Drying models to estimate moisture change in switchgrass and corn stover based on weather conditions and swath density

Abstract.

An environmental chamber was built to evaluate the effect of weather parameters and swath density that affect the drying rate of crops during field drying. A series of 52 drying experiments were conducted on corn stover (CS) of which 27 were used for model development and 25 were used for model validation. Similarly, 80 experiments were performed on switchgrass of which 72 were used for model development and eight were used for model validation. Regression models were developed for switchgrass and CS that predicted the drying rate based on environmental conditions and swath density. During the day, radiation was found to be the most significant variable that affected the drying rate of switchgrass with a correlation coefficient (r) of 0.5 and 0.49 during different maturity stages. During the night, VPD was the most significant variable that affected the drying rate with r of 0.69 for corn stover (CS) and 0.83 to 0.85 for switchgrass. The effect of wind speed was variable and was found to be dependent on solar radiation. During the day time, an increase in wind speed removed the heat produced by radiation and thus decreased the drying rate. However, at night, the wind speed was positively correlated with drying rate. Swath density was negatively correlated ($r = -0.38$) with the drying rate of switchgrass which suggested that biomass should be dried in wide swaths if possible. The model should be a useful tool for planning field logistics and transportation operations for biomass supply.

Keywords. Drying rate, biomass, weather conditions, swath density, empirical model, harvest strategy, wind tunnel, drying chamber.

1. Introduction

Switchgrass has a wide harvest window and is harvested from late July to February of the following year (Sharma et al., 2011). When harvested at an early maturity stage, switchgrass has a higher moisture of 70%, and it reduces to less than 10% after the killing frost (Khanchi et al., 2013). Womac et al. (2005) also reported that corn stover, when harvested at early maturity stage, has significantly higher moisture of 34.1% compared to 15.3% for late harvest. These crops when harvested early require a field drying period to reduce the moisture to a safe storage level of less than 18% (Rotz, 1995). The field drying period can vary depending on crop characteristics, environmental conditions and swath structure. As the crop lays in the field,

moisture migration takes place between the crop and the environment, until suitable equilibrium moisture is attained. Field drying time of grasses varies from 2 to 7 days. Drying time is reduced to 2 to 4 days when the grasses are spread in thin layers and weather conditions are favorable (Haghighi, 1990; Moore and Peterson, 1995).

Crop characteristics such as yield, stem diameter, leaf to stem ratio, and swath structure can increase or decrease the moisture migration during field drying (Rotz and Shinnerson, 2007). Density and thickness of the windrow significantly impact the drying rate of the crop in the field. High yield and narrow width results in high-density windrow, which dries slowly compared to a thin and wide swath containing the same amount of biomass (Moore and Peterson, 1995). A thick windrow also blocks the air movement, which carries moisture away from the lower layers to the ambient atmosphere. Freshly harvested biomass is also high in initial moisture and forms a compact windrow that resists the wind penetration. Wind circulation through the windrow can be enhanced by making the windrow more fluffy by raking (Moore and Peterson, 1995).

Environmental factors such as solar radiation, wind speed, air temperature, relative humidity, and soil moisture influence the drying behavior of crops in the field. These weather parameters are highly correlated in field conditions and it becomes difficult to analyze the effect of an individual parameter on drying potential of crop (Borreani and Tabacco, 1998). From all the environmental factors solar radiation has the most impact on the drying rate (Bartzanas et al., 2010; Khanchi et al., 2013; Smith, 1990). The impact of wind was also related to solar radiation. It was reported that at high radiation intensity, an increase in wind speed decreases the drying rate of switchgrass (Khanchi et al., 2013) as some of the heat used to enhance the temperature of swath was carried away by the wind. However, at a low radiation intensity, an increase in wind speed improves the drying of switchgrass depending on the vapor pressure deficit (VPD) of the air (Khanchi et al.,

2013). Wright et al. (2000) observed a similar variable effect of wind during drying of rye grass. They suggested drying the grass in fluffy windrows to improve wind circulation under cloudy conditions.

Some models have been developed that simulate the influence of environment on field drying of crops. The model developed by Womac et al. (2005) estimates the stover moisture content based on days after sowing, soil moisture, rainfall, RH, evapotranspiration, minimum air temperature, soil temperature, and wind speed. The model can predict the moisture content at the end of the day. However, the model developed in the present study can predict hourly as well as daily moisture fluctuation in addition to the moisture content at the end of the day. Shinnars et. al. (2007) also evaluated the influence of shredding, swath density and weather conditions on final moisture content of corn stover in Wisconsin, U.S. They found that at an average daily temperature of 5 °C in mid to late October, only shredded corn stover placed flat in windrows reached safe storage moisture of less than 20% in 5-7 days. In the second study, none of the treatments reached below 40% in a 10 day drying period showing the importance of weather conditions in the drying of biomass. In 2003, when the drying conditions were right, the treated stover reached a moisture content of less than 20% in 4 days. However, when drying was interrupted by rain, none of the treatments reached 20% after 10 days of drying. Manstretta and Rossi (2015) also developed a model for estimating moisture fluctuation in CS residues as an inoculum source for several fungal pathogens in maize. They used rainfall and VPD to predict the moisture in CS residue after harvest. The model developed in the present study utilizes environmental variables as well as swath density for moisture prediction of CS. Additionally, in other studies (Bartzanas et al., 2010; Khanchi et al., 2013; Smith, 1990) solar radiation was found to be the most important factor affecting the drying of crops in the field. Thus solar

radiation should be included in the models for predicting drying rates of crops in the field conditions.

When compared to corn stover, drying studies on switchgrass are more limited. Shinnars et. al. (2010) studied field drying rates of switchgrass and reed canary grass. They found that under good drying conditions (14 to 30 °C) switchgrass dried more quickly when placed in wide swath. In all the cases, the crop was below 20% moisture in the afternoon of the day after cutting and in some cases reached baling moisture in a single day of drying. Khanchi et. al. (2013) developed an empirical model based on maturity stage and environmental conditions for thin layer drying of switchgrass. However, drying models to predict the drying behavior of switchgrass and corn stover which incorporates swath density are still lacking in the literature. Specific objectives of this present study were to: 1) develop drying models to predict field moisture change of corn stover and switchgrass based on weather conditions, swath density, and maturity stage, 2) evaluate the effect of individual weather parameters and swath density on the drying rate of switchgrass and corn stover, and 3) validate the developed models. The previous design (Khanchi et al., 2013) of the environmental chamber was also improved to reduce the variation or radiation intensity and wind speed in the test section.

2. Material and methods

2.1 Construction of an environmental chamber

The environmental chamber (Fig. 1) was constructed from a wooden framed structure and was 4.6 m long and 1.77 m high. The environmental chamber was divided into a settling section and a test section. The settling section was 1.0 m high, 1.0 m wide and 0.85 m long. The test section was 0.45 m tall, 0.45 m wide and 2.0 m long. There was a transition nozzle in between, which was 0.64 m long. The dimensions of the settling section and test section were selected to achieve

the desired uniformity and wind speed in the test section where the drying trays were placed for testing. The test section had a door with a plexiglass inspection window for loading and unloading of trays.

2.2 Radiation intensity control

Solar radiation was simulated by six equally spaced custom built 500W and 240 Volt quartz radiant heaters. The heaters were fitted in the roof of the test section at the height of 0.46 m. The dimensions of one radiant panel were 0.1 m by 0.36 m (MORGQFX10113 Mor Electric Heating Assoc. Inc., MI) and it held a quartz heating element (MORGQQT10305 Mor Electric Heating Assoc. Inc., MI) with an overall length of 0.31 m and the heating length of 0.2 m. The radiation intensity was controlled by a single solid state power controller (Model no. VHC 32, Fostoria Ind., TN). The radiation intensity was measured by a pyranometer (Model no. LP 02, Hukseflux Thermal Sensors, Netherlands) with a detection range of 285 to 3000 nm. The radiation intensity variation was measured at every 2.5 cm along the length of the test section. A standard deviation of 19 watt m⁻² was observed at a radiation intensity of 410 watt m⁻² along the length of the test section.

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118 Fig 1. Front and side view of environmental chamber

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120 2.3 Vapor pressure deficit control

121 Temperature and humidity were controlled by a PGC 400-700 CFM vertical conditioner (Model

122 no. 9240, Parameter Generation and Control, NC). The conditioner unit maintained the air

123 temperature and relative humidity levels within 0.1 °C and 0.5% RH, respectively from the set

values in the test section. The inlet and outlet of the conditioner unit were connected to the sides of the settling section before the honeycomb and the screen (Fig 1). The temperature and relative humidity were also recorded at one-minute interval by two temperature and humidity data loggers (Model no. UX 100-011, Onset Computer Corp., MA) placed just before the test section. Vapor pressure deficit (VPD) of air in Pa was calculated by using temperature (T) and humidity (Rh) data in the equation below.

$$VPD (Pa) = \left(1 - \frac{Rh}{100}\right) \left(6.11 * \exp\left(\frac{17.47*T}{239+T}\right)\right) * 100 \quad (1)$$

2.4 Wind speed control

The PGC unit attached to the environmental chamber provided an air flow of $0.25 \text{ m}^3 \text{ s}^{-1}$ inside the settling section. A 0.31 m diameter and 560 W axial fan (Model no. D 3702, Sukup Manufacturing Co., IA) controlled by a variable frequency drive (Model no. ATV12H055M2, Schneider Electric, France) were added to the circulation loop of the environmental chamber to change wind speed in the test section. A maximum speed of 5 m s^{-1} was attained at the center of the test section with a variation of 0.3 m s^{-1} along the height of the test section. The axial fan creates lateral mean velocity variation as well as swirls in the air flow which have to be minimized before it reaches the test section. A honeycomb, screens, and transition nozzle were used to improve the flow of air inside the wind tunnel. The details about the functionality and selection criteria of the honeycomb, screens and turning vanes is discussed in detail in the previous study (Khanchi et al., 2013). A honeycomb structure made of PVC tubing having a cell diameter of 0.0254 m and a length of 0.15 m was used in the present study. A single screen with a porosity of 0.6 was placed after the honeycomb structure. The transition nozzle placed in between the settling and test section had an area ratio of 5. A typical area ratio of 7 to 12 are used

in low-speed wind tunnel designs but lower and higher values are also common (Barlow et al., 1999). A screen was also installed at the end of the test section to avoid material blowing into the circulating fan. The desired wind speed was set and measured before the start of each experiment by an air flow meter (Model no. 922, Fluke Corporation, WA).

2.5 Tray design and automatic weight measurement

The weighing trays were made from galvanized hard cloth with a mesh size of 6.35 mm to provide adequate ventilation during the drying process. The trays were supported by an aluminum frame structure (25.4 mm wide) to provide structural integrity at the bottom. The trays used to simulate different densities had the same surface area but different height. The trays measured 0.36 m by 0.25 m in length and breadth, respectively. The height of the tray for low density (LD), medium density (MD) and high density (HD) were 0.1, 0.1, 0.15 m, respectively. At any given time, six trays were randomly placed in the test section with two trays of each LD, MD, and HD. Each tray was kept on a weighing balance (Model no EK-2000i, A&D Weighing, CA) which was connected to a computer via RS-232 interface and the weight readings were recorded in every 5-minute intervals.

2.6 Selection of weather data for drying experiments

Weather data was collected from July to November for switchgrass during which drying in windrows is required to bring the moisture to a safe storage level. For corn stover harvest, data was collected for the month of September to November. The Iowa Mesonet website (Mesonet, 2015) was used to collect the weather data from the year 1986 to 2013 and for 13 weather stations. Daily average values for air temperature ($^{\circ}\text{C}$), relative humidity (%), wind speed at 3 m height (m s^{-1}), and solar radiation (Langley) were used to calculate the range of variables tested in the drying study. Wind speed measured at the height of 3 m will be higher than the wind speed

received by swaths lying close to ground level. Therefore, wind speed data was converted from a height of 3 m to 0.31 m elevation by use of the equation below (Chayaprasert and Maier, 2010).

$$U_h = U_{ref} \left(\frac{h}{h_{ref}} \right)^a \quad (2)$$

Where, U_h is the local wind velocity measured at height h (m), U_{ref} is the wind velocity at a reference height (h_{ref}) (example: 3 m), a , the exponent value, 0.14 represents an atmospheric wind boundary layer in open terrain. The calculated wind speed at 0.31 m height was used to dry switchgrass and corn stover in the environmental chamber. The wind speed was converted again to 2 m height for model development so that the end user does not have to convert it again during the drying time calculations.

2.7 Drying experiments

A representative sample of corn stover was collected from agricultural farms (41°58'37"N 93°46'14"W) owned by Iowa State University in Boone, IA. Corn stover was collected and packed as round bales after a single pass harvest operation in which corn stover was directly fed into a round baler without making any ground contact. Samples were collected immediately after the harvest by breaking several round bales randomly located in the field. Samples were placed in plastic bags and stored in cold storage at 5 °C until they were placed in the environmental chamber for drying experiments. Switchgrass samples were manually harvested and collected from research and demonstration farms (41°24'48"N 92°52'10"W) in Pella, Iowa. The harvested switchgrass was packed in plastic bags and stored in cold storage at 5 °C until placed in the environmental chamber. The harvesting and sampling schedule is given in Table 1.

Table 1. Harvesting schedule and experiments performed from 2013 to 2015 on corn stover and switchgrass

Biomass	Corn stover	Switchgrass

Harvest date	17th Aug 2013	19 th Oct 2014, 2015 (6 th Aug, 18 th Sep, 16 th Oct, 4 th Nov), 6 th Aug 2016
Drying experiments performed	21st Nov 2013 to 11th March 2014	10 th Dec 2014 to 8 th Jan 2015, 7 th Aug 2015 to 20 th Jan 2016, 9 th Aug to 19 th Sept 2016
[†] Dry density of biomass in trays (kg m ⁻²)	0.78 (LD), 1.31 (MD), 2.61 (HD)	0.58 (LD), 1.44 (MD), 2.30 (HD)

[†] LD, MD and HD represent low density, medium density and high density trays of biomass.

190 In the case of corn stover, 60 drying experiments were performed of which 36 (27 day and 9
191 night) were used in model development and 24 experiments were used for model validation. In
192 the case of switchgrass, 80 experiments were performed in which 72 were used for model
193 development and 8 were used for model validation. For the model development of switchgrass,
194 36 (27 day and 9 night) were performed in the seed development stage of maturity and similarly,
195 36 were performed in seed shattering and seed shattered stage of maturity. For daytime, a 3X3X3
196 factorial design was used with three levels of solar radiation, vapor pressure deficit (VPD) and
197 wind speed as the variables (Table 2). For the night, a 3X3 factorial design was used with three
198 levels of VPD and three levels of wind speed. The upper and lower level of weather conditions
199 are based on the extreme weather condition recorded during the harvesting period and the middle
200 value was calculated from the average of the extreme values.

Table 2. Experimental plan for drying of corn stover and switchgrass with environmental conditions tested during the study

Crop, Maturity stage, Duration	Vapor pressure deficit (kPa)	Solar radiation (W m ⁻²)	Wind speed (m s ⁻¹ at 2 m above ground)
Corn stover (Day)	1.20, 0.85, 0.50	400, 115, 0	5.83, 3.25, 1.30
Corn stover (Night)	1.20, 0.85, 0.50	0	5.83, 3.25, 1.30
Switchgrass, Seed development stage (Aug, Sept), Day	2.20, 1.40, 0.60	450, 275, 100	5.83, 3.25, 1.30
Switchgrass, Seed development stage (Aug, Sept), Night	2.00, 1.15, 0.30	0	5.83, 3.25, 1.30
Switchgrass, Seed shattering (Oct), and seed shattered stage,	1.80, 1.10, 0.35	400, 225, 50	5.83, 3.25, 1.30

Day			
Switchgrass, Seed shattering (Oct), and seed shattered (Nov) stage, Night	2.00, 1.13, 0.25	0	5.83, 3.25, 1.30

During each experiment, two trays of each LD, MD and HD were randomly placed in the test section as discussed earlier. Whole switchgrass plant including stems and leaves were cut to fit the dimensions of the tray. No further size reduction was performed on corn stover samples as the highly conditioned samples were easily fitted into the trays. The material density of the samples in the trays for CS and switchgrass is given in Table 1. The switchgrass and CS samples were oriented in a direction perpendicular to the air flow. Before each experiment, CS and switchgrass samples were taken out of cold storage and brought to room temperature. Once the desired conditions of VPD, radiation and wind speed were achieved in the environmental chamber, the samples were filled in the trays and placed on the weighing balances inside the test section. The experiment was stopped when the moisture reached less than 15% or no change in tray weights were recorded continuously for 5 hours.

A drying rate constant was determined for each tray by performing the regression analysis between moisture ratio and drying time data for each tray. Moisture ratio (MR) is given by Eq. (3).

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (3)$$

Where, M is the moisture content at time t, M₀ is the initial moisture content, M_e is the equilibrium moisture content (EMC). An exponential model was used to fit the moisture ratio data with the time given by Eq. (4).

$$\frac{M-M_e}{M_0-M_e} = e^{-k(t)} \quad (4)$$

Where, k is the drying rate constant (h^{-1}) and is obtained by plotting the graph of moisture ratio versus drying time. Since the drying time was recorded in hours, the units of the drying rate constant are given in h^{-1} in the following sections. For corn stover, M_e was calculated from the Modified Oswin equation (eq. 5) between the temperature and humidity range of 10 to 40 °C and 11 to 98%, respectively, and was given by Igathinathane et al. (2005).

$$M_e = (10.9137 - 0.0746 * T) \left[\frac{ERh}{1-ERh} \right]^{0.4147} \quad (5)$$

Where, T is the temperature in °C and ERh is the equilibrium relative humidity in decimal form. For switchgrass, M_e was calculated from the Modified Halsey equation (Eq. 6) between the temperature and humidity range of 20 to 40 °C and 12 to 89%, respectively, and was given by Karunanithy et al. (2013).

$$M_e = \left[\frac{-\exp(15.85 - 0.0856 * T)}{\ln(ERH)} \right]^{0.186} \quad (6)$$

Additionally, experiments were performed in the environmental chamber to find the M_e between the temperature and humidity range of 10 to 19 °C and 55 to 92%, respectively for switchgrass, as it lacked in the literature. Six trays of switchgrass, each weighing 200 g were kept in the environmental chamber at the desired temperature and humidity and dried until a weight change of less than 0.01 g was recorded in five hours. After drying in the environmental chamber, the trays were further dried in an oven at 105 °C for 24 hours to obtain the equilibrium moisture content of the switchgrass samples. The equilibrium moisture content and temperature and humidity data were fitted to the Modified Halsey equation by using the NLIN procedure in SAS 9.4 (SAS Institute, 2015) to obtain Eq. 7 below.

$$M_e = \left[\frac{-\exp(4.9679 + 0.0201 \cdot T)}{\ln(ERH)} \right]^{0.562} \quad (7)$$

The drying rate constant obtained for each tray during the drying experiments was used to develop a regression model that related the drying rate constant with the weather conditions and swath density tested during the experimentation. Regression analysis was completed using Proc Mixed in SAS 9.4 (SAS Institute, 2015).

3. Results

3.1 Regression equations to predict moisture content of corn stover and switchgrass

During drying, switchgrass and CS followed a falling rate drying period. In this period, the drying rate of crop decreased with time and approached zero as it came in equilibrium with the environment. The exponential drying rate model and regression equations relating the drying rate constant with environmental conditions and swath density are given in Table 3. The model uses environmental conditions such as hourly radiation, wind speed, VPD and wet crop density to calculate the hourly drying rate of switchgrass and CS. The drying rate, k , is then fitted into the exponential drying model to estimate the moisture content of crop at that time interval. Average daily weather conditions can also be used to assess the moisture content of switchgrass and CS at the end of the day. For CS, models were developed for day and night time conditions. For switchgrass, models were developed for different maturity stages in addition to day and night conditions. These models can predict change in moisture of the crop due to drying and rewetting by dew at night. However, these models cannot predict an increase in moisture due to a rainfall event. Further experimentation is required to estimate the moisture gain after rainfall as well as drying of the crop after the rainfall event. The model was divided into day and night time because the effect of wind speed on drying rate was different in day and night conditions. During

263 the day, the wind speed was negatively correlated with the drying rate whereas, at night, the
 264 wind speed was positively correlated and is explained in the next section.

Table 3. Drying rate model and drying rate constant equation developed for corn stover and switchgrass based on environmental conditions and swath density

Time of the day	Maturity Stage	Drying rate model	Drying rate constant	R ²
Corn Stover				
Day	Oct and Nov	$M = M_e + (M_0 - M_e) * \exp(-k * t)$	$k = \exp(-2.5238 + 0.005564 * Rad - 0.1430 * WS + 0.0001081 * VPD - 0.2212 * Dens - 0.00074 * Rad * WS)$	0.884
Night	Oct and Nov	$M = M_e + (M_0 - M_e) * \exp(-k * t)$	$k = \exp(-3.19 + 0.001856 * VPD + 0.1421 * WS - 0.1403 * Dens)$	0.871
Switchgrass				
Day	Aug and Sept	$M = M_e + (M_0 - M_e) * \exp(-k * t)$	$k = \exp(-3.0147 + 0.002082 * Rad - 0.05172 * WS + 0.000192 * VPD - 0.1623 * Dens)$	0.881
Night	Aug and Sept	$M = M_e + (M_0 - M_e) * \exp(-k * t)$	$k = \exp(-3.3462 + 0.03942 * WS + 0.000304 * VPD - 0.02056 * Dens)$	0.946
Day	Oct and Nov	$M = M_e + (M_0 - M_e) * \exp(-k * t)$	$k = \exp(-2.6004 + 0.001539 * Rad - 0.06246 * WS + 0.000248 * VPD - 0.1401 * Dens)$	0.877
Night	Oct and Nov	$M = M_e + (M_0 - M_e) * \exp(-k * t)$	$k = \exp(-2.4726 - 0.02091 * WS + 0.000261 * VPD - 0.02346 * Dens)$	0.951

Where, M is the moisture at time t (% db), M₀ is the initial moisture (% db), M_e is the equilibrium moisture (% db). For corn stover, M_e was calculated by Modified Oswin equation

$M_e = (10.9137 - 0.0746 * T) \left[\frac{ERh}{1-ERh} \right]^{0.4147}$ between the temperature and humidity range of 10 to 40 °C and 11 to 98%, respectively and was given by Igathinathane et al. (2005). For switchgrass, M_e was calculated from the Modified Halsey Equation $M_e = \left[\frac{-\exp(15.85-0.0856*T)}{\ln(ERH)} \right]^{0.186}$ given by Karunanithy et al (2013) between the temperature range 20 to 40 °C and $M_e = \left[\frac{-\exp(4.9679+0.0201*T)}{\ln(ERH)} \right]^{0.562}$ in the temperature range of 10 to 19 °C. T is the temperature (°C) and ERH is the equilibrium relative humidity in decimal, k is drying rate constant (hr⁻¹), t is the time (hr), Rad is the average radiation intensity for the hour (watt/m²), WS is wind speed (m/s), VPD

is vapor pressure deficit (Pa) estimated from $VPD (Pa) = \left(1 - \frac{Rh}{100}\right) \left(6.11 * \exp\left(\frac{17.47*T}{239+T}\right)\right) * 100$, Dens is the wet swath density (kg/m²)

3.2 Influence of weather conditions and swath density on drying behavior of corn stover and switchgrass

The coefficient of correlation between drying rate of switchgrass and CS and the variables tested during the study are provided in Table 4. Correlation coefficients for the daytime drying of CS were not presented as an interaction of radiation and wind speed was observed as shown in Table 3 above. Radiation and VPD were found to be the most important factor affecting the drying of these crops during the day and nighttime, respectively.

Table 4 Pearson correlation coefficients between corn stover and switchgrass drying rates and variables tested for different maturity stages in environmental chamber

Variable	Correlation coefficients, r					
	Corn Stover			Switchgrass		
	Seed development stage (Aug., Sept.)			Seed shattering and seed shattered stage (Oct., Nov.)		
Time of day	Night	Day	Night	Day	Night	
Radiation	-	0.50**	-	0.49**	-	
VPD	0.69**	0.24**	0.83**	0.38**	0.85**	
WS	0.42**	-0.20**	0.29**	-0.36**	-0.22	
Density	-0.11	-0.38**	-0.10	-0.38**	-0.13	

*Significant at 5% level, **Significant at 1% level

3.3 Model validation

The developed empirical models were validated by plotting the predicted drying rate of CS and switchgrass as a linear function of experimental drying rate. The experimental drying rates were obtained from experiments performed on randomly selected weather conditions in between the range of weather conditions used for model development given in Table 2. A perfectly fitted model will have a slope of 1.0, intercept of zero and correlation coefficient of 1.0 (Khanchi et al.,

2013; Wright et al., 2001). In the present study on corn stover, a correlation of 0.79 was observed with a slope and intercept of 0.7082 and 0.0017, respectively. Similarly, a correlation coefficient of 0.97 was observed for switchgrass with a slope and intercept of 0.77 and 0.0045, respectively. The resulted error might have occurred during experimentation or model development in the statistical package. The switchgrass and CS drying rate models were also compared with field drying trials. An example of the model output is presented for switchgrass and CS in Fig 4 and 5, respectively. The plot of field experimental moisture and model predicted moisture did not show any systematic deviations. Most of the predicted moistures for switchgrass and CS were within the standard deviations of the field experimental moisture content, indicating a good fit of the models developed in this study.

Fig 2. A plot of experimental and predicted drying rates of corn stover

Fig 3. A plot of experimental and predicted drying rates of switchgrass

Fig 4. A plot of model predicted and experimental field moisture variation with standard deviation bars for switchgrass. Here, pred, exp, LD, MD, and HD are the abbreviation for predicted, experimental, low density, medium density and, high density, respectively.

Fig 5. A plot of model predicted and experimental field moisture variation with standard deviation bars for corn stover. Here, Pred, Exp, LD, MD, and HD are the abbreviation for predicted, experimental, low density, medium density and, high density, respectively.

4. Discussion

Regression models were developed to predict the drying rate of CS and switchgrass based on environmental conditions and swath density. A similar model that can estimate the moisture content of these crops utilizing swath density and time of day is not available in the literature. Models that predict drying rates of switchgrass are also limited and currently no model takes swath density into account while predicting the drying rate of switchgrass. It is important to compare the models developed in lab studies to the field trials to estimate how well they perform in field conditions. In the present study, both field and lab studies were performed and the results of the field drying experiments will be published in future publications.

During the day, radiation and vapor pressure deficit were positively, and swath density and wind speed were negatively correlated with the drying rate of switchgrass. During both maturity stages of switchgrass, radiation was the most important factor influencing the drying rate of switchgrass with a correlation of 0.5 and 0.49 (Table 4). Solar insolation was also found to be the most significant factor by Rotz and Chen (1985) during field drying of alfalfa with a correlation of 0.58 to 0.70. They reported that solar insolation explained more variation in the drying data than the other combined 13 variables, tested during the study. Wright, Frost, & Kilpatrick (2000) also observed that radiation was more important than VPD or wind speed in determining grass drying rate as it aids in the removal of internal moisture from the grass plants. Therefore, it is recommended that solar radiation should be included in drying rate models while simulating the field drying behavior of crops. It is also recommended that field operations such as wide swath drying should be implemented to yield the benefit of solar radiation during field drying. High radiation intensity and low wind speed also favored quick drying of switchgrass. In the environmental chamber, when the radiation intensity and VPD were kept constant, an increase in

wind speed decreased the drying rate of switchgrass. The slower drying of switchgrass at higher wind speed could be due to heat loss caused by the wind. The lower temperatures of switchgrass at higher wind speed also indicate that part of the heat generated by radiation was carried away by the wind. VPD was the second most important variable affecting the drying of switchgrass during daytime conditions. A correlation of 0.24 and 0.38 was observed during the different maturity stages of switchgrass. A correlation varying from 0.25 to 0.48 was also observed between VPD and the drying rate of alfalfa during a seven-year field drying study (Rotz and Chen, 1985).

At night, VPD and wind speed were positively correlated whereas density was negatively correlated with the drying rate of switchgrass. VPD was the most important variable ($r = 0.83$ to 0.85) influencing the drying of switchgrass at night. Contrary to the day time increased wind speed helped in the drying of switchgrass at night. A similar variable effect of wind was also observed by Wright, Frost, & Kilpatrick (2000) during drying of ryegrass under controlled conditions. They also concluded that when radiation is medium (432 W m^{-2}) or high (1081 W m^{-2}) the effect of wind is to decrease the drying rate and at night the effect of wind is to increase the drying rates of ryegrass at moderate (10 mbars) or high (16 mbars) VPD. In the present study, the effect of wind speed was not significant during later maturity stages of switchgrass. A possible reason could be the low temperature and high humidity conditions during the night in the month of October and November. No significant improvement in drying rates was observed by increasing the wind speed when the drying conditions were poor (low VPD). In the case of CS, the VPD was the most critical factor affecting drying during the night ($r = 0.69$) and increase in wind speed helped in drying at night. These results suggest that field operations such as raking should be used to make the windrow structure more airy to intersect more wind at night.

Windrow density was negatively correlated with drying rate of both crops during day and night conditions. For switchgrass, a negative correlation of 0.38 during daytime and 0.1 to 0.13 was observed during the night (Table 4). A negative correlation of 0.15 to 0.20 was also noted by Rotz and Chen (1985) during field drying of alfalfa and concluded that drying rates consistently decreased as swath density was increased.

Models were divided into day and night conditions as the effect of wind was found to be contrary during day and night. An environmental chamber was also designed and fabricated which offered more control on environmental conditions and assisted in evaluating the effect of each variable on the drying rate of switchgrass and CS. The environmental chamber developed in this study can be used to study the drying behavior of other crops and factors which were not covered in this study.

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References

- Barlow, J.B., Rae, W.H. and Pope, A., 1999. Low-speed wind tunnel testing. Wiley, New York, pp. 713.
- Bartzanas, T., Bochtis, D.D., Sørensen, C.G., Sapounas, A.A. and Green, O., 2010. A numerical modelling approach for biomass field drying. Biosyst. Eng. 106, 458-469.
- Borreani, G. and Tabacco, E., 1998. Effects of crop properties, weather conditions and mechanical treatments on the wilting rate of dipliod and tetraploid Italian ryegrass for silage. Grass Forage Sci. 53, 179-188.

373 Chayaprasert, W. and Maier, D.E., 2010. Evaluating the effects of sealing quality on gas leakage
374 rates during structural fumigation by pressurization testing and cfd simulations. Trans.
375 ASABE. 53, 9.

376 Haghighi, K., 1990. Finite element simulation of the thermo-hydro stresses in a viscoelastic
377 sphere during drying. Drying Technol. 8, 466-498.

378 Igathinathane, C., Womac, A.R., S., S. and Pordesimo, L.O., 2005. Sorption equilibrium
379 moisture characteristics of selected corn stover components. Trans. ASAE. 48, 1449-
380 1460.

381 Karunanithy, C., Muthukumarappan, K. and Donepudi, A., 2013. Moisture sorption
382 characteristics of switchgrass and prairie cord grass. Fuel, 103, 171-178.

383 Khanchi, A. et al., 2013. An empirical model to predict infield thin layer drying rate of cut
384 switchgrass. Biomass Bioenerg. 58, 128-135.

385 Manstretta, V. and Rossi, V., 2015. Modelling the effect of weather on moisture fluctuations in
386 maize stalk residues, an important inoculum source for plant diseases. Agric. For.
387 Meteorol. 207, 83-93.

388 Mesonet, I., 2015. ISU agclimate/ legacy network daily download/ Daily data resquest form.
389 <http://mesonet.agron.iastate.edu/agclimate/hist/dailyRequest.php>.

390 Moore, K.J. and Peterson, M.A., 1995. Post-harvest physiology and preservation of forages.,
391 American Society of Agronomy, Crop Science Society of America. CSSA Special
392 Publication Madison, Wisconsin, pp. 39-66.

393 Rotz, C.A., 1995. Field curing of forages, in: K.J. Moore and M.A. Peterson (Editors), Post-
394 harvest physiology and preservation of forages. CSSA Special Publication, Madison, WI,
395 pp. 39-66.

396 Rotz, C.A. and Chen, Y., 1985. Alfalfa drying model for the field environment. Trans. ASAE.
397 28, 1686-1691.

398 Rotz, C.A. and Shinnars, K.J., 2007. Hay harvest and storage, in: Barnes, R.F., Nelson, C. J.
399 Moore, K.J, Collins, M. (Eds.), Forages: The science of grassland agriculture. Blackwell
400 Publishing, Ames, IA, pp. 601-616.

401 SAS Institute, 2015. Cary, NC, USA.

402 Sharma, B., Jones, C.L. and Khanchi, A., 2011. Tensile strength and shear strength of
403 switchgrass before and after frost. Biol. Eng. 4, 43-54.

404 Shinnars, K.J., Binversie, B.N., Muck, R.E. and Weimer, P.J., 2007. Comparison of wet and dry
405 corn stover harvest and storage. Biomass Bioenerg. 31, 211-221.

406 Shinnars, K.J., Boettcher, G.C., Muck, R.E., Weimer, P.J. and Casler, M.D., 2010. Harvest and
407 storage of two perennial grasses as biomass feedstocks. Trans. ASABE. 53, 359-370.

408 Smith, E.A., 1990. A review on field drying of grass. Drying Technology, 8(3): 465-498.

409 Womac, A.R., Igathinathane, C., Sokhansanj, S. and Pordesimo, L.O., 2005. Biomass moisture
410 relations of an agricultural field residue: corn stover. Trans. ASAE. 48, 2073-2083.

411 Wright, D.A., Frost, J.P. and Kilpatrick, D.J., 2000. The influence of weather factors on the
412 drying rate of cut perennial ryegrass herbage under controlled conditions. Grass Forage

413   Sci. 55, 331-342.

414   Wright, D.A., Frost, J.P., Patterson, D.C. and Kilpatrick, D.J., 2001. PA--Precision Agriculture:
415   Development of a Model to predict Drying Rates of Cut Ryegrass. J. Agric. Eng. Res. 79,
416   23-35.