Allometric model for quantification of sorghum canopy formation

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Introduction

Canopy architecture has a prominent role in fundamental processes of crop growth including light transmission and interception, evapotranspiration and photosynthesis. Leaf Area Index (LAI) is a commonly used parameter for analyzing vegetative canopy structure and it can directly quantify canopy architecture (Welles and Norman, 1991). Tewolde et al. (2005) identified LAI as the key parameter in the analysis of crop growth and productivity. Leaf area index and total dry matter increment determine the transpiration efficiency and water use efficiency in a sparse crop (Kato et al.,2004). Quantification of LAI has potential in understanding resource use efficiency and productivity of a crop. Several complex models have been proposed to simulate leaf area index (LAI) in sorghum (*Sorghum bicolor* (L.) Moench)(Hammer et al., 1993), but a thorough inclusion of total mature and immature leaf area is lacking in these models.

Objective: Develop a simple quantitative model to predict LAI for sorghum from emergence to flag leaf stage.

Materials and Methods

Field procedures:

Eight sorghum lines differing in canopy architecture were planted on May 28, 2010 at Colby, Kansas, in completely randomized design with 4 replications. Supplemental irrigation was provided just prior to anthesis, post anthesis and during grain filling. Soil fertility was supplemented with 102 kg N ha^{-1} and 34 kg P ha^{-1}. Weekly measurements were made on LAI using LiCor 2000 Plant Canopy Analyzer. Measurements on leaf length, maximum leaf width and total number of mature leaves were made biweekly on identified plants for all lines. Individual leaf area was measured using CI-203 Leaf Area Meter after destructive harvest of leaves from randomly selected plants.

Theory:

- Phyllochron was defined here as the interval between ligule formation of successive leaves on the same culm and was expressed in terms of thermal time
- Phyllochron was calculated as the inverse of slope of the regression line between growing degree days $[GDD = \sum (T_{average} - T_{base})$;T base was 7ºC (Vanderlip and Arkin, 1977] and leaf number (Figure 1)
- From the collected data, a shape factor (figure 2) was derived based on the following relationship,

$$A = L \times W \times F \quad (1)$$

where A = area of leaf, L = length of leaf, W = maximum width of leaf and F = shape factor

- From the collected data, following mathematical formulations were derived for mature leaves of sorghum lines;

$$LN_{ij} = GDD_j / P_i \quad (2)$$

$$L_{iLN_j} = f(LN_j) \quad \text{and} \quad f(LN_j) = a_i(LN_j)^3 + b_i(LN_j)^2 \quad (3)$$

$$W_{iLN_j} = f(L_{iLN_j}) \quad \text{and} \quad f(L_{iLN_j}) = a_i(L_{iLN_j})^3 + b_i(L_{iLN_j}) \quad (4)$$

$$W_{iLN_j} = f(LN_j) \quad \text{and} \quad f(LN_j) = a_i(LN_j)^3 + b_i(LN_j) + c_i \quad (5)$$

where i = line, LN_{ij} = number of leaves produced by a plant for i^{th} line on j^{th} day after planting (DAP), GDD_j = GDD on j^{th} DAP, P_i = phyllochron of i^{th} line, LN_j = leaf sequence number of j^{th} leaf, $L_{i\,LNj}$ = length of j^{th} leaf for i^{th} line, $W_{i\,LNj}$ = maximum leaf width of j^{th} leaf for i^{th} line, a_i, b_i and c_i = coefficients for i^{th} line

- Total area of all mature leaves (TA_{mature}) on any plant was calculated as,

$$TA_{mature} = \sum_{i=1}^{L_n} L_i \times W_i \times F \quad (6)$$

where L_n = total number of mature leaves on the plant, L_i = length of i^{th} leaf, W_i = width of i^{th} leaf and F = shape factor

- Apparent leaf age (in ºC) of immature leaves was calculated as,

$$ALG_{ij} = ALG_{j-1} + (P_i / 4) \quad (7)$$

where ALG_{ij} = apparent age of j^{th} immature leaf for i^{th} line, P_i= phyllochron of i^{th} line. ALG of top immature leaf ($ALG_{j=4}$) and top mature leaf ($ALG_{j=0}$) was assigned as zero and one phyllochron respectively.

- Length and area of immature leaves were measured as the length and area of that portion of leaf which had unwound from the whorl
- Expected length and expected maximum width [$E(L_i)$ and $E(W_i)$ respectively] of i^{th} immature leaf was defined as the length and maximum width of i^{th} leaf when it actually forms a ligule; $E(L_i)$ and $E(W_i)$ were calculated using equations 3 and 4 respectively
- Following equations were derived for immature leaves;

$$E(A_i) = E(L_i) \times E(W_i) \times F \quad (8)$$

$$RL_i = L_i / E(L_i) \quad (9)$$

$$RA_i = A_i / E(A_i) \quad (10)$$

$$RL_i = f(ALG_i) \quad \text{and} \quad f(ALG_i) = a(ALG_i) + c \quad \text{(figure 3)} \quad (11)$$

$$RA_i = f(RL_i) \quad \text{and} \quad f(RL_i) = a(RL_i) + c \quad \text{(figure 4)} \quad (12)$$

$$TA_{immature} = \sum_{i=1}^{L_n} RA_i \times E(A_i) \quad (13)$$

Materials and Methods cont.

where $E(A_i)$ = expected area of i^{th} leaf, $E(L_i)$ = expected length of i^{th} leaf , $E(W_i)$ = expected width of i^{th} leaf, F = shape factor, RL_i = relative length of i^{th} leaf, L_i = length of i^{th} leaf, RA_i = relative area of i^{th} leaf, A_i = area of i^{th} leaf, ALG_i = apparent age of i^{th} leaf , 'a' and 'c' = coefficients of linear regression, $TA_{immature}$ = total immature leaf area and L_n = total number of immature leaves on the plant. (All the variables in equations 8 to 12 are estimated values except L_i and A_i)

Model development:

- Statistical analyses were done by Proc GLM and Proc REG in SAS 9.1, 2002-2003
- Number of leaves (LN_{ij}) produced by any plant of i^{th} line on j^{th} DAP was calculated using equation 2
- Length, width and area of mature leaves were calculated using equations 3,4 and 6 respectively
- Relative length, relative area and expected area of immature leaves were calculated using equations 11,12 and 8 respectively
- Total area of immature leaves ($TA_{immature}$) was calculated using equation 13
- Total leaf area per plant was calculated as,

$$TLA = TA_{mature} + TA_{immature} \quad (14)$$

where TLA = total leaf area per plant, TA_{mature} = total mature leaf area and $TA_{immature}$ = total immature leaf area

- LAI was calculated as,

$$LAI = TLA * PLN \quad (15)$$

where TLA = total leaf area per plant and PLN = plant population

Results

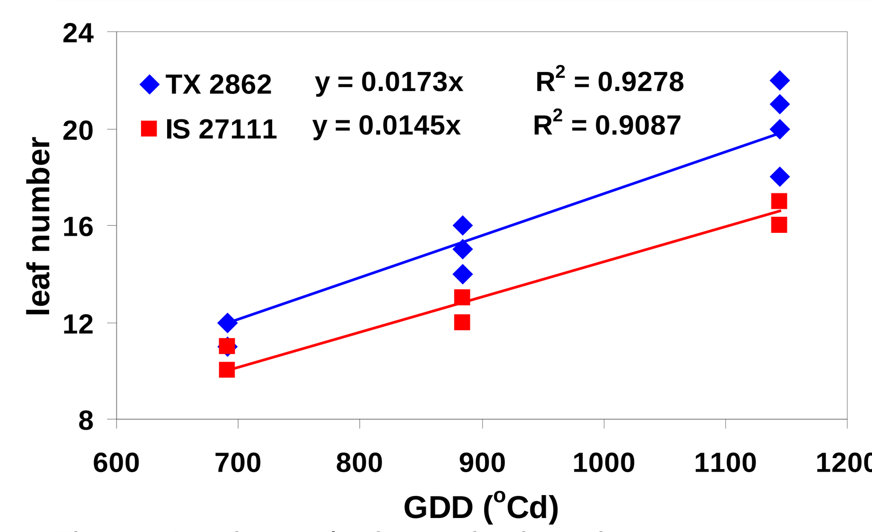

Fig.1: Sorghum leaf production in response to accumulation of thermal time. Inverse slope of the regression line represents phyllochron.

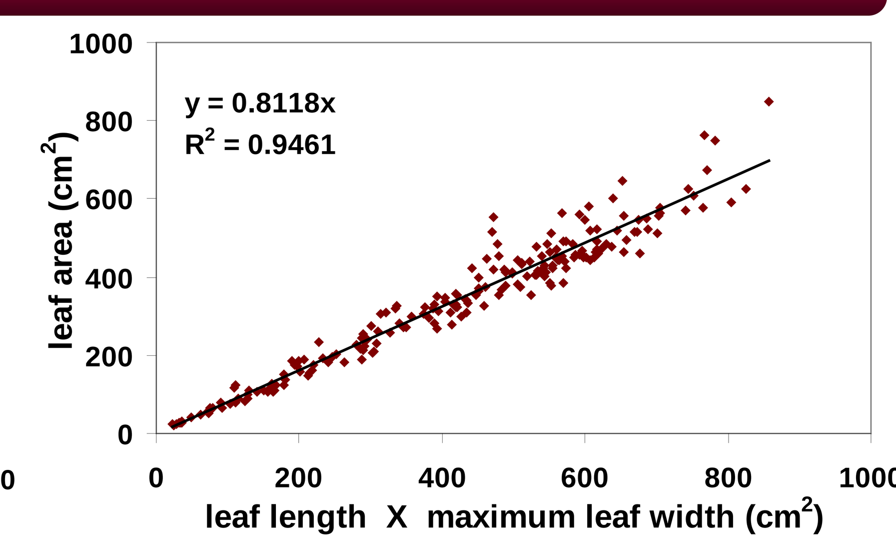

Fig. 2: Depiction of shape factor in sorghum. Shape factor was derived as the slope of the regression line between leaf area and product of leaf length and maximum leaf width. Intercept did not turn to be different from zero.

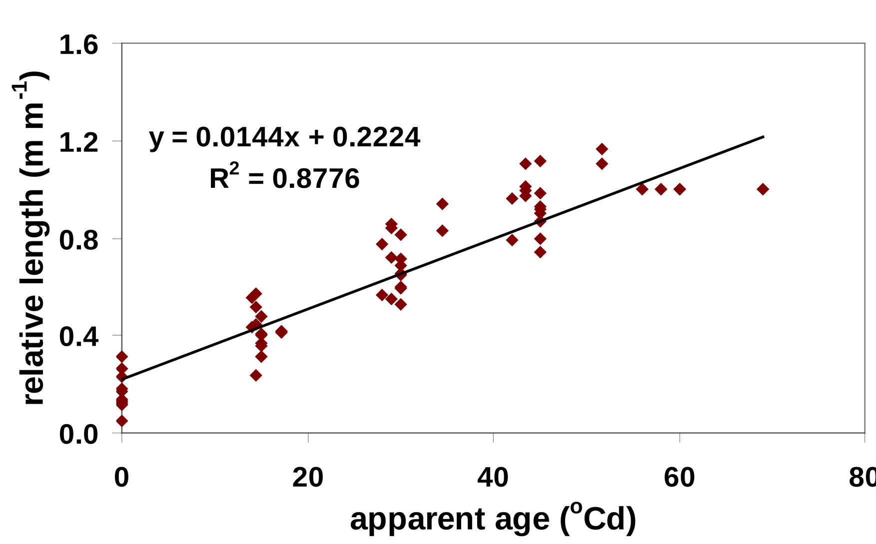

Fig. 3: Relative length of immature leaves in sorghum as a function of their apparent age. Relative length is the ratio of length of that portion of leaf which had unwound from the whorl to the expected length of that leaf at ligule formation. Apparent age of j^{th} immature leaf for i^{th} line (ALG_{ij}) was calculated as ALG_{ij} = ALG_{j-1} + (P_i/4), where P_i= phyllochron of i^{th} line. ALG of top immature leaf ($ALG_{j=4}$) was assigned as zero.

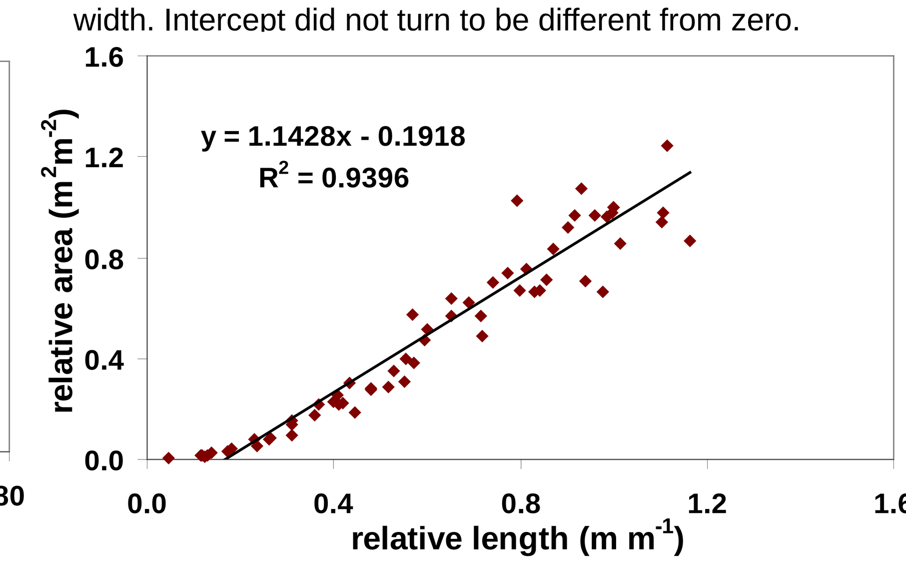

Fig.4: Relative area of sorghum immature leaves expressed as a function of their relative length. Relative length is the ratio of length of that portion of leaf which had unwound from the whorl to the expected length of that leaf at ligule formation. Relative area is the ratio of area of that portion of leaf which had unwound from the whorl to the expected area of that leaf at ligule formation

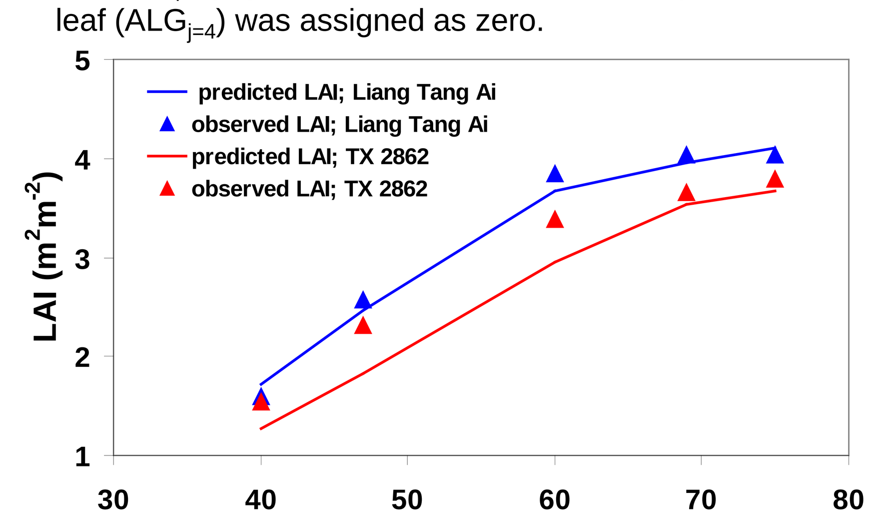

Fig. 5: Predicted and observed values of LAI through time for two lines used in this study

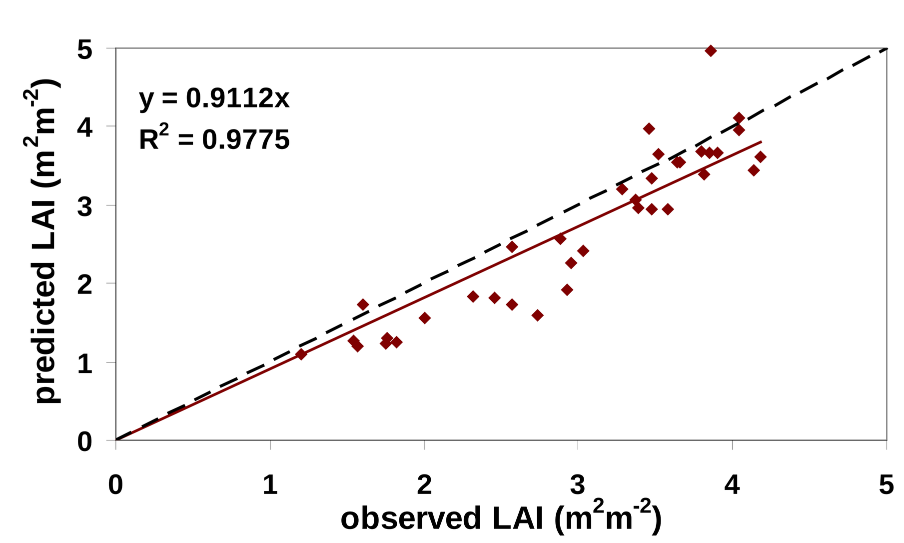

Fig. 6: predicted Vs observed leaf area index in sorghum. The dotted line is 1:1 line.

Results cont.

Model parameterization:

- Phyllochron varied with lines (Figure 1) and it ranged between 56ºC and 69ºC
- The tall photoperiod sensitive sorghum line (IS 27111) had the largest value for phyllochron (69ºC) among all other lines
- Shape factor was constant (0.81 with R^2 = 0.946 and SE = 0.006) irrespective of leaf number, line and developmental stage (Figure 2)
- Shape of leaves changed as a cubic function of leaf number
- Cubic function of leaf number accounted for more than 96% of variation in leaf length and more than 70 % of variation in maximum leaf width
- Cubic function of leaf length accounted for more than 96% of variation in maximum leaf width

Model evaluation:

- A good correlation was found between modeled and observed LAI. (table 1, figure 5 and figure 6) The measured LAI for the sorghum lines considered in this study ranged from 1.20 to 4.18. Intercept for the fitted line was not significantly different from zero (figure 6).

Table 1: Linear regression coefficient of determination (R^2), slope, standard error (SE), root mean square error (RMSE) and mean absolute error (MAE) of predicted Vs. observed values of LAI for sorghum from emergence to maximum leaf number

Parameter	R^2	slope	SE	RMSE	MAE
LAI	0.978	0.911	0.023	0.438	0.314

Discussion

Testing of this model was done on independent data collected by actual measurement in field. The estimated values of LAI compared well with observed values (Figure 6). The errors showed a slight negative bias from the 1:1 line. Projected LAI values were slightly under estimated with a root mean square error of 0.438; which shows a very small error spread. The fact that senescence of leaves and tiller leaves' area are not considered in this model explains the under estimation of projected LAI by this model. Apparent age of immature leaves remains constant in this model from leaf tip appearance until ligule formation and this is one of the limitations of this model. The prediction range of this model is from emergence to maximum leaf number production. This model can also predict the interception of radiation by a crop canopy with a known extinction coefficient. The performance of this model shows promising application in crop growth models those help in further understanding of canopy structure and development.

Conclusion

- Dimensions of leaf elements are predictable for sorghum and can be represented as simple functions of leaf number
- Given inputs of daily maximum and minimum temperature, total leaf area of a plant with a known phyllochron can be calculated and extended to leaf area index with the knowledge on plant population

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