Plant Growth Model for WEPS (Wind Erosion Prediction System)

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INTRODUCTION

The presence of residue on the soil surface and living plants provides some protection from soil loss by wind erosion (Skidmore and Nelson, 1992). The primary purpose of the CROP submodel is to obtain realistic estimates of plant growth so that the influence of vegetative cover on soil loss by wind erosion can be properly evaluated. The CROP submodel, one of seven submodels of WEPS, was adapted from the Erosion Productivity Impact Calculator (EPIC) crop growth model (Williams et. al., 1989). Additional capabilities and modifications have been developed and incorporated into CROP to meet the need for predicting effects of a growing crop on wind erosion. Some of the factors that affect wind erosion are the flexibility and arrangement of individual plant parts, distribution of plant parts by height, and number of plants per unit area (Shaw and Periera, 1982). Leaves and stems have to be accounted for separately for several reasons. (1) On a per-unit-area basis, stems of young seedlings are roughly 10 times more effective than leaves in depleting wind energy, but the effectiveness of leaves increases as the crop develops (Hagen, 1991; Armbrust and Bilbro, 1995). (2) Leaves are more sensitive to sandblast damage than are stems (Armbrust, 1982; Fryrear, 1971). (3) Leaves and stems decompose at different rates. Future improvements in the WEPS residue decomposition submodel may include decompsition rates of leaves and stems Thus, one of the requirements of the CROP submodel is to give daily estimates of leaf and stem growth. An important consideration is the effect of plant density on the amount of vegetative cover. The lower the number of seedlings is per unit area, the less cover is provided by the growing vegetation. Hence, another requirement of the CROP submodel is to account for differences in plant cover resulting from differences in plant population. At physiological maturity, the CROP submodel provides final estimates of masses of root, leaf, stem, grain, and chaff to other submodels of WEPS so that appropriate estimates of the amount of fresh residue left on the soil surface can be made.

The CROP submodel calculates daily biomass production; partitions daily biomass into root, leaf, stem, reproductive, and "grain" parts; estimates growth of leaf and stem; and, at harvest, calculates economic (grain or other yield) and noneconomic (chaff) parts. The objective of this paper is to briefly describe the methods and approaches used in the CROP submodel to calculate plant growth parameters as needed for the wind erosion prediction system.

MODEL DESCRIPTION

Phenological development

Phenological development of the crop is based on relative growing-degree-day or heat unit accumulation (GDD_r) which is calculated according to equations [1] & [2]. It is the ratio of cumulated heat units from planting to the day of simulation (GDD_s) and the total heat units needed from planting to physiological maturity (GDD_p). Annual plants "grow" from planting to the date when GDD_s equals GDD_p for the crop. Emergence occurs when the current value of

GDD_r equals the GDD_r required for emergence. For annual winter crops (e.g., wheat), GDD accumulation (therefore, growth) does not occur during the period of dormancy. Perennial crops also are not allowed to "grow" during the period of winter dormancy. However, aboveground biomass may be reduced as a function of temperature during winter dormancy. After the end of dormancy, plants start growing when the average daily air temperature exceeds the base temperature of the plant. For crops such as alfalfa, GDD_s is reinitialized after every cut.

$$GDD_s = \sum_{i=1}^{k} \frac{T_{\max} + T_{\min}}{2} - T_{bas} \qquad \textbf{(1)}$$

$$GDD_r = \frac{GDD_s}{GDD_p} \qquad \textbf{(2)}$$

where:
T_{max} = daily maximum temperature (°C),
T_{min} = daily minimum temperature (°C),
T_{bas} = base temperature (°C),
GDD_r = ratio of GDD_s to GDD_s at physiological maturity,
GDD_s = summation of heat units from planting to the current day of simulation,
GDD_p = total heat units from planting to physiological maturity.
k = number of days after planting
Note: heat units are accumulated if $(T_{max} + T_{min})/2 > T_{bas}$.

Dormancy for cold-season crops is a function of day length. Winter dormancy occurs during the period when the day length is less than about one hr (depending on latitude) greater than the minimum day length for the location. Day length is calculated as follows:

$$SD = 0.4102 \; SIN\left(\frac{2\Pi}{365}\right)(JD - 80.25) \qquad \textbf{(3)}$$

$$HRLT = 7.64 \; COS^{-1}\left[-TAN\left(\frac{2\;\Pi\;XLAT}{365}\right)\; TAN(SD)\right] \qquad \textbf{(4)}$$

Where:
XLAT = latitude of location (degrees),
HRLT = day length (hr),
π = 3.14159,
SD = the sun’s declination angle (rad.),
JD = day of year since January 1.

Biomass growth and partitioning

Shortwave radiation at the top of the canopy is multiplied by the factor C to estimate the amount of photosynthetically active radiation (PAR). Intercepted PAR is calculated using the exponential function (Beer's law) for distribution of light within a canopy. Potential daily biomass production is calculated by multiplying the intercepted light by the radiation use efficiency factor (BE). These relationships are shown in equation [5].

$$PDDM = 0.001\ (C)\ (RA)\ (BE)\ \left[1 - EXP(-K_c * LAI)\right] \quad \textbf{(5)}$$

where,
0.001 is a conversion factor to t/ha.
PDDM = potential daily biomass production (t/ha),
BE = radiation use efficiency (kg/MJ),
RA = solar radiation (MJ/m^2),
C = fraction of shortwave solar irradiance that is photosynthetically active (C=0.5),
K_c = radiation extinction coefficient,
LAI = leaf area index.

The radiation use efficiency factor (BE) can be adjusted for elevated CO$_2$ levels.
Daily produced biomass is partitioned to roots and aboveground plant parts. The root mass partitioning ratio (P_{rt}) is calculated using equation [6] (Williams, et al., 1990a).

$$P_{rt} = 0.4 - 0.2\ GDD_r \quad \textbf{(6)}$$

Where:
P_{rt} = root mass partitioning ratio.
The daily increment in root mass is calculated as a product of daily converted biomass and P_{rt}. The balance is aboveground biomass, which is subdivided further into leaf, stem, and reproductive masses. The leaf mass partitioning is calculated using equation [7]. The reproductive mass partitioning fraction also is calculated using equation [7] by replacing the leaf parameters (A_{lf}, B_{lf}, C_{lf}, D_{lf}) with reproductive parameters. The stem partitioning ratio is obtained by subtraction, because, by definition, the sum of leaf, stem, and reproductive partitioning ratios must equal 1.0. Before the onset of the reproductive phase, aboveground biomass is partitioned only to leaf and stem masses. After about 80% (depending on the crop) of the season has elapsed, no biomass is allocated to leaves and stems.

$$P_{lf} = A_{lf} + \frac{B_{lf}}{\left[1 + EXP\left(\frac{-(GDD_r - C_{lf})}{D_{lf}}\right)\right]} \quad \textbf{(7)}$$

where:

P_{lf} = leaf mass partitioning ratio,
A_{lf}, B_{lf}, C_{lf}, D_{lf} are leaf partitioning parameters.

Reproductive mass is partitioned into "grain"' and non-"grain" parts using equations [8] and [9].

$$GIF = -0.02 + \frac{1.11}{\left[1 + EXP\left(\frac{0.64 - GDD_r}{0.075}\right)\right]} \qquad \textbf{(8)}$$

$$YLD = GIF * GI * RPW \qquad \textbf{(9)}$$

where:
GI = Grain index (ratio of grain to reproductive mass),
GIF = Grain index factor (0<= GIF <= 1),
YLD = Grain mass (t/ha),
RPW = Reproductive mass (t/ha).

Leaf and stem area growth

Leaf area per plant is calculated as a product of leaf mass and the specific leaf area (SLA) of the crop. Leaf area index (LAI) then is computed by dividing leaf area per plant by the gound area per plant as shown in equation [10]. Stem area index (SAI) is calculated in the same way. Although the relationship of leaf area and leaf weight is linear for most crops, the relationship of stem area and stem weight is linear for some crops but nonlinear for other crops (Retta and Armbrust, 1995).

$$LAI = \frac{(BM_{lf})\ (SLA)}{PAREA} \qquad \textbf{(10)}$$

where:
LAI = leaf area index,
BM_{lf} = leaf mass (kg/plant),
SLA = specific leaf area (m^2/kg),
PAREA = ground area (m^2/plant).

During the leaf senescence period (triggered when GDD_r equals about 0.8 for most crops), LAI is estimated using equation [11].

$$LAI_i = LAI_{i-1}\left[\frac{1}{1+EXP\left(\frac{0.5\,C_{lf}-GDD_x}{D_{lf}}\right)}\right]^{\frac{1}{n}} \tag{11}$$

where:
LAI_i = LAI on day I,
LAI_{i-1} = LAI on day I-1,
GDD_x = difference between current GDD_r and GDD_{rs},
GDD_{rs} = relative GDD when leaf senescence starts,
n = a value of 4 seems to work for the crops tested.

Plant height

Plant height is estimated using the sigmoid function [12]. The parameters C_{ht} and D_{ht} were obtained by fitting plant height data to the two-parameter sigmoid function.

$$PCHT = 0.01 + \frac{HMX}{\left[1 + EXP\left(\frac{GDD_r - C_{ht}}{D_{ht}}\right)\right]} \tag{12}$$

where:
PCHT = potential crop height (m),
HMX = maximum crop height (m),
C_{ht}, D_{ht} : height parameters (can be replaced by C_{lf} and $D_{lf,}$ respectively).

Rooting depth

Rooting depth is calculated using equation [12] by replacing the plant height coefficients with rooting depth coefficients. Root mass distribution by soil layers is calculated using equation [13] (Jones et al., 1991).

$$RWT_i = RWT_i + DRW\frac{\left(1-\frac{ZA_i}{3}\right)^{wcg}}{\sum_{i=1}^{i=ir}\left(1-\frac{ZA_i}{3}\right)^{wcg}} \tag{13}$$

Where:
RWT_i = root mass in a layer (t/ha),
DRW = daily increase in root mass (t/ha),
ZA_i = depth to the middle of the i^{th} soil layer that has roots (m),
wcg = genotype-specific rooting coefficient,
ir = deepest layer to which roots have penetrated.

Growth constraints

Potential growth and yield seldom are achieved because of stress caused by suboptimal conditions. The CROP submodel adjusts daily growth of biomass and area for water, temperature, and nutrient stresses. These stress factors range from 0, where no growth will occur, to 1 for no limitation in growth. For any simulation day, the minimum value of the water, nutrient, or temperature stress factor adjusts daily produced biomass. The water stress factor is calculated as a ratio of actual to potential transpiration. These calculations are made in the HYDROLOGY submodel and are provided as inputs to the CROP submodel. Temperature stress is estimated using equation [14]. This equation is the same as given in EPIC (Williams et al., 1990a) except that the soil surface temperature is replaced with average air temperature, because soil temperatures are not readily available. This function produces a symmetrical temperature stress factor about the optimum temperature.

$$T_s = \sin\left(\frac{\pi}{2} \cdot \frac{T_{av} - T_{bas}}{T_{opt} - T_{bas}}\right) \tag{14}$$

where:
T_{av} = average air temperature,
T_{bas} = base temperature (°C)
T_{opt} = optimum temperature (°C).
T_s = temperature stress factor

Frost damage is assessed using equation [15]. Frost stress is applied primarily to winter crops but can be applied to summer crops, if freezing temperatures occur before the crop reaches physiological maturity. Calculation of frost damage stress is triggered whenever the minimum temperature is at or below -1.0 °C.

$$F_s = \frac{|T_{\min}|}{|T_{\min}| - EXP(A_f + B_f\ T_{\min})} \tag{15}$$

where:
F_s = frost damage factor,
T_{min} = daily minimum air temperature (°C),
A_f, B_f = parameters in the frost damage ’s-curve’.

Nutrient stress

Algorithms from EPIC for supply, demand, uptake and stress of nitrogen and phosphorous were incorporated into CROP with some minor modifications,. These equations are described in the EPIC model documentation manual (Williams et al., 1990a) and will not be discussed here.

Crop parameters

Crop parameters are critical parts of the CROP submodel and are considered to be constant for a given crop. Many of the crop parameters were taken from EPIC (Williams et al., 1990b). Parameters for calculating leaf and stem areas and for partitioning aboveground biomass into leaf, stem, and reproductive masses were developed for soybean, corn, grain sorghum, winter wheat, oats, and rice (Retta and Armbrust, 1995; Retta et al., 1996). Parameters for partitioning reproductive mass into "grain" and non-"grain" parts were developed for several of the field crops. Specific leaf area values for many crops were obtained from the literature (van Keulen, 1986). For crops for which measured parameters were lacking, values of a nearest crop type were used as defaults. These will be replaced as measured data become available.

Validation

Data for soybean, corn, grain sorghum, winter wheat, and oats were used to test the accuracy of the CROP submodel in simulating biomass and organ growth of crop plants. All data contained detailed measurements of plant state variables taken at approximately weekly intervals. Data were obtained from experimental plots located in Manhattan, Kansas. Details of site and growth conditions for each crop are described elsewhere (Retta and Armbrust, 1995). We had two seasons of data for each crop, except sorghum, for which we had 1 year of data. However, we obtained additional data for grain sorghum, including dry weights of leaf, stem, reproductive, and aboveground masses and leaf area per plant. These data were measured every 5 days from emergence to physiological maturity by Reeves (1971) for three grain sorghum hybrids (representing three maturity groups) over a 2-year period. However, Reeves' data did not contain measurements of stem area. A stand-alone version of the CROP submodel was used for the simulations.

Measured and simulated leaf, stem, reproductive, and aboveground masses and leaf and stem areas were compared for all crops (Fig. 1). There was good agreement between measured and simulated values for LAI, reproductive, and aboveground masses (slopes close to 1, intercepts close to 0, and high coefficients of determination; Table 1.). However, the model underestimated SAI and to a lesser extent stem mass and leaf mass. The reasons for model underestimation of SAI are not readily apparent. Part of the problem was that there was much less data collected for stem area than for other plant state variables. In WEPS the degree of protection from wind erosion provided by growing crops is calculated as function of SAI and LAI.

The underestimation of SAI by the CROP submodel means assessment of the protective value of growing crops from wind erosion will be underestimated. More field data collection may be required before improvements in SAI simulation can be realized. However, the model appears to give satisfactory estimates of LAI, reproductive mass ("yield") and aboveground mass for the crops tested.

REFERENCES

Armbrust, D. V. 1982. Physiological responses to wind and sandblast damage by grain sorghum plants. Agron. J. 74(3):133-135.

Armbrust, D. V. and J. B. Bilbro. 1997. Relating plant canopy characteristics to soil transport capacity by wind. Agron. J. 89: 157-162.

Fryrear, D. W. 1971. Survival and growth of cotton plants damaged by windblown sand. Agron. 63(4):638-642.

Hagen, L. J. 1991. A wind erosion prediction system to meet user needs. J. Soil Water Cons. 46(2):106-111.

Jones, C. A., W. L. Blad, J. T. Richie, and J. R. Williams. 1991. Simulation of root growth. p. 91-123. *In* Modeling plant and soil systems. J. Hanks and J. R. Ritchie (eds.). Agronomy Monograph no. 31.

Reeves, H. E. 1971. Growth and dry-matter accumulation in grain sorghum (Sorghum Bicolor (L.) Moench). Ph. D. diss. Kansas State Univ., Manhattan (diss. Abstr. 71-26, 617).

Retta, A. and D. V. Armbrust. 1995. Estimation of leaf and stem area in the wind erosion prediction system (WEPS). Agron. J. 87:93-98.

Retta, A., D. V. Armbrust, and L. J. Hagen. 1996. Partitioning of biomass in the crop submodel of WEPS (wind erosion prediction system). Trans. ASAE 39(1):145-151.

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

Siddoway, F. H., W. S. Chepil, and D. V. Armbrust. 1965. Effect of kind, amount, and placement of residue on wind erosion control. Trans. ASAE 8:327-331.

Skidmore, E.L. and R. G. Nelson. 1992. Small-grain equivalent of mixed vegetation for wind erosion control and protection. Agron. J. 84:98-101.

van Keulen, H. 1986. Plant data. p. 235-247. In H. van Keulen and J. Wolf (ed.). Modeling of Agricultural Production: Weather, Soils and Crops. Pudoc, Wageningen, the Netherlands.

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

Williams, J. R., C. A. Jones, and P. T. Dyke. 1990a. The EPIC model. In EPIC -- Erosion /Productivity Impact Calculator: 1. Model Documentation. eds. A. N. Sharply and J. R. Williams. U. S. Department of Agriculture Technical Bulletin No. 1768. 235 pp.

Williams, J. R., P. T. Dyke, W. W. Fuchs, V. W. Benson, O. W. Rice, and E. D. Taylor. 1990b. EPIC--Erosion/Productivity Impact Calculator: 2. User Manual. A. N. Sharply and J. R. Williams, Eds, Tech. Bull. No. 1768. springfield, Va.: Nat. technical Information Service.

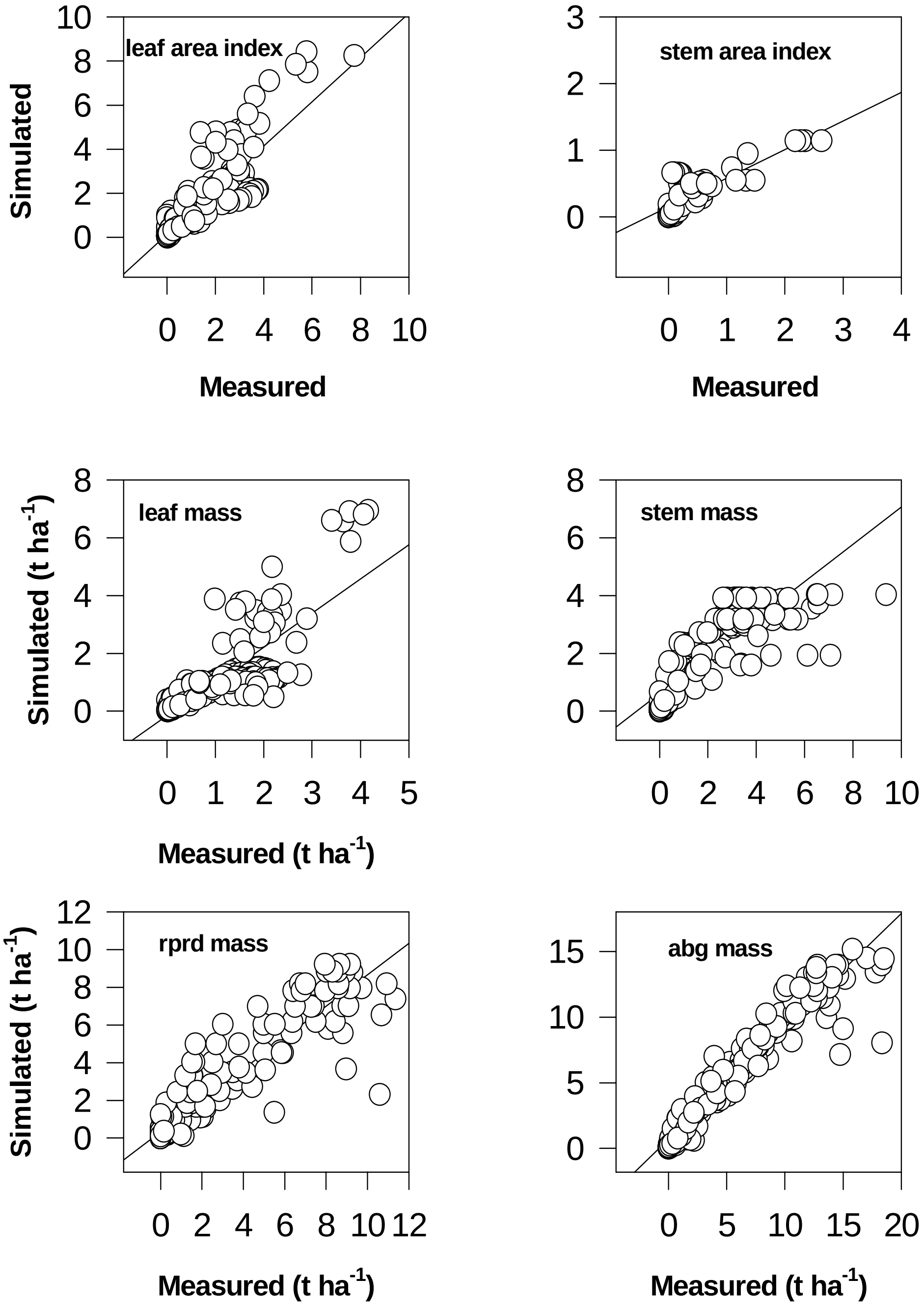

Fig. 1. Comparison of simulated versus measured data for soybeans, corn, grain sorghum, winter wheat, and oats.

Table 1. Parameters of linear regression of measured on simulated plant variables.

Plant variable	Slope	Intercept	r^2	n
LAI	1.00	0.13	0.70	190
SAI	0.43**	0.15**	0.67	58
Leaf mass	1.18*	-0.15**	0.62	190
Stem mass	0.66**	0.61**	0.73	190
Reproductive mass	0.83**	0.34**	0.85	190
Aboveground mass	0.86**	0.70**	0.92	190

* & ** indicate significance at the 0.05 and 0.01 levels, respectively.

LIST OF SYMBOLS

Symbol	Description	Unit
A_f, B_f	parameters in the frost damage 's-curve'	
A_{lf}, B_{lf}, C_{lf}, D_{lf}	leaf partitioning parameters	
BE	radiation use efficiency	kg/MJ
BM_{lf}	leaf mass	kg/plant
C	fraction of shortwave solar radiation that is photosynthetically active (C=0.5)	MJ/MJ
C_{ht}, D_{ht}	plant height parameters	
DMAG	aboveground biomass	t/ha
DRW	daily increase in root mass	t/ha
F_s	frost damage factor	
GDD_p	total GDDs from planting to physiological maturity	^oCd
GDD_r	relative GDD (ratio of cumulated GDDs at any time to the GDDp at physiological maturity)	$^oCd/^oCd$

Symbol	Description	Unit
GDD_{rs}	relative growing degree days to the start of leaf senescence	$^{o}Cd/^{o}Cd$
GDD_x	GDD_r since the start of senescence	$^{o}Cd/^{o}Cd$
GI	"grain" index	
GIF	"grain" index factor	
HMX	maximum plant height	m
HRLT	day length	hr
JD	day of year since January 1	d
K_c	radiation extinction coefficient	
LAI	leaf area index	m^2/m^2
n	exponent in the leaf senescence function	
PAREA	ground area	m^2/plant
PCHT	plant height	m
PDDM	potential daily biomass production	t/ha
P_{lf}	leaf mass partitioning ratio	t/t
P_{rt}	root mass partitioning ratio	t/t
RA	solar radiation	MJ/m^2
RPW	reproductive mass	t/ha
RWT_i	root mass in a layer	t/ha
SD	the sun’s declination angle	rad
SLA	specific leaf area	m^2/kg
SSA	specific stem area	m^2/kg
T_{av}	average air temperature	^{o}C
T_{bas}	base temperature	^{o}C
T_{max}	daily maximum temperature	^{o}C
T_{min}	daily minimum temperature	^{o}C
T_{opt}	optimum temperature	^{o}C

Symbol	Description	Unit
T_s	temperature stress factor	
wcg	rooting coefficient	
XLAT	latitude of location (negative for southern hemisphere)	deg
YLD	economic yield	t/ha
ZA_i	depth to the middle of the ith soil layer that has roots	m