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Relating Plant Canopy Characteristics to Soil Transport Capacity by Wind

Dean V. Armbrust* and James D. Bilbro, Jr.

ABSTRACT

Federal legislation mandates that wind erosion soil losses be kept to a "tolerable" limit to maintain eligibility for federal farm programs on highly erodible land. Therefore, much interest has been generated in devising wind erosion models that accurately determine the potential erosion from a given site and also evaluate the effectiveness of any control measure. These models require mathematical relationships between surface properties and the transport capacity of the wind. Such relationships are available for soil surface roughness and plant residues, but not for growing crops. Our objective was to establish these relationships for growing crops. We developed a theoretical approach that accounts for the effect of stem area, leaf area, and canopy cover of growing crops on the soil loss ratio, threshold velocity, and transport capacity. The predictive ability of the theory was tested using published data sets from growing plants tested in a wind tunnel. Measured soil loss ratios were highly correlated to predicted values ($r^2 = 0.99$, $P = 0.001$). The results showed that plant area index and canopy cover are highly correlated with reduction in the transport capacity of the wind and, therefore, serve as indicators of the soil protection afforded by growing plants. A plant area index of 0.02 and a canopy cover of 4% reduced the transport capacity of a 16 m s^{-1} wind by 50%. This method for determining the protective ability of a combination of growing plants and standing residue will improve predictive capabilities of wind erosion models for more diverse farm management conditions.

WIND EROSION is common throughout much of the world. It has many consequences, including soil degradation, air pollution, plant and equipment damage, and exacerbation of respiratory ailments. Federal legislation has increased interest in the cause, prediction, and control of wind erosion (Food Security Act of 1985; Food, Agriculture, Conservation, and Trade Act of 1990).

Various types of soil cover have been shown to be effective in reducing wind erosion, including flat crop residues (Chepil, 1944), cotton gin trash (Fryrear and Koshi, 1974), artificial clods (Fryrear, 1984), growing crops (Armbrust and Lyles, 1985), and standing crop residues (Siddoway et al., 1965, Lyles and Allison, 1981). Standing residue is more effective than flat residue, because it absorbs more of the wind's energy (Siddoway et al., 1965).

Prediction models are generally used to design erosion control systems. The Wind Erosion Equation is the most widely used model for prediction of wind erosion (Woodruff and Siddoway, 1965). For future long-term use, a physically based simulation model dubbed WEPS, for Wind Erosion Prediction System, is being developed (Wagner, 1995). To improve near-term prediction capabilities, a Revised Wind Erosion Equation (RWEQ) is also being developed (Fryrear et al., 1994).

Relationships are needed in WEPS and RWEQ to describe the protective role of growing crops. In WEPS, the protective effect is defined as the reduction in above-canopy horizontal shearing stress by the canopy as a function of the leaf area index (LAI) and silhouette area index (SAI). The LAI is defined as the flat area of leaves per unit ground area, and SAI is defined as the silhouette area of stalks and stems per unit ground area. Both LAI and SAI are simulated by the WEPS crop growth submodel.

In the case of RWEQ, the protective effect is the fraction reduction in saltation–creep transport capacity on a loose, smooth surface caused by a growing crop. Because RWEQ does not have a crop growth submodel, it is desirable to express the protection level as a function of crop canopy cover (CP). The CP is the percentage of ground covered by growing canopy when viewed from directly overhead (i.e., nadir view). Use of CP in RWEQ will permit inputs from the RUSLE (Revised Universal Soil Loss Equation) data base (SWCS, 1993), which already contains a large number of CP predictions. Also, the availability of commercial instruments permits additional canopy cover measurements to be obtained quickly and accurately (Armbrust, 1990).

Our objective was to determine the reduction in the transport capacity of the saltation–creep component of wind erosion on a smooth, loose soil surface as a function of plant canopy characteristics (leaf area index, silhouette area index, and canopy cover percent) for a range of wind speeds.

OVERVIEW OF METHODS

To attain the study objective, a number of analytical procedures were used. Earlier studies (van de Ven et al., 1989: Lyles and Allison, 1976) demonstrated that the reduction in

D.V. Armbrust, USDA-ARS, Wind Erosion Res. Unit, Throckmorton Hall, Kansas State Univ., Manhattan, KS 66506; J.D. Bilbro, USDA-ARS, Conservation and Production Systems Res. Unit, P.O. Box 909, Big Spring, TX 79721-0909. Contribution from the USDA-ARS, in cooperation with the Kansas Agric. Exp. Stn., Contribution no. 95-206-J. Received 13 Sept. 1995. *Corresponding author (armbrust@weru.ksu.edu).

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Abbreviations: C_{enb}, base surface emission coefficient; C_{env}, vegetated surface emission coefficient; CP, canopy cover percent; d, stalk diameter; LAI_{FE}, fraction effective LAI; h, stalk height; L, length of tray; LAI, leaf area index; PAI, plant area index; PAI_e, effective plant area index; Q_b, saltation discharge from bare surface; Q_{cb}, saltation discharge transport capacity without stalk interception; Q_{cv}, saltation discharge transport capacity of a vegetated surface; Q_v, soil loss from vegetated trays; R, reduction in saltation–creep transport capacity; RWEQ, Revised Wind Erosion Equation; RUSLE, Revised Universal Soil Loss Equation; SAI, silhouette area index; SLR, soil loss ratio; T, interception coefficient; U_{fs}, freestream wind velocity; U_{tv}, threshold velocity of vegetated surface; WEPS, Wind Erosion Prediction System.

Table 1. Range of values for soil loss ratio (SLR) and plant parameters for four field crops, tested in a wind tunnel (data from Armbrust and Lyles, 1985).

Parameter†	Corn	Cotton	Grain sorghum	Soybean
SLR	0.018–0.97	0.005–0.88	0.004–0.87	0.008–0.96
Stem length, cm	2.50–14.40	2.08–29.78	1.64–15.10	4.75–31.08
Stem diameter, mm	2.79–9.60	2.39–5.96	1.49–8.05	2.59–2.94
Leaf area, cm²‡	17.8–542.6	20.7–469.0	4.4–322.6	12.6–418.3
Stem area, cm²‡	0.70–13.83	0.98–17.77	0.24–7.79	1.23–9.14
Dry mass, g plant⁻¹	0.04–1.76	0.15–4.32	0.01–0.62	0.07–0.99
CP, %§	0.09–11.16	0.26–33.65	0.03–12.47	0.39–8.68
LAI	0.009–0.84	0.004–0.36	0.002–0.50	0.007–0.36
SAI	0.0004–0.02	0.0002–0.01	0.0002–0.02	0.0006–0.01
Population, plants ha⁻¹	53 235–155 610	8 190–165 847	34 807–165 847	53 235–155 610

† SLR, soil loss ratio; CP, canopy cover percent; LAI, leaf area index; SAI, silhouette stem area index.
‡ Determined with a leaf area meter (LI-COR Model LI-3000).
§ Determined from overhead photographs.

soil loss by wind erosion is related closely to the SAI of simulated standing residues.

To assess the protective level of growing crops, it is useful to consider them as composed of two elements: stems, which remain stationary, and leaves, which tend to orient with the airflow. In this study, wind tunnel data on growing corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), grain sorghum [*Sorghum bicolor* (L.) Moench] and soybean [*Glycine max* (L.) Merr.], exposed to a fixed wind speed, were analyzed to determine the effectiveness of the leaf area relative to the stem area in reducing loss of sand (0.297–0.42 mm diameter) from trays (data from Armbrust and Lyles, 1985). Young, flexible leaves contribute little to the reduction of the wind velocity, but as they mature and become larger and less flexible, their effectiveness increases. An effective plant area index (PAI_e) was defined for growing crops as the sum of the SAI and an effective LAI. Effective LAI is the fraction of the total LAI that aids in reducing soil loss more than stems alone.

Next, increases in threshold wind velocities for increasing levels of PAI_e were determined. The threshold velocity, or the wind speed needed to initiate soil movement, is an essential parameter for calculating transport capacity. Because direct

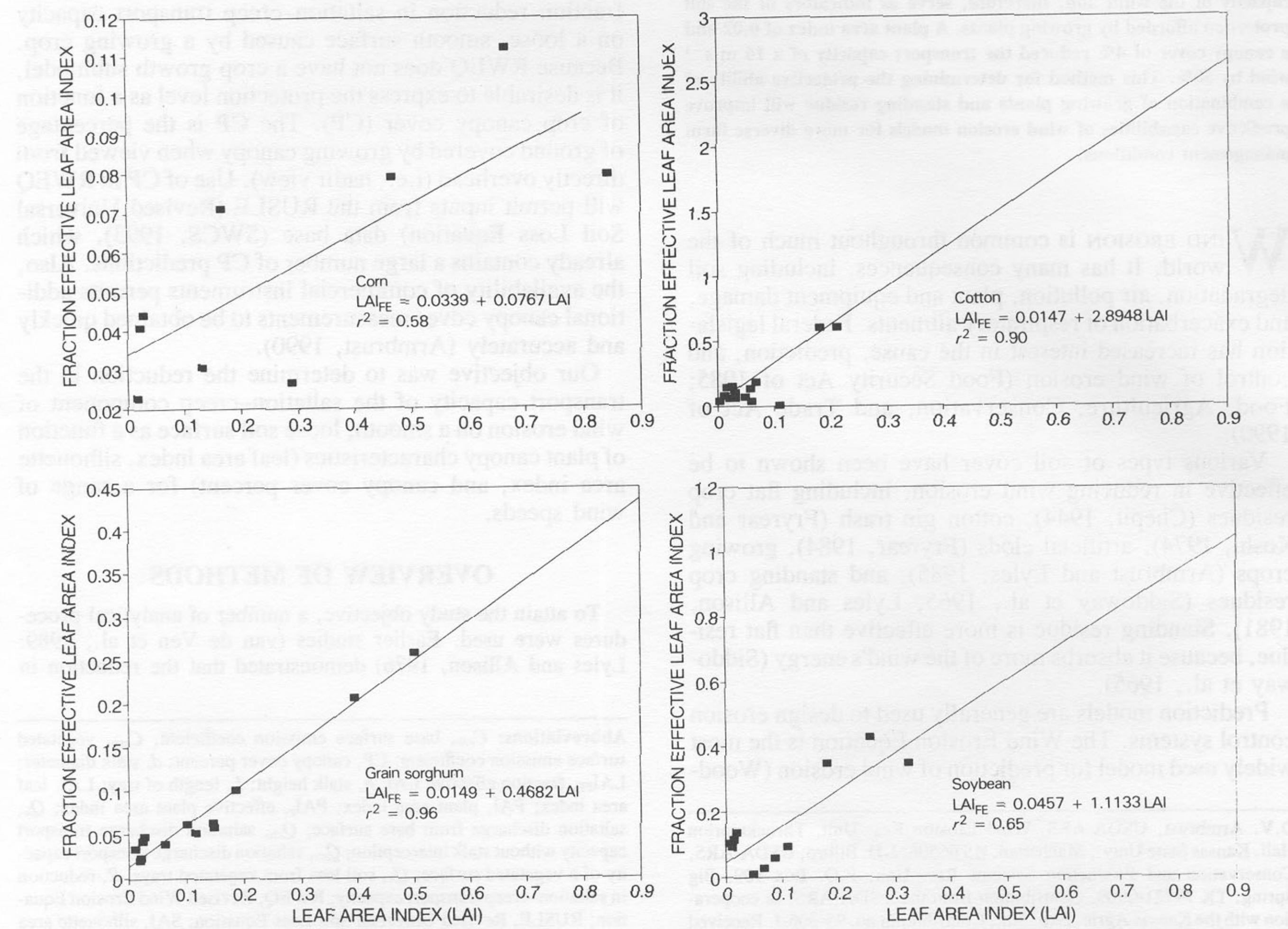

Fig. 1. Relationship of leaf area index (LAI) to fraction effective leaf area index (LAI_{FE}) for corn, cotton, grain sorghum, and soybean plants tested in a wind tunnel.

Table 2. Prediction equations for fraction effective leaf area index (LAI_{FE}) and effective plant area index (PAI_e) as a function of canopy cover percent (CP) for plants of four field crops, tested in a wind tunnel (data from Armbrust and Lyles, 1985).

Crop	LAI_{FE}	r^2	PAI_e	r^2
Corn	$0.0336 + 0.0058CP$	0.58	$0.0006 + 0.0043CP + 0.0004CP^2$	0.95
Cotton	$0.0325 + 0.0482CP$	0.91	$0.0012 + 0.0012CP + 0.0005CP^2$	0.76
Grain sorghum	$0.0250 + 0.0186CP$	0.98	$0.0013 + 0.0027CP + 0.0008CP^2$	0.96
Soybean	$0.0267 + 0.0429CP$	0.65	$-8.8^{-6} + 0.0009CP + 0.0018CP^2$	0.71

measurements of the threshold velocity were not available, threshold velocities were calculated using measured soil loss data to determine parameters for a theoretical equation (Hagen and Armbrust, 1994) that describes the wind tunnel saltation discharge. With this information, the reduction in saltation–creep transport capacity (R) as a function of PAI_e was calculated for a range of wind speeds for the indoor-grown crops.

Unfortunately, the indoor-grown crops used in the wind tunnel differed from field-grown crops in their canopy structure. Stems were smaller in diameter and had longer internodes, and leaves were longer and narrower. Also, total aboveground dry mass was lower than that of field plants of the same age. Thus, measured SAI and LAI of field-grown crops were used to calculate their PAI_e and R. Finally, measured SAI and LAI of field-grown crops were related to their measured CP. This permitted calculation of the PAI_e, and subsequently R, as a function of CP for various crops for a range of wind speeds.

THEORY AND ANALYSES

Determination of Effective Plant Area Index (PAI_e)

From wind tunnel studies using erodible sand particles (0.15–0.59 mm diam.) (Lyles and Allison, 1976; van de Ven et al., 1989), the effect of stalks on the soil loss ratio (SLR_{stalk}) from protected and bare trays at 13.41 m s^{-1} free stream wind speed has the exponential form

$$SLR_{stalk} = \exp[-A(PAI^B)] \quad [1]$$

where A and B are shape parameters and PAI is the plant area index (which, for canopy composed of stalks only, is equal to the SAI).

Assuming that the same form is valid for a growing crop canopy, but now

$$PAI_e = SAI + LAI_{FE}\, LAI \quad [2]$$

where LAI_{FE} is the fraction of effective LAI. Eq. [1] becomes

$$SLR = \exp[-A(PAI_e^B)] \quad [3]$$

Using data from wind tunnel studies (Lyles and Allison, 1976; van de Ven et al., 1989), average values of 20.05 and 0.669 were calculated for A and B, respectively. Next, using wind tunnel data on SLRs of growing crops with rows perpendicular to the wind (Armbrust and Lyles, 1985), Eq. [2] and [3] were solved for LAI_{FE}. Ranges of values used to determine LAI_{FE} for the four crops are given in Table 1. The calculated values for LAI_{FE} as a function of LAI are illustrated in Fig. 1, along with estimating equations for each crop. To further characterize the structure of the wind tunnel plants, the relationship of LAI_{FE} to CP was determined using linear regression (Table 2).

Finally, to test the concept that the form of Eq. [3] is applicable to growing crops, the three replications of data obtained at a constant wind speed of 13.4 m s^{-1} (Armbrust and Lyles, 1985) were split. Using one replication of the data, prediction equations for SLR were determined for each crop and also a composite equation for all crops (Fig. 2). The other two replications were then used to develop the relationship between the predicted and measured SLRs (Table 3).

Determination of Reduction in Transport Capacity (R)

Unfortunately, SLR is a function of wind speed and does not provide a direct measure of the effect of growing crops on transport capacity of the wind; hence, additional analyses were required. A model to predict soil loss (Hagen and Armbrust, 1994) was adapted to derive needed coefficients and determine reduction in transport capacity as a function of wind speed.

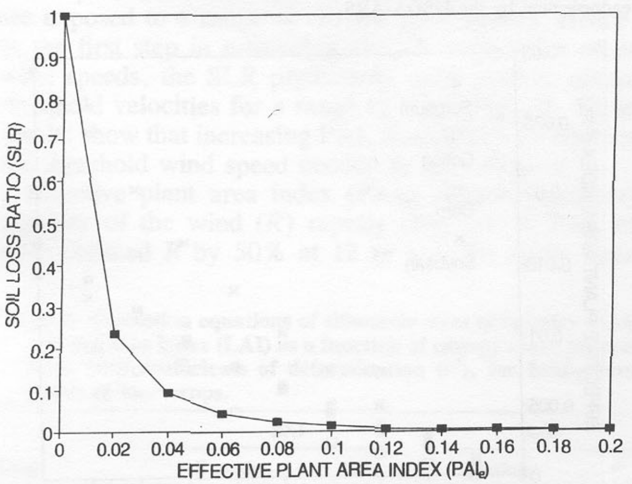

Fig. 2. Relationship of effective plant area index (PAI_e) of all crops tested in a wind tunnel to the *soil loss ratio (SLR)* at 13.4 *m s^{-1}* free stream wind speed.

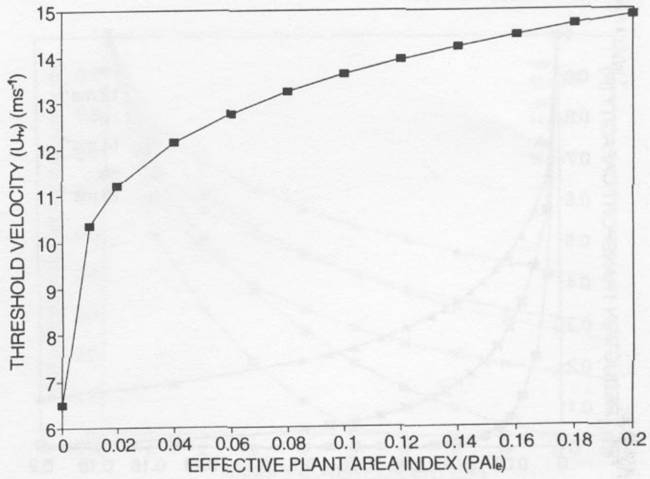

Fig. 3. Predicted effect of effective plant area index (PAI_e) of plants tested in a wind tunnel on the threshold freestream wind velocity (U_{tv}).

Table 3. Prediction equations for soil loss ratio (SLR) as a function of effective plant area index (PAL_e) and coefficients of determination (r^2), slope, and y-intercept of predicted vs. measured SLR for plants of four field crops, tested in a wind tunnel (data from Armbrust and Lyles, 1985).

		Simulated vs. measured SLR		
Crop	SLR equation	r^2	Slope	y-intercept
Corn	$\exp(-20.0571PAI_e^{0.6694})$	0.998	0.94	−0.0002
Cotton	$\exp(-20.2525PAI_e^{0.6761})$	0.999	1.02	0.0002
Grain sorghum	$\exp(-20.4161PAI_e^{0.6803})$	0.985	0.97	0.0071
Soybean	$\exp(-15.1759PAI_e^{0.5841})$	0.999	0.84	0.0088
All crops	$\exp(-22.9179PAI_e^{0.7064})$	0.984	0.95	0.0084

Bare Tray Case

Sand loss from a loose, bare tray can be modeled as

$$Q_b = Q_{cb}[1 - \exp(-C_{enb}L)] \quad [4]$$

where Q_b is the saltation discharge from bare surface, in kg m^{-1} s^{-1}; Q_{cb} is the saltation discharge transport capacity without stalk interception, in kg m^{-1} s^{-1}; C_{enb} is the emission coefficient, bare surface, in m^{-1}; L is the length of tray, in m; and

$$Q_{cb} = 0.00014U_{fs}^2(U_{fs} - 6.5) \quad [5]$$

where U_{fs} is the freestream wind velocity, in m s^{-1}. Using the measured soil loss from bare trays (Armbrust and Lyles, 1985) and Eq. [5], we solved Eq. [4] for C_{enb}.

Vegetated Tray Case

We then calculated the emission coefficient (C_{env}) for the vegetated surface for all plant populations of the four crops, assuming that emission is restricted over two residue diameters downwind plus the soil area protected directly from the wind by the stalk basal area.

$$C_{env} = C_{enb}(1 - 0.0023d\,SAI/h) \quad [6]$$

where d is the stalk diameter in mm and h is the stalk height in m. Stalks also intercept saltating soil, and the interception coefficient T, in m^{-1}, was calculated as

$$T = SAI/h \quad [7]$$

In Eq. [7], we assumed that leaves were above most of the saltating soil or oriented parallel to the streamlines in the wind tunnel, and so did not contribute to interception.

Saltation–creep loss from a loose surface with growing vegetation can be expressed with the following equation (Hagen and Armbrust, 1994).

$$Q_v = Q_{cv}[C_{env}/(C_{env} + T)]\{1 - \exp[-(C_{env} + T)L]\} \quad [8]$$

Eq. [8] was solved for the saltation discharge transport capacity of a vegetated surface (Q_{cv}) using measured soil losses from vegetated trays (Q_v). Next, we determined the threshold velocities (U_{tv}) of the vegetated surfaces from Eq. [9], as illustrated in Fig. 3.

$$Q_{cv} = 0.00014[U_{fs}^2(U_{fs} - U_{tv})] \quad [9]$$

Finally, the reduction of transport capacity (R) by the vegetation was calculated using Eq. [10] for a range of wind tunnel freestream wind speeds (Fig. 4).

$$R = [C_{env}/(C_{env} + T)](Q_{cv}/Q_{cb}) \quad [10]$$

To apply Eq. [10] to either greenhouse or field-grown crops, one needs both LAI and SAI. Hence, to facilitate use in RWEQ, prediction equations were developed for LAI and SAI as functions of CP, using regression techniques. To develop these relationships for field-grown crops, data from weekly samplings of SAI, LAI, and CP for cotton (*Gossypium hirsutum* L.) (Bilbro, 1991), grain sorghum [*Sorghum bicolor* (L.) Moench] (Armbrust and Bilbro, 1993), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (unpublished data) were used. For all crops, the leaf area and stem area was measured with a LI-COR[1] LI-3000 leaf area meter, or the stem area was calculated from length × diameter. Canopy cover was obtained by method of Armbrust (1990) (Tables 4 and 5).

Using the relationships in Table 5 and Fig. 1, PAI_e was calculated as a function of CP for the four field crops (Fig. 5). Next, predictions of R as a function of CP were calculated

[1] Use of brand names is for information only and does not indicate an endorsement by the USDA-ARS.

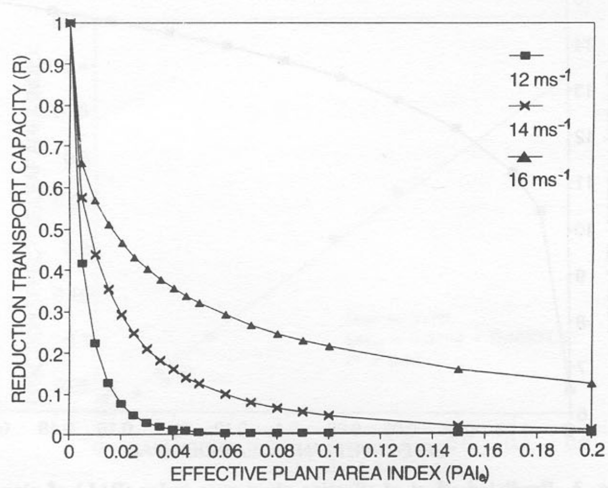

Fig. 4. Predicted effect of effective plant area index (PAI_e) of plants tested in a wind tunnel on the reduction of saltation–creep transport capacities (R) for various wind speeds.

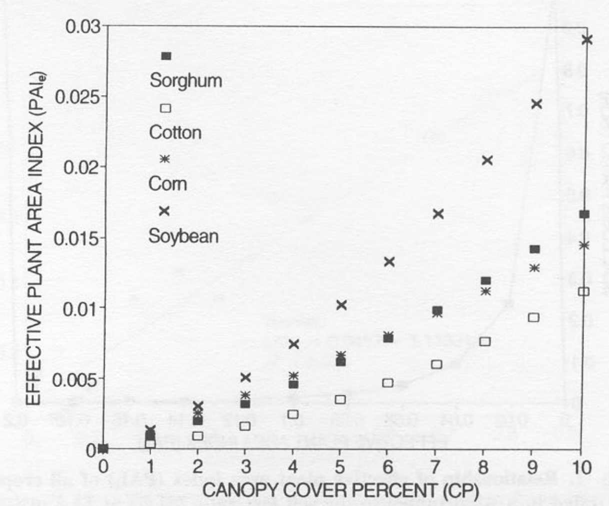

Fig. 5. Effective plant area index (PAI_e) as a function of canopy cover (CP) for field crops.

Table 4. Prediction equations for silhouette stem area index (SAI) and leaf area index (LAI) as a function of canopy cover percent (CP) for plants of four field crops, tested in a wind tunnel (data from Armbrust and Lyles, 1985).

	SAI		LAI	
Crop	Equation	r^2	Equation	r^2
Corn	0.0006 + 0.0018CP	0.996	−0.00009 + 0.0746CP	0.999
Cotton	0.0008 + 0.0004CP	0.958	0.0108 + 0.0096CP	0.963
Grain sorghum	0.0009 + 0.0014CP	0.954	0.0152 + 0.0415CP	0.960
Soybean	0.0006 + 0.0008CP	0.972	−0.0228 + 0.0420CP	0.986

for field crops (Fig. 6). Last, predictions of R were calculated directly from the measured LAI and SAI of the field-grown crops and compared with the R-values obtained from predictions based on canopy cover (Table 6).

DISCUSSION

Fraction effective leaf area index (LAI_{FE}) differed by crop and increased as leaf area index (LAI) increased (Fig. 1). While intercepts were not statistically different (SAS, 1985) for the four crops, the slopes for cotton and soybean were different. Among the tested crops, cotton leaves were the most effective on a per unit area basis. Leaves of young seedlings tend to orient along wind streamlines and are less effective than stems in controlling wind erosion. For the smallest plants, effective leaf area was often 5% or less of the total leaf area.

While plants used in this analysis are small (LAI < 1.0), all crops controlled soil loss (SLRs near 0 at 13.4 m s^{-1} free stream wind speed) at some plant population and canopy size (Table 1). For these small plants, the LAI_{FE} varied linearly with CP (Table 2). This result was expected, because canopy cover is determined mainly by leaf area. However, prediction equations for PAI_e as a function of CP were nonlinear, because of the strong influence of the stem area on erosion (Table 2).

The relationship between predicted and measured SLR had slopes near 1, intercepts near 0, and high coefficients of determination (r^2 = 0.984–0.999), indicating that SLR values can be reliably predicted from PAI_e (Table 3). However, the SLR values are valid only for the test wind speed (13.4 m s^{-1}); under field conditions, plants are exposed to a range of erosive wind speeds. Hence, as the first step in estimating erosion control for other wind speeds, the SLR predictions were used to obtain threshold velocities for a range of PAI_e (Fig. 3). These results show that increasing PAI_e from 0 to 0.08 doubles the threshold wind speed needed to start erosion.

Effective plant area index (PAI_e) reduced transport capacity of the wind (R) rapidly (Fig. 4). A PAI_e of 0.02 reduced R by 50% at 12 m s^{-1}. To apply these results to various field wind speed distributions in a range of climates, average R-values weighted by duration of each wind speed must be calculated. Standing vegetation reduces wind erosion through three mechanisms: raising the threshold wind speed, reducing shear stress at the soil surface, and intercepting saltating particles. All of these mechanisms are incorporated into the calculation of R.

To facilitate application of RWEQ, canopy cover percent (CP) was also investigated as a predictor of R. The CP of both greenhouse- and outdoor-grown plants was linearly related to silhouette area index (SAI) and leaf area index (LAI) (Tables 4 and 5). Differences in the plant canopy structure of greenhouse-grown vs. field-grown plants accounts for the differences in the equations. Greenhouse plants had longer and narrower stems and leaves than field plants of the same age.

A PAI_e was calculated for the field crops for various levels of CP, using the equations in Fig. 1 and Table 5 (Fig. 5). While the greenhouse and field plants had different proportions of leaves and stems, the PAI_e of the field plants as a function of CP was also nonlinear and varied among plants (Fig. 5). For all canopy covers less than 10%, soybean had the highest PAI_e levels among the four row crops tested. Calculations of R as a function of CP are illustrated in Fig. 6. As the wind speed increased, more canopy cover (CP) was needed to reduce the transport capacity of the wind. Growing plants were very effective in controlling wind erosion; e.g., a 50% reduction in transport capacity of a 16 m s^{-1} wind was obtained with a canopy cover of 4%. Differences in R

Table 5. Prediction equations of silhouette stem area index (SAI) and leaf area index (LAI) as a function of canopy cover percent (CP), with coefficients of determination (r^2), for field-grown plants of four crops.

	SAI		LAI	
Crop	Equation	r^2	Equation	r^2
Corn	0.0006CP	0.963	0.0179CP	0.948
Cotton	0.0002CP	0.882	0.0054CP	0.915
Grain sorghum	0.0006CP	0.994	0.0136CP	0.953
Soybean	0.0007CP	0.776	0.0125CP	0.917

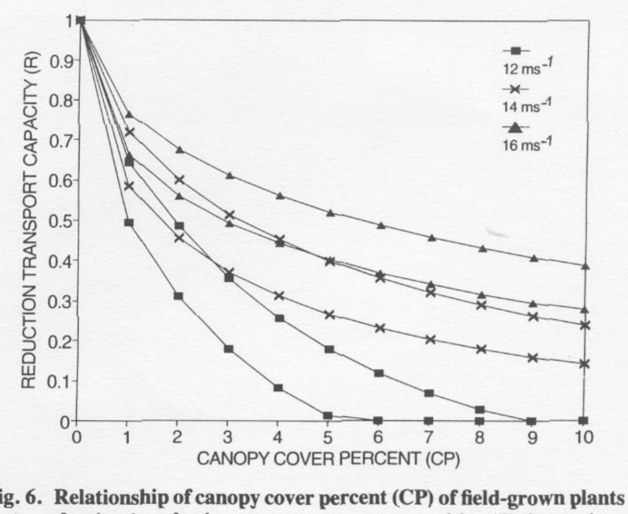

Fig. 6. Relationship of canopy cover percent (CP) of field-grown plants to reduction in saltation–creep transport capacities (R) for various freestream wind speeds. Lines with same symbol are maximum and minimum values.

Table 6. Coefficient of determination, slope, and *y*-intercept for reduction in transport capacity (*R*) calculated from canopy cover percent (CP) vs. calculated from measured leaf area index (LAI) and stem area index (SAI), for four field crops.

Crop	r^2	Slope	*y*-intercept
Corn	0.951	1.008	−0.0400
Cotton	0.970	0.9846	−0.0218
Grain sorghum	0.983	0.9243	0.0106
Soybean	0.858	1.0437	0.0364

among crops are somewhat smaller than differences in *R* among wind speeds.

The use of LAI and SAI predicted from CP was compared with the use of measured LAI and SAI values in the calculating reductions in transport capacity (*R*). While using LAI and SAI directly is preferred, estimating those values from CP also gives reasonable estimates of the reduction in transport capacity (Table 6).

While the equations developed in this study may not apply to all crops, they provide a means of estimating the protective effect of growing row crop plants, using SAI and LAI from the CROP submodel of WEPS or estimated canopy cover (from the RUSLE data base) in RWEQ. The equations provide a way to combine the effects of growing plants and standing residue by adding their silhouette area indices. These results will improve the predictive capabilities of wind erosion models (WEPS, RWEQ) for farm management systems that maintain growing crops and standing crop residues on the soil surface for wind erosion control.

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