An ASAE/CSAE Meeting Presentation **Paper Number: 041162**

Vertical Mass and Moisture Distribution in Standing Corn Stalks

C. Igathinathane, Ph.D.

Post Doctoral Research Associate, 2506 E.J. Chapman Drive, Department of Biosystems Engineering and Environmental Science, The University of Tennessee, Knoxville, TN 37996-4531, igathi@utk.edu

Alvin R. Womac, Ph.D., P.E.

Professor, 2506 E.J. Chapman Drive, Department of Biosystems Engineering and Environmental Science, The University of Tennessee, Knoxville, TN 37996-4531, awomac@utk.edu

Shahab Sokhansanj, Ph.D., P.E.

Research Leader, Oak Ridge National Laboratory, Environmental Sciences Division, P.O. Box 2008, Oak Ridge TN 37831-6422, sokhansanjs@ornl.gov

Lester O. Pordesimo, Ph.D.

Former Associate Professor, 2506 E.J. Chapman Drive, Department of Biosystems Engineering and Environmental Science, The University of Tennessee, Knoxville, TN 37996-4531, lpordesimo@utk.edu

Written for presentation at the
2004 ASAE/CSAE Annual International Meeting
Sponsored by ASAE
Fairmont Chateau Laurier, The Westin, Government Centre
Ottawa, Ontario, Canada
1 - 4 August 2004

Abstract. *Vertical distribution of mass and moisture in the stalks and above-ground components of standing corn plants were evaluated over time. Obtaining these measures prior to irreversible mechanical action of the harvest would provide a baseline of the exact mass and moisture status of standing crop components. DeKalb 743 variety corn plant samples, soil moisture and temperature, and environmental parameters were collected from two months prior to corn grain harvest until one month after harvest. Plant samples were separated by physical components. Stalks were cut into 254 mm (10") long sections and numbered up to about 12 to 14. Sections were quantified for wet mass, dry matter, and moisture contents. Among the stover components, stalks had the greatest wet mass followed by leaf and husk. Mass and moisture variation of above-ground plant components exhibited two moisture-reduction trends. The first trend was a period of rapid reduction. The second trend was a gradual reduction and stabilization of moisture. Fourth order polynomial regression equations effectively described the wet mass of whole plant, stalk, leaf, whole ear, husk, stover, stalk dry matter, and stover to dehusked ear ratio, and moisture contents of stalk, leaf, husk, and grain as a function of days after sowing (DAS) with* R^2 *ranging from 0.811 to 0.997. Stalk section below the typical ear generally had increased wet mass and dry matter. Wet mass and moisture content of stalks were not significantly influenced by the observed soil and environmental parameters. On an average, the bottom 1 to 4 stalk sections had 66±3% of total wet mass, and 61±3% of total dry matter. Individual stalk section fourth order polynomial equations using DAS as the primary independent variable gave good performance with wet mass (*$R^2 = 0.95 \pm 0.02$*), dry matter (*$R^2 = 0.84 \pm 0.11$*), and moisture content (*$R^2 = 0.96 \pm 0.01$*). Overall multiple regression equations involving DAS and section number valid for any stalk section also produced comparable performance (*$R^2 > 0.93$*). This study provided information on biomass availability and vertical distribution of mass and moisture in standing corn stalks, which would serve as benchmark data for utilizing corn stover and selecting appropriate process operations.*

Keywords. Biomass, Corn, Distribution, Mass, Moisture, Regression, Stalk, Stover, Vertical

Introduction

Corn stover was conceived as a strategic biomass for bioenergy conversion and bio-based industrial products (Hettenhaus and Wooley, 2000). Potential uses of corn stover include farm animal feed, fuel, particle board, building panel, pulp and paper, ethanol, cellulose derivatives, potting soil, and roadside mulching (Kadam and McMillian, 2003). Corn (*Zea mays*, L.) is a major U.S. crop annually planted on approximately 28.8 million ha producing 256.9 million t of wet grain (USDA, 2003). Sokhansanj et al. (2002) estimated a dry corn stover mass of 216 million t from the 2001 U.S. corn grain production of 254 million t. Their assumptions were grain at 15% moisture content wet basis (w.b.) and dry matter to grain ratio of 1:1. Not all of the dry mass produced is available for removal. Stover availability depends upon the amount needed to be left on the farm for soil conservation, nutrients, and soil carbon maintenance. Other stover availability estimates ranged from 64 to 91 million dry t/y (Iowa State University, 1993) and 153 million dry t/y (Glassner et al., 1999). A recent conservative estimate of corn stover availability was 82 million dry t/y (Kadam and McMillian, 2003). Another conservative estimate of feedstock demand for biorefineries was 172 million t/y by 2010 and more than 508 million t/y by 2020 for stated goals (Sokhansanj and Wright 2002).

Physical properties of corn stover are needed to design systems for harvesting, handling, and storing the material. Temporal quantification of corn stover properties after grain physiological maturity is needed for postharvest handling systems development (Pordesimo et al., 2004). Similar studies were conducted by Cummins (1970), Leask and Daynard (1973), and Russell (1986) up to, but not after, physiological maturity of grain. Shinners et al. (2003) and Pordesimo et al. (2004) have studied corn stover harvest, above-ground biomass distribution, components proportions, field drying after harvesting, and storage issues.

Moisture content of corn stover is a critical factor for efficient collection, processing, transportation, and storage (Edens et al., 2002). Corn stover with high moisture content increases machine harvest difficulty, affects the selection of processing equipment, increases transportation cost, increases spoilage rate, and presents safety hazards when moldy (Edens et al., 2002; Jenkins and Sumner, 1986). Basic factors, such as environmental factors, soil conditions, days after sowing (DAS), and component proportions, are expected to directly affect mass and moisture distributions of above-ground components of the corn plant.

Biomass is generally collected following the crop harvest, wherein some amount of biomass loss due to weathering and soil contamination is inevitable. Stalks constitute the major portion of stover biomass after corn ear harvest (Pordesimo et al., 2004). Modern grain combines tend to strip ears and leave much of the stover uncut on the field (Sokhansanj et al., 2002). Hence, it is also useful to study the dry matter and moisture history of stalks above and below the typical ear level. A detailed study would document biomass availability up the tapered cross-section along stalk length. Obtaining these measures prior to irreversible mechanical action of the harvest would provide a baseline of the exact mass and moisture status of standing crop components. Hence, data on biomass availability and vertical distribution of mass and moisture would serve as a benchmark for selecting process operations for the range of potential uses of corn stover.

The specific objectives of this research were:

1. To determine the mass and moisture characteristics of corn plant above-ground components over time.
2. To evaluate the vertical distribution of mass and moisture in the stalks of standing corn plants.
3. To develop relationships for estimating mass and moisture content of corn plant above-ground components and stalk sections over time.

Materials and Methods

Experimental plot and sample collection

Ten rows of corn plants of a field plot (201 $\times$ 48 m) at the Knoxville Experiment Station, The University of Tennessee, Knoxville were selected for the study. The field had a well-drained alluvial soil (Sequatchie loam) on the first terrace of Fort Loudon Lake (Tennessee river). Corn variety Dekalb 743 was planted on May 20, 2003, and this date was considered as 0 days after sowing (DAS). The crop was given the standard agronomical practices recommended for Tennessee (Flinchum, 2001). Crop rows were spaced at 0.76 m and in-row plant spacing was approximately five to six plants/m. To avoid plot edge effects, plots had a minimum of seven border rows.

The experimental plot was divided into 3 blocks (replications) along the length to study the effect of variation in location and to aide sample collection. Two corn plants (sub samples) from each block were obtained each sample day. Corn plant samples were identified by replications and sub samples and were labeled during collection. Whole plants were cut just above the node having brace roots (fig. 1). Samples were collected in the mid morning hours except weekends.

Figure 1. Corn plant sample collection from field plots

Sample period ranged from grain milky stage (11 August; 83 DAS) to well past the normal harvesting date (24 October; 157 DAS). Corn plants were over 3.5 m high when the experiment was started and they generally had two corn ears. The main corn ear was always found above a smaller rudimentary ear (Aldrich and Leng, 1966), which was characteristic of the single-ear corn varieties like Dekalb 743.

Soil samples, one from each block, were collected each sample day at a depth of approximately 200 mm and were held in moisture proof WHIRL-PAK® bags (Nasco, Fort Atkinson, Wisc.). One soil temperature measurement at an approximate depth of 140 mm from each block was recorded simultaneously, using a dial type soil thermometer. Collected plant and soil samples were transported to the laboratory within 30 minutes for analysis.

Sample preparation and mass measurements

In the laboratory, wet mass of whole plant samples was measured using high capacity top-loading digital balance (0.1 g resolution). Corn ears were manually removed and their whole masses with husk were measured. Corn ears were further separated manually by pealing the husk to leave cob with kernels and husk components. Cob component of the ear was arbitrarily not included in the study, since the cobs may be detached from the plant during de-shelling. Rudimentary ears, when found on the plant, were counted, though excluded for moisture measurements. Leaves were carefully extracted from stalks with scissors cutting attachment junctions. Tassel portion was left attached to the stalks. All separated plant components such as stalk, leaf, husk, and dehusked ear were separately weighed and the total was compared to whole plant sample mass. Component mass was separately recorded and stored for each of the six daily plant samples. Stalk lengths were measured and marked into 254 mm (10”) length sections and numbered serially from base of the plant upward. Marked stalks were cut into sections (fig. 2), and their wet masses were measured individually with top-loading digital balance (0.01 g resolution) and recorded with corresponding stalk section numbers.

Figure 2. Cut stalk sections numbered for mass and moisture measurements

Extracted leaves from all plants samples were mixed well and a few representative sample leaves were drawn for moisture measurement. Pieces of approximately 55 mm length with the existing leaf width were cut from the drawn leaves, and around 25 g of material was collected in perforated aluminum trays for moisture measurement. Similar procedure was also followed with the husk. For the grain moisture measurement, six samples of approximately 25 g of kernels separated manually from ears of each plant were taken in sample cups. From the collected soil, three samples of around 25 g from each block (total 9) were prepared and held in sample cups.

Moisture content measurement

Initial wet weight of grain and soil samples were measured using a sensitive digital balance of 0.001 g resolution. ASAE Standard S358.2 (*ASAE Standards, 2003*) for forages (air oven at 103°C for 24 h) was followed to determine moisture contents of all corn and soil samples using the same air oven. Final dry weight of all samples were determined after 24 h. From the known initial and final weights, the moisture contents of samples were determined and expressed as a percentage wet basis. In this paper all moisture contents are expressed in percent wet basis, unless stated otherwise.

Environmental parameter collection and evapotranspiration estimation

Weather data with 30 minutes interval from an automatic weather station (Model: CM10, Campbell Scientific Inc., Logan, Utah) were downloaded and the data were consolidated on a daily basis. Component instruments of the automatic weather station were pyranometer (Model: LI2005, ±3% typical error), tipping bucket rain guage (Model: TE525, ±1% accuracy), temperature and relative humidity probes (Model: HMP45C, ±0.4°C and ±2-3% relative humidity accuracy), and wind measurement (Model: 03001-5 R.M. Young wind sentry set with anemometer ±0.5% m/s accuracy and wind direction vane 5° to 10° accuracy), and data logger (Model: CR10(X)). Environmental parameters monitored included solar radiation ($MJ/m^2 \cdot s$), rainfall (mm), maximum and minimum temperatures (°C), mean air temperature (°C), air relative humidity (%), wind speed (m/s) and wind direction (°N).

From the measured environmental parameters, evapotranspiration was calculated using the REF-ET Reference Evapotranspiration Calculator software, Ver. 2.0 developed by Allen (2000). Of the different evapotranspiration methods available in the software, FAO-56 Penman-Monteith method was used in this study. The observed environmental conditions and calculated evapotranspiration values are given in table 1.

Table 1. Measured environmental conditions and calculated evapotranspiration values for Knoxville during 11 August to 24 October 2003

Variable	Mean	SD[a]	Minimum	Maximum
Days after sowing (day)	122.32	21.64	83	157
Soil moisture (% w.b.)	11.49	2.80	2.35	19.18
Soil temperature (°C)	21.42	3.85	13	29
Solar radiation ($MJ/m^2{\cdot}s$)	16.83	5.32	2.55	23.58
Rainfall (mm/day)	1.10	5.47	0.0	37.08
Mean air temperature (°C)	19.08	5.30	9.25	28.73
Maximum air temperature (°C)	26.30	4.73	14.5	33.4
Minimum air temperature (°C)	14.20	5.87	2.1	23.2
Air relative humidity (%)	79.02	7.49	57.01	95.9
Wind direction (°N)	139.29	40.45	62.13	243.8
Wind speed (m/s)	0.88	0.44	0.392	2.722
ET_o FAO56-PM[b] (mm/day)	2.80	1.00	0.67	4.33

[a] SD = Standard deviation

[b] Evapotranspiration by FAO-Penman-Monteith method

Four periods of rainfall with 16.7, 13.2, 10.7, and 37.1 mm were recorded on 89, 103, 118 and 125 DAS, respectively.

Data analysis

Effects of the various independent variables in predicting dependent variables such as wet mass, dry matter, and moisture content were evaluated using PROC CORR of SAS (2002). For practical purposes, relationships estimating wet mass, dry matter and moisture content from the simpler independent variables like DAS and section numbers were prioritized as most useful. PROC REG of SAS (2002) was used in developing such relations involving polynomial and multiple regression techniques. Statistical *t*-test was also performed to compare the overall group means of closely related trends of corn stover components.

Results and Discussion

Mass and moisture of above-ground plant components

Mean wet mass of fresh material of above-ground components during the experimental period is shown in figure 3. The curves exhibited two distinct zones of wet mass reduction. The first zone was up to about 120 DAS. The second zone was after 120 DAS. It should be noted that 120 DAS corresponds with typical corn harvest, though grain was not harvested in this experiment. In general, the normal harvest period of the crop corresponds to the grain moisture level of about 25%.

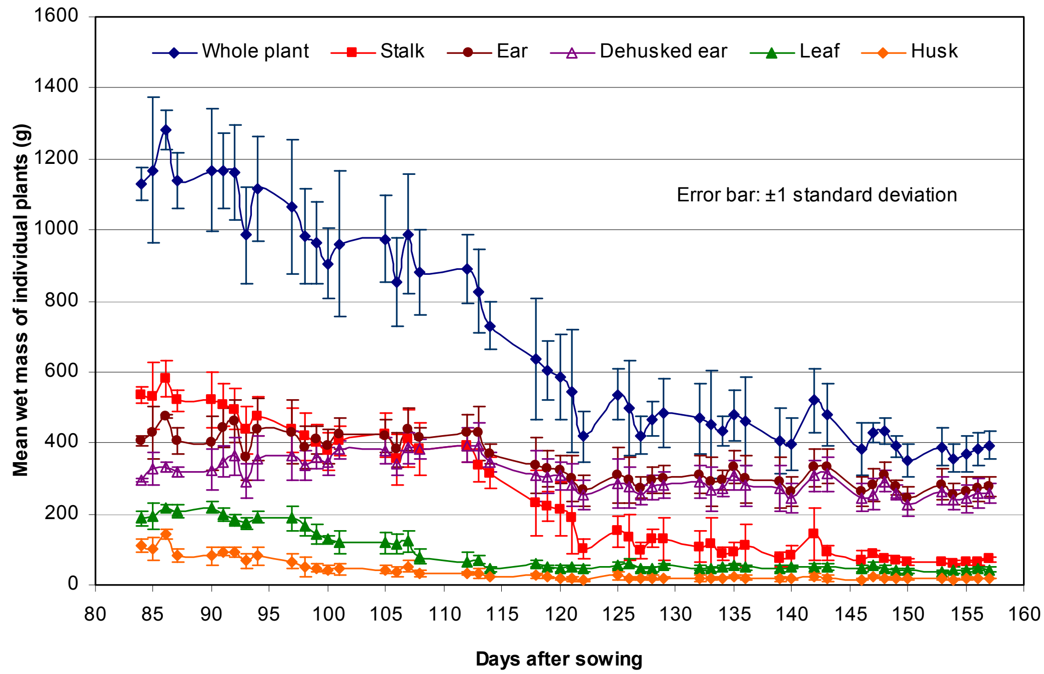

Figure 3. Wet mass of above-ground components of the standing corn plants

In the first zone the whole plant lost wet mass rapidly, almost linearly from an initial value about 1.2 kg/plant to a final value of about 0.5 kg/plant at about 120 DAS. In the second zone the rate of wet mass reduction was less for initial and final values of about 0.5 to 0.4 kg/plant, respectively. Stalk wet mass dominated the dehusked ear wet mass initially, but after about 112 DAS the ear wet mass dominated all other components. Stalk wet mass followed the whole plant mass trend almost in a parallel manner. Though leaf and husk wet mass reductions had similar trends, wet mass of leaf component was 2.6 ± 0.5 (average ± 1 standard deviation) times greater than that of the husk.

Based on *t*-test, the overall mean of leaf and husk wet mass ($t = -5.70$, $p < 0.0001$), and the overall mean of ear and dehusked ear ($t = -3.33$, $p < 0.0012$) were found to be significantly different. Leaf and husk components lost wet mass rapidly during the first zone and the reduction stabilized about two weeks before the normal harvest period. Of all the components, dehusked ear exhibited almost constant wet mass throughout the test period. This was possibly due to grain material addition during grain maturation, which offset moisture loss. Among biomass components, the stalk had the greatest wet mass. Therefore, stalks would provide more collectable biomass compared to leaves and husks, especially considering high leaf and husk losses during machine harvest.

Moisture content status of above-ground corn plant components during the experiment is shown in figure 4. Moisture content reduction of leaf, husk, and grain followed trends similar to wet mass reduction trends (fig. 3). Pordesimo et al. (2004) also observed similar trends of moisture reduction with corn components. During the first zone (<120 DAS), leaf, husk, and grain moisture decreased rapidly and approached a stabilized moisture content during the second zone (>120 DAS). Stalks had a somewhat stable high moisture content (> 70%) in the first zone, and the moisture content reduced almost linearly to 10% in the second zone. Shinners et al. (2003) reported that the stalk moisture remained over 65% until grain harvest.

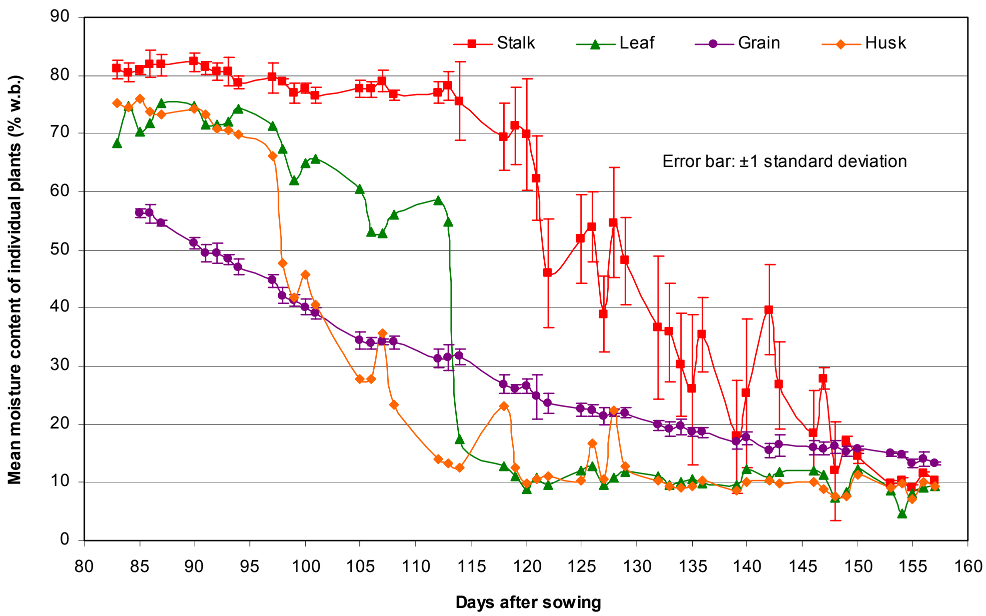

Figure 4. Moisture reduction of above-ground components of the standing corn plants

Group means comparison *t*-test revealed that the overall means of leaf and husk moisture contents were found to be not significantly different (t = -0.96, p = 0.3405). Stalk, leaf, husk, and grain achieved a mean final moisture content of 10.3%, 9.2%, 9.3%, and 13.3%, respectively. Four rainfall events (89, 103, 118, and 125 DAS) with rainfall depth ranging from 10.7 to 37.1 mm did not have a noticeable effect on stalk moisture contents. This may possibly because moisture quickly drained off the stalk skin of standing stalks with little opportunity for internal moisture penetration.

Fitted equations of wet mass and moisture content of above-ground components are presented in table 2. Polynomial relationships with DAS as the independent variable conveniently express the wet mass and moisture contents of whole stalk, leaf, whole ear, and husk. A fourth order polynomial fit described the observed moisture reduction and produced a high coefficient of determination (R^2) for wet mass and for moisture content of components (table 2). Stover to dehusked ear wet mass ratio got reduced from 2.85 to 0.47 during the experiment with a value of 1.20±0.74 (average ± 1 standard deviation). But after the normal harvest period, this ratio was observed to be 0.62±0.14, because the stover was close to a stable dry moisture level.

Table 2. Wet mass and moisture content polynomial regression equations of above-ground components of standing corn plant as a function of DAS

Equation[a]	R^2	RMSE[b]
Wet mass (g)		
Whole plant = $-36259.0 + 1305.88DAS - 16.54DAS^2 + 9.02E\text{-}02DAS^3 - 1.80E\text{-}04DAS^4$	0.9682	57.00
Stalk = $-10728.0 + 388.00DAS - 4.78DAS^2 + 2.47E\text{-}02DAS^3 - 4.62E\text{-}05DAS^4$	0.9724	31.12
Leaf = $-12135.0 + 450.62DAS - 5.99DAS^2 + 3.44E\text{-}02DAS^3 - 7.21E\text{-}05DAS^4$	0.9705	11.27
Whole ear = $-12068.0 + 419.04DAS - 5.14DAS^2 + 2.74E\text{-}02DAS^3 - 5.37E\text{-}05DAS^4$	0.8111	30.83
Husk = $-550.3 + 37.98DAS - 0.65DAS^2 + 4.35E\text{-}03DAS^3 - 1.00E\text{-}05DAS^4$	0.9639	5.49
Stover[c] = $-24383.0 + 913.03DAS - 11.91DAS^2 + 6.62E\text{-}02DAS^3 - 1.34E\text{-}04DAS^4$	0.9860	33.27
Stalk dry matter (g) = $-2639.5 + 93.33DAS - 1.16DAS^2 + 6.19E\text{-}03DAS^3 - 1.21E\text{-}05DAS^4$	0.8422	7.26
Stover to ear ratio[d] = $2.5 + 0.24DAS - 0.005DAS^2 + 3.66E\text{-}05DAS^3 - 8.26E\text{-}08DAS^4$	0.9850	0.09
Moisture content (% w.b.)		
Stalk = $1336.8 - 50.57DAS + 0.74DAS^2 – 4.72E\text{-}03DAS^3 + 1.08E\text{-}05DAS^4$	0.9624	5.49
Leaf = $-6680.4 + 232.36DAS - 2.92DAS^2 + 1.59E\text{-}02DAS^3 - 3.18E\text{-}05DAS^4$	0.9493	6.62
Husk = $-3256.2 + 125.29DAS - 1.70DAS^2 + 9.84E\text{-}03DAS^3 - 2.07E\text{-}05DAS^4$	0.9597	5.33
Grain = $209.5 - 1.86DAS - 0.01DAS^2 + 1.24E\text{-}04DAS^3 - 3.35E\text{-}07DAS^4$	0.9970	0.75

[a] Means of the 6 plant samples per sampling day were used as the input data, and DAS varies from 83 to 157

[b] RMSE is root mean square error [c] Stover mass is whole plant mass less the dehusked ears

[d] Wet mass ratio of stover and dehusked ear.

Typical vertical distribution of wet mass and moisture of stalks

Figure 5 shows the typical distribution of wet mass and moisture content of stalk sections at two days arbitrarily chosen days one during the starting (83 DAS) and another near the end (156 DAS) of the experiment. As dry matter of stalks was relatively similar for the two days, it was concluded that the moisture contributed to the major difference in wet mass for the two days. It was also interesting to note that the wet mass and the dry matter of the 4th stalk section had slightly higher values than expected for a smooth upward trend. In fact, the wet mass and the dry matter of the 4th section were greater than that of the 3rd section (fig. 5) at a frequency of 21% and 15%, respectively. The reason for this may be due to the presence of corn ear in the 5th section. The 4th section may have acted as a storage of moisture and material to aide the developing ear above. It was observed that the main ear appeared at the 5th section at a frequency of 69% and at 6th and 4th sections around 29% and 2%, respectively, during the experiment. Increased wet mass and dry matter in the section below the ears were observed with all plant samples throughout the experiment. Tassels occurred above the 11th section and had very little wet mass.

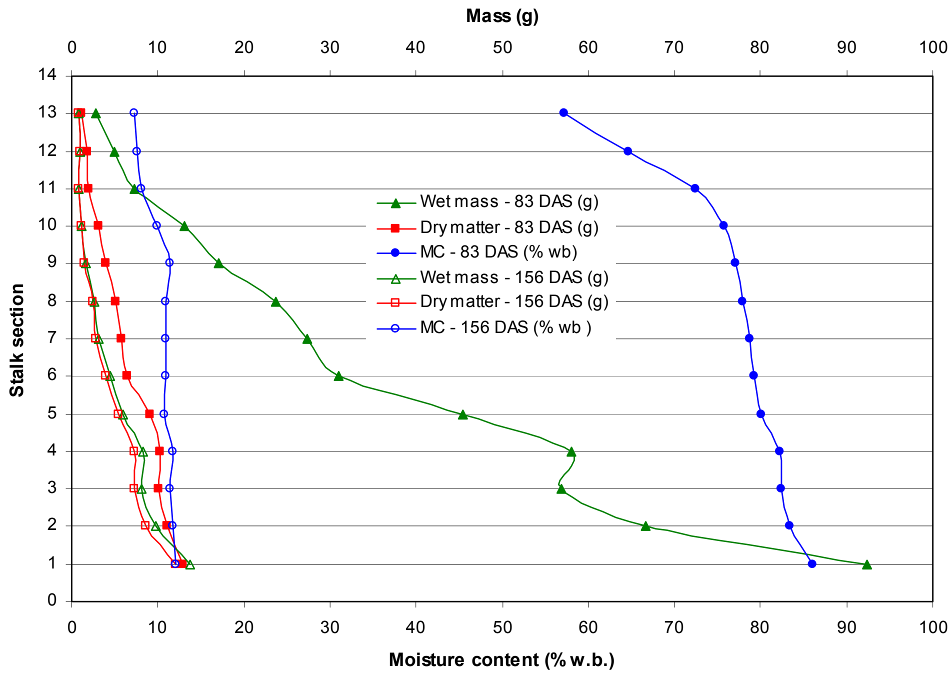

Figure 5. Typical mass and moisture distribution on the stalk during the start (83 DAS) and end (156 DAS) days

Based on the modern harvesting practice (Sokhansanj et al., 2002), maintaining the 5th section as the reference ear location, stalks are divided into two portions as above and below the reference ear location. Therefore to determine dry matter and moisture of stalk sections 1 to 4 typically not cut by the harvester in field (below ear level), versus harvester-cut stalk sections 5 to 14 (above ear level), were plotted (figs. 6 and 7).

Dry matter in stalk sections (fig. 6) below the typical ear level (1-4 sections) was greater than in stalk sections above the typical ear level (5-14 sections). The averaged stalk dry matter before and after the normal harvest period (120 DAS) were 50.51±4.85 and 36.95±.2.69 g for below ear sections, 38.19±4.33 and 21.23±1.49 g for above ear section, respectively. This result shows the importance of the sections below the typical ear level. Relative flatter trends before and after normal harvest period was again noted with the below and above typical ear level stalk sections.

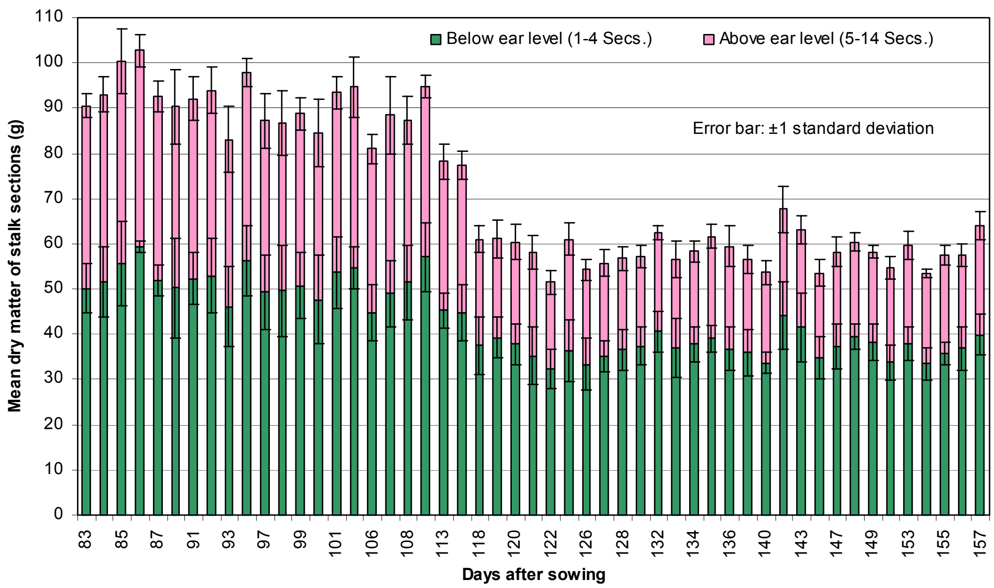

Figure 6. Daily average cumulative dry matter history of stalk sections with reference to typical corn ear location

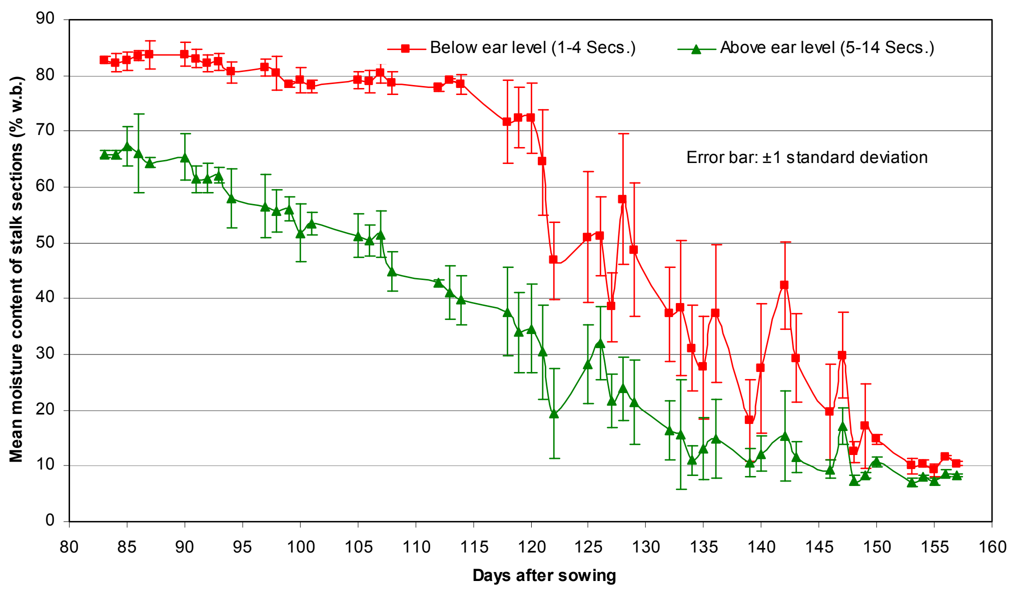

Figure 7. Daily average moisture content history of stalk sections with reference to typical corn ear location

Vertical distribution of wet mass and moisture content of stalk sections

Vertical distribution of wet mass of stalks based on weekly average is shown in figure 8. Reduction in wet mass during initial weeks among sections was higher than latter weeks and it gradually reduced as time progressed. Since, a wide separation in the curves distribution was seen around the 5th week (118-122 DAS), which coincided with the normal harvest period.

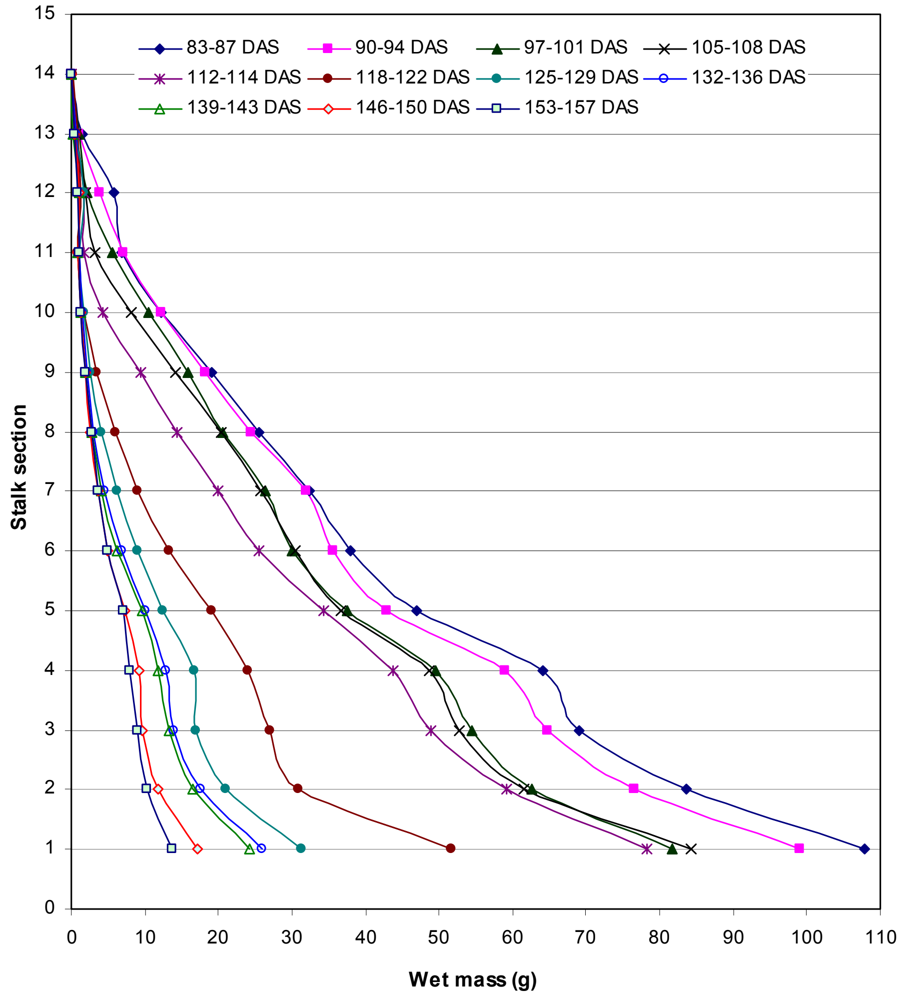

Figure 8. Vertical distribution of weekly average wet mass of stalk sections

Reduction in wet mass among stalk sections along the vertical direction was high before the harvesting period, and the variation reduced considerably after that. It can be observed that a major reduction of wet mass occurred among the first six sections, with the maximum reduction between the 1st and the 2nd sections, and the wet mass reduction decreased gradually upward. Greater mass of the 1st section emphasize the importance of cutting plants at a lowest possible level above the ground for maximized biomass collection. Johnson and Lamp (1966) reported that cutting corn plants at the soil surface would add 10% more to stover yields over normal harvesting practices. Cuts too close to the ground level increased soil contamination and the biomass may require additional cleaning. Sections having the tassel (≥ 11th section) always had little wet mass, but had slightly higher wet mass values before the harvesting period.

Figure 9 shows the vertical distribution of dry matter of stalks sections based on weekly average data. Grouping of curves separated by the normal harvest period was highly evident with dry matter vertical distribution. Closeness of the curves after 120 DAS indicated that not much dry matter reduction had occurred after the normal harvest period. Therefore, stover can be

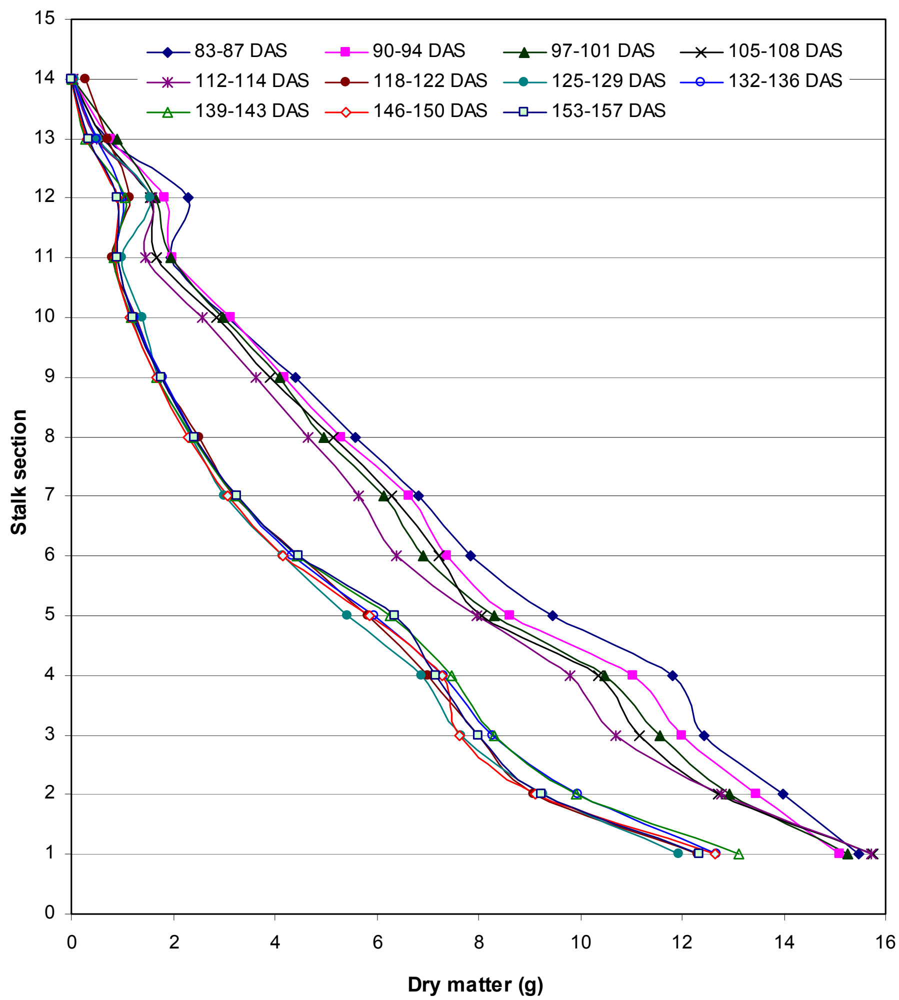

Figure 9. Vertical distribution of weekly average dry matter of stalk sections

considered ready for collection soon after harvest, based on the dry matter availability. Dominance of dry matter at bottom sections were due to the natural cross sectional area increase from top to bottom of any plant species in general. Departure from the smooth reduction trend in curves around the 12^{th} section was caused by greater dry matter of tassel portion, which had several branches on the 12^{th} section than thinner stalk below and single strand tassel tip in above sections. In any case, tassel having little dry matter cannot contribute much to the collectable biomass, because of its composition difference from the fibrous stalk.

Vertical distribution of moisture content of stalks sections based on weekly average is given in figure 10. It was evident from the figure that moisture loss occurred at a slower rate at the bottom sections and at a faster rate at the top sections. Top stalk sections above 10^{th} reached a stable moisture content of less than 11.3% by the normal harvest period (118-122 DAS), but the mean moisture content of 1 to 4 sections was around 65.5% during the normal harvest period. In general, the middle 3 to 8 sections had approximately the same moisture levels before the normal harvest period and towards the end of the experimental period. Before reaching the final stabilized moisture level, all the stalk sections were found to dry collectively, and more rapid moisture loss was observed around the normal harvest period.

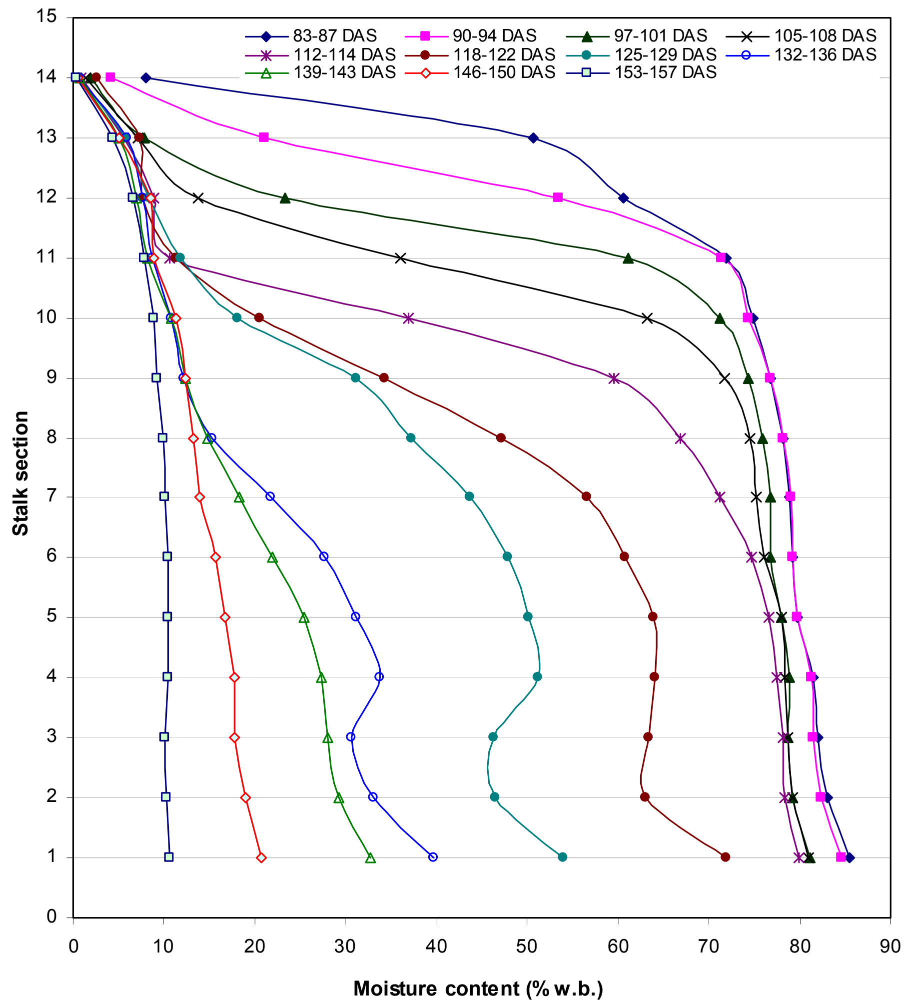

Figure 10. Vertical distribution of weekly average moisture content of stalk sections

Greater moisture content at bottom stalk portions reduce the biomass quality and it would be advantageous to collect them after natural drying in the fields, as there was not much loss in dry matter after the normal harvest period (fig. 9), provided other factors permit delayed collection. Almost a vertical profile with a moisture level of 10.4% was observed during the final period (153-157 DAS) among the stalks.

On an average based on the weekly combined data, the wet mass and dry matter in the bottom 1 to 4 stalk sections were 66.13±3.20% and 60.57±3.49%, respectively. Whereas, the average values for the bottom 1 to 3 sections were as high as 53.50±3.04% and 48.41±3.33% for the wet mass and dry matter, respectively. Shinners et al. (2003) also observed that roughly 50% of total stover dry matter was present at the bottom ¼ of the stalk.

Results of correlation analysis

Correlation analysis results of different independent variables in explaining the observed reduction of wet mass, dry matter, and moisture content of stalk sections are shown in table 3. Stalk section wet mass was well correlated with dry matter (r = 0.84), moisture present (r = 0.99), and moisture content (r = 0.72), because these parameters were directly derived from wet mass and vice versa. Among the other independent variables, DAS (r = -0.55), stalk section (r = -0.62), and air temperature (r = 0.49), had relatively good correlation with wet mass. Negative correlation observed with DAS and stalk section indicate the inverse relationship with stalk wet mass. It should be noted that the environmental factors had only low correlation coefficient with wet mass (r < 0.49) and dry matter (r < 0.23), whereas relatively better correlation coefficients with moisture content (r < 0.72). Rainfall was found to be less correlated (r < -0.04) with wet mass, dry matter, and moisture content of stalk sections.

Table 3. Results of correlation analysis on the selected dependent variables

Variables	Pearson correlation coefficients (r) and p values					
	Wet mass (g)		Dry matter (g)		Moisture content (% w.b.)	
	r	p	r	p	r	p
DAS	-0.547	<.0001	-0.256	<.0001	-0.802	<.0001
Replication	0.050	0.0033	0.030	0.0812	0.060	0.0004
Sample	-0.066	0.0001	-0.025	0.1342	-0.092	<.0001
Stalk section	-0.624	<.0001	-0.887	<.0001	-0.342	<.0001
Wet mass (g)	1.000	---	0.840	<.0001	0.719	<.0001
Dry matter (g)	0.840	<.0001	1.000	---	0.512	<.0001
Moisture present (g)	0.993	<.0001	0.771	<.0001	0.734	<.0001
Moisture content (% w.b.)	0.719	<.0001	0.512	<.0001	1.000	---
Soil moisture (% w.b.)	-0.255	<.0001	-0.148	<.0001	-0.298	<.0001
Soil temperature (°C)	0.408	<.0001	0.192	<.0001	0.612	<.0001
Solar radiation (MJ/m^{2}s)	0.241	<.0001	0.113	<.0001	0.344	<.0001
Rainfall (mm/day)	-0.042	0.0136	-0.033	0.0493	0.004	0.8193
Air temperature (°C)	0.491	<.0001	0.231	<.0001	0.722	<.0001
Air relative humidity (%)	0.086	<.0001	0.039	0.0206	0.184	<.0001
Wind direction (°N)	0.030	0.0829	0.018	0.2823	0.060	0.0004
Wing speed (m/s)	-0.163	<.0001	-0.091	<.0001	-0.201	<.0001
ET_o FAO56-PM (mm/day)	0.441	<.0001	0.209	<.0001	0.630	<.0001

Similarly, dry matter was highly correlated (r > 0.89) with stalk section, and wet mass. Less correlation of DAS (r = -0.26) with dry matter explained that the available dry matter will not vary with time after physiological maturity. In the case of moisture content, independent variables like DAS, wet mass, moisture present, soil temperature, air temperature, and evapotranspiration had good correlation (r > 0.61).

Fitting of mass and moisture relationship for stalk sections

The fitted wet mass, dry matter, and moisture content relationships of individual stalk sections are presented in table 4. As mentioned earlier, the 4th order polynomial using DAS as the

Table 4. Fitted fourth order polynomial mass and moisture relationships of individual stalk sections from DAS

Section	Independent variable polynomial fit coefficients[a]					R^2	RMSE[b]
	Intercept	DAS	DAS^2	DAS^3	DAS^4		
	Wet mass (g)						
1	-1813.90	62.95	-0.73	3.56E-03	-6.18E-06	0.9293	9.68
2	-1629.45	57.44	-0.69	3.45E-03	-6.22E-06	0.9257	7.96
3	-1493.53	51.46	-0.60	2.96E-03	-5.21E-06	0.9392	6.07
4	-1277.13	44.57	-0.53	2.61E-03	-4.63E-06	0.9440	5.33
5	-1086.60	37.54	-0.45	2.22E-03	-3.98E-06	0.9398	3.96
6	-961.96	32.88	-0.39	1.90E-03	-3.36E-06	0.9487	3.14
7	-1521.21	52.40	-0.64	3.35E-03	-6.39E-06	0.9596	2.53
8	-1286.24	44.56	-0.55	2.90E-03	-5.58E-06	0.9649	1.87
9	-1201.22	41.99	-0.53	2.83E-03	-5.58E-06	0.9768	1.14
10	-974.75	34.41	-0.44	2.40E-03	-4.83E-06	0.9805	0.68
11	-510.48	18.58	-0.24	1.37E-03	-2.82E-06	0.9693	0.46
12	239.30	-7.06	0.08	-3.87E-04	7.14E-07	0.9319	0.43
	Dry matter (g)						
1	-352.07	12.31	-0.15	7.99E-04	-1.56E-06	0.5382	1.28
2	-387.66	13.83	-0.17	9.45E-04	-1.89E-06	0.7427	1.13
3	-352.27	12.43	-0.15	8.26E-04	-1.62E-06	0.8222	0.90
4	-341.96	12.28	-0.16	8.47E-04	-1.69E-06	0.8390	0.82
5	-144.01	5.40	-0.07	3.68E-04	-7.17E-07	0.8237	0.63
6	-168.26	5.91	-0.07	3.68E-04	-6.87E-07	0.8851	0.53
7	-280.10	9.68	-0.12	6.26E-04	-1.21E-06	0.8998	0.54
8	-188.56	6.51	-0.08	4.12E-04	-7.80E-07	0.9082	0.44
9	-180.21	6.20	-0.08	3.95E-04	-7.55E-07	0.9165	0.36
10	-135.54	4.63	-0.06	2.93E-04	-5.58E-07	0.9241	0.25
11	-104.50	3.65	-0.05	2.46E-04	-4.86E-07	0.9193	0.15
12	41.68	-1.26	0.02	-8.18E-05	1.66E-07	0.8235	0.21
	Moisture content (% w.b.)						
1	1800.37	-65.38	0.92	-5.57E-03	1.23E-05	0.9636	5.50
2	531.70	-22.31	0.38	-2.68E-03	6.53E-06	0.9461	6.72
3	896.89	-35.84	0.57	-3.77E-03	8.90E-06	0.9440	6.89
4	1417.48	-53.72	0.79	-4.99E-03	1.13E-05	0.9585	5.82
5	1659.55	-63.23	0.93	-5.83E-03	1.32E-05	0.9600	5.72
6	1672.12	-64.17	0.95	-6.00E-03	1.37E-05	0.9630	5.54
7	1192.57	-48.39	0.76	-5.05E-03	1.20E-05	0.9618	5.79
8	-202.92	-0.40	0.15	-1.75E-03	5.41E-06	0.9609	5.98
9	-2207.73	70.65	-0.77	3.48E-03	-5.48E-06	0.9493	6.85
10	-5428.29	187.07	-2.32	1.24E-02	-2.43E-05	0.9734	4.82
11	-6131.02	220.50	-2.86	1.60E-02	-3.29E-05	0.9565	5.88
12	-409.38	29.08	-0.51	3.48E-03	-8.16E-06	0.9362	5.24

[a] Polynomial fit; Example: Wet mass = $-1813.9+62.9535\times DAS-0.733\times DAS^2+3.56E-3\times DAS^3-6.18E-6\times DAS^4$

[b] RMSE = Root mean square error; DAS varies from 83 to 157.

primary independent variable conformed the nature of the observed trend and produced better performance with wet mass (R^2 = 0.95±0.02), dry matter (R^2 = 0.84±0.11), and moisture content (R^2 = 0.96±0.01). The polynomial equations for individual stalk sections given by the coefficients (table 4) produce accurate predictions, but require individual coefficients for each section.

It would be useful to have an overall equation for the dependent variables valid for any stalk section. The developed overall equations for wet mass, dry matter, and moisture content of the stalk sections using multiple regression are presented in table 5.

Table 5. Overall mass and moisture multiple regression relationships of stalk section using DAS and section number

Equation	R^2	RMSE[a]
Wet mass (g) = $-92.62 + 7.95\text{DAS} - 8.79\text{E-}02\text{DAS}^2 + 2.67\text{E-}04\text{DAS}^3 - 30.83S + 3.55\text{E-}01S^2 + 0.25\text{DAS}\times S - 5.24\text{E-}04\text{DAS}^2\times S$	0.9485	5.45
Dry matter (g) = $-11.82 + 1.02\text{DAS} - 1.06\text{E-}02\text{DAS}^2 + 3.27\text{E-}05\text{DAS}^3 - 3.55S + 7.41\text{E-}02S^2 + 0.02\text{DAS}\times S - 6.77\text{E-}05\text{DAS}^2\times S$	0.9645	0.80
Moisture content (% w.b.) = $-926.01 + 25.05\text{DAS} - 1.97\text{E-}01\text{DAS}^2 + 4.76\text{E-}4\text{DAS}^3 + 8.79S - 4.01\text{E-}01S^2 - 0.83\text{DAS}\times S + 3.52\text{E-}3\text{DAS}^2\times S$	0.9281	7.91

[a] RMSE = Root mean square error; DAS varies from 83 to 157

S = section number varies from 1 to 12.

Overall multiple regression equation suitable for any stalk section needs to involve the stalk section number (S) as the additional variable along with DAS. Higher order variables of S (S^2) and interaction between DAS and S (DAS×S, $\text{DAS}^2\times S$) were also required for proper fitting of the whole data. The developed overall equations were efficient in prediction ($R^2 > 0.928$) and were comparable in performance to the individual equations with fewer constants (table 4). Wet mass, dry matter, and moisture content of any segment of stalk, consisting of series of stalk sections, can be obtained by suitably integrating the stalk section predicted values using the individual (table 4) or overall equation (table 5).

Conclusions

The following conclusions can be drawn from the study of vertical distribution of mass and moisture the standing corn stalks:

- Among the biomass contributing components, stalk component dominated the wet mass followed by leaf and husk. Stover to dehusked ear wet mass ratio had varied from 2.85 to 0.47 with an average of 1.2.
- Above-ground plant components mass and moisture reduction exhibited two trends of rapid reduction during the first zone and stabilization during the second zone, separated by the normal harvest period (118-122 DAS) when grain moisture was around 25% w.b.

- Fourth order polynomial regression relationship as a function of DAS adequately expressed the above-ground plant components such as whole stalk, leaf, whole ear, and husk, including whole plant wet mass.
- Stalk section immediately below the typical ear level had increased wet mass and dry matter, and possibly acted as storage of materials to the developing corn ear.
- Stalk dry matter did not show much reduction throughout the experiment.
- Stalk section wet mass, dry matter, and moisture content displayed two trends of reduction separated by the normal harvest period. In the first zone rapid reduction of these factors occurred and stabilization was noticed in the second zone, which was similar to the trend observed for above-ground components.
- Stalk sections below the typical ear level (1-4) dominated dry matter and moisture content compared to the above sections (5-14). Based on the daily averages, the wet mass and dry matter in the 1 to 4 stalk sections was estimated as 65.95±3.48% and 60.61±3.64%, respectively.
- Major reduction of wet mass and dry matter was occurred among the first six sections, and the maximum reduction occurred between the 1st and the 2nd sections.
- Stalk sections lost moisture collectively in a more rapid manner around the normal harvest period before attaining the final stabilized moisture level.
- Soil and environmental parameters, including rainfall, had negligible effect on wet mass, dry matter and moisture content of standing stalks in the field.
- Wet mass of stalk sections was well correlated with dry matter, moisture present, and moisture content. Dry matter had good correlation with stalk section, and wet mass. Moisture content also had good correlation with DAS, wet mass, moisture present, soil temperature, air temperature, and evapotranspiration values.
- Individual stalk section fourth order polynomial equations as a function of DAS gave good performance with wet mass (R^2 = 0.95±0.02), dry matter (R^2 = 0.84±0.11), and moisture content (R^2 = 0.96±0.01).
- Overall equations valid for any stalk section involving DAS and section number were developed using multiple regression, and they produced comparable performance ($R^2 > 0.93$) with individual polynomial equations.

Acknowledgements

The authors appreciate gratefully the financial support by the Bioenergy Feedstock Development Program of the Oak Ridge National Laboratory with Subcontract No. 34000008088. Assistance extended by Bobby R McKee, Senior Farm Crew Leader and his crew members of the Knoxville Experiment Station is highly appreciated. Thanks are extended to Wesley C Wright for his help with weather data acquisition and its analysis, and Hong Y Jeon, Michael R Williams, Gnanambiga Lalida Sahiram, and Manlu Yu for their help with field sample collection and measurements.

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