Reprinted from *Agronomy Journal*
Vol. 85, No. 3

Predicting Grain Sorghum Canopy Structure for Soil Erosion Modeling

D. V. Armbrust* and J. D. Bilbro

ABSTRACT

Development of modern water and wind erosion prediction technology requires information on the canopy structure of various plant species to accurately predict the canopy effect on the falling raindrop or the erosive force of the wind. The objective of this study was to develop equations to predict grain sorghum [*Sorghum bicolor* (L.) Moench] canopy structure characteristics. Grain sorghum plants were sampled weekly from emergence to maturity at Big Spring, TX (1986–1987), and Manhattan, KS (1987), to measure the following crop canopy parameters: plant height, stem length, leaf area, stem area, and canopy cover. Manhattan data were used to develop equations that relate canopy structure parameters of grain sorghum to the total above-ground dry weight, and Big Spring data were used to validate those equations. Leaf and stem area distributions with height also were determined. Coefficients of determination of predicted values using the Manhattan equations and Big Spring above-ground dry weight and the measured Big Spring data ranged from 0.987 for leaf area to 0.922 for stem length. Distribution of leaf and stem area with height remained essentially constant with plant age through the first 7 wk after planting. The equations can be used to supply canopy structure information needed by wind and water erosion prediction models currently under development.

PLANT GROWTH SIMULATION MODELS range from the relatively simply, such as SUCROS (van Keulen et al., 1982), to the extremely complex process-oriented SIMCOTT II (McKinion et al., 1975) and from the universal models that simulate many different plants, such as EPIC (Williams et al., 1984), to models that simulate the growth of only one particular species (Arkin et al., 1976; Johnson et al., 1983; Holt et al., 1975; Wann et al., 1978) or only a specific plant part (Hoogenboom and Huck, 1986). One common output of all these models is dry weight of the biomass produced. Although dry weight is often required in soil erosion modeling, the new Wind Erosion Research Model (WERM) (Hagen, 1991) and Water Erosion Prediction Project (WEPP) (Lane and Nearing, 1989) also require information on the structure of the plant canopy.

The soil erosion models WEPP and WERM are daily simulation models of modular structure consisting of a MAIN (supervisory) program; a user-interface input section; submodels to simulate processes related to wind and water erosion along with their associated data bases; and an output section. Daily plant dry matter production will be simulated with a modified version of the EPIC plant growth model (Williams et al., 1989).

Canopy structure characteristics such as height, structure, and flexibility of individual plants, the size and arrangement of plant parts, and the number of plants occupying a given area help to determine the aerodynamic roughness of the canopy, which determines the friction velocity at the top of the canopy (Shaw and Pereira, 1982). The distribution of leaf and stem area with height is needed to determine the reduction of air-flow through the plant canopy and, thus, the velocity near the soil surface (Bache, 1986). Distinguishing between stem and leaf area is necessary because leaves tend to streamline with the wind flow and have a drag coefficient (C_d) of about 0.1, whereas stems remain rigid and have a C_d of about 1.0. Thus, on a unit area basis, stems are about 10 times more effective than leaves in reducing air-flow through the canopy.

The energy of a falling raindrop available at the soil surface for detachment of soil particles depends on the canopy height and fraction of canopy cover (Wischmeier and Smith, 1978; Quinn and Laflen, 1983). The plant canopy increases the drop size, alters the spatial distribution (Armstrong and Mitchell, 1987), and decreases the volume of rain reaching the soil surface once 50% cover is produced (Morgan, 1985).

Wind tunnel tests to determine the small grain equivalent of growing grain sorghum plants indicate that wind erosion is prevented when dry weight of sorghum plants on 0.76-m rows exceeds 300 kg ha^{-1} (Armbrust and Lyles, 1985).

Research was conducted to develop and validate equations for predicting the crop canopy structure characteristics of grain sorghum. These equations will be useful in the soil erosion prediction technology now under development.

MATERIALS AND METHODS

Grain sorghum was grown in 1986 (ORO G) and in 1987 (Golden Acres TE-Dinero) on an Amarillo fine sandy loam (fine-loamy, mixed, thermic Aridic Paleustoll) at Big Spring, TX, and in 1987 (Golden Acres TE-Dinero) on Reading silt loam (fine, mixed, mesic Typic Argiudoll) at Manhattan, KS. Growing conditions for both locations and years are given in Table 1. Thirty plants (10 from each of three replications) were sampled every 7 d from emergence to maturity. Plants were cut at the soil surface, placed in sealed plastic bags with wet paper towels, and returned to the laboratory where the following measurements were made: (i) plant height—base of plant to top leaf curve or top of head; (ii) stem length—base of plant to top leaf collar; (iii) stem diameter—20 mm above base and

Table 1. Practices used to grow grain sorghum at Manhattan, KS, and Big Spring, TX.

Parameter	Manhattan	Big Spring	
Planting date	9 June 1987	7 July 1986	5 June 1987
Row width (m)	0.76	1.0	1.0
In-row spacing (m)	0.14	0.1	0.1
Growing season rainfall (mm)	262	301	140
Growing season length (d)	126	75	96

D.V. Armbrust, USDA-ARS, Rm 105-B East Waters Hall, Kansas State Univ., Manhattan, KS 66506; and J.D. Bilbro, USDA-ARS, Big Spring, TX 79721-0909. Contribution from the U.S. Department of Agriculture, Agricultural Research Service in cooperation with Kansas Agric. Exp. Stn., Contribution number 89-502-J. Received 25 Jan. 1991. *Corresponding author.

Published in Agron. J. 85:664–668 (1993).

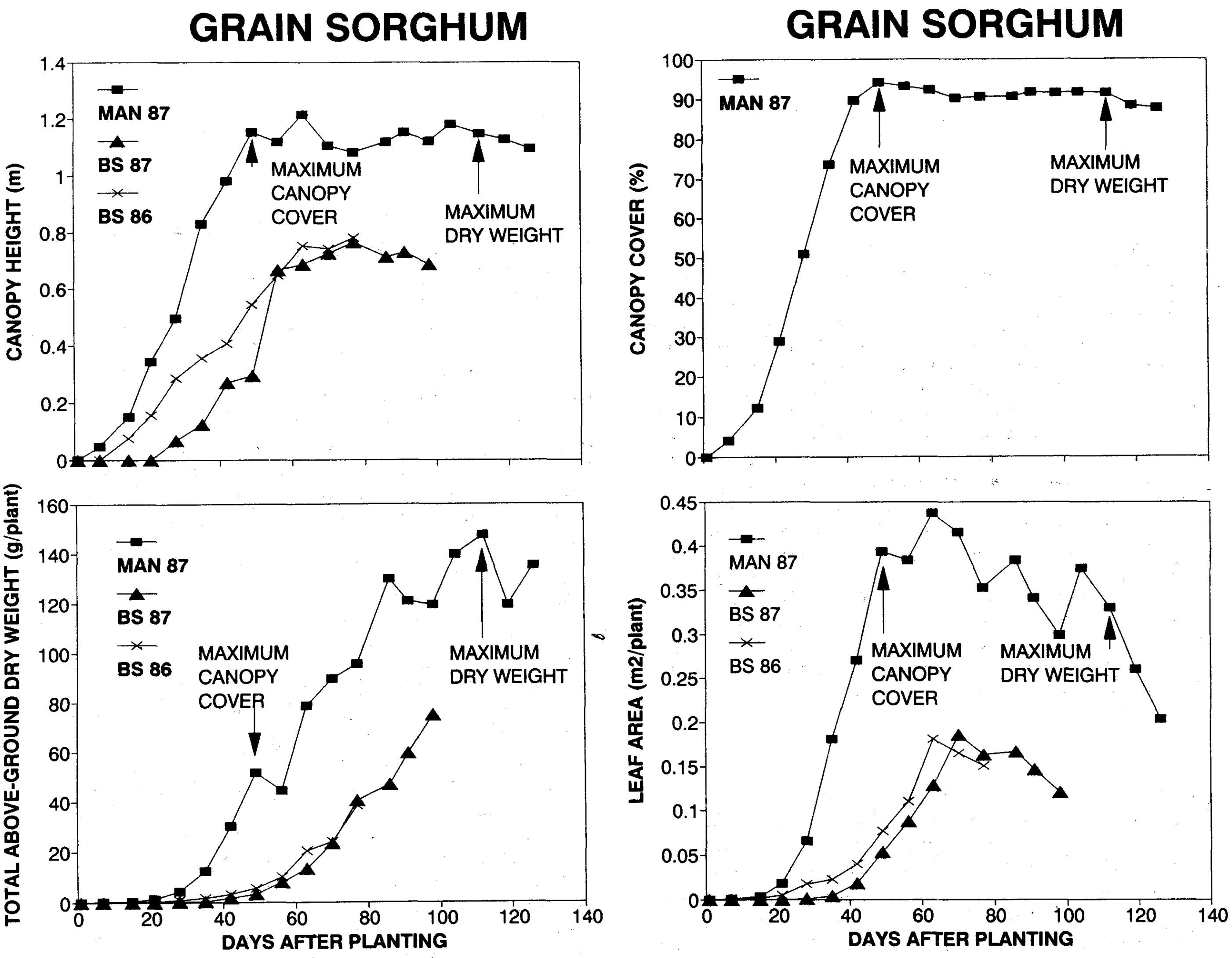

Fig. 1. Aboveground dry weight, canopy height, leaf area, and canopy cover of grain sorghum at Manhattan, KS, and Big Spring, TX.

at top leaf collar, including sheath; (iv) peduncle length—above top leaf collar to bottom of head; (v) peduncle diameter—above top leaf collar and at bottom of head; (vi) length and width of head, if present—width at midpoint of length; (vii) dry weight of head—only that part of head emerged from leaf sheath; (viii) and leaf area and dry weight of stems and leaves for each one-fifth increment of plant height.

Field measurements of canopy cover were made weekly within 1 h of solar noon (1234 CDT) in three areas, each 2 by 0.76 m, selected immediately after planting. Five positions in each area were marked as locations for canopy cover determination by the meter stick method (Adams and Arkin, 1977). Rows were oriented north–south in 0.76-m spacing with final stand of 96 970 plants ha^{-1}. Canopy cover was not determined at Big Spring.

Stem silhouette area was calculated with the following equation:

$$SA = [(BD + TD)/2] \times SL \quad [1]$$

where BD = base diameter, TD = top leaf collar diameter, and SL = stem length.

Because the EPIC plant growth model produces daily estimates of aboveground biomass, total above ground biomass was used as the independent variable to predict canopy cover, plant height, stem length, leaf area per plant, and stem area per plant. Estimation equations were developed with Manhattan data and then applied to data collected at Big Spring. Two

Table 2. Estimation equations developed from the Manhattan data for the periods of emergence to maximum canopy cover and emergence to maximum dry weight in 1987.

Variables	Equation	r^2	SE	Samples
	Maximum canopy cover			
Canopy height (m)	$1.07(1 - e^{-0.1314TDW})$	0.972	0.080	8
Leaf area (m^2/plant)	$0.4778(1 - e^{-0.0315TDW})$	0.992	0.014	8
Stem area (m^2/plant)	$0.0077(1 - e^{-0.0733TDW})$	0.998	0.0002	8
Stem length (m/plant)	$0.39(1 - e^{-0.0994TDW})$	0.969	0.030	8
Canopy cover (%)	$90(1 - e^{-0.1694TDW})$	0.983	5.336	8
	Maximum dry weight			
Canopy height (m)	$1.13(1 - e^{-0.1146TDW})$	0.982	0.062	17
Leaf area (m^2/plant)	$0.3725(1 - e^{-0.0558TDW})$	0.954	0.037	17
Stem area (m^2/plant)	$0.0188(1 - e^{-0.0163TDW})$	0.962	0.001	17
Stem length (m/plant)	$100(1 - e^{-0.0146TDW})$	0.945	0.081	17
Canopy cover (%)	$89(1 - e^{-0.1647TDW})$	0.991	3.455	17

TDW = Total aboveground dry weight (g/plant).

Table 3. Linear regression coefficients of determination (r^2), slope, and standard error of predicted vs. measured values for grain sorghum plants from emergence to maximum canopy cover at Big Spring, TX. Values were predicted by equations developed from the Manhattan data (Table 2).

	1986				1987			
Parameter	R^2	Slope	SE	Y	R^2	Slope	SE	Y
Canopy height (m)	0.899	0.741	0.08	0.12	0.960	0.763	0.06	0.063
Leaf area (m^2/plant)	0.987	0.865	0.005	0.003	0.986	0.797	0.006	0.003
Stem area (m^2/plant)	0.963	0.947	0.0004	0.0001	0.983	0.908	0.0002	0.0003
Stem length (m)	0.922	0.714	0.02	0.03	0.960	0.861	0.03	0.02

sets of equations were developed; one set for the period from emergence to maximum aboveground dry matter production and the other for the period from emergence to maximum canopy cover. Maximum canopy cover was selected as a cutoff point because at that point the soil surface should be sufficiently protected to prevent wind erosion (Armbrust and Lyles, 1985). Although canopy cover was not measured at Big Spring, it was assumed that maximum canopy cover would occur at approximately the same time (near maximum leaf area) at Big Spring as at Manhattan.

Leaf and stem areas were plotted against normalized height to ascertain how the distributions changed as the sorghum plants increased in size through the growing season. Heights were normalized by the leaf and stem areas for each one-fifth of the plant height divided by the total leaf and stem areas at the time the plants were sampled.

All equations were best-fitted to the natural growth function equation (Parton and Innis, 1972) below, by nonlinear regression (PROC NLIN) in SAS (SAS Institute Inc., 1985).

$$Y = a(1 - e^{bX}) \quad [2]$$

where Y = parameter to be estimated, X = total above-ground dry weight, a = asymptotic value of Y, and b = rate at which Y approaches a. Linear regression coefficients of determination

Table 4. Linear regression coefficients of determination (r^2), slope, standard error, and Y intercept of predicted vs. measured values for grain sorghum plants from emergence to maximum dry matter production at Big Spring, TX. Values were predicted by equations developed from the Manhattan data (Table 2).

	1986				1987			
Parameter	R^2	Slope	SE	Y	R^2	Slope	SE	Y
Canopy height (m)	0.928	0.603**	0.06	0.15	0.942	0.592**	0.08	0.098
Leaf area (m^2/plant)	0.935	0.551**	0.02	0.008	0.854	0.429**	0.03	0.014
Stem area (m^2/plant)	0.957	1.008	0.0007	0.0003	0.910	0.678	0.001	0.0008
Stem length (m)	0.958	1.268	0.04	0.044	0.949	0.934	0.06	0.058

** Slope different from 1.0 at P = 0.01.

(r^2) of the predicted vs. measured values for Manhattan and Big Spring were calculated for each sample date.

RESULTS AND DISCUSSION

Measured values of aboveground dry weight, canopy height, leaf area, and canopy cover for Manhattan and Big Spring are given in Fig. 1. Estimation equations developed from the Manhattan data are given in Table 2. The coefficients of determination, slope, and the standard error for the values predicted, using the Manhattan equations and Big Spring total dry weight, vs. the measured values for the Big Spring data are shown in Tables 3 and 4.

Judging by the coefficients of determination, the equations developed from the Manhattan data fit the Big Spring data well, even though the latter included 2 yr and two different grain sorghum hybrids grown under different environments. The r^2 values for the period emergence to maximum canopy cover ranged from 0.995 to 0.899 (Ta-

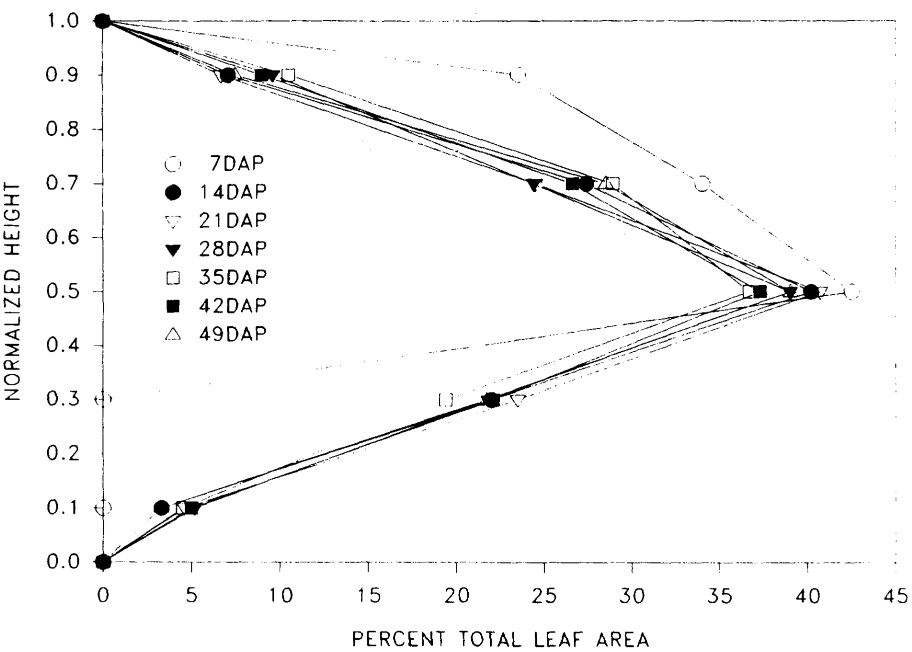

Fig. 2. Leaf area distribution with normalized plant height for Manhattan grain sorghum from emergence to maximum canopy cover.

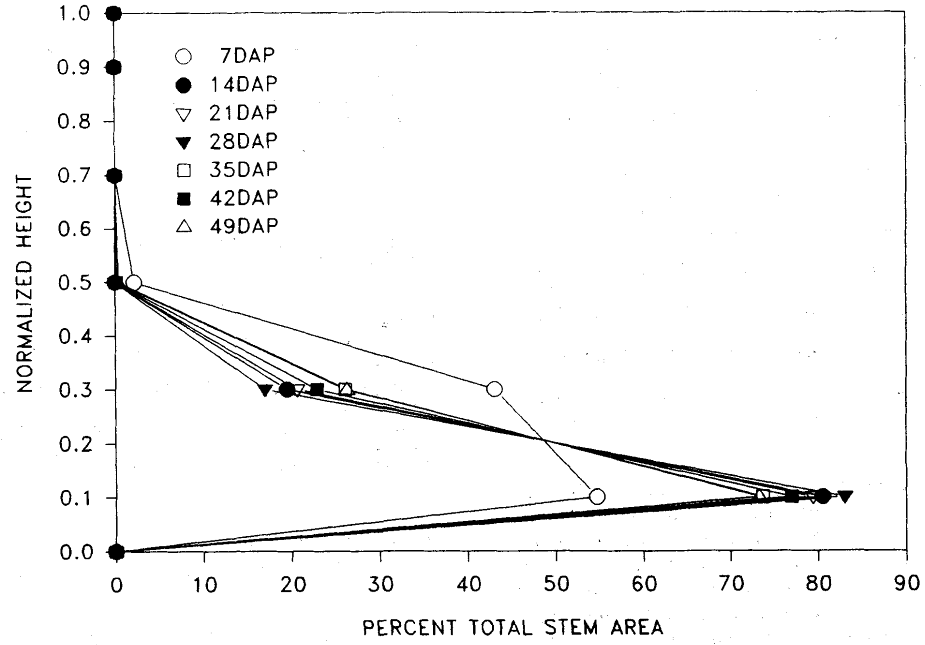

Fig. 3. Stem silhouette area distributions with normalized plant height for Manhattan grain sorghum from emergence to maximum canopy cover.

ble 3) and for emergence to maximum dry matter, from 0.958 to 0.854 (Table 4). The slope of the regression line was different from the 1:1 line for plant height and leaf area for the period emergence to maximum dry weight for both years (Table 4). The plants at Big Spring continued to increase in dry weight after leaf area began to decrease and the plant height had reached a maximum, so the equations based on total dry weight overestimated the leaf area and plant heights at Big Spring.

For wind and water erosion prediction, the period of greatest importance is that from emergence to maximum canopy cover. Crop canopy structure characteristics that reduce wind and water erosion reach their maximum during this period (Morgan, 1985; Armbrust and Lyles, 1985). The equations developed for the period from planting to maximum canopy cover at Manhattan do a good job of predicting the canopy structure for sorghum grown at Big Spring (Table 3).

Leaf and stem area distributions for the first seven harvests at Manhattan, expressed as a percentage of the

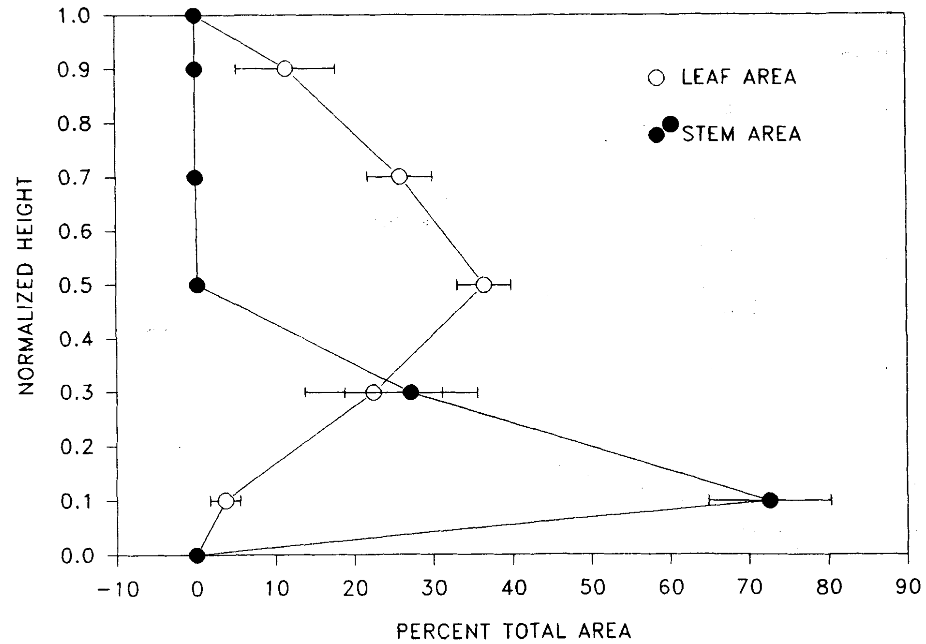

Fig. 4. Mean leaf area and stem area distributions with normalized plant height. Data are average for all sample dates at Manhattan and Big Spring from emergence to maximum canopy cover. Error bars represent ±1 SD.

total area, are shown in Fig. 2 and 3. The data for only the first seven harvests were used because wind erosion was assumed to be zero by this time and rain drop energy remains constant after maximum canopy cover is obtained (Armbrust and Lyles, 1985; Morgan, 1985). Leaf area distribution is triangular, with the maximum leaf area occurring between 40 to 60% of the total height of the plant (Fig. 2). The distribution of the leaf area with height remained constant regardless of the age of the plant. Stem area remained in the bottom 80% of the plant height (Fig. 3). Average leaf and stem areas for all samples are given in Fig. 4. No statistical differences were found between locations in the distribution of normalized leaf area and stem area. Normalized leaf and stem area distributions with height determined in this study are similar to other grass species such as winter wheat, oat, and corn during early growth stages (unpublished data) and should be applicable to all grain sorghum cultivars.

Although WERM is still under development and sensitivity analyses have not been conducted, we believe that the accuracy of the parameters estimated by the equations developed in this study will not adversely influence the accuracy of the predicted soil loss.

The equations developed from this study will be applied in the new wind erosion model, WERM, in the following manner. The crop submodel in WERM will predict the amount of aboveground dry weight present on a field of grain sorghum 20 d after planting. The estimation equations will calculate the height of the canopy, leaf area per plant, and stem area per plant. The leaf and stem areas will be distributed as a function of height through the canopy using the percentages in five heights segments shown in Fig. 4. Using the proper relationships, the friction velocity above the canopy and the loss of wind energy through the canopy can be calculated and the amount of wind energy available at the surface to move soil particles determined. Similar calculations can be done to predict the effect of the canopy on water erosion.

SUMMARY

Cumulative biomass production of grain sorghum can be used to predict the canopy structure parameters of plant height, stem length, leaf area, stem area, and canopy cover from emergence to maximum canopy cover development. Distribution of leaf and stem area with height remained essentially constant with age of the plant through the first 7 wk after planting. Leaf area distribution remained nearly constant until maturity. The prediction equations can be used to obtain values of canopy structure for use in the new wind and water erosion models.

REFERENCES

Adams, J.E., and G.F. Arkin. 1977. A light interception method for measuring row crop ground cover. Soil Sci. Soc. Am. J. 41:789–792.

Arkin, G.F., R.L. Vanderlip, and J.T. Ritchie. 1976. A dynamic grain sorghum growth model. Trans. ASAE 19:622–626, 630.

Armbrust, D.V. and Leon Lyles. 1985. Equivalent wind-erosion protection from selected growing crops. Agron. J. 77:703–707.

Armstrong, C.L. and J.K. Mitchell. 1987. Transformations of rainfall by plant canopy. Trans. ASAE 30:688–696.

Bache, D.H. 1986. Momentum transfer to plant canopies: influence of structure and variable drag. Atmos. Environ. 20:1369–1378.

Hagen, L.J. 1991. A wind erosion prediction system to meet user needs. J. Soil Water Conserv. 46:106–111.

Holt, D.A., R.J. Bula, G.E. Miles, M.M. Schrieber, and R.M. Peart. 1975. Environmental physiology, modeling, and simulation of alfalfa growth. I. Conceptual Development of SIMED. Purdue Univ. Agric. Exp. Stn. Res. Bull. no. 907. Lafayette, IN.

Hoogenboom, G., and M.G. Huck. 1986. ROOTSIMU V4.0 A dynamic simulation of root growth, water uptake, and biomass partitioning in a soil-plant-atmosphere continuum: update and documentation. Ala. Agric. Exp. Sta. Agron. and Soils Dept. Ser. no. 109.

Johnson, I.R., T.E. Ameziane, and J.H.M. Thornley. 1983. A model of grass growth. Ann. Bot. (London) 51:599–609.

Lane, L.J. and M.A. Nearing, Ed. 1989. USDA-Water erosion prediction project: hillslope profile model documentation. NSERL REP. no. 2.

McKinion, J.M., D.N. Baker, J.D. Hesketh, and J.W. Jones. 1975. Part 4-SIMCOT II: a simulation of cotton growth and yield. p. 27–82. *In* Computer simulation of a cotton production system. ARS-S-52. U.S. Gov. Print. Office, Washington, DC.

Morgan, R.P.C. 1985. Effect of corn and soybean canopy on soil detachment by rainfall. Trans. ASAE 28:1135–1140.

Parton, W.J. and G.S. Innis. 1972. Some graphs and their functional forms. U.S. Int. Biol. Program Tech. Rep. 153, Nat. Resource Ecol. Lab., Fort Collins. CO.

Quinn, N.W., and J.M. Laflen. 1983. Characteristics of raindrop through fall under corn canopy. Trans. ASAE 26:1445–1450.

SAS Institute Inc. 1985. SAS/STAT guide for personal computers. Version 5 ed. SAS Institute, Inc., Cary NC.

Shaw, Roger H. and A.R. Pereira. 1982. Aerodynamic roughness of a plant canopy: A numerical experiment. Agric. Meteorol. 26:51–65.

van Keulen, H., F.W.T. Penning de Vries, and E.M. Drees. 1982. A summary model for crop growth. p. 87–97. *In* F. W. T. Penning de Vries and H. H. van Laar (ed.) Simulation of plant growth and crop production. Simulation Monographs, Wageningen, Netherlands.

Wann, M., C.D. Raper, Jr., and H.L. Lucas, Jr. 1978. A dynamic model for plant growth: a simulation of dry matter accumulation for tobacco. Photosynthetica 12:121–136.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27:129–144.

Williams J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel. 1989. The EPIC crop growth model. Trans. ASAE 32:497–511.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses-a guide to conservation planning. USDA Agric. Handbook no. 537.