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Enhancing Switchgrass Drying Rate

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Abstract Rapid drying to baling moisture reduces weather-related risks when harvesting perennial grasses to be used as biomass feedstocks. Drying switchgrass can be challenging due to large, dense swaths and unfavorable autumn drying conditions, so new methods to improve drying are needed. Two techniques to enhance switchgrass drying rate were investigated, which are intensive conditioning and wide-swath drying. Intensive conditioning involved rolls that crushed the stem along its length accompanied by differential roll speed to disrupt the waxy epidermis of the stem. Wide-swath drying involved a post-conditioning tedding operation that distributed the crop across most of the cut width. A mower-tractor-intensive conditioner-tedder combination was configured so that intensive conditioning, wide-swath drying, or both could be achieved in a single pass. Although not consistent across all trials, intensive conditioning and wide-swath drying were about equally effective at improving switchgrass drying rate compared to conventional conditioning alone. However, the combination of intensive conditioning followed by wide-swath drying consistently resulted in the most rapid drying rate. In eight separate trials, this combination produced switchgrass moisture contents well below 20% (w.b.) on the second or third day after cutting. An empirical model of switchgrass drying rate was developed, which can be used to predict switchgrass drying time based on weather conditions, conditioning level, and swath density.

Keywords Conditioning · Drying · Switchgrass · Swath

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Introduction

Switchgrass (*Panicum virgatum* L.) has been identified as a viable herbaceous feedstock for cellulosic bioenergy production [1]. It is a perennial, warm-season grass that is an attractive biomass crop because it does not have annual establishment requirements, requires moderate herbicide and fertilizer inputs, is relatively drought tolerant, and produces large yields [2]. When destined for use as a biomass feedstock, switchgrass is typically harvested as a single cutting in the autumn and packaged with conventional hay-harvesting equipment. It is generally accepted that when packaged in large-round or large-square bales, the material moisture should be near or ideally below 20% (w.b.) to insure adequate conservation in storage and to maximize the transported dry matter [3].

In northern climates, switchgrass targeted as a biomass feedstock will typically be harvested in the autumn after senescence [2] so the standing crop moisture is typically less than 65% (w.b.) [4, 5]. The drying time of switchgrass has been reported to be shorter than that reported for alfalfa or forage grasses when harvested in the autumn [5] despite the fact that switchgrass yields were much greater than typical forage crops. Faster drying was attributed to lower initial moisture, well-structured swaths that did not slump after cutting, thereby promoting good air movement through the swath and large leaf surface area. Although drying to harvest moisture is possible in 2 to 3 days [5], in northern climates, autumn drying is challenged by short daylight length, low ambient temperatures, and frequent poor weather so drying can take much longer [6].

Grasses have many built-in mechanisms used to regulate moisture. The cutin layer of the stem resists moisture loss through the epidermis, and the leaf stomata serve as an egress for water vapor. Stomatal opening is regulated by many parameters, but the water turgidity of the plant is an important

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factor. After cutting, solar insolation heats water in the plant cells, increasing internal vapor pressure. Movement of the vaporized water is resisted both physically by the cell wall, cutin layer, and closing stomata and chemically by osmotic forces within the cell. Vapor pressure differential between water inside the plant and the micro-environment in the swath influences the rate of water loss. Vapor pressure properties in the swath are affected by temperature, humidity, wind speed, and soil moisture [7]. Radiation intensity, vapor pressure, wind speed, and moisture content at cutting have been shown to influence switchgrass drying rate in a drying chamber [8, 9]. Harvesting parameters that can be used to alter the rate of water loss include swath width, swath porosity (i.e., openness and uniformity), cutting height, and level of stem conditioning. Wide swaths capture more solar insolation and well-formed, porous swaths promote air exchange so that saturated air conditions do not exist in the swath micro-environment. Conditioning by crushing, crimping, or abrading the stem increases its specific surface area, disrupts the cutin layer, and provides an egress for moisture within the stem.

Although switchgrass dries more quickly than typical forage grasses, shorter field drying time would reduce the risk of losses from adverse weather, enhance overall harvest productivity and logistics management, and reduce the need to artificially dry biomass if thermochemical conversion is planned. Therefore, the primary objective of this research was to investigate intensive conditioning and wide-swath drying to enhance the drying rate of switchgrass grown in climates north of 42°N latitude. A final objective was to use data collected from the field trials to develop an empirical model of switchgrass drying rate.

Materials and Methods

Drying Treatments

Drying trials were conducted in 2012, 2013, 2015, and 2016 at the University of Wisconsin Arlington Agricultural Research Station (AARS) (43.3453°N, 89.4125°W) using Shawnee switchgrass established in 2004 [5]. Weather conditions measured by an automated weather station located at AARS were collected during the daylight drying periods for the trial dates shown in Table 1. Conditioning roll clearance was quantified using a foil gauge procedure described in [10].

Four treatments were investigated in 2012 using three separate trials (Table 1), conventionally and intensively conditioned (CC and IC, respectively) at two different swath densities. Material for the CC treatments was harvested with a John Deere (Moline, IL) model 4995 disk cutterbar windrower (4.5-m cut width) equipped with urethane conditioning rolls (2-mm clearance). An Agland model 6600 re-conditioner (AgLand Industries, St. Tite, QC, Canada) was used in a second pass to produce material for the IC treatments. The re-conditioner had a windrow pickup to collect the windrowed

Table 1 Average ambient conditions during the daytime drying period for switchgrass drying rate experiments conducted in 2012, 2013, 2015, and 2016

	Standing crop moisture (% w.b.)	Ambient temperature (°C)	Solar radiation (W m^{-2})	Wind speed (m s^{-1})	Relative humidity (%)
Trial no. 1[a]					
14 August 2012	78	25	538	1.9	50
15 August 2012		25	549	3.9	53
Trial no. 2[a]					
20 August 2012	68	22	678	2.8	45
21 August 2012		23	655	1.3	42
Trial no. 3[a]					
18 September 2012	58	12	348	5.8	46
19 September 2012		18	401	9.2	40
Trial no. 4[a]					
8 October 2013	59	23	481	6.8	37
9 October 2013		20	509	5.0	43
10 October 2013		21	496	4.1	48
Trial no. 5[a]					
28 October 2013	40	5	138	5.0	66
29 October 2013		8	238	3.4	73
Trial no. 6[a]					
15 September 2015	61	26	607	6.2	53
16 September 2015		26	601	7.0	59
Trial no. 7[a]					
21 September 2015	61	22	600	4.9	45
22 September 2015		23	434	2.4	59
23 September 2015		24	478	2.7	52
Trial no. 8[a]					
31 August 2016	63	23	714	4.5	60
1 September 2016		21	563	5.2	65
2 September 2016		22	658	3.1	66

[a] Average yields were 9.4, 10.1, 10.0, and 10.4 Mg DM ha^{-1} for 2012, 2013, 2015, and 2016, respectively

material, followed by two pairs of conditioning rolls. The first pair were intermeshing tire-core rolls (3-mm clearance), which fed the knurled steel IC rolls set at 2-mm clearance and operating at 57% speed differential. It was hypothesized that stem crushing from multiple conditioning rolls and scuffing of the cutin layer of the stem by the roll speed differential would enhance switchgrass drying rate (Fig. 1).

Two trials were conducted in 2013 at the same location and field (Table 1). The crop had been subjected to a hard frost 7 days before the second replicated trial. The following three treatments were investigated: CC, IC, and IC tedded (ICT). Full-width swaths are typically produced using a post-cutting operation known as tedding. A tedder uses rotating baskets of tines to lift, spread, and re-orient swathed grasses, typically dispersing the crop across the full cut width. Although current mower conditioners could reasonably be modified to intensively condition as practiced here, a second operation of tedding would still be required. Combining the unit operations of cutting, intensive conditioning, and tedding into a single field operation could provide the best drying results but only require a single pass through the field. Such a machine has been shown to significantly increase alfalfa drying rate [10]. This was the motivation for developing the mower/tractor/intensive conditioner/tedder that was configured to complete the unit operations of cutting, conditioning, and tedding in a single pass. A Kuhn (Brodhead, WI) model 313 mower conditioner (3.1-m cut width) was mounted to the front three-point hitch of a John Deere model 7830 tractor. The mowers intermeshing rubber rolls were set at 3-mm clearance to create the CC treatment. To create the IC treatment, the Agland model 6600 re-conditioner described above was pulled by the tractor so that the windrow made by the front-mount mower was immediately picked up and intensively conditioned. The ICT treatment was created by mounting a tedder at the exit of the re-conditioner. The tedder speed was adjusted so the width of the resulting swath was approximately equal to the cut width. The re-conditioner was not capable of producing a swath as wide as the front-mount mower, so the swath width as a fraction of cut width was approximately 60, 75, and 100% for the IC, CC, and ICT treatments, respectively. Each treatment was replicated four times so that there were four blocks of three treatments each with the treatments randomly assigned within the blocks. Prior to applying the treatments, a border swath was mowed around the perimeter of the plots so that no treatment would be bordered by uncut crop. After the experiment, the border material was round baled and the bales weighed on a 1800-kg capacity platform scale with a resolution of 0.5 kg. The bale dry mass and length and width of the area required to make each bale were used to estimate the yield in the plots. The treatment swath widths were measured to the nearest 10 cm in at least 10 random locations in each plot. The swath width as a fraction of the cut width, along with the estimated yield, was used to calculate the swath density of each treatment. On the final day of trials 4 through 8, all treatments were raked with a single-rotor rotary rake (Kuhn model GA6501, Brodhead, WI) forming a windrow that was approximately 1 m wide, so after that point, the swath density was roughly equivalent for all treatments.

Two trials in 2015 and a single trial in 2016 were conducted at the same location as described above (Table 1). In both years, the crop had not been subjected to a frost and the randomized block experiments were conducted in a similar fashion as described above. In the first 2015 trial, the following four treatments were investigated: CC, CC tedded (CCT), IC, and ICT. The CCT treatment involved tedding the conventionally conditioned material with a Kuhn model GF5001T tedder with the rotor speed adjusted to create a swath approximately equal to the cut width. In the second 2015 trial, the following four treatments were investigated: CC, CCT, ICT, and unconditioned (UC). The CC, IC, CCT, and ICT treatments in both trials were created using the John Deere windrower and AgLand re-conditioner as described above. The unconditioned treatments were created by using the John Deere windrower with the rolls blocked open to approximately 8 cm. In 2016, the following five treatments were investigated: CC, CCT, IC, ICT, and UC. The experimental procedures for forming the plots and collecting data were the same as that described above for 2013.

Measurement Procedures

After material preparation in 2012, sub-samples were randomly collected by hand from the cut swaths and spread evenly on 0.9 × 1.5-m drying trays made with screen with eight openings per centimeter. The trays were then randomly placed in four replicated blocks where the crop had been cut with the location of the four treatments randomly assigned within the blocks. Material was placed on the trays at densities which

Fig. 1 Switchgrass stems subjected to intensive conditioning. Note the crushed node on lower stem and longitudinal cracks in both stems

simulated two swath widths roughly equivalent to 60 and 100% of the cut width. The latter treatments were used to investigate the effect of both conditioning and tedding the crop (CCT and ICT). The trays and their contents were weighed approximately every 2 h over 2 days using a hanging scale of 23-kg capacity and 0.1-kg resolution. At the end of the second day, the contents of each tray were gathered and size-reduced in a lab-scale precision-cut chopper. Three subsamples were then collected from each replicate treatment, placed in paper bags, weighed, and then oven dried for 24 h at 103 °C as per ASABE Standard S358.2 [11]. The dry matter (DM) content was used to calculate the dry mass of the tray contents at removal, which was used to calculate the moisture content of the material at each weighing period.

In 2013, 2015, and 2016, samples were collected at random locations from each replicate immediately after cutting and then three or four additional times during the daylight hours. Duration between sampling was typically 2 or 3 h and samples were collected for 2 or 3 days, depending upon drying conditions. For each replicate sample, about 0.5 m of material was collected across the full width and depth of the swath and then size-reduced by chopping in a lab-scale precision-cut chopper. The chopped material was homogenized, and two subsamples per replicate were oven dried for 24 h at 103 °C per ASABE Standard S358.2 [11].

For all trials, the drying data was analyzed assuming that the data fit the following exponential drying rate model [7]:

$$\frac{M_i}{M_0} = e^{-kt} \tag{1}$$

where M_i is the dry basis moisture at the end of the time interval, M_0 is the dry basis moisture at the beginning of the time interval, k is the drying constant (h^{-1}), and t is the length of time interval (h).

Since the time of cutting was not the same for all plots, the initial time interval was not the same for all treatments and plots. This difference was typically 15 to 30 min. For each day and treatment, the drying constant was transformed based on the least squares linear regression model of several data points [12]:

$$k_t = \frac{n\sum t_i \ln M_i - (\sum t_i)\sum \ln M_i}{n\sum {t_i}^2 - (\sum t_i)^2} \tag{2}$$

where t_i is the time interval between each moisture value (h), k_t is the transformed daily drying rate constant (h^{-1}), and n is the number of observations in each day.

A transformed drying rate constant (k_t) for each day was calculated for each treatment, and an average drying constant was also determined over the multi-day drying period. A two-way analysis of variance was used to block confounding effects of different days when analyzing the data across multiple days. The mixed linear model in the fit model platform in JMP Pro version 11 (SAS Institute Inc., Cary, NC) was used to determine statistical differences between treatments. The least significant difference (LSD) with a probability of 95% was calculated using Microsoft Excel.

Drying Rate Model

Rotz and Chen [7] developed a model of alfalfa field drying and later modified the model for grasses intended for animal feed [13]. These drying models used weather data as major inputs to predict drying rate constants for hay crops. Swath density, windrow structure, and maturity significantly differ between grasses intended for animal feed and those to be used as biomass feedstocks. Therefore, data collected from the eight drying trials were used to create a field drying model specifically for biomass switchgrass. Weather variables considered included solar insolation, vapor pressure differential, ambient temperature, and wind speed. Additional variables considered included swath density, day indicator, conditioning treatment, and raking indicator. Swath density is a function of yield and swath width. Alfalfa drying was found to be faster on the day in which the crop was mowed [7], so a day indicator was included here as a binary variable equal to one on the first drying day, otherwise zero. Intensive conditioning was shown to have a positive effect on drying rate, so it was considered as a binary variable equal to one for IC treatments, otherwise zero. Raking not only inverts the swath and exposes the moist lower layers to the sun but also alters the swath density and restructures the windrow, potentially allowing greater air exchange. Since raking could have larger impact on drying rate than simply altering swath density, a separate binary raking coefficient was considered for the model where the raking indicator was equal to one at the time of raking and for the rest of the day that raking occurred, otherwise zero. Swath density was changed to reflect the density after raking. The generalized linear model in the fit model platform in JMP Pro version 11 was used to screen these eight variables to determine significance for predicting drying rate. Variables with a p value less than 0.005 were considered for further model development.

Microsoft Excel with the Solver data analysis package was used to iteratively solve for all the model coefficients by minimizing the sum of squares of the differences between the actual and model data. The combination of eight drying trials with multiple treatments and two to three drying days per trial resulted in 80 separate observations (i.e., drying rate constants), which were used to determine the model coefficients. A leave-one-out cross-validation (LOOCV) technique was used to develop and validate the model [14]. Each of the eight drying trials was iteratively removed from the data set and the model coefficients were determined. The eight sets of model coefficients were then averaged, the prediction errors were determined for all eight trials, and the root-mean-square error of cross validation (RMSECV) and root-mean-square deviation (RMSD) were determined.

Table 2 Drying rate constants for three drying trials of switchgrass conducted in 2012

Conditioning treatment	Swath density (g DM m^{-2})	Drying rate constant (h^{-1})		
		First day	Second day	Average[c]
Trial no. 1[a]				
CC	1650	0.100 a	0.117 a	0.108 a
CCT	1370	0.132 b	0.128 a	0.130 b
IC	1900	0.141 b	0.146 a	0.143 b
ICT	1690	0.182 c	0.210 b	0.196 c
LSD[b] ($P = 0.05$)		0.023	0.035	0.021
Trial no. 2[a]				
CC	1940	0.109 a	0.123 a	0.116 a
CCT	1130	0.166 b	0.162 b	0.164 b
IC	1750	0.156 b	0.167 b	0.162 b
ICT	1090	0.252 c	0.242 c	0.247 c
LSD[b] ($P = 0.05$)		0.012	0.020	0.012
Trial no. 3[a]				
CC	1750	0.088 a	0.123 a	0.106 a
CCT	1040	0.104 b	0.147 a	0.120 a
IC	1720	0.144 c	0.197 b	0.171 b
ICT	1120	0.169 d	0.222 b	0.196 c
LSD[b] ($P = 0.05$)		0.011	0.033	0.018

[a] *CC* conventional conditioning, *CCT* CC with tedding, *IC* intensive conditioning, *ICT* IC with tedding. Trial dates and ambient conditions provided in Table 1

[b] Least significant difference. Means within columns with different letters are significantly different at 95% confidence

[c] Data were pooled by treatment and analyzed using two-way analysis of variance

Results and Discussion

Field Drying Trials

Compared to CC, switchgrass drying rate was consistently improved by IC in all three trials in 2012 (Table 2). In two of the three trials, the IC treatment dried at the same rate as the CCT treatment, suggesting that conditioning intensity and swath density had a similar impact on improving drying rate. Compared to CC, stems subjected to IC were observed to have greater stem cutin disruption, stem nodes flattened, and more cracks in the stem (Fig. 1), all of which were likely to have

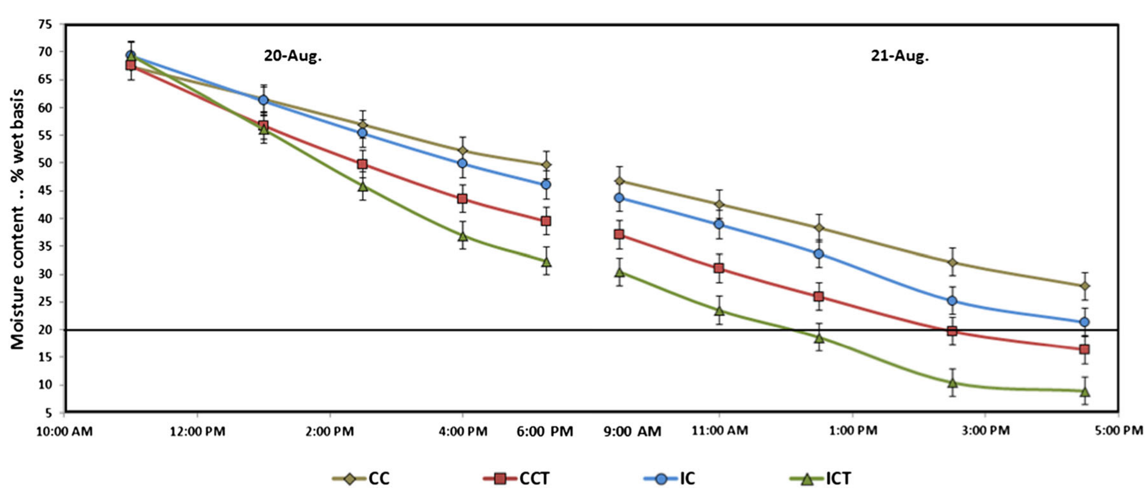

Fig. 2 Field drying characteristics for trial 2 (20–21 August 2012) using four treatments—conditioned (CC), conditioned-tedded (CCT), intensive conditioned (IC), and intensive conditioned-tedded (ICT). *Horizontal line* indicates the target moisture for baling (20%), and *vertical bars* associated with each data point are the 5% LSD value for comparing treatments within time points

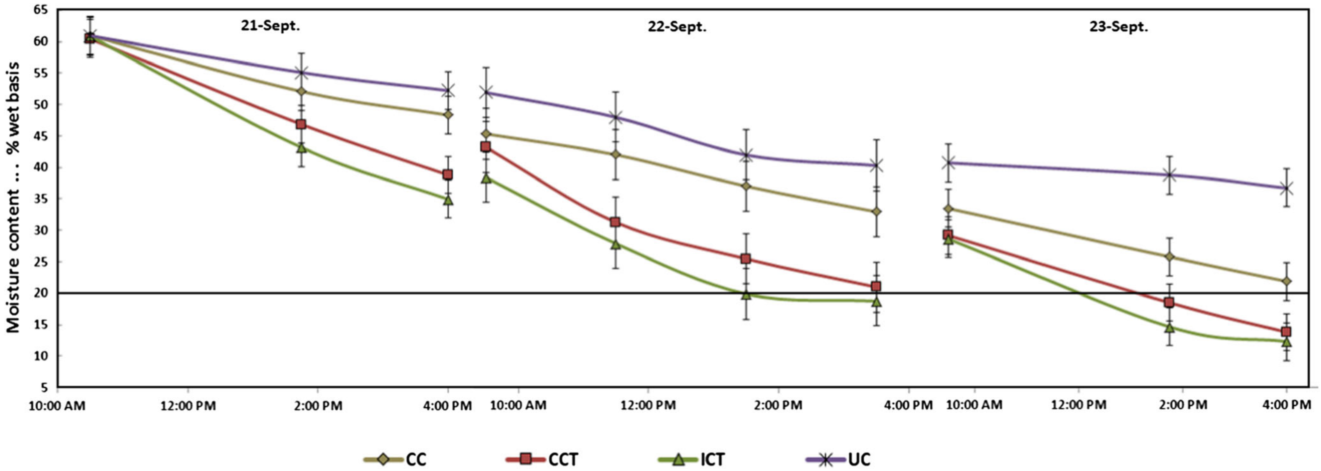

Fig. 3 Switchgrass field drying characteristics for trial 7 (21–23 September 2015)—conditioned (CC), conditioned-tedded (CCT), intensive conditioned-tedded (ICT), and unconditioned (UC). *Horizontal line* indicates the target moisture for baling (20%), and *vertical bars* associated with each data point are the 5% LSD value for comparing treatments within time points

improved water vapor egress. Greater swath width captures more solar insolation, promoting faster drying. The combination of IC and wide-swath drying (ICT) consistently had the greatest drying rate in 2012 and achieved the desired moisture content of less than 20% (w.b.) by the afternoon of the second day (Figs. 2 and 3 and Table 3). This treatment was able to dry switchgrass to less than 15% (w.b.) moisture in all three trials. Drying to this low moisture would improve the efficiency of thermochemical conversion processes, although if

Table 3 Moisture content of each treatment at the end of drying period for all drying trials

Conditioning[a] treatment	Moisture[c] (% w.b.) Trial 1	Baling time[d]	Moisture (% w.b.) Trial 2	Baling time	Moisture (% w.b.) Trial 3	Baling time
CC	34.9 c	NA	25.5 c	5:30 PM	28.1 d	5:30 PM
CCT	23.8 b	5:00 PM	19.7 b	1:30 PM	22.1 c	3:00 PM
IC	21.4 b	4:00 PM	21.3 b	3:30 PM	14.9 b	12:00 PM
ICT	11.9 a	12:30 PM	8.9 a	10:00 AM	11.4 a	10:30 AM
LSD[b] ($P = 0.05$)	6.5		3.2		3.4	
	Trial 4		Trial 5			
CC	20.5 b	12:30 PM	24.4 c	6:00 PM		
IC	13.4 a	11:00 AM	20.9 b	2:30 PM		
ICT	12.1 a	11:00 AM	17.1 a	10:30 AM		
LSD[b] ($P = 0.05$)	3.8		1.0			
	Trial 6		Trial 7		Trial 8	
CC	17.9 d	1:00 PM	21.9 b	2:30 PM	19.5 b	2:00 PM
CCT	12.2 b	8:00 AM	13.8 a	11:00 AM	14.5 a	11:00 AM
IC	13.9 c	10:00 AM			15.5 a	11:30 AM
ICT	9.6 a	8:00 AM	12.3 a	10:30 AM	11.6 a	9:30 AM
UC			36.7 c	NA	29.4 c	NA
LSD[b] ($P = 0.05$)	0.9		3.7		3.9	

[a] *CC* conventional conditioning, *CCT* CC with tedding, *IC* intensive conditioning, *ICT* IC with tedding. Trial dates and ambient conditions provided in Table 1

[b] Least significant difference. Means within columns with different letters are significantly different at 95% confidence

[c] Average moisture content of treatments at the end of each drying trial

[d] Theoretical time of day, rounded to nearest half-hour, when crop reached baling moisture (i.e., 20% (w.b.)), using moisture content at start of last day of trial and drying rate constant. NA indicates that the treatment would not have reached baling moisture before 6:00 PM that day

stored for long durations at high humidity, bales would likely equilibrate to slightly greater moisture [15].

Tedding the CC treatment (CCT) statistically increased the drying rate on the first day, but on subsequent days, drying rate differences were not always statistically different (trials 6–8; Table 4). The average first-day CCT drying rate was twice that of the CC treatment. Field drying of grasses is a falling rate process, so the rate of water loss is less when the crop moisture content is low [16]. When the moisture at the start of the day is low (i.e., <25% (w.b.)), the drying rate constant will be small [16]. Therefore, the CCT drying rate constant was low on subsequent days because its moisture content was already low. The crop reached baling moisture 3 to 5 h sooner when drying the CC treatment in a wide swath (CCT) (trials 6–8; Table 3).

Single-pass IC had a statistically greater drying rate than the CC treatment only in trial 4. A confounding factor was that the IC machine was not capable of producing as wide a swath as the mower conditioner used to create the CC treatment, and the greater swath density of the IC treatment might have contributed at least partially to slower than expected drying. However, the IC treatment resulted in statistically lower final moisture than the CC treatment in all trials and the crop reached baling moisture 1.5 to 3.5 h sooner (Table 3).

Table 4 Drying rate constants for drying trials conducted in 2013, 2105, and 2016

Conditioning treatment	Swath density (g DM m^{-2})	Drying rate constant (h^{-1})			
		First day	Second day	Third day	Average[c]
Trial no. 4[a]					
CC	1440	0.122 a	0.114 a	0.148 a	0.128 a
IC	1840	0.158 b	0.121 ab	0.168 b	0.149 b
ICT	1040	0.176 c	0.159 b	0.179 b	0.171 c
LSD[b] ($P = 0.05$)		0.005	0.015	0.013	0.010
Trial no. 5[a]					
CC	1460	0.032 a	0.058 a		0.045 a
IC	1770	0.045 b	0.052 a		0.049 a
ICT	1080	0.072 b	0.075 b		0.074 b
LSD[b] ($P = 0.05$)		0.032	0.012		0.012
Trial no. 6[a]					
CC	1800	0.090 a	0.132 a		0.111 a
CCT	1080	0206 b	0.138 a		0.172 b
IC	1960	0.103 a	0.124 a		0.113 a
ICT	1120	0.228 b	0.182 b		0.205 b
LSD[b] ($P = 0.05$)		0.058	0.037		0.033
Trial no. 7[a]					
CC	1960	0.095 ab	0.083 a	0.108 b	0.095 b
CCT	1060	0.162 bc	0.154 b	0.173 c	0.163 c
ICT	1120	0.196 c	0.158 b	0.195 c	0.183 c
UC	2000	0.065 a	0.076 a	0.031 a	0.057 a
LSD[b] ($P = 0.05$)		0.037	0.037	0.045	0.022
Trial no. 8[a]					
CC	2290	0.074 a	0.111 a	0.128 ab	0.104 ab
CCT	1060	0.161 b	0.128 a	0.129 ab	0.139 cd
IC	2320	0.096 a	0.139 a	0.145 b	0.126 bc
ICT	1060	0.201 b	0.127 a	0.152 b	0.160 d
UC	2230	0.053 a	0.089 a	0.089 a	0.077 a
LSD[b] ($P = 0.05$)		0.051	0.05	0.050	0.030

[a] *CC* conventional conditioning, *CCT* CC with tedding, *IC* intensive conditioning, *ICT* IC with tedding, *UC* unconditioned. Trial dates and ambient conditions provided in Table 1

[b] Least significant difference. Means within columns with different letters are significantly different at 95% confidence

[c] Data was pooled by treatment and analyzed using two-way analysis of variance

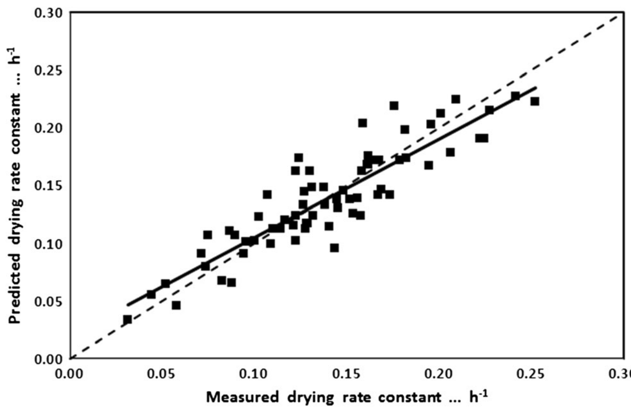

Fig. 4 Measured versus predicted switchgrass drying rate constants using Eq. 3 across all eight drying trials and all treatments (80 separate observations). Model R^2 was 0.791 and root-mean-square error of cross validation (RMSECV) was 0.067

Single-pass ICT produced a numerically greater drying rate than the CCT treatment in trials where these two treatments were compared, but the results were not statistically significant in trials 6–8 (Table 4). These results combined suggest a trend where swath density has greater influence on switchgrass drying rate than conditioning level, and that the benefits of intensive conditioning may be diminished when wide-swath drying is employed.

The CC treatment would have required at least an additional night in the field in four of the eight trials (trials 1–3, 5) because the crop reached 20% (w.b.) moisture so late in the day that baling could not be completed before rewetting with dew occurred. During October and November in the Upper Midwest, the daily probability of precipitation is often greater than 50% [17], so increasing the field drying time from 2 to 3 or 4 days greatly increases the chance of adverse weather disrupting harvest and reducing product quality. The two trials that included the UC treatment show the importance of conditioning switchgrass. In both trials, the UC treatment dried significantly slower than all other treatment combinations (trials 7–8; Tables 3 and 4; Fig. 3), and the unconditioned crop moisture was much too great for safe baling at the end of the trials.

Table 5 Model fit for measured versus predicted (Eq. 3) switchgrass drying rate constants for each omitted drying trial using the leave-one-out cross-validation technique

Omitted drying trial	Model fit for omitted drying trial		
	Slope	Intercept	R^2
1	1.190	−0.019	0.877
2	0.863	0.001	0.924
3	0.613	0.041	0.561
4	1.360	0.044	0.646
5	1.673	−0.028	0.793
6	0.617	0.067	0.770
7	0.877	0.015	0.755
8	1.124	0.009	0.920

Drying Rate Model

Temperature ($p = 0.9865$), day ($p = 0.6291$), and wind speed ($p = 0.1430$) did not significantly influence prediction of drying rate constants and were not included in further model development. Although temperature likely affects drying, it was part of the vapor pressure deficit (VPD) calculation. An alfalfa drying model developed by Rotz and Chen [7] that included VPD did not include temperature for this reason. Although day indicator was a significant variable in alfalfa drying models [7], day was likely not a significant variable here because the initial moisture was much lower with switchgrass than with alfalfa. Moisture that is readily evaporated on the first day of drying of high-moisture alfalfa was already gone when switchgrass drying began. Rotz and Chen [7] suggested that the influence of the VPD and SI variables can mask the effect of wind speed in drying rate models. The remaining variables were significant ($p < 0.005$) predictors of switchgrass drying rate and were used to determine model coefficients. The chosen form of the model equation was similar to that suggested by Rotz and Chen [7], but here, the drying rate constant was directly proportional to solar insolation, vapor pressure differential, conditioning treatment, and raking and inversely proportional to swath density (Eq. 3).

The final model (Eq. 3) had an R^2 of 0.791 and RMSECV and RMSD of 0.067 and 6.4%, respectively (Fig. 4). The average model coefficients from the LOOCV technique were successful at predicting the drying rate constants for each of the respective omitted drying trials (Table 5). Within the range of the variables from the drying trials, swath density had the greatest influence on predicted drying rate (Table 6). Solar insolation and vapor pressure differential had about equal influence on drying rate, and conditioning treatment had the least influence.

$$k = \frac{0.67(\mathrm{SI}) + 237.7(\mathrm{VPD}) + 205.4(\mathrm{CD}) + 449.6(\mathrm{RK})}{4.01(\mathrm{SD})} \tag{3}$$

where k is the drying rate constant (h^{-1}), SD is the swath density (g DM m^{-2}), SI is the solar insolation (W m^{-2}), VPD is the vapor pressure deficit (kPa), CD is the conditioning indicator (1 if intensively conditioned, otherwise 0), and RK is the raking indicator (1 if crop raked, otherwise 0).

Table 6 Influence of environmental, crop, and machine variables on predicted switchgrass drying rate constants

	Solar insolation (SI; (W m^{-2})	Vapor pressure deficit (VPD; (kPa)	Conditioned treatment (CD)	Raking treatment (RK)	Swath density (SD; g DM m^{-2})	Predicted drying rate constant (k; h^{-1})	Theoretical[b] drying time (h)
Baseline at mowing[a]	500	1.25	0	0	1500	0.105	19.0
Solar insolation							
Maximum[c]	750	1.25	0	0	1500	0.133	15.0
Minimum[c]	150	1.25	0	0	1500	0.066	30.3
Vapor pressure differential							
Maximum[c]	500	1.75	0	0	1500	0.125	16.0
Minimum[c]	500	0.25	0	0	1500	0.066	30.4
Swath density							
Maximum[c]	500	1.25	0	0	2300	0.069	29.2
Minimum[c]	500	1.25	0	0	1000	0.158	12.7
Conditioning							
Intensive	500	1.25	1	0	1500	0.140	14.4
Baseline at raking[d]	500	1.25	0	0	1500	0.105	9.2
Raked[e]	500	1.25	0	1	2000	0.135	7.2

[a] Baseline values represent approximate average conditions across all eight drying trials conducted

[b] Theoretical drying time to reach 20% (w.b.) moisture assuming that initial moisture was 65% (w.b.), with dew rewetting and night periods excluded (after Rotz [18])

[c] Approximate maximum and minimum values experienced across all eight drying trials

[d] This baseline assumes that raking occurred when crop moisture was the 40% (w.b.) and drying time represents time to reach 20% (w.b.) moisture from moisture at raking

[e] Raking is a binary variable that is also accompanied with a change in swath density

The model was used to predict the switchgrass drying rate constants for data collected in 2004 and 2005 from Shinners et al. [5]. In this work, switchgrass was only conventionally conditioned, but it was dried in windrows, swaths, and tedded, so swath density was variable. The developed model predicted the drying rate constant with R^2 = 0.802 (Fig. 5).

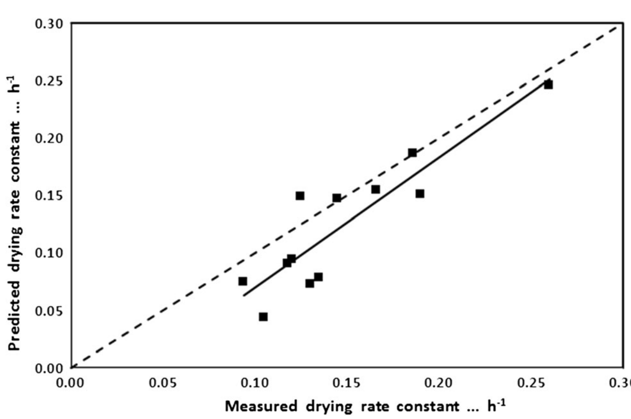

Fig. 5 Measured versus predicted switchgrass drying rate constants (R^2 = 0.802) for switchgrass drying data from Shinners et al. [5] and predicted with Eq. 3

Conclusions

Switchgrass yields are great and swath density large compared to most forage crops harvested for animal feed. Tedding immediately at cutting/conditioning enhanced drying rate by creating wide swaths that decreased swath density and enabled greater capture of solar insolation. Swath density and solar insolation had the greatest influence on predicted drying rate using an empirical drying rate model. Switchgrass drying rate was also improved through intensive conditioning that crushed and scuffed the stems. These actions disrupted the stem cutin layer and flattened the stem nodes, providing an improved egress for water vapor to leave the stem. However, drying improvements with intensive conditioning were inconsistent, and this variable had the least influence on predicted drying rate. Switchgrass was dried to below 20% (w.b.) moisture in 2 or 3 days of field drying using a combination of intensive conditioning and wide-swath drying, while the control treatment often required at least another night in the field before baling the next day. Wide-swath drying will require an additional field operation to rake wide swaths into windrows compatible with the pickup width of currently available balers.

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