# Vertical Mass and Moisture Distribution in Standing Corn Stalks

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C. Igathinathane
Alvin R. Womac
Shahab Sokhansanj
Lester O. Pordesimo

Department of Biosystems Engineering and Environmental Science
The University of Tennessee, Knoxville, TN





## Potential uses of corn stover

- Strategic biomass for bioenergy
- Animal feed
- Fuel
- Particle board
- Building panel
- Pulp and paper
- Ethanol
- Cellulose derivatives
- Potting soil
- Roadside mulching





## Corn stover availability estimates

64 to 91 million dry t/y (Iowa State University, 1993).
82 million dry t/y (Kadam and McMillian, 2003).
153 million dry t/y (Glassner et al., 1999).
216 million dry t/y for 2001 (Sokhansanj et al., 2002).

Feedstock demand for biorefineries (Sokhansanj and Wright 2002)
172 million dry t/y by 2010
508 million t/y by 2020 .

*Wide variation in estimates exists.*





## Study justification

Moisture content is a critical factor for:
Efficient collection, processing, transportation, and storage (Edens et al., 2002).

High moisture problems:
Machine harvest difficulty
Affects processing equipment selection
Increases transportation cost
Increases spoilage rate
Presents safety hazards when moldy
(Edens et al., 2002; Jenkins and Sumner, 1986).

Stalks constitute the major portion of stover biomass (Pordesimo et al., 2004).

*Standing stalks would provide a baseline of vertical distribution and exact mass and moisture status of crop components.*





## Objectives

1. Mass and moisture characteristics of corn plant above-ground components over time.
2. Vertical distribution of mass and moisture in the stalks of standing corn plants.
3. Relationships development for estimating mass and moisture of above-ground components and stalk sections over time.





## Experimental plot and sample collection

Field plot (201 × 48 m) of the Knoxville Experiment Station, The University of Tennessee was used.

Corn (variety Dekalb 743) planted on May 20, 2003.

10 rows plants : 3 replication blocks × 2 sub samples = 6 plant samples.

7 border rows .

## Sample collection

Plant sample collection
(6 Nos. / sample day)

Soil temperature measurement
(3 Nos. / sample day)

Soil sample collection
(3 Nos. / sample day)





## Sample preparation

Collected plant samples
(6 Nos. / sample day)

Separated above-ground components

Stalk sections
254 mm (10") length





## Sample preparation (Contd..)

Combined leaf and husk samples
(3 Nos. each / sample day)

Grain and soil samples





## Moisture content determination

ASAE Standard S358.2 (ASAE Standards, 2003) for forages
(air oven at 103°C for 24 h)





## Measured environmental condition

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 (DAS) | 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 rainfall events with 16.7, 13.2, 10.7, and 37.1 mm were recorded on 89, 103, 118 and 125 DAS, respectively.





## Data analysis

**PROC CORR of SAS (2002) :**

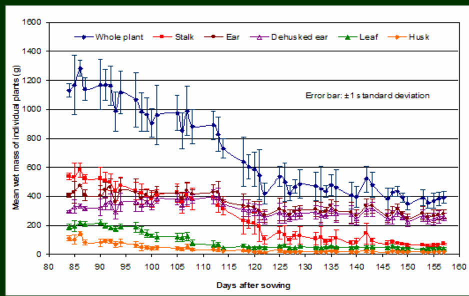
Correlation of different independent variables (vs.)
Wet mass, dry matter, and moisture content.

**PROC REG of SAS (2002) :**

Polynomial equations as a function of DAS and section numbers (vs.)
Wet mass, dry matter, and moisture content.

*Results and Discussion*

## Mass of above-ground plant components

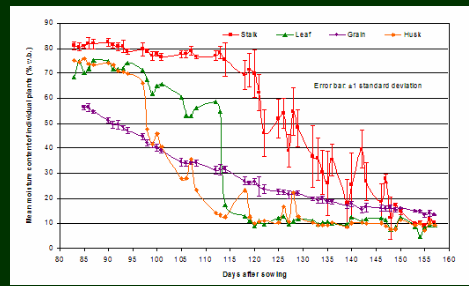



Wet mass of above-ground components of the standing corn plants



*Results and Discussion*

## Moisture of above-ground plant components




Moisture content (% w.b.) of above-ground components of the standing corn plants

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*Materials and Methods*

## Above-ground component regression equations

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.

*Fourth order regression equations gave good performance*

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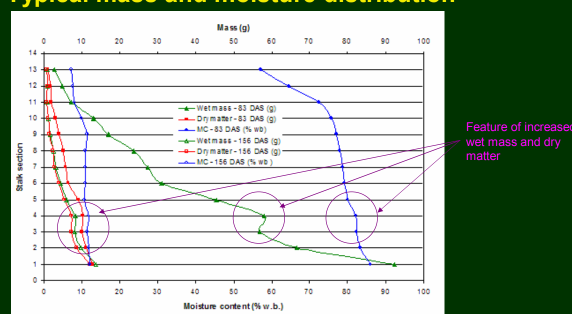
*Results and Discussion*

## Typical mass and moisture distribution




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

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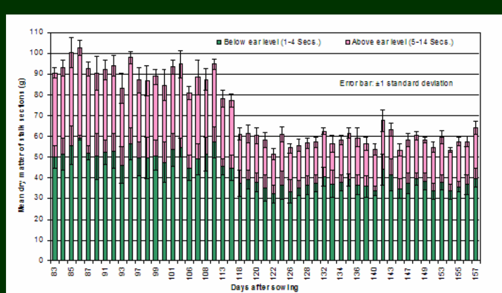
*Results and Discussion*

## Dry matter above and below ear level




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

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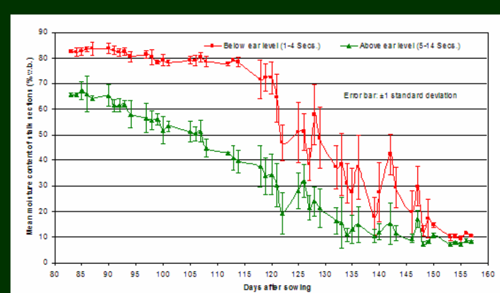
*Results and Discussion*

## Moisture content above and below ear level




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

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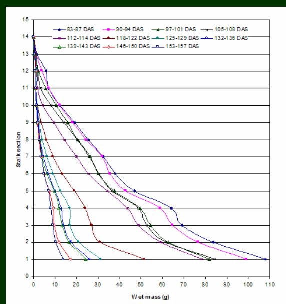
## Stalk section weekly average wet mass




Rapid reduction before harvest period.

Wet mass reduction stabilization after harvest period.

Increased wet mass below typical ear level is observed by the departure from smooth trend.

Mass domination of the bottom sections is evident.

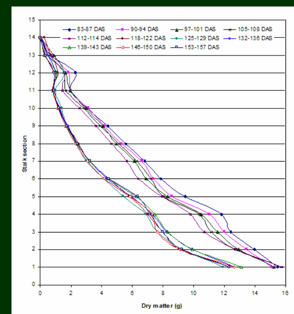
Tassel contribute negligible amount of wet mass

**Vertical distribution of weekly average wet mass of stalks sections**





## Stalk section weekly average dry matter




Before and after harvest period grouping of curves is clearly seen.

Closeness of dry matter curves illustrate less reduction of dry matter over time.

Increased dry matter below typical ear level is observed by the departure from smooth trend.

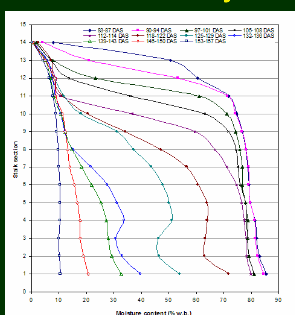
Dry matter dominance of the bottom sections is evident. Follows the natural cross sectional area of the stalks.

**Vertical distribution of weekly average dry matter of stalk sections**





## Stalk section weekly average moisture content




Moisture reduction was slower at the bottom and rapid at the top sections.

The intermediate sections (3-8) dried as a whole.

More moisture reduction occurred around the normal harvesting period.

Allowing the stalks to dry in the field may be advantageous for biomass collection.

**Vertical distribution of weekly average moisture content of stalk sections**





## Correlation analysis results

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 ($MJ/m^2s$) | 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 |

**Direct variables like wet mass, dry matter, and moisture are well correlated**

**Indirect variables line soil temp., air temp., and evapotranspiration had higher correlation than the rest in the group.**





## Polynomial regression results

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) | | | | | | |
| | -352.27 | 12.43 | -0.15 | 8.26E-04 | -1.62E-06 | 0.8222 | 0.90 |
| | \| | \| | \| | \| | \| | \| | \| |
| | -104.50 | 3.65 | -0.05 | 2.46E-04 | -4.86E-07 | 0.9193 | 0.15 |
| | Moisture content (% w.b.) | | | | | | |
| | 1800.37 | -65.38 | 0.92 | -5.57E-03 | 1.23E-05 | 0.9636 | 5.50 |
| | \| | \| | \| | \| | \| | \| | \| |
| | -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×DAS-0.733×$DAS^2$+3.56E-3×$DAS^3$-6.18E-6×$DAS^4$

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

Approximate range of DAS coefficients are shown

**Fourth order polynomial equation followed the observed trend.**
**Individual equations are accurate but need more constants.**
**Any stalk length can be accommodated by suitable integration.**





## Multiple regression results

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 + 7.95DAS - 8.79E-02$DAS^2$ + 2.67E-04$DAS^3$ - 30.83*S* + 3.55E-01$S^2$ + 0.25DAS×*S* -5.24E-04$DAS^2$×*S* | 0.9485 | 5.45 |
| Dry matter (g) = -11.82 + 1.02DAS - 1.06E-02$DAS^2$ + 3.27E-05$DAS^3$ - 3.55*S* + 7.41E-02$S^2$ + 0.02DAS×*S* - 6.77E-05$DAS^2$×*S* | 0.9645 | 0.80 |
| Moisture content (% w.b.) = -926.01 + 25.05DAS - 1.97E-01$DAS^2$ + 4.76E-4$DAS^3$ + 8.79*S* - 4.01E-01$S^2$ - 0.83DAS×*S* + 3.52E-3$DAS^2$×*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 equations performance is comparable to individual equations ($R^2$ > 0.928).**

**Any stalk length can be accommodated by suitable integration.**

## Conclusions

### Above-ground stover components

1. Stalk component dominated the wet mass followed by leaf and husk.
2. Stover to dehusked ear wet mass ratio varied from 2.85 to 0.47 with an average of 1.2.
3. Mass and moisture reduction exhibited two trends:
   1. Rapid reduction during the first zone and
   2. Stabilization during the second zone.
4. Fourth order polynomial equation as a function of DAS adequately expressed the mass and moisture of components.

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## Conclusions

### Stalk sections

5. Stalk section below the typical ear level had increased wet mass and dry matter. Possibly acted as material storage to the corn ear.
6. Dry matter did not show much reduction throughout the experiment.
7. Wet mass, dry matter, and moisture content displayed two trends of reduction. 1. Rapid reduction and 2. Gradual stabilization.
8. Sections below the typical ear level (1-4) dominated the dry matter and the moisture content compared to above sections (5-14).
   Wet mass in 1-4 stalk sections = 65.95±3.48%
   Dry matter in 1-4 stalk sections = 60.61±3.64%.
9. Major reduction of wet mass and dry matter occurred among 1-6 sections. Maximum reduction was between the 1st and the 2nd sections.
10. Sections lost moisture collectively in rapid manner around the normal harvest period and finally stabilized.

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## Conclusions

### Correlation analysis

11. Soil and environmental parameters had negligible effect on mass and moisture content of standing stalks in the field.
12. Wet mass of stalk sections was well correlated with:
    Dry matter, Moisture present, Moisture content.

    Dry matter had good correlation with:
    Stalk section, Wet mass.

    Moisture content had good correlation with:
    DAS, Wet mass, Moisture present, Soil temperature, Air temperature, Evapotranspiration.

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## Conclusions

### Developed regression equations

13. Individual stalk section fourth order polynomial equations with DAS gave good performance:
    Wet mass ($R^2$ = 0.95±0.02)
    Dry matter ($R^2$ = 0.84±0.11)
    Moisture content ($R^2$ = 0.96±0.01).
14. Overall equations involving DAS and section number produced comparable performance ($R^2 > 0.93$) to the individual equations.

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