Biomass Moisture Relations of an Agricultural Field Residue: Corn Stover

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Abstract. *Moisture of corn stover was field monitored under southeast U.S. ambient conditions to aid biomass collection decisions. Timing to collect stover at low moisture depended on elapsed time on field, elapsed time after precipitation, time of day, contact with soil, and conditioning effect by combine header. Grain had been combine-harvested at kernel moistures of either 25% or 15% wet basis (w.b.). Stover moisture was determined by weighing large in-situ baskets for a month and with frequent grab samples. Experiment controls included stover dried under tent shelter and mower-cut stover for combine-conditioning effect. Stover moisture asymptotically declined over time from approximately 70% (w.b.) to an equilibrium of approximately 20% (w.b.) for 25% (w.b.) grain harvest. Moisture reduction was not constant due to daily diurnal variation of eight percentage points (w.b.), and light precipitation that re-hydrated the stover. Stover moisture was significantly greater in the morning compared to afternoon and was greater for stover in contact with soil. A combine corn stalk conditioning effect reduced mean moisture (approx. 10 percentage points) for high-moisture stover at early harvest, yet conditioning increased moisture for a period after light precipitation. Correlation of daily stover moisture with the corresponding day's evapotranspiration factor was not as strong as correlations with other combinations of environmental factors. Stover moisture generally peaked two days after rain events, so correlations and regressive predictions used previous data (2-day delay) for rainfall, air relative humidity, and evapotranspiration data. In addition to mechanical harvest method (stalk conditioning effect), the strongest environmental/timing correlations to predict stover moisture on the field after grain harvest included the following daily-averaged factors: elapsed time (days) after sowing (collect later for reduced moisture), time of day (evening collection preferred over morning collection), soil moisture, 2-day previous rainfall amount, 2-day previous relative humidity, and 2-day previous evapotranspiration factor. Thus, increased elapsed time after sowing/harvest, evening harvest times, and the immediate (2-day) exposure history of corn stover to available moisture and drying potential are useful in determining strategies to collect corn stover with minimum moisture content.*

Keywords. *Bioenergy, Biomass collection, Biomass storage, Drying, Environmental factors, Evapotranspiration, Feedstock, Harvest strategy, Harvest timing, In-situ moisture, Moisture measurement, Precipitation, Processing, Quality control.*

Moisture is a fundamental component of living organisms, including biomass crops. Biomass moisture influences the management of feedstock streams (Sokhansanj et al., 2002) and the energy economy of conversion processes (Brammer and Bridgewater, 2002). Moisture content also affects biomass physical processes involving grinding (Mani et al., 2002) and manufacturing of composite products (Panigrahi et al., 2002).

Direction of U.S. biomass use development was well planned (DOE, 1999, 2002, 2003a, 2003b) and included crop residues such as corn stover. Corn stover is generally recognized as an underutilized source of biomass and is available at a ratio of about 1:1 stover:grain fresh weight, although Shinners et al. (2003) and Pordesimo et al. (2004) determined that a ratio of 0.8:1 stover:grain fresh weight was more realistic at a grain harvest moisture range of 18% to 31% wet basis (w.b.). Some conservative estimates projected corn stover availability at 61 to 91 million dry tones/year (Kadam and McMillan, 2003).

Strategies differ on collecting corn stover either dry (Perlack and Turhollow, 2003) or wet (Shinners et al., 2003). Selection of collection strategy may depend on end use and other factors. One rationale for collecting biomass allowed to dry on the field is to utilize the solar gain as an energy source (Liang et al., 1996). Field drying of other crops has been documented. Pan evaporation was used to predict forage crop drying in the field (Pitt, 1984). Barr and Brown (1995) developed a model to predict bulk swath forage moisture content, and they applied the Penman-Monteith equation and considered rewetting by dew and rain. Evapotranspiration was used to predict the field-wilting rate of ryegrass for silage (Borreani and Tabacco, 1998). A limited number of studies examined field drying of corn stover. Edens et al. (2002) determined that corn stalks had the highest moisture content

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and made up one-half of the dry plant material, excluding the grain. Shinners et al. (2003) also noted that the stalk remained wet compared to leaf and husk fractions, and remained at a high moisture content throughout the test compared to that reported by Edens et al. Shinners attributed the lack of dry down to ambient differences between the Upper Midwest and Tennessee.

Corn stover contains moisture at varying levels depending on environmental conditions and elapsed time after harvest. Prediction of moisture in corn stover would be helpful in the management of harvest, storage, and biomass conversion operations. General observations attribute differences in field drying of corn stover to environmental conditions. There is lack of information to develop mathematical prediction of corn stover moisture as a function of measured ambient conditions.

The overall objective herein was to evaluate the biomass field moisture relationships of corn stover under southeast U.S. conditions after harvest as a function of time and environmental factors. The secondary objective was to determine the effect of stalk conditioning on moisture relations. Knowledge of environmental and conditioning effects on stover moisture may contribute to a general understanding of stover moisture relations applicable to other locations and practices.

MATERIALS AND METHODS

STOVER HARVEST STRATEGY

Two stages of corn harvest provided a range of initial moisture conditions. An early harvest was conducted at grain moisture content of about 25% w.b. on 24 September 2003. A late harvest took place at grain moisture content at approximately 15% w.b. on 8 October 2003. The moisture range coincided with typical grower practice. The stover on the field from both harvests was monitored until 24 October, or 157 days after sowing (DAS).

Harvesting method was used to vary the degree of stalk conditioning and shattering. Some plots were harvested with an Allis Chalmers Gleaner K2 combine, with a Model 330 corn head and operational discharge shredder. The header damaged and "conditioned" many stalks as the corn ears were snapped off. The other harvest method was with a tractor-operated sickle mower. The mower simply sheared the stalks above the brace roots, allowing the corn plants, ear and all, to fall to the ground. This method was selected to provide a means of cutting the corn stalks without the conditioning effect. It was considered a control treatment that was included to establish baseline data for intact stalks.

IN-SITU STOVER MOISTURE MEASUREMENT

Steel baskets were constructed to facilitate rapid *in situ* weights of corn stover for large-scale, gravimetric moisture determinations. Stover, laid on the field per the harvest methods described above, was transferred and randomly laid on a basket. The basket footprint determined the field area in which to obtain stover. Any stalk or brace root sticking out of the soil under the basket was removed to allow unfettered basket contact with the soil. After loading, basket locations were flagged because stover-laden baskets visually blended well with the remaining field stover.

Steel basket construction provided an efficient means to lift and weigh a fixed sample of stover. Baskets did not have sides that could hinder natural air convection across the field surface. Stover blow-off was not a problem under the observed low wind conditions. A 2.5 × 2.5 m frame supported a wire grid of 200 × 200 mm spacing. A total of 18 baskets were distributed, two per plot (i.e., two subsamples) over nine plots. Random locations were selected in the plots, and corn stover from a 2.5 × 2.5 m sample area was distributed onto the baskets to resemble field distribution.

A certified digital crane scale was used to measure stover-loaded basket mass (fig. 1). Mass sampling times included mornings and afternoons of most weekdays and some weekends. Near the end of the sampling period for the

Figure 1. A typical afternoon mass determination of a basket loaded with corn stover using a suspended crane scale.

late harvest period, when moisture changes were small, only afternoon measurements were taken. The Intercomp CS1500 scale (Intercomp Co., Minneapolis, Minn.) had 250 kg capacity, 0.1 kg resolution, and an overall accuracy of ±0.1% of applied load. A tractor boom raised the scale and basket to weigh the stover. The tractor avoided field locations for grab samples.

Dry matter content on baskets was determined by sampling stover for moisture content determinations during basket loading. Previous measures of each basket mass established tare mass. Potential concerns about dry matter loss were minimal because the major biomass component, by mass, was in corn stalk (Pordesimo et al., 2004). Corn stalk was very stable for the time period of the test, especially compared to biomass subjected to size reduction or if leaves constituted the greatest mass component.

Grab-Sample Stover Moisture Measurement

Grab samples were selected as an alternate means of sampling, since they are used widely. The overall project objective was moisture relations over time, so grab samples facilitated numerous temporal samples from the field. Grab samples also facilitated moisture determinations of stover touching the ground versus stover not touching the ground, which provided insight into moisture relations between biomass and soil. Grab samples of stover were obtained in morning and afternoon collections and coincided with *in situ* moisture measurements. Two 200 mm long stalk sections from the middle of different stalks were combined in a sample bag and regarded as a sampling unit. Leaves were removed from stalk sections during placement in the bags. Two sampling units for stover samples in direct contact with soil (down) and two sampling units not in direct soil contact (up) were taken from each plot in each sampling period. ASAE Standard S358.2 for forage moisture content determination (103°C oven temperature for 24 h) was used (*ASAE Standards*, 2000).

Control Treatment in Field

A control treatment of intact, mowed stalks on baskets under a tent shelter was included to establish baseline data for intact stalks not subjected to direct sun and precipitation. Tents covered about 2.5 × 2.5 m positioned about 1.5 m above the baskets. One tent each covered mower-cut early and late harvest treatments.

Corn Field

A one-hectare corn field (201.2 × 48.5 m) at the Knoxville Experiment Research Station, The University of Tennessee, Knoxville, was used for the experiment. The field had a deep, well drained alluvial soil (Sequatchie loam) on the first terrace of the Tennessee River. Field corn variety Dekalb 743 was planted on 20 May 2003 and given standard agronomic practices recommended for Tennessee. Row spacing was 0.76 m with plants spaced at 5 to 6 plants/m in the rows (79,000 plants/ha). At least seven border rows avoided potential field edge effects on plots.

Field plots were laid out to accommodate the early and late harvests with the combination of combine and mower harvesting methods (fig. 2). The combine harvested three replicate blocks during both early and late harvest stages. The mower harvested two blocks early and one block in the late harvest stage.

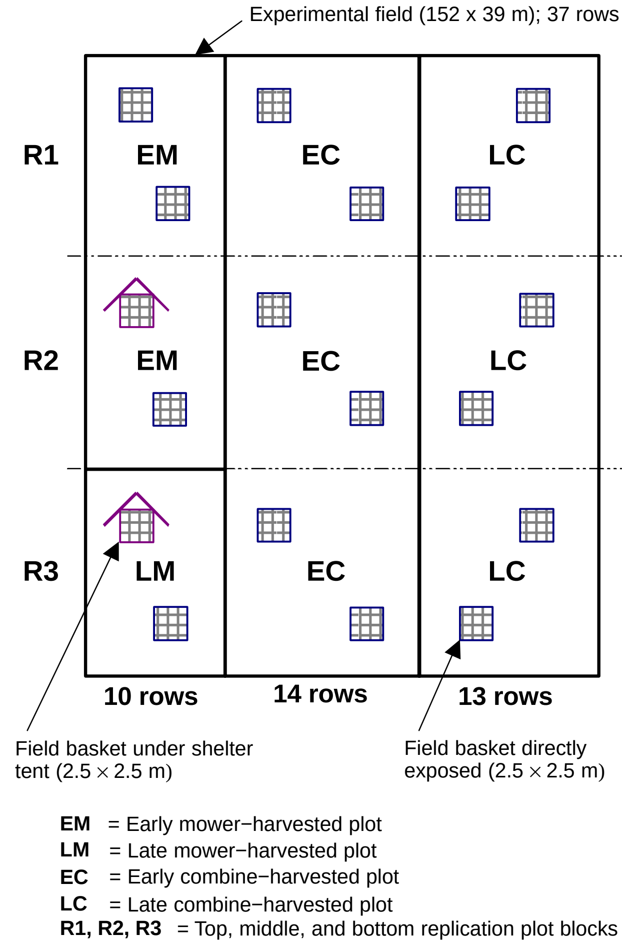

Figure 2. Experimental field layout for corn stover field moisture relationship study.

Environmental, Soil, and Evapotranspiration Parameters

Weather and soil measures taken during the experiment period were used to determine the effect of environmental, soil, and evapotranspiration parameters on the corn stover moisture relations. Weather data came from an automatic weather station (model CM10, Campbell Scientific, Inc., Logan, Utah) located about 200 m from the field. Hourly data were logged as averages from at least 30 min readings. Instrument sensors included pyranometer (model LI2005, ±3% typical error), tipping bucket rain gauge (model TE525, ±1% accuracy), temperature and relative humidity probes (model HMP45C, ±0.4°C and ±2-3% relative humidity accuracy), and wind measurement sensors (model 03001-5 R.M. Young wind sentry set with anemometer, ±0.5% accuracy, and wind direction vane, 5° to 10° accuracy). Environmental parameters monitored included solar radiation ($MJ/s \cdot m^2$), rainfall (mm), maximum and minimum air temperatures (°C), mean air temperature (°C), air relative humidity (%), wind speed ($m\ s^{-1}$), and wind direction (°N).

One soil sample per plot per sampling event was obtained for moisture content using the same previously described oven method for stover. In addition, one soil temperature measure (±1°C) per plot per sampling event was obtained with a probe thermometer inserted 200 mm into the soil surface under stover.

Evapotranspiration was calculated using measured environmental parameters as input into the REF-ET Reference Evapotranspiration Calculator software, Ver. 2.0, developed by Allen (2000). Specifically, the FAO-56 Penman-Monteith method was used.

Daily averages of environmental, soil, and transpiration data were reported. Maximum and minimum values for test periods were selected from daily averages, and therefore extremes on any given day may have exceeded reported values. In some correlations, previous days' effects on stover moisture were examined, as indicated.

Data Analysis

Data were compiled and subjected to analysis of variance (ANOVA), mean separation, correlations, and regression analyses using statistical software (SAS, 2002). The dependent variable was generally stover moisture content. Independent variables included days after sowing (DAS), measures of environmental/weather conditions, soil conditions, and evapotranspiration. Data were subjected to a mixed-model ANOVA macro (Saxton, 2002) with a 5% level of significance. Tukey-Kramer mean separation analysis was conducted to compare all the possible pairwise combinations among the means. Pearson correlations between daily combinations of the dependent and continuous independent variables were examined. Multiple linear regressions were determined and sensitivity analyses were used to predict daily moisture content using the fewest, most important variables measured for that day. Coefficient of determination (r^2) and root mean square error were used to determine regression performances. The delayed effects of stover soaking up moisture due to rain, relative humidity, and

Table 1. Mean daily environmental conditions and calculated evapotranspiration (ET_o) values during experiment in Knoxville, Tennessee.

Variable	Mean	SD[a]	Min.	Max.
	Early Harvest			
Days after sowing (DAS)	139	8.8	127	157
Soil moisture (% w.b.)	13.7	1.1	11.8	16.4
Soil temperature (°C)	18.8	2.4	10.4	22.8
Solar radiation (MJ/m^2·s)	15.1	4.5	3.7	20.5
Rainfall (mm day^{-1})	0.17	0.44	0.00	1.52
Mean air temperature (°C)	14.8	3.4	9.2	19.9
Maximum air temp. (°C)	22.1	4.0	14.5	28.3
Minimum air temp. (°C)	8.7	4.1	2.1	15.3
Air relative humidity (%)	79.1	8.0	57.0	92.1
Wind direction (°N)	135	33	84	213
Wind speed (m s^{-1})	0.90	0.45	0.39	2.02
ET_o FAO56-PM[b] (mm/day)	2.10	0.52	0.75	3.02
	Late Harvest			
Days after sowing (DAS)	148	5.7	141	157
Soil moisture (% w.b.)	13.0	0.8	11.8	14.4
Soil temperature (°C)	19.0	3.3	10.4	20.8
Solar radiation (MJ/m^2·s)	14.0	4.5	3.7	18.7
Rainfall (mm day^{-1})	0.20	0.50	0.00	1.52
Mean air temperature (°C)	15.1	3.5	9.9	19.4
Maximum air temp. (°C)	22.3	3.7	14.5	26.0
Minimum air temp. (°C)	9.2	4.3	3.8	15.3
Air relative humidity (%)	78.9	10.7	57.0	90.6
Wind direction (°N)	129	25	84	169
Wind speed (m s^{-1})	0.67	0.28	0.39	1.16
ET_o FAO56-PM[b] (mm day^{-1})	1.89	0.46	0.75	2.30

[a] SD = standard deviation.
[b] Evapotranspiration by FAO-56 Penman-Monteith method.

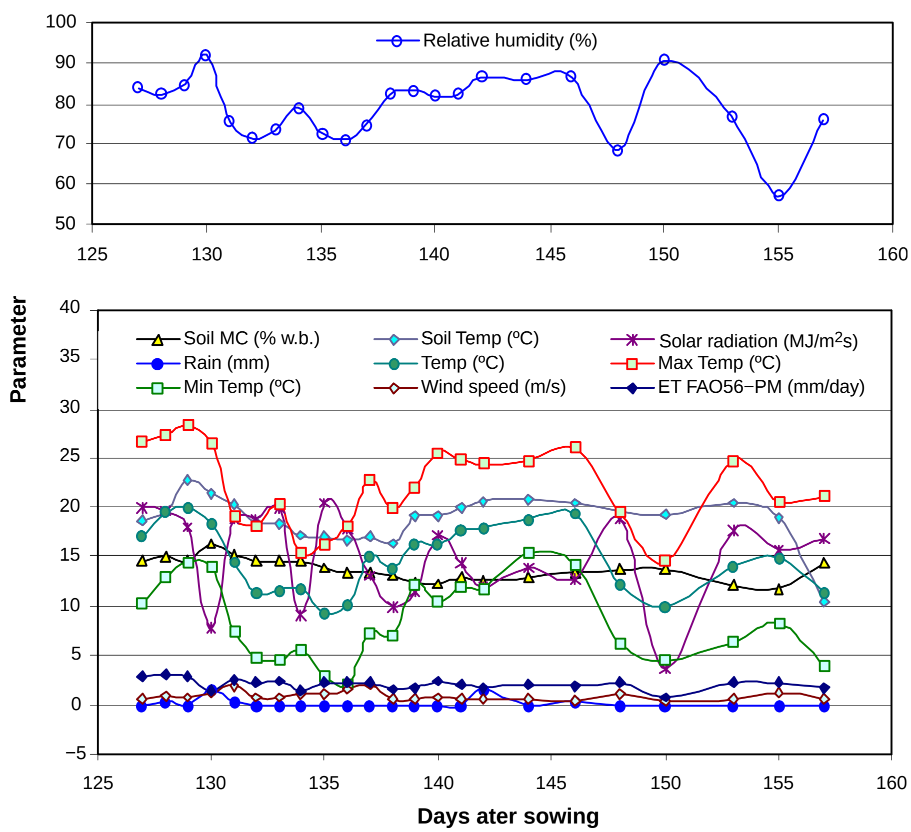

Figure 3. Average daily environmental parameters during the experimental period at research station, Knoxville (24 Sept. to 24 Oct. 2003).

evapotranspiration were examined for individual days up to a week after a rain event. For a day falling between sampling periods, interpolation was used to fill data gaps while examining the moisture delayed effect. Results were presented for the different data analyses typically sorted based on harvest stage, combine/mower harvest method, moisture determination method, morning/evening sampling time, stover above/below sample location, and/or treatment control (shelter).

RESULTS

ENVIRONMENTAL CONDITIONS

Mean daily environmental conditions indicated that evapotranspiration exceeded rainfall (table 1). Although this moisture deficit favored stover drying, observed high relative humidity and low temperatures indicated low water holding capacity of the air, compared to arid conditions. Moderate wind speeds were observed. Mean wind direction indicated predominant wind from across the terrestrial landscape, and not from a nearby river.

A fall-season trend was observed for environmental conditions through the experiment (fig. 3). Mean air temperature had an overall downward trend and a sharp decline near the end of the experiment. Corresponding decreases in maximum and minimum air temperatures and soil temperature were measured. Soil moisture declined slightly. Mean wind speed was low and uniform. Wide fluctuation in mean daily solar radiation was due to varying cloud cover. Mean relative humidity fluctuated from about 60% to 90%, with a sharp decline near the experiment end. Evapotranspiration had a slight reduction trend throughout the experiment.

MAIN EFFECTS ON MEAN STOVER MOISTURE

Use of *in situ* baskets provided a large integrated measure of stover field moisture (table 2). Early harvest moisture was significantly greater than late harvest moisture. Daytime drying and nighttime rewetting of stover was indicated by late day measures that were seven to eight percentage points lower that morning measures. Stover moisture varied among replication blocks, indicating field variation although it was on a first river terrace with <1% slope. No significant differences were noted among subsamples (baskets) within a given experimental unit. A corn stalk conditioning effect due to the combine harvest reduced moisture, although the effect only pertained to stover subjected to the early harvest. The tent shelter with non-conditioned mowed stalks had significantly less moisture than stover under the open sky, but only for the late harvest. Evidently, the tent shelter did not significantly affect the internal plant moisture from the early har−

Table 2. Mean separations (Tukey) of on-field moisture content data.

Category	Combined Data[a]			Early Harvest[b]			Late Harvest[c]		
	Mean	SD[d]	Group	Mean	SD[d]	Group	Mean	SD[d]	Group
	Field Basket Method								
Early harvest	34.1	12.6	A	--	--	--	--	--	--
Late harvest	15.3	9.5	B	--	--	--	--	--	--
Morning measurement	38.3	10.9	A	38.3	10.9	A	--	--	--
Evening measurement	26.7	14.0	B	31.4	12.8	B	15.3	9.5	--
Replication − block 1	25.1	14.6	B	32.1	13.1	B	14.0	8.8	B
Replication − block 2	32.6	13.0	A	34.7	11.9	A	16.2	10.0	A
Replication − block 3	32.2	13.9	A	34.6	13.0	AB	17.8	10.4	A
Subsample 1	32.2	13.8	A	35.8	11.8	A	14.9	9.1	A
Subsample 2	27.0	14.1	A	30.7	13.4	A	15.8	10.0	A
Combine harvesting	28.0	14.4	B	30.9	13.6	B	16.0	10.7	A
Mower harvesting	36.0	12.4	A	41.1	7.1	A	15.7	7.1	A
Shelter tent − control[e]	33.3	12.5	A	38.9	5.5	A	10.8	3.5	B
	Grab Sample Method								
Early harvest	25.8	18.1	A	--	--	--	--	--	--
Late harvest	21.2	15.0	A	--	--	--	--	--	--
Morning measurement	29.0	16.9	A	29.0	16.9	A	--	--	--
Evening measurement	22.8	17.7	B	23.5	18.6	B	21.2	15.0	--
Replication − block 1	23.2	17.5	A	24.0	18.5	A	20.9	13.7	A
Replication − block 2	25.8	17.2	A	26.4	17.3	A	22.4	16.4	A
Replication − block 3	25.8	18.2	A	26.8	18.5	A	20.4	15.4	A
Subsample 1	25.8	18.0	A	26.6	18.5	A	21.5	15.4	A
Subsample 2	25.4	17.6	A	26.2	18.0	A	21.0	14.4	A
Stover above[f]	21.9	17.1	B	22.1	17.0	B	21.0	17.3	A
Stover below[g]	28.0	17.7	A	29.5	18.4	A	21.4	12.3	A
Combine harvesting	24.1	17.9	B	24.9	18.5	B	21.5	15.4	A
Mower harvesting	26.7	17.0	A	27.4	17.3	A	19.3	12.0	A

[a] Early and late harvest data combined.
[b] Early harvest at grain moisture around 25% (w.b.).
[c] Late harvest at grain moisture around 15% (w.b.); only evening measurement was taken.
[d] SD = standard deviation.
[e] Mower-harvested stover.
[f] Stover not touching the ground.
[g] Stover touching the ground.

vest. Less variability in moisture content was observed for stover under tent shelters for late harvest, as indicated by a reduced standard deviation.

The grab sample method indicated that early harvest moistures were slightly greater than late harvest values (table 2) and differed from the strong trend indicated by the *in situ* basket method. Morning measures of moisture were about seven percentage points greater than afternoon measures. The grab sample method indicated no differences between field replication blocks and subsamples. Stover in contact with the ground had mean moisture content about six percentage points greater than stover not in soil contact. *In situ* basket measures did not distinguish between individual stalks in contact with soil or not in contact. Grab samples indicated that combine harvesting produced significantly less moisture (approx. 2 percentage points) than mower harvesting for the early harvest.

Stover Moisture Trends

Precipitation increased stover moisture to a peak about two to six days after the rain event (figs. 4 through 8). The delay, or offset, in the rain effect varied depending on harvest timing, harvest method, and to some extent moisture measurement method. It should be noted that absolute peak moisture may have been missed due to discrete sampling times, but the current data set captures the idea of the trend. Combine-harvested stover had greater moisture absorption than mowed stover, which is attributed to increased exposure of internal stalk components due to conditioning.

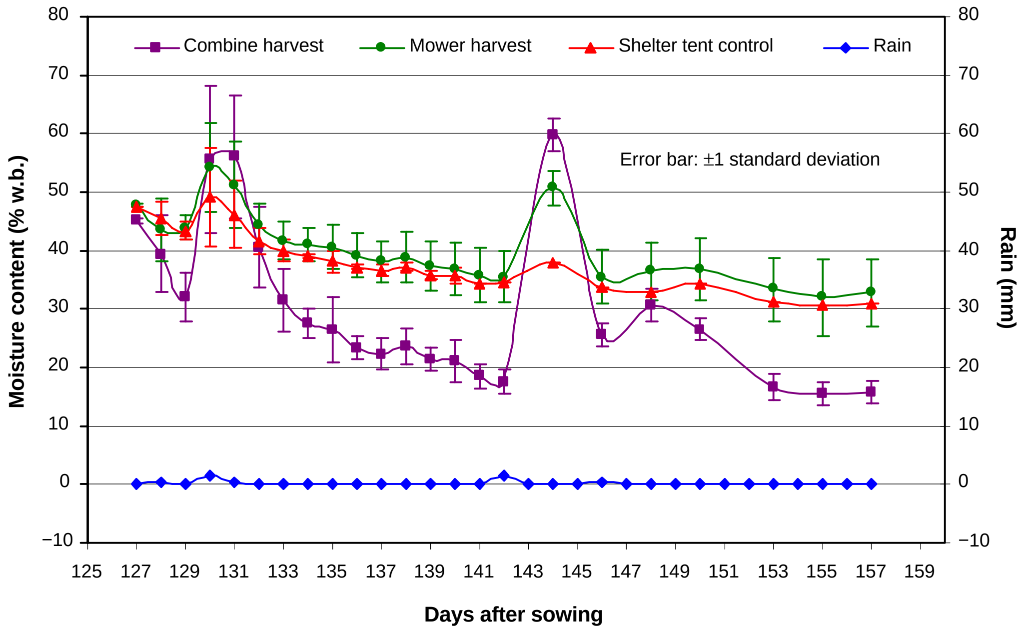

Figure 4. Early-harvested on-field corn stover moisture average curves by field basket method.

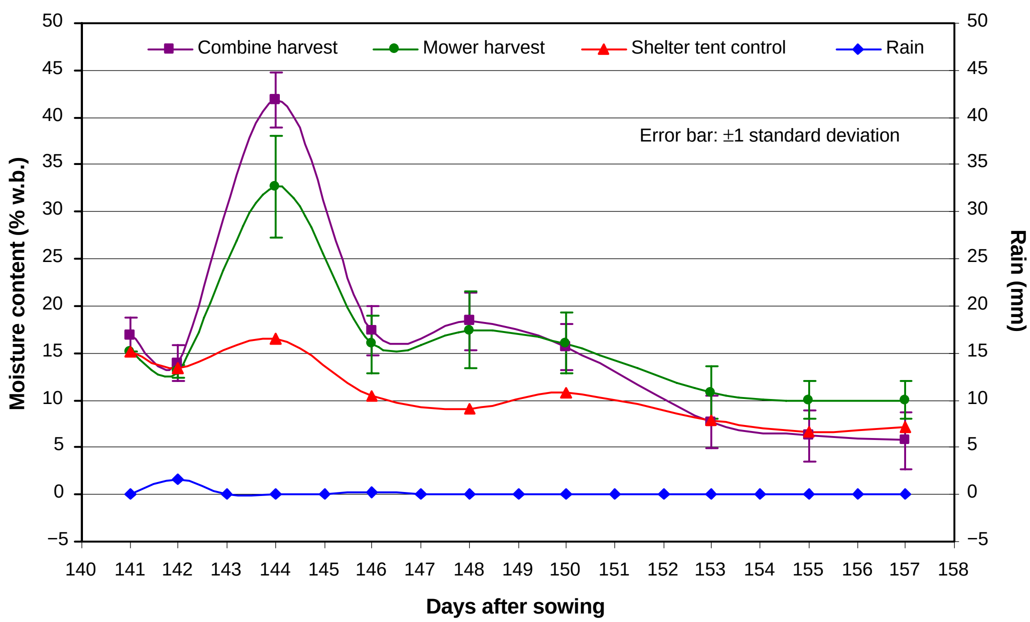

Figure 5. Late-harvested on-field corn stover moisture average curves by field basket method.

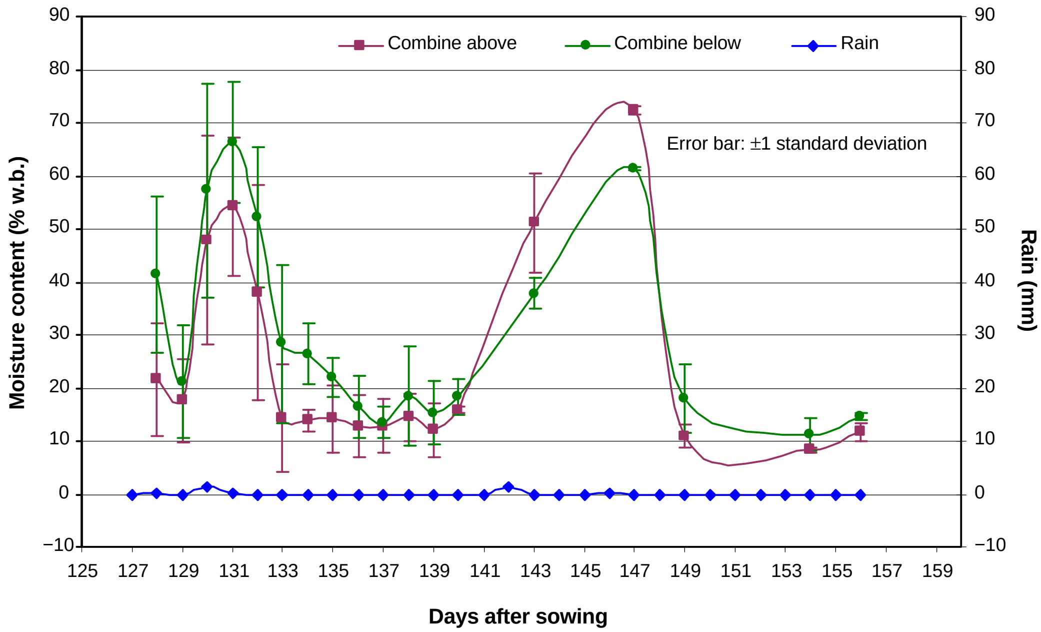

Figure 6. Early combine-harvested on-field corn stover moisture curves by grab samples method.

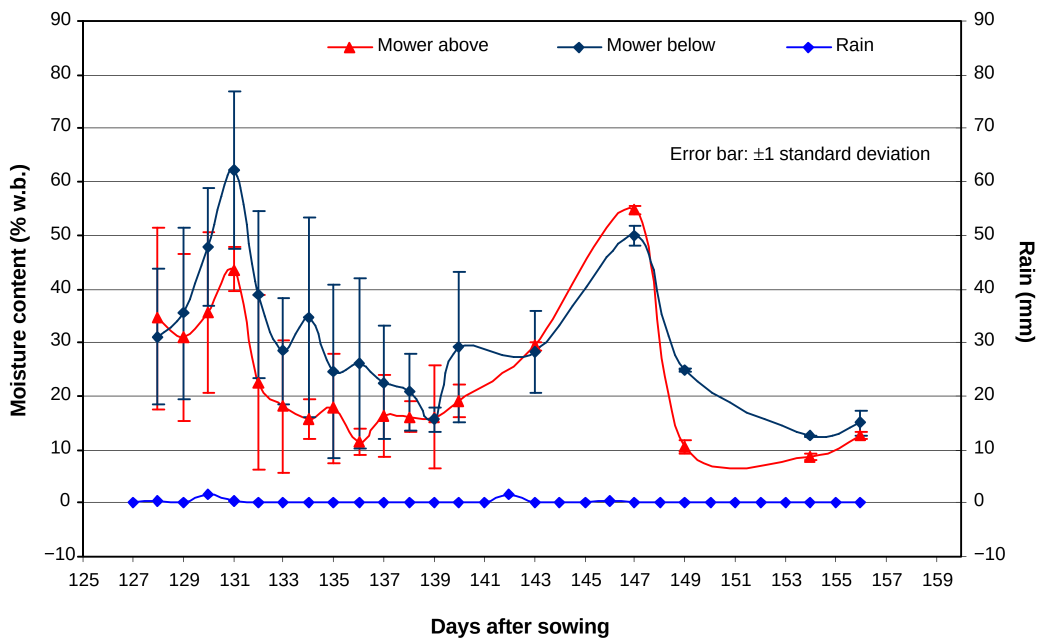

Figure 7. Early mower-harvested on-field corn stover moisture curves by grab samples method.

The rate of moisture reduction for combine-harvested stover was greater than for mowed stover, and was greater than mowed stover under the tent shelter (fig. 4). Allowing internal corn stover components to be exposed was a very effective means of removing moisture, even with susceptibility to increased rewetting.

A light rain event initially boosted stover moisture of the late harvest, as measured with *in situ* field baskets (fig. 5). Moisture of stover under the tent shelter was also affected by rain for two to three days after the precipitation event.

The grab sample method indicated that stover in contact with the ground had increased levels of moisture, except for days after a light rain event that tended to increase moisture of upper stover not in contact with soil (fig. 6). A similar trend was observed for the mowed stover (fig. 7).

Near the end of the late-harvested stover, the grab sample method indicated that all stover, no matter whether harvested by combine or mower or in contact with soil or not, approached the same moisture level at about 12 days after the light rain (fig. 8).

Correlations Between Stover Moisture and Environmental Factors

Pearson correlation coefficients between stover moisture and environmental factors for the *in situ* field baskets are listed in table 3. Strong inverse correlations between stover moisture content and days after sowing (DAS) for both early and late harvest stages (table 3) were noted. Increased exposure between conditioned stover and relatively dry soil

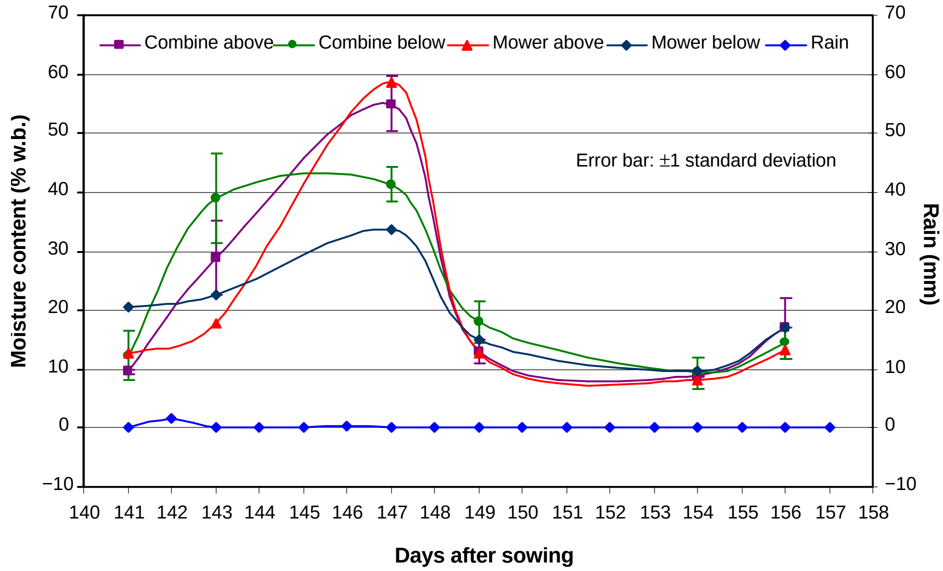

Figure 8. Late-harvested on-field corn stover moisture average curves by grab samples method.

Table 3. Stover on field baskets Pearson correlation coefficients between moisture content and selected factors.

	Combine Field Basket[a]		Mower Field Basket[b]		Shelter Tent Control Basket[c]	
	MC[d]		MC[d]		MC[d]	
Variable	*r*	*p*	*r*	*p*	*r*	*p*
			Early Harvest			
DAS	−0.52	<0.001	−0.58	<0.001	−0.82	<0.001
Soil MC (% w.b.)	0.60	<0.001	0.49	<0.001	0.85	<0.001
Soil temperature	0.20	0.004	0.20	0.088	0.24	0.168
Solar radiation	0.07	0.277	0.03	0.801	0.12	0.479
Rain	0.34	<0.001	0.35	0.003	0.38	0.023
2-day delay[e]	0.44	<0.001	0.32	0.003	0.26	0.106
Air temperature	0.24	<0.001	0.21	0.082	0.30	0.081
Relative humidity	0.26	<0.001	0.28	0.020	0.32	0.059
2-day delay[e]	0.46	<0.001	0.33	0.003	0.11	0.501
Wind direction	0.30	<0.001	0.23	0.0543	0.23	0.176
Wind speed	0.22	0.001	0.24	0.044	0.26	0.123
Maximum temp.	0.15	0.028	0.14	0.241	0.26	0.134
Minimum temp.	0.29	<0.001	0.24	0.041	0.29	0.089
ET_o FAO56-PM	0.18	0.007	0.14	0.227	0.31	0.062
2-day delay[e]	0.26	<0.001	0.32	0.004	0.45	0.003
			Late Harvest			
DAS	−0.59	<0.001	−0.49	0.041	−0.89	0.001
Soil MC (% w.b.)	0.20	0.150	0.34	0.168	0.23	0.546
Soil temperature	0.55	<0.001	0.44	0.064	0.67	0.049
Solar radiation	−0.16	0.260	−0.14	0.580	−0.32	0.407
Rain	−0.06	0.656	−0.14	0.591	0.27	0.485
2-day delay[e]	0.64	<0.001	0.64	<0.001	0.57	0.027
Air temperature	0.46	<0.001	0.37	0.130	0.62	0.078
Relative humidity	0.43	0.001	0.38	0.121	0.65	0.058
2-day delay[e]	0.55	<0.001	0.50	0.004	0.50	0.055
Wind direction	0.19	0.168	0.20	0.427	−0.20	0.596
Wind speed	−0.24	0.083	−0.20	0.414	−0.43	0.247
Maximum temp.	0.21	0.136	0.14	0.577	0.36	0.339
Minimum temp.	0.64	<0.001	0.56	0.016	0.73	0.025
ET_o FAO56-PM	0.03	0.851	0.01	0.968	−0.07	0.856
2-day delay[e]	−0.27	0.009	−0.26	0.164	−0.27	0.323

[a] Combine-harvested stover.
[b] Mower-harvested stover.
[c] Mower-harvested stover under shelter tent.
[d] MC = moisture content (% w.b.).
[e] Daily rainfall, air relative humidity, and evapotranspiration data also had delayed effect on moisture content. Results for the previous two days' data (2-day delay) were calculated using cubic spline interpolation.

may explain the early harvest strong correlation between soil moisture and stover moisture, especially for combine-harvested stover and mowed stover under the tent shelter. Soil temperature had a greater correlation with stover moisture in the late harvest, although the correlation coefficient was positive. Solar radiation was not significantly correlated with stover moisture, which may indicate that conduction and convection heat transfer were more important than radiation, at least during the fall season. Rain was correlated with stover moisture for early harvest stover, and not correlated for late harvest all using same-day measurements. Using two-day previous rain measurements strengthened correlations with moisture content. Air temperature and relative humidity were more important, in terms of correlation with stover moisture, for the combined stover than for the mowed stover. Stover moisture had a stronger correlation with two-day previous relative humidity. Wind direction was somewhat correlation-important. Wind speed correlation coefficients were both positive and negative, indicating that drying potential may have been decreased and increased, respectively. Maximum temperature was generally not important. Minimum temperature correlation with stover moisture indicated that this factor was more important for combine than mower harvest, and late harvest. Evapotranspiration had a weak correlation with stover moisture using same-day measures, except for one case during early combine harvest. However, using two-day previous evapotranspiration calculations strengthened correlations with moisture content.

Correlations between grab sample−determined stover moisture and factors are shown in table 4. The negative coefficient for DAS was consistent with the *in situ* basket method. A strong correlation between soil moisture and stover moisture was noted for grab samples. Solar radiation had low correlation coefficients with stover moisture, and was consistent with the same correlation using *in situ* baskets. Rain was more significant for grab sample correlation with stover moisture than *in situ* baskets for same-day data. Two-day rain delay effects similar to field basket data were observed, although exceptions were noted. Air temperature and relative humidity correlations with stover moisture for both harvest methods had higher correlations for late harvests than early harvests. Using two-day previous relative humidity measures generally strengthened correlations with moisture content, although the late harvest mower treatment was an exception. Wind direction was more important, in terms of correlation, for early combine harvest than other conditions and agreed with the *in situ* basket method. Wind speed had significant negative correlations with stover moisture for the late harvest. Maximum air temperature was more important for combine harvest, especially the late harvest. Minimum air temperature had very significant correlations with stover moisture, and coefficients for the late harvest were about two times larger than those for the early harvest. Evapotranspiration was important for the late combine harvest. Using two-day previous evapotranspiration calculations had mixed results.

Table 4. Stover grab samples Pearson correlation coefficients between moisture content and selected factors.

	Combine Grab Sample[a]		Mower Grab Sample[b]	
	MC[c]		MC[c]	
Variable	*r*	*p*	*r*	*p*
	Early Harvest			
DAS	−0.25	<0.001	−0.31	<0.001
Soil MC (% w.b.)	0.53	<0.001	0.49	<0.001
Soil temperature	0.14	0.002	0.13	0.049
Solar radiation	0.00	0.971	0.08	0.195
Rain	0.46	<0.001	0.40	<0.001
2-day delay[d]	0.53	<0.001	0.52	<0.001
Air temperature	0.23	<0.001	0.22	<0.001
Relative humidity	0.28	<0.001	0.27	<0.001
2-day delay[d]	0.54	<0.001	0.52	<0.001
Wind direction	0.16	<0.001	0.14	0.037
Wind speed	0.05	0.308	0.07	0.262
Maximum temp.	0.13	0.006	0.13	0.044
Minimum temp.	0.26	<0.001	0.25	<0.001
ET_o FAO56-PM	0.01	0.905	0.09	0.154
2-day delay[d]	−0.02	0.632	−0.05	0.367
	Late Harvest			
DAS	−0.33	<0.001	−0.27	0.199
Soil MC (% w.b.)	0.50	<0.001	0.57	0.003
Soil temperature	0.48	<0.001	0.39	0.061
Solar radiation	−0.22	0.010	−0.21	0.335
Rain	0.46	<0.001	0.18	0.391
2-day delay[d]	0.52	<0.001	−0.25	0.289
Air temperature	0.46	<0.001	0.41	0.049
Relative humidity	0.67	<0.001	0.65	<0.001
2-day delay[d]	0.52	<0.001	0.38	0.094
Wind direction	−0.10	0.243	−0.21	0.320
Wind speed	−0.50	<0.001	−0.55	0.005
Maximum temp.	0.40	<0.001	0.35	0.091
Minimum temp.	0.58	<0.001	0.56	0.005
ET_o FAO56-PM	−0.24	0.004	−0.28	0.185
2-day delay[d]	−0.10	0.056	−0.34	0.136

[a] Combine-harvested stover.
[b] Mower-harvested stover.
[c] MC = moisture content (% w.b.).
[d] Daily rainfall, air relative humidity, and evapotranspiration data also had delayed effect on moisture content. Results for previous two days' data (2-day delay) were calculated using cubic spline interpolation.

Regression Equations to Predict Stover Moisture Content

Table 5 lists multiple linear regression equations to predict moisture content. No one general equation best predicted stover moisture. Multiple equations were provided based on sampling method, harvest stage, and harvest method. For each combination, two equations are listed with and without the DAS factor. The difference in equation performance with and without the DAS factor ranged from no effect on R^2 to a difference of 33 percentage points. Regressions were performed using previous two-day measures of rainfall, air relative humidity, and evapotranspiration. Using same-day moisture-related independent variables yielded lower regression results.

Conclusions

- Measured moisture relations of corn stover depended on several factors, including environmental conditions, harvest method, and to a lesser degree moisture measurement method.
- A combine provided a significant conditioning effect on stover that enhanced moisture removal and moisture uptake after rain events.

Table 5. Multiple linear regressions predicting on-field corn stover moisture content, primarily as a function of environmental conditions, using previous two-day rainfall, air relative humidity, and evapotranspiration and data interpolation.

Moisture Relations[a]	R^2	RMSE
Field basket method - Early harvest:		
Combine-harvested stover		
$MC = -85.12 - 0.05\ DAS + 2.97\ SM + 9.02\ RF + 0.77\ RH + 9.06\ EP$	0.61	8.42
$MC = -95.59 + 3.05\ SM + 9.13\ RF + 0.79\ RH + 9.41\ EP$	0.61	8.41
Mower-harvested stover		
$MC = 27.31 - 0.23\ DAS + 1.16\ SM + 2.96\ RF + 0.28\ RH + 3.57\ EP$	0.50	5.21
$MC = -22.08 + 1.55\ SM + 3.38\ RF + 0.38\ RH + 5.08\ EP$	0.46	5.40
Stover under shelter tent − control		
$MC = 115.42 - 0.67\ DAS + 1.34\ SM + 3.69\ RF - 0.12\ RH + 1.86\ EP$	0.72	5.01
$MC = -32.96 + 3.97\ SM + 4.27\ RF + 0.07\ RH + 3.46\ EP$	0.55	6.33
Field basket method − Late harvest:		
Combine-harvested stover		
$MC = 374.37 - 2.20\ DAS + 0.64\ SM + 10.30\ RF - 0.37\ RH - 4.51\ EP$	0.88	3.80
$MC = -64.52 + 1.78\ SM + 14.67\ RF + 0.60\ RH + 3.70\ EP$	0.62	6.83
Mower-harvested stover		
$MC = 261.52 - 1.39\ DAS - 0.90\ SM + 6.90\ RF - 0.25\ RH - 3.48\ EP$	0.82	3.36
$MC = -3.69 - 1.12\ SM + 9.69\ RF + 0.38\ RH + 1.60\ EP$	0.55	5.14
Stover under shelter tent − control		
$MC = 131.98 - 0.74\ DAS + 0.81\ SM + 2.21\ RF - 0.22\ RH - 2.13\ EP$	0.90	1.22
$MC = -9.24 + 0.69\ SM + 3.69\ RF + 0.11\ RH + 0.57\ EP$	0.48	2.62
Grab samples method - Early harvest:		
Combine-harvested stover		
$MC = -135.51 + 0.34\ DAS + 5.60\ SM - 1.97\ ST + 13.59\ RF + 0.73\ RH + 1.83\ MT$	0.57	13.37
$MC = -75.53 + 4.53\ SM - 2.02\ ST + 13.21\ RF + 0.78\ RH + 1.80\ MT$	0.56	13.54
Mower-harvested stover		
$MC = -86.95 + 0.07\ DAS + 4.23\ SM - 2.03\ ST + 9.96\ RF + 0.93\ RH + 1.29\ MT$	0.54	12.01
$MC = -73.42 + 3.96\ SM - 2.05\ ST + 9.95\ RF + 0.93\ RH + 1.29\ MT$	0.54	12.00
Grab samples method − Late harvest:		
Combine-harvested stover		
$MC = -132.53 + 0.01\ DAS + 0.97\ RF + 1.33\ RH - 8.16\ WS + 2.42\ MT + 17.16\ EP$	0.80	8.12
$MC = -130.25 + 0.96\ RF + 1.32\ RH - 8.13\ WS + 2.42\ MT + 17.01\ EP$	0.80	8.10
Mower-harvested stover		
$MC = -611.57 + 2.62\ DAS + 14.39\ SM - 4.20\ RF + 0.48\ RH + 2.64\ MT$	0.82	6.60
$MC = -106.69 + 7.66\ SM - 5.18\ RF + 0.19\ RH + 2.15\ MT$	0.79	6.98

[a] RMSE = root mean square error, *MC* = moisture content (% w.b.), *DAS* = days after sowing, *SM* = soil moisture content (% w.b.), *RF* = rainfall (mm), *RH* = air relative humidity (%), *EP* = evapotranspiration by FAO-56 Penman-Monteith method (mm day^{-1}), *MT* = minimum air temperature (°C), *ST* = soil temperature (°C), *WS* = wind speed (m s^{-1}).

- The full effect of rain events on increasing stover moisture occurred several days after the event. Same-day correlations and regressions were improved using previous two-day rain, relative humidity, and evapotranspiration data.
- Stover moisture was significantly greater in the morning compared to afternoon, and was greater for stover contacting the soil compared with stover not in soil contact.
- In addition to mechanical harvest method (stalk conditioning effect), the strongest environmental/timing correlations to predict stover moisture on the field after grain harvest included the following daily-averaged factors: elapsed time (days) after sowing/harvest (collect later for reduced moisture), time of day (evening collection preferred over morning collection), soil moisture, 2-day previous rainfall amount, 2-day previous relative humidity, and 2-day previous evapotranspiration factor. Thus, increased elapsed time after sowing/harvest, evening harvest times, and the immediate (2-day) exposure history of corn stover to available moisture and drying potential are useful in determining strategies to collect corn stover with minimum moisture content.
- Regressive predictions of stover moisture content by environmental factors provide a means of predicting moisture relations, and were generally improved upon with an additional factor based on time since planting. The usefulness of moisture prediction equations should emphasize simplicity balanced with accuracy.

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