 20 L/h ($8/h) for the macerator. Labour was estimated at $10/h.

The purchase price of the dryer was estimated at $200,000. The fixed annual cost was assumed to be $30,000. The variable cost was essentially the cost of natural gas to dehydrate alfalfa. An evaporation enthalpy of 3250 kJ/kg of water in alfalfa was assumed as suggested by data from Berney (1991). Although macerated forage might be expected to free its water more easily than conventional forage, no difference was assumed in enthalpy of evaporation except in the sensitivity analysis. The price of delivered natural gas was assumed to be $4.62/GJ. This amounts to a variable dryer cost of $15/t of water evaporated.

Table IV: Initial and final moisture contents in the field assuming k_c is 0.10 h^{-1} and k_m is 0.17 h^{-1}, as a function of mower and non-rain sequence

Period	Initial moisture		Final moisture (kg/kg)				
	Wet basis (%)	Dry basis (kg/kg)	Conventional mower-conditioner			Macerator	
			1DNR[1]	*2DNR*	*3DNR*	*1DNR*	*2DNR*
C1-W1	84	5.25	2.61	1.29	0.64	1.60	0.49
C1-W2	82	4.56	2.26	1.12	0.56	1.39	0.42
C1-W3	80	4.00	1.99	0.99	0.49	1.22	0.37
C1-W4	78	3.54	1.76	0.87	0.43	1.08	0.33
C1-W5	76	3.17	1.57	0.78	0.39	0.96	0.29
C1-W6	74	2.85	1.41	0.70	0.35	0.87	0.26
C2	78	3.54	1.95	1.07	0.59	1.28	0.46
C3	82	4.56	2.76	1.68	1.02	1.95	0.83

[1] Symbols related to climatic conditions 1DNR, 2DNR and 3DNR represent one day without rain, 2 consecutive days without rain, and 3 or more consecutive days without rain, respectively.

Sensitivity analysis

A number of parameters were varied to consider their impact on the analysis. They included the rainfall probability, the actual effectiveness of maceration on the field drying rate, the field capacity of the mower-macerator compared to the mower-conditioner, the number of hours available daily for mowing, the dryer capacity, and the enthalpy of evaporation of macerated forage.

RESULTS AND DISCUSSION

Moisture at harvest

Table IV illustrates the variation of final field moisture content of alfalfa mowed either with a conventional mower-conditioner or with a mower-macerator based on a ratio of k_m/k_c of 1.7. As more rain-free days were available, the forage was harvested at a lower moisture content. The final moisture content averaged over first growth alfalfa with the conventional mower-conditioner was 1.93 kg/kg after a single day without rain, 0.96 kg/kg after a 2-day non-rain sequence and 0.48 kg/kg after a 3-day non-rain sequence. With the macerator, the average final moisture during first cutting was 1.18 kg/kg after a single day and 0.36 kg/kg after a 2-day sequence. Since the target moisture after dehydration was set at 0.08 kg/kg, a 2-day non-rain sequence would reduce by more than half the amount of water remaining to be evaporated artificially compared to a single day sequence for either mower. Compared to the conventional mower-conditioner, the macerator reduced the moisture load to be evaporated by 40% on a single non-rain day, by 68% on a 2-day sequence, and by 29% on a 3-day sequence. In the latter case, the macerated forage was assumed to be harvested no later than during the second day. Under favourable weather conditions, the macerated forage would lay for a significantly shorter time than the conventional windrows, thereby reducing respiration losses and bleaching.

Artificial drying requirements

The quantity of water remaining to be evaporated artificially by the dryer is shown in Table V. When forage was mowed and harvested in a single day, the amount of water to be evaporated artificially ranged between 11 and 24 t/h of mower-conditioner operation and between 6 and 12 t/h of mower-macerator operation. Averaged over the first growth cycle for a single day sequence, the conventional mower produced a water load at the dryer twice as high (17.8 t/h) as the macerator (8.8 t/h). It should be pointed out that the macerator was assumed to have a field capacity 17% lower than the conventional mower.

As expected, the water load to be evaporated decreased when a longer sequence of non-rainy days was available. The macerator was always more efficient than the mower-conditioner. Averaged over the first growth cycle for a 2-day sequence, the macerator had a water load of 2.2 t/h of mowing compared to 8.5 t/h for a 2-day sequence or 3.8 t/h for a 3-day sequence with the conventional mower-conditioner.

Mowing time

Three constraints were considered with respect to mowing time: weather, i.e. mowing was restricted to non-rainy days, the artificial dryer capacity, and the number of hours the mower could be operated in the field each day. Land area and available crop were not considered as constraints. By assuming a dryer capacity of 4000 kg water evaporation per hour (96 t/d = E_d in Eq. 6), mowing time had to be cut short when the crop was very wet and would overload the dryer. This is seen in Table VI. The daily mowing time had to be restricted to as little as 4 h/d with the conventional mower-conditioner

Table V: Quantity of water to be evaporated artificially per hour of mower operation

Period	Water to be evaporated (t/h of mower operation)				
	Conventional mower-conditioner			Macerator	
	1DNR	*2DNR*	*3DNR*	*1DNR*	*2DNR*
C1-W1	24.3	11.7	5.4	12.1	3.2
C1-W2	20.9	10.1	4.6	10.4	2.7
C1-W3	18.3	8.7	3.9	9.1	2.3
C1-W4	16.1	7.6	3.4	8.0	2.0
C1-W5	14.3	6.7	3.0	7.1	1.7
C1-W6	12.8	6.0	2.6	6.3	1.5
C2	17.9	9.5	4.9	9.6	3.0
C3	10.7	6.4	3.7	6.3	2.6

under a single-day non-rain sequence. When the harvested crop was drier, the number of hours available for mowing daily became the constraint. This mowing time constraint was set at 14 h/d and was limiting especially under favourable weather. The dryer could have handled a greater quantity of crop. In practice, the manager might decide to increase daily mowing time with a night shift. This could bring up daily mowing time to close to 21 h/d, considering 3 h for daily maintenance, and would maximize the use of the dryer when a sequence of several good drying days was forecast.

The hours available for mowing per week are shown in Table VII. These integrate daily mowing time from Table VI and the probabilities of various harvest conditions in Table III. The geographical location of a dehydration plant and its associated rainfall probability will greatly influence the time available for mowing. With the conventional mower-conditioner, the yearly available time for mowing decreased by half between a 0.2 daily rain probability (1228 h) and a 0.5 rain probability (616 h).

Table VI: Maximum number of hours of mowing per non-rainy day that will not exceed drier capacity or maximum available mowing time (14 h)

Period	Maximum time for mowing (h/day)				
	Conventional mower-conditioner			Macerator	
	1DNR	*2DNR*	*3DNR*	*1DNR*	*2DNR*
C1-W1	4.0	8.3	14.0	7.9	14.0
C1-W2	4.6	9.6	14.0	9.2	14.0
C1-W3	5.2	11.0	14.0	10.6	14.0
C1-W4	6.0	12.6	14.0	12.0	14.0
C1-W5	6.7	14.0	14.0	13.6	14.0
C1-W6	7.5	14.0	14.0	14.0	14.0
C2	5.4	10.1	14.0	10.0	14.0
C3	8.9	14.0	14.0	14.0	14.0

The macerator increased the number of hours available for mowing under all rainfall probabilities (0.2 to 0.5) because macerated windrows were harvested at a lower moisture content than conventional windrows and the dryer, with a fixed water evaporation capacity, was able to process more macerated DM per day. The number of hours of mowing was increased with the macerator by 11%, 17%, 24%, and 31% under 0.2, 0.3, 0.4, and 0.5 daily rainfall probability, respectively. Since the macerator was assumed to have a throughput 17% less than the conventional mower-conditioner, only under 0.4 and 0.5 rainfall probability would the macerator actually increase total processed forage dry matter.

Energy savings

Tables VIII and IX show examples of processed dry matter and water evaporated weekly and yearly. The total dry matter processed under a rain probability of 0.3 (Table VIII) was similar with the conventional mower-conditioner and the mower-macerator (about 7500 t DM/y). However, the quantity of water that had to be dried artificially was 30% less with the macerator.

Under a 40% rainfall probability (Table IX), the macerator processed 5% more dry matter per year. The intensive conditioning technology reduced the amount of water to be evaporated by 27% annually. Table X summarizes annual dry matter processed and artificial water evaporation for daily rainfall probabilities in the range of 0.2 to 0.5. In a dry climate ($p_R = 0.2$), the macerator processed 6% less forage than a conventional mower-conditioner. In a wetter climate ($p_R \geq 0.3$), the macerator processed 0 to 12% more DM annually because it could operate more hours than the conventional mower which was limited by its wetter crop and the dryer's capacity. The macerator reduced the annual amount of water to be evaporated artificially by 25 to 33%. On a per unit DM basis, the reduction averaged 30%: 0.67 t water to be evaporated/t DM with the macerator versus 0.97 t water/t DM with the conventional mower.

Economics of maceration

Table XI summarizes the costs of mowing and dehydration for a single self-propelled mower and a 4000 kg water/h evaporation dryer over the rainfall probability range of 0.2 to 0.5.

The fixed and variable costs of the macerator were always higher than those of the conventional mower-conditioner because of a higher assumed purchase price for the mowing machine ($90,000 versus $60,000), higher maintenance costs, and higher operating costs due to a slower assumed field throughput. The annual fixed and variable costs of the macerator were between $17,248 and $20,126 higher than the mower-conditioner costs.

The dryer fixed costs were the same for both mowers. However, dryer variable costs were always lower for the macerated forage because it entered at a lower moisture in the dehydrator. They were between $20,014 and $35,237 less for the macerated forage than for the conventionally conditioned forage. Since total yearly dry matter processed varied between machines and between climatic conditions, total costs

Table VII: Number of mowing hours per week as a function of mower and daily rainfall probability

Period	Time available for mowing (h/week)							
	Conventional mower-conditioner				Macerator			
	Rainfall probability							
	0.2	0.3	0.4	0.5	0.2	0.3	0.4	0.5
C1-W1	61.9	47.7	36.3	26.2	71.6	59.6	48.6	38.3
C1-W2	63.8	50.1	38.7	28.5	73.0	61.5	50.7	40.6
C1-W3	65.9	52.6	41.2	31.0	74.5	63.5	53.0	43.0
C1-W4	68.1	55.3	43.9	33.6	76.2	65.7	55.5	45.5
C1-W5	70.2	57.9	46.5	36.2	77.9	68.0	58.1	48.3
C1-W6	71.1	59.0	47.9	37.6	78.4	68.6	58.8	49.0
C2	65.2	51.8	40.5	30.4	73.9	62.7	52.1	42.0
C3	72.7	61.2	50.3	40.2	78.4	68.6	58.8	49.0
Weighted total (h/yr)	1228	1001	799	616	1366	1175	990	810

Table VIII: Quantity of dry matter processed and water evaporated in the drier weekly and for the whole season, for a daily rainfall probability of 0.30

Period	Conventional mower-conditioner		Macerator	
	Dry matter (t/week)	Water evap. (t/week)	Dry matter (t/week)	Water evap. (t/week)
C1-W1	459	422	477	297
C1-W2	481	395	492	272
C1-W3	505	373	508	252
C1-W4	531	355	525	236
C1-W5	555	338	544	223
C1-W6	567	315	549	200
C2	498	404	502	287
C3	245	360	233	253
Weighted total (t/yr)	7551	6780	7507	4727

Table IX: Quantity of dry matter processed and water evaporated in the drier weekly and for the whole season, for a daily rainfall probability of 0.40

Period	Conventional mower-conditioner		Macerator	
	Dry matter (t/week)	Water evap. (t/week)	Dry matter (t/week)	Water evap. (t/week)
C1-W1	348	372	388	276
C1-W2	371	354	406	258
C1-W3	395	340	424	243
C1-W4	421	329	444	231
C1-W5	447	317	465	221
C1-W6	460	299	470	200
C2	389	360	417	267
C3	201	330	200	239
Weighted total (t/yr)	5982	6149	6298	4479

were converted on a per t DM basis.

Over the whole range of rainfall probability, forage treated with the macerator always had a lower total mowing and drying cost than forage treated with a conventional conditioner. The reduction of drying cost was always greater than the cost increase due to the more expensive field macerator. The macerator was more profitable than a conventional self-propelled mower-conditioner under all climates in the range of 0.2 to 0.5 rainfall probability.

The cost reduction was more appreciable under the wetter climate. The economy in favor of the macerator was \$0.36, \$1.31, \$2.29, and \$3.88 per t DM under 0.2, 0.3, 0.4, and 0.5 daily rainfall probability, respectively. For the wetter climates of 0.4 and 0.5 rain probability, this meant an increased yearly benefit ranging between \$14,000 and \$20,000 per mower-macerator unit.

Although there was also a small economy at 0.2 rainfall probability, the macerator might appear less acceptable under such a dry climate because it actually reduced by 6% the quantity of dry matter that could be processed with a single mower per year. For rainfall probabilities of 0.3 or more, the macerator increased both the profit and the amount of dry matter which could be processed with a single mower.

Sensitivity analysis

Table XII shows results of a sensitivity analysis on some of the important variables related to mowing, conditioning, and dehydration of alfalfa. One of the most important assump-

Table X: Dry matter processed and water evaporated artificially for the whole season under four daily rainfall probabilities

	Daily rainfall probability			
	0.2	0.3	0.4	0.5
DM processed (t/yr)				
Conv. mower-conditioner	9351	7551	5982	4566
Macerator	8761	7507	6298	5134
Diff. in favor of macerator	- 6%	0%	+5%	+12%
Water evap. (t/yr)				
Conv. mower-conditioner	7181	6780	6149	5423
Macerator	4832	4727	4479	4089
Diff. in favor of macerator	+33%	+30%	+27%	+25%
Water evap. per unit DM (t/t)				
Conv. mower-conditioner	0.768	0.900	1.028	1.188
Macerator	0.552	0.630	0.711	0.797
Diff. in favor of macerator	+28%	+29%	+31%	+33%

tions is the actual gain in drying rate with maceration compared to conventional conditioning. A drying rate increase of 70% (i.e. a ratio k_m/k_c of 1.7) was assumed. Since this was a relatively conservative assumption in view of numerous observations of greater drying rate improvements, a k_m/k_c ratio of 2.0 would be technically possible. This would improve the economic gain of the macerator over the conventional mower-conditioner to \$2.70, \$3.78, \$4.96, and \$6.84 per t DM under 0.2, 0.3, 0.4, and 0.5 daily rainfall probability, respectively. This is an average gain of \$2.61 over the k_m/k_c = 1.7 assumption.

If implementation of maceration on a self-propelled mower proved to be technically more difficult than expected, a low gain in drying rate of only 40% (k_m/k_c = 1.4) might occur. This would mean that mat making would never be profitable. The reduced benefit in dehydration costs would not compensate for the high fixed and variable costs of the machine.

Another assumption was that the actual capacity of the macerator would be 17% less than the capacity of the conventional mower-conditioner (10 t DM/h versus 12 t DM/h maximum throughput). If the macerator could be designed to have a capacity equal to the capacity of the conventional machine (a 20% increase of macerator capacity), it would procure an additional saving between \$1.92 and \$2.31/t DM (average \$2.12) over the rainfall probability range. On the other hand, if maceration slowed down the field machine more than expected (20% less than the already lowered value of 10 t DM/h), maceration would be only marginally profitable (\$1.10/t DM) and only in a very wet climate (0.5 rain probability).

It was assumed that water evaporation in the dryer required the same energy (3250 kJ/kg) from macerated or conventional forage. The highly bruised surface of macerated forage would likely facilitate water evaporation (Patil et al. 1992). This was modeled by assuming that water evaporation enthalpy decreased by 10% with maceration (2925 kJ/kg). The average additional saving with the macerator would be \$1.01/t DM for this improved energy use in the dryer.

As observed in Table VI, the dryer capacity was sometimes the limiting factor and prevented the mower from being used more hours per day. In Table XII, the sensitivity of this factor was analyzed by assuming that two dryers (8 t water/h drying capacity) were available per mower. Although the second dryer allowed processing more forage per year, it resulted in a higher cost (averaging \$4.33/t DM) with either mower. One mower per dryer unit was therefore a better match than one mower per two dryer units under the present assumptions. An additional dryer did not change the advantage of the macerator over the conventional mower.

Another assumption that was tested was the 14 h/d operation limit on the mower. A third work shift could be set up and mow throughout the night. This would increase the practical time available for mowing daily to 21 h (considering minimal maintenance and operator shift within a 24-h pe-

Table XI: Comparison of mowing and drying fixed costs (FC) and variable costs (VC) in CDN \$ for dehydrated alfalfa mowed with either a conventional or a macerator self-propelled mower under four daily rainfall probability levels

Item	Conventional mower-conditioner				Macerator			
	Daily rainfall probability							
	0.2	0.3	0.4	0.5	0.2	0.3	0.4	0.5
Mower FC (\$/yr)	9,000	9,000	9,000	9,000	13,500	13;500	13,500	13,500
Mower VC (\$/yr)	34,400	28,000	22,300	17,300	50,500	43,400	36,600	30,000
Drier FC (\$/yr)	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Drier VC (\$/yr)	107,700	101,700	92,200	81,300	72,500	70,900	67,200	61,300
Total (\$/yr)	181,100	168,700	153,600	137,600	166,500	157,800	147,300	134,800
Total (\$/t DM)	19.37	22.34	25.68	30.14	19.01	21.03	23.39	26.26

Table XII: Sensitivity analysis of total mowing and drying costs ($/t DM) as a function of changes in the assumed values in the model

Changed parameters	Total mowing and drying costs ($/t DM)							
	Conventional mower-conditioner				Macerator			
	Daily rainfall probability							
	0.2	0.3	0.4	0.5	0.2	0.3	0.4	0.5
Basic values	19.37	22.34	25.68	30.14	19.01	21.03	23.39	26.26
$k_m/k_c = 2.0$	19.37	22.34	25.68	30.14	16.67	18.56	20.72	23.30
$k_m/k_c = 1.4$	19.37	22.34	25.68	30.14	22.18	24.30	26.84	30.01
Mac. throughput up 20%	19.37	22.34	25.68	30.14	17.09	18.97	21.20	23.95
Mac. throughput down 20%	19.37	22.34	25.68	30.14	21.44	23.60	26.07	29.04
Evaporation enthalpy down 10% with maceration	19.37	22.34	25.68	30.14	18.18	20.09	22.32	25.07
2 driers (8 t water/h)	23.27	26.78	30.49	34.94	22.46	24.92	27.76	31.23
Mower operation 21 h/day	17.48	20.07	23.12	27.55	16.93	18.59	20.62	23.20
2 driers and mowing 21 h/d	20.52	23.63	27.01	31.24	19.73	21.81	24.17	26.97

riod). This would allow processing more forage daily and reduce idle time of the dryer, especially during favorable drying sequences. Allowing a 21-h per day mowing period reduced the cost averaged over the whole rainfall range by $2.33/t DM for the conventional mower and by $2.59/t DM for the macerator, representing an average savings greater than $15,000/y per mower unit compared to a 14-h per day work period. Disadvantages such as organizing a night shift for mowing and excessive respiration loss of forage mowed in the evening (i.e. remaining very wet during the first 12 hours of wilting) might hinder application of a 21-h per day mowing schedule.

Using the mower 21 h per day and adding a second dryer allowed the processing of even more forage. However this was not profitable due to the extra investment cost for the second dryer. Averaged over both mowers, the total mowing and drying cost was $3.44/t DM more with two dryers than with a single dryer on a 21 h/d schedule.

CONCLUSIONS

1. A mathematical analysis indicated that maceration, implemented on a self-propelled (SP) mower, considerably reduced the fuel requirement of a dehydration plant that processed partially field dried forage. An average 30% less water remained in macerated forage compared to forage treated with a conventional mower-conditioner under a wide range of climates, between 0.2 to 0.5 daily rainfall probability.
2. Under conservative assumptions of 70% drying rate increase, 17% capacity decrease, and 50% greater machine cost, the total mowing and drying costs of a SP macerator were always lower than those of a conventional SP mower-conditioner. The net benefit in favor of the macerator was $0.36, $1.31, $2.29, and $3.88 per t DM under 0.2, 0.3, 0.4, and 0.5 daily rainfall probability, respectively. This represented annual savings between $14,000 and $20,000 per mower unit in the wetter climate (0.4 to 0.5 rain probability).
3. If a SP macerator could be designed to increase the drying rate by 100% instead of 70%, an additional economy of $2.61/t DM could be achieved. An improvement in the throughput capacity to a level equal to current mower-conditioners would bring an additional benefit of $2.12/t DM.

ACKNOWLEDGEMENTS

The authors thank the Natural Science and Engineering Research Council of Canada (NSERC) for continued support through the research grant program which allowed initiating this research project.

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