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Leaf and Stem Area Relationships to Masses and Their Height Distributions in Native Grasses

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ABSTRACT

A recently developed wind erosion model (wind erosion prediction system, WEPS) for crop lands is being extended for estimating soil erosion from rangelands, military lands, and desert ecosystems. Wind velocity near the soil surface is calculated as a function of the aerial distribution of stem silhouette area and leaf area of both live plants and standing residue. Grasses either dominate or form a significant part of the plant species growing in the noncrop lands of the world. Several grass species were studied to determine the aerial distribution of stem and leaf masses and areas. Plant samples were taken weekly from pure stands of big bluestem (*Andropogon gerardii* Vitman), switch grass (*Panicum virgatum* L.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], Indian grass [*Sorghastrum nutans* (L.) Nash], gamagrass (*Tripsacum dactyloides* L.), blue grama [*Bouteloua gracilis* (Kunth) Lag. ex Griffiths), and sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.]. Plants were cut from a 0.2 m^2 area and five tillers were randomly selected and cut into five equal segments. Leaves and stems were separated and their areas and dry weights were measured. For each species a straight line with a zero intercept fit the data of leaf area vs. leaf mass with $r^2 \geq 0.87$. Stem area vs. stem mass data fit a power function with $r^2 \geq 0.92$. Normalized leaf and stem masses were fit to a hyperbolic tangent ($r^2 \geq 0.96$) and exponential ($r^2 \geq 0.98$) functions, respectively. The empirical regression coefficients obtained for each species will be included in the WEPS plant growth data base.

Standing vegetation influences the extent of soil removal by wind erosion, mainly by reducing the wind velocity near the soil surface. The degree of reduction in wind velocity is a complex function of the flexibility, arrangement, and density of leaf and stem parts of plants (Shaw and Pereira, 1982) and the distribution of leaf and stem areas by height (Bache, 1986). It is daunting to adequately describe the complex arrangement and aerial distribution of leaf and stem parts and their relationship to wind erosion. Consequently, several researchers have based predictions of wind shear stress at the soil surface on single vegetation parameters that are empirically derived from one or a few easily measured plant characteristics. For example, Musick et al. (1996), Musick and Gillette (1990), and Marshall (1971) developed a vegetation (roughness element) parameter based on the outer silhouette area of the vegetation element. Other wind and water erosion models calculate soil erosion as a function of the amount of aboveground biomass.

In the erosion submodel of WEPS, the plant parameter used is the plant area index (PAI) (Hagen and Armbrust, 1994). For standing residue, PAI is equal to the stem silhouette area index (SAI). For a growing canopy, PAI is the sum of SAI and a fraction (effective) of the leaf area index (LAI) (Armbrust and Bilbro, 1997). A fraction rather than the whole of LAI is used because leaves of young plants streamline with the wind and are much less effective in protecting the soil than are stems (Hagen, 1991; Armbrust and Bilbro, 1997). In WEPS, not only is the total PAI important but its distribution by height also is important, because the wind speed at the bottom of the canopy (near the soil surface) is calculated as a function of both these variables.

Several empirical relationships have been used to describe leaf area distribution as a function of plant height. Dwyer et al. (1992) used a third degree polynomial to characterize the LAI distribution of corn (*Zea mays* L.). The crop–weed competition model INTERCOM used a constant or parabolic function to distribute leaf area along the height of both crop and weed plants (Kropff, 1993). Graf et al. (1990) used a function that gave a skewed distribution for rice (*Oryza sativa* L.) leaf area distribution. However, the functions used by Kropff (1993) and Graf et al. (1990) did not adequately represent the leaf area distribution data observed in this study. No comparable study dealing with the height distribution of stem mass and area was found in the literature.

There are several additional applications for LAI and SAI relationships. For example, knowledge of the aerial distribution of leaf and stem area is useful in evaluating potential damage to plants by abrasion from sand and soil particles. Crop models use the distribution of LAI by height to calculate attenuation of radiation fluxes within plant canopies. Leaf and stem mass relationships to height can aid land managers when determining how much standing biomass can be removed while still maintaining protection from erosion. The amount of residue left is a function of the height of cut. Water erosion models, such as the Revised Universal Soil Loss Equation (Renard et al., 1991), also need height distribution of leaf area to estimate the fall-height of rain drops from standing canopies. Thus, for these and other appli-

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Abbreviations: WEPS, wind erosion prediction system; LAI, leaf area index; SAI, stem silhouette area index; PAI, plant area index; SLA, specific leaf area; RUSLE, Revised Universal Soil Loss Equation.

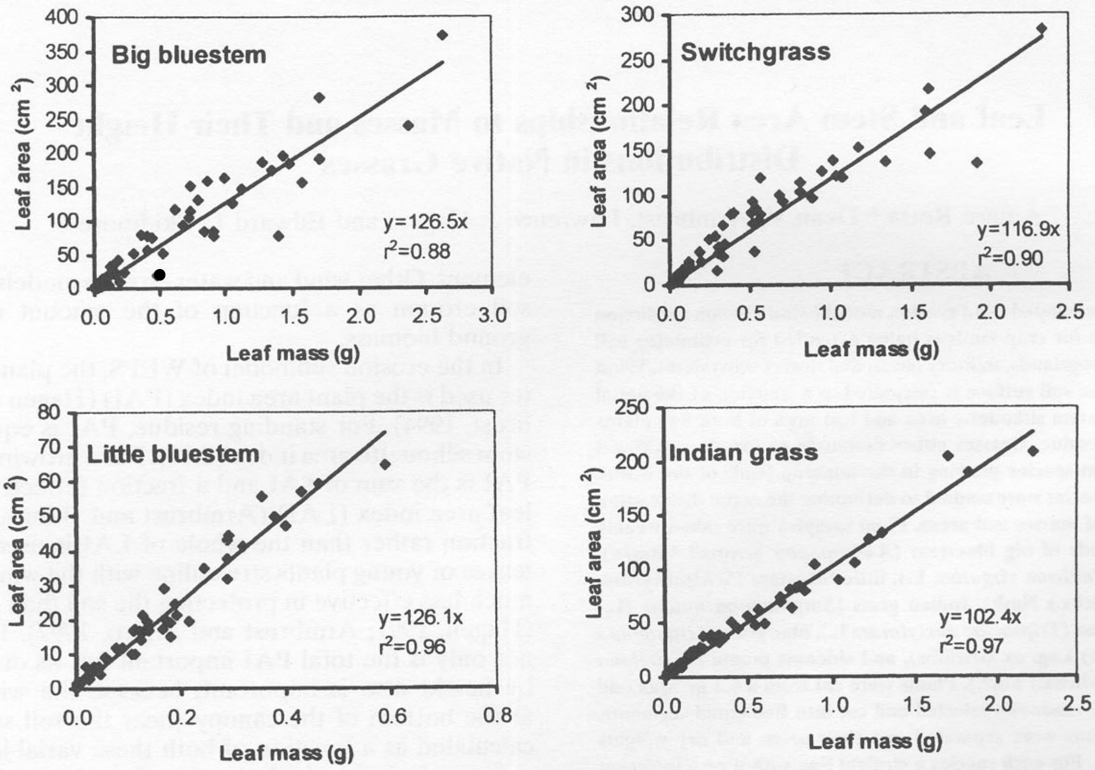

Fig. 1a. Measured (symbols) and regressed (line) leaf mass vs. leaf area data of big bluestem, switch grass, little bluestem, and Indian grass.

cations, relationships need to be developed among leaf and stem mass and leaf and stem area and their height distributions.

The rangelands of the Great Plains, where soil erosion can be a problem, are dominated by the Tall-Grass Prairie and Short-Grass Plains grassland associations (Sampson, 1951). It is therefore important to obtain parameters for all the common grasses (and other plant types) prevalent in the rangelands of the Midwest. The objectives of this study were to (i) determine parameters for calculating leaf and stem areas of grass species from their respective masses and (ii) develop functions for computing the height distribution of leaf and stem masses and areas of grasses.

MATERIALS AND METHODS

Plant samples of seven grass species were taken during the spring and summer of 1996 from large plots of pure stands being grown at the USDA-NRCS Plant Materials Center near Manhattan, KS. The grass species were big bluestem, switch grass, little bluestem, Indian grass, gamagrass, blue grama, and sideoats grama. Precipitation for the months of May through August was 509 mm, which was 79 mm above the 30-yr average. Air temperatures were warmer in May and June and cooler in July and August than the 30-yr mean. Plots were irrigated as needed and none of the grasses showed any visual symptoms of water stress. About once a week, the grass from a 0.2 m^2 area of each plot was cut close to the ground level and transported to the laboratory in a cooled box. Five tillers were selected randomly and the height of each tiller was measured. The tillers were laid on a flat, glass-covered table and cut into five equal segments. The leaves and stems from each segment were separated. Leaf area and stem silhouette area of each segment were measured using a leaf area meter (LI-3000, LI-COR[1], Lincoln, NE). The samples were dried for at least 48 h at 70°C, and the leaf and stem dry weights of each segment measured using a precision balance (Mettler AK160, resolution 0.1 mg, Mettler, Columbus, OH). The sheath was included with the stem. Care was taken to lay the tillers on the table so that their heights in a flat position were about the same as their heights in their natural standing position. After flowering, reproductive parts of each species were separated from the stem and leaf parts, dried, and weighed. Sampling started on 1 May and ended on 29 August. Leaf mass (dry weight) data were normalized by dividing the leaf mass in each height segment by the total leaf mass. The normalized leaf mass data were summed to give values ranging from 0 to 1. Stem mass data in each segment were normalized in the same way. The length of each segment was divided by the plant (canopy) height and summed to obtain relative height values of 0.2, 0.4, 0.6, 0.8, and 1.0. Statistical analyses were made using the TableCurve and SigmaStat software (SPSS, Chicago, IL) .

RESULTS AND DISCUSSION

Relationship of Area to Mass

Straight line regressions of leaf area on leaf mass were performed using both zero and nonzero intercepts. The intercept was significantly different from zero ($P > 0.05$) only for switch grass and Indian grass. There were minor differences in r^2 (coefficient of determination) between the two forms, but in all cases the r^2 was 0.87 or better (Fig. 1a and 1b). A zero intercept is preferable, because only one parameter (i.e., the slope) for each species

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[1] Mention of a product does not imply approval of this product to the exclusion of other products.

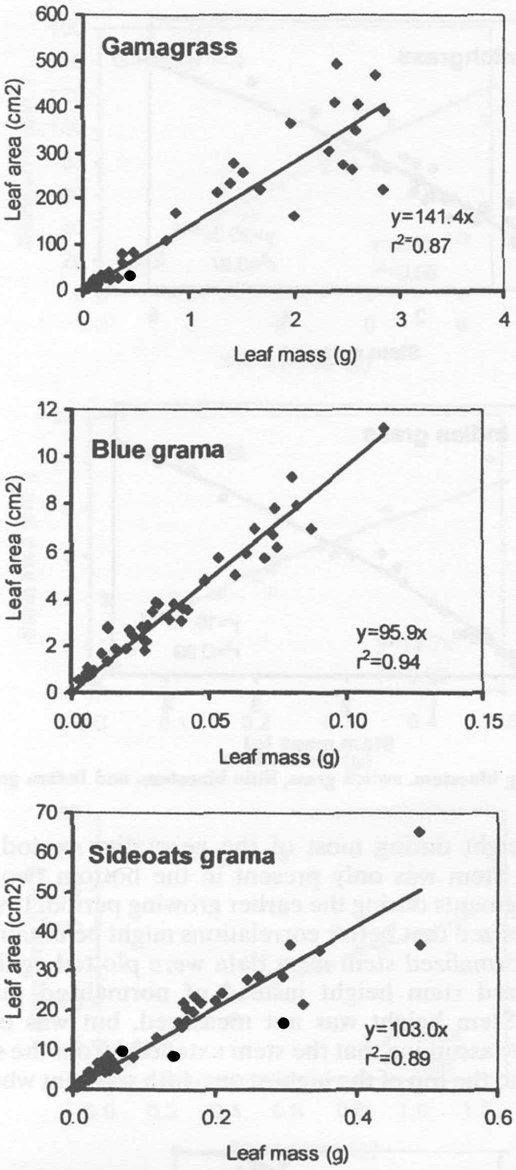

Fig. 1b. Measured (symbols) and regressed (line) leaf mass vs. leaf area data of eastern gamagrass, blue grama, and sideoats grama.

needs to be entered into the WEPS plant database. Also, physiological considerations preclude attaching any physical meaning to values of leaf area (positive or negative) when the independent variable (leaf mass) is zero. For these data, there was little loss of accuracy as a result of using straight line regressions with zero intercepts (Table 1). The slopes represent the specific leaf area (SLA) and ranged from 95.9 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ for blue grama to 141.4 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ for eastern gamagrass. For comparative purposes the SLA of winter wheat (*Triticum aestivum* L.) was found to be 128.0 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ by Retta and Armbrust (1995a).

Plots of stem silhouette area to stem mass showed a curvilinear relationship. A two parameter power function ($y = ax^b$) fit the data well with $r^2 > 0.92$ (Fig. 2a and 2b). The slopes ranged from 13.7 to 22.7 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ and exponents from 0.46 to 0.79 (Table 1).

Height Distribution of Leaf and Stem Masses

Examination of graphs of normalized leaf mass data vs. normalized plant height indicated a sigmoid relationship. The normalized leaf mass data as a function of normalized plant height were fit to four types of sigmoid functions: the logistic, the 3rd degree polynomial, the Weibull, and the hyperbolic tangent. A function was judged acceptable if it met the following criteria: it has a high correlation, the regression line passes through (or very close to) the points (0,0) and (1,1), and has the fewest number of coefficients. The hyperbolic tangent (Eq. [1]) was chosen because it met the overall criteria:

$$y = a - b\tanh(c - dx) \qquad [1]$$

where y = normalized leaf mass; x = normalized plant height; and a, b, c, and d = regression parameters.

The resulting fits for big bluestem and switch grass are shown in Fig. 3. Similar plots were obtained for the other species (graphs not shown). The high r^2 and the regression line passing through or very close to the points (0,0) and (1,1) indicated that the hyperbolic tangent function adequately described the leaf mass distribution of the different grasses. The regression parameters are given in Table 2. Because leaf mass and leaf area showed a strong relationship (Fig. 1a and 1b), the same equations derived for leaf mass distribution can be applied to calculate leaf area distribution along the height of the plant.

Differentiating Eq. [1] with respect to plant height twice results in Eq. [2]. Setting Eq. [2] to 0 and solving for x shows that the relative height at which maximum concentration of leaf mass (or area) occurs can be calculated as a ratio of c/d (in Eq. [1]).

$$\frac{d^2y}{dx^2} = -2b\tanh(-c + dx)[1 - \tanh(-c + dx)^2]d^2 \qquad [2]$$

Using the c/d ratio, the relative height of maximum leaf concentration was calculated for each species and varied from 0.37 for sideoats grama to 0.68 for switch grass. The fall-height of a rain drop, a parameter needed in the

Table 1. Parameters for calculating leaf and stem areas (y, cm^2) when leaf and stem masses (x,g) are known.

	Leaf: $y = ax$				Stem: $y = ax^b$					
Species	a	SE	n	r^2	a	SE	b	SE	n	r^2
Big bluestem	126.5	4.3	55	0.88	20.7	0.90	0.71	0.03	55	0.97
Switch grass	116.9	3.6	60	0.90	20.3	0.61	0.66	0.03	60	0.97
Little bluestem	126.1	2.5	55	0.96	22.7	0.57	0.46	0.03	55	0.95
Indiangrass	102.4	1.7	50	0.97	16.1	0.29	0.77	0.02	50	0.99
Eastern gamagrass	141.4	6.0	40	0.87	22.3	1.67	0.79	0.04	40	0.96
Blue grama	95.9	2.1	45	0.94	13.7	1.02	0.60	0.04	45	0.92
Sideoats grama	103.0	3.5	55	0.89	18.9	0.51	0.71	0.04	55	0.96

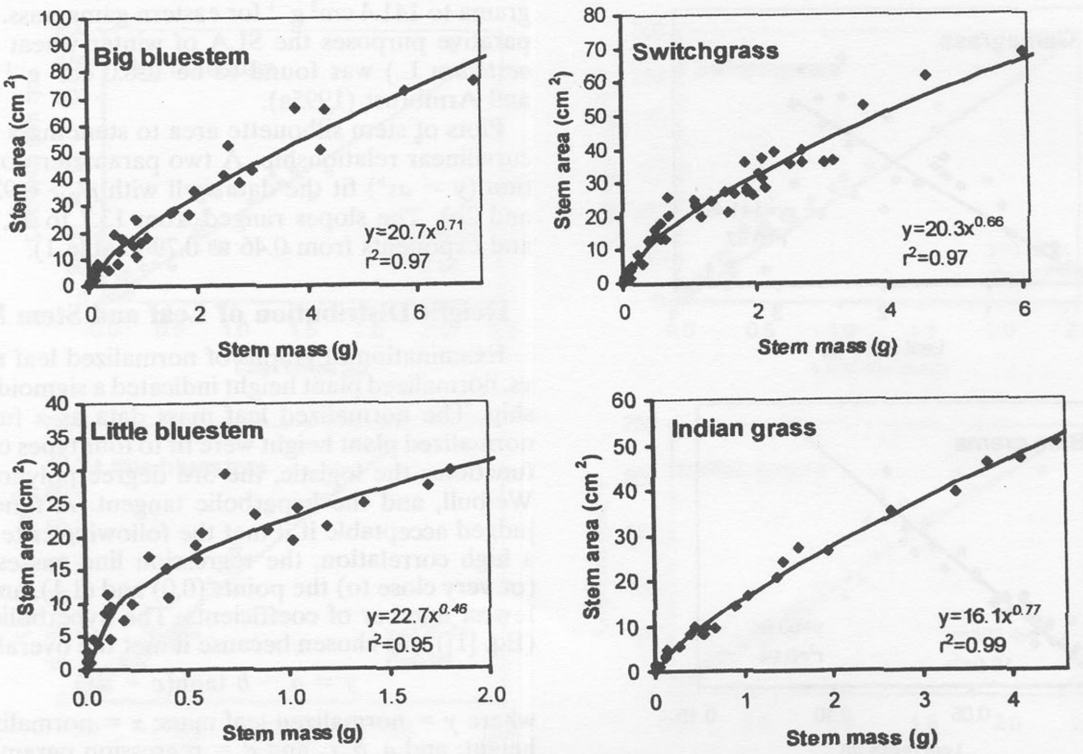

Fig. 2a. Measured (symbols) and regressed (line) stem mass vs. stem area data of big bluestem, switch grass, little bluestem, and Indian grass.

Revised Universal Soil Loss Equation, can be estimated using the *c/d* ratio (fall-height = *c/d* times plant [canopy] height).

Examination of graphs of normalized stem mass data vs. normalized plant height showed a high degree of scatter and no single function could fit all the data (graphs not shown). Part of the lack of fit of normalized stem mass vs. normalized plant height appeared to be caused by the fact that the stem remained well below plant height during most of the vegetative period of growth. Stem was only present in the bottom two or three segments during the earlier growing period. It was hypothesized that better correlations might be obtained if the normalized stem mass data were plotted against normalized stem height instead of normalized plant height. Stem height was not measured, but was estimated by assuming that the stem extended from the soil surface to the top of the highest one-fifth segment where

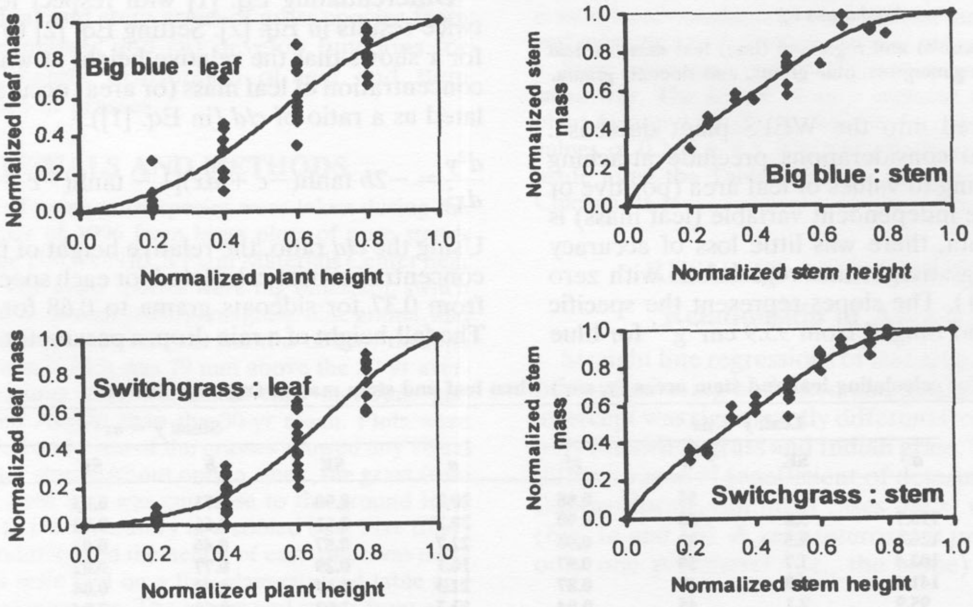

Fig. 3. Normalized cumulative leaf mass vs. normalized cumulative plant height (left) and normalized cumulative stem mass vs. normalized cumulative stem height (right) of big bluestem and switch grass for all dates of sampling. Note: 0 height = soil surface.

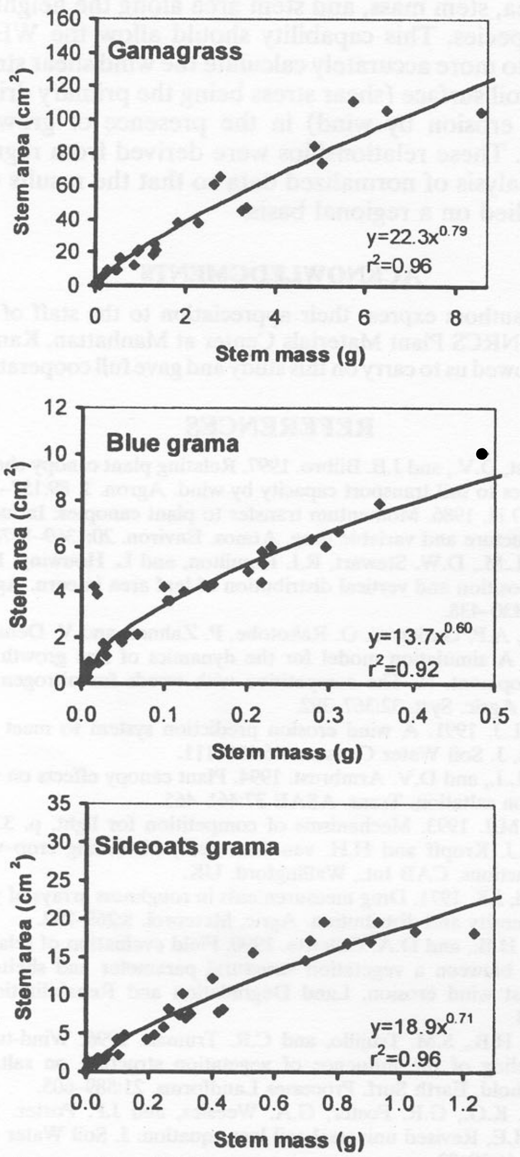

Fig. 2b. Measured (symbols) and regressed (line) stem mass vs. stem area data of eastern gamagrass, blue grama, and sideoats grama.

stem was observed. Normalized stem heights were calculated using the estimated stem heights. Plots of normalized stem height vs. normalized stem mass showed a strong exponential relationship. The next step was to find a function that fit the stem data and also met the criteria established for the leaf mass data (see previous paragraph). An exponential function of the form given in [Eq. 3] fit the stem data well (Fig. 3) with $r^2 > 0.98$ (Table 3).

Table 2. Parameters for computing cumulative leaf mass and leaf area distribution by height using a hyperbolic tangent function Eq. [1].

	Parameter				
Species	*a*	*b*	*c*	*d*	r^2
Big bluestem	0.52	0.58	1.41	2.56	0.99
Switch grass	0.56	0.58	2.09	3.09	0.96
Little bluestem	0.50	0.51	2.44	4.62	0.96
Indian grass	0.50	0.53	1.66	3.42	0.98
Eastern gamagrass	0.50	0.55	1.50	3.11	0.99
Blue grama	0.46	0.57	1.11	2.92	0.97
Sideoats grama	0.46	0.56	1.14	3.10	0.97

$$y = 1 - \exp(ax + bx^2 + cx^3) \qquad [3]$$

where y = normalized stem mass; x = normalized stem height; and a, b, and c = regression parameters.

The exponential shape of the data demonstrate that stem mass per unit height was largest in the stem segment nearest the ground. Below 50% stem height, the cumulative fractions of stem mass ranged from 0.70 for switch grass to 0.84 for eastern gamagrass.

The WEPS plant growth model simulates daily plant height growth (Retta and Armbrust, 1995b) but does not simulate stem height. The stem height needs to be calculated daily so that Eq. [3] can be solved. Stem height can be estimated as follows. At each sampling date, ratios of plant height to maximum plant height (height of plant after flowering) were calculated. Similarly, ratios of stem height to maximum plant height were calculated. These ratios then were plotted and found to fit a zero intercept, second degree polynomial:

$$y = ax + bx^2 \qquad [4]$$

where y = stem height / maximum plant height, x = plant height / maximum plant height, and a and b are regression parameters. The maximum plant heights are input data.

Sample plots of normalized plant height vs. stem height normalized relative to maximum plant height are shown in Fig. 4. The regression parameters for all species are given in Table 4. The results show that as the grass grew, stem height increased at a faster rate than the overall plant height. As a consequence, stem height generally exceeded 80% of plant height as the plant approached maximum height. Thus, Eq. [4] can be incorporated into the WEPS plant growth model and used to estimate stem height.

The WEPS plant growth model calculates daily potential biomass growth using parameters that reflect conditions of maximum growth. The actual daily increment in biomass is computed by adjusting the potential biomass by a water or temperature stress factor. Thus it was necessary to obtain these parameters under conditions that favor optimum or near optimum growth.

CONCLUSIONS

Parameters for calculating leaf and stem areas of seven grass species were determined. Relatively simple relationships were obtained for distribution of leaf mass,

Table 3. Parameters for calculating cumulative stem mass and stem area distribution by stem height using Eq. [3].

	Parameter			
Species	*a*	*b*	*c*	r^2
Big bluestem	−2.968	4.962	−7.878	0.99
Switch grass	−2.594	4.227	−7.829	0.99
Little bluestem	−2.060	1.071	−3.540	0.99
Indiangrass	−2.518	3.297	−7.814	0.99
Eastern gamagrass	−4.637	5.299	−6.597	0.98
Blue grama	−2.841	0.089	−2.180	0.99
Sideoats grama	−1.672	−1.707	−1.395	0.99

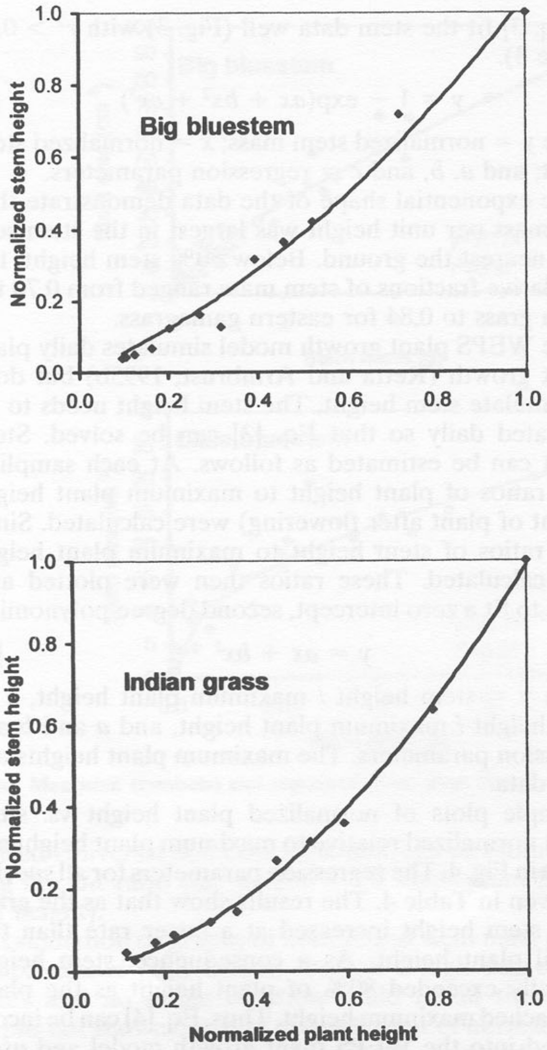

Fig. 4. Measured (symbols) and regressed (line) normalized plant height vs. normalized stem height relative to maximum plant height data for big bluestem and switch grass.

Table 4. Parameters for calculating stem height using Eq. [4].

	Parameter		
Species	***a***	***b***	***r^2***
Big bluestem	**0.505**	**0.536**	**0.98**
Switch grass	**0.574**	**0.484**	**0.98**
Little bluestem	**0.346**	**0.714**	**0.95**
Indiangrass	**0.159**	**0.828**	**1.00**
Eastern gamagrass	**0.313**	**0.657**	**0.98**
Blue grama	**0.702**	**0.348**	**0.98**
Sideoats grama	**0.505**	**0.557**	**0.98**

leaf area, stem mass, and stem area along the height of grass species. This capability should allow the WEPS model to more accurately calculate the wind shear stress at the soil surface (shear stress being the primary driver of soil erosion by wind) in the presence of growing grasses. These relationships were derived from regression analysis of normalized data so that the results can be applied on a regional basis.

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