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Effect of canopy leaf distribution on sand transport and abrasion energy

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ABSTRACT

During times when crop canopies are short or sparse, wind erosion can uncover plant roots, deplete the soil resource, and damage plants by abrasion and desiccation. Few studies have considered the effects of position and number of leaves on sand transport and the distribution of the sand abrasion energy. The objectives of this study were to determine the effects of number and distribution of leaves on threshold velocities, sand transport rates, and relative abrasion energy among simulated dicotyledonous plant canopies. Six canopies were tested in a wind tunnel with two levels of leaf area index (LAI), two different maximum leaf heights, and either two or four leaves per plant with maximum freestream wind speeds from 12 to 17 m s^{-1}. The leaf heights were selected to position the lowest leaves to be either intercepting saltating sand or largely above the saltation layer. The wind tunnel was a 1.52 W × 1.82 H × 15.3 L m push-type recirculating tunnel with the floor covered with a layer of sieved sand. Sand discharge and relative abrasion energy were measured during 3-min duration test runs. For canopies with two leaves, the experimental sand transport capacity was reduced most when the leaves were highest above the surface even though they were intercepting saltation when in their lowest positions. As expected, canopy LAI was directly related to threshold velocity and inversely related to sand transport capacity. Total abrasion energy impacting the target soil channel containers located vertically in the canopy increased with wind speeds above the threshold. Within canopies, high wind speeds increased height of maximum abrasion but often still caused less total abrasion per unit sand discharge than over a bare, sandy surface. When leaves were located nearest the surface, they modified the vertical abrasion profiles by deflecting a portion of the sand impact energy upward in the wind stream. Overall, the canopies modified both the profiles and normalized abrasion energy of the sand discharge when compared with a bare, sandy surface. Hence, it may be important to place test plants within a canopy of similar plants—to allow development of a fully developed velocity profile in the canopy by using a minimum upwind fetch of about 70 canopy heights in a wind tunnel—when conducting plant abrasion tests using sand to achieve results representative of plants in the interior of a field. In contrast, abrasion on inter-row flat soil containers was independent of wind speeds, but was higher without a canopy compared with measurements in the canopy for a given sand discharge.

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1. Introduction

During times when crop canopies are short and/or sparse, wind erosion can damage plants by abrasion and desiccation. Standing biomass controls wind erosion by reducing the friction velocity under the biomass to lower levels at the soil surface and intercepting a portion of the mobile particles to further reduce transport capacity. Young plants can provide thin, standing biomass canopies but are susceptible to damage from the wind and from mobile particles they intercept during a wind erosion event. Current information on the effect of canopy and aerodynamic variables is limited.

In laboratory wind tunnel tests seedling green beans suffered severe damage under various treatments of wind and sandblasting (Skidmore, 1966). Wind speeds of 13.4 m s^{-1} and higher with any tested sand flux above zero resulted in high plant damage levels. Duration of exposure, from 5 to 15 min, resulted in a linear increase in damage score, with scores assigned based on visual inspection. In a similar study (Armbrust, 1972), soybean seedlings sustained changes in metabolic processes due to sandblast injury before there was any visual damage.

Erosion also may uncover plant roots as well as deplete the soil resource. Several studies have reported sand transport among standing stalks (Lyles et al., 1974; Lyles and Allison, 1981; Van de Veen et al., 1989; Hagen, 1996). Plant abrasion studies,

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however, typically have not considered effects of position and number of leaves on sand transport and the distribution of the sand abrasion energy within a plant canopy (Fryrear, 1971; Baker et al., 2009). Because of the effect of the plant canopy on the velocity profile in the wind stream, and thus on the particle transport, results from studies with a few plants rather than a large area of plant canopy likely only apply at the edge of a field. The plants in the interior of the field will be subject to different velocity profiles and different abrasion characteristics than those at the edge of the field.

Wind erosion control by low populations of standing real or simulated biomass has often been measured in wind tunnels as a soil loss ratio (SLR), defined as the ratio of tray soil loss with standing biomass to tray soil loss at the reference condition of the tray surface (Lyles and Allison, 1976, 1981; Armbrust and Lyles, 1985; van de Veen et al., 1989). Mendez and Buschiazzo (2008) measured SLR under field conditions and found good agreement with the form of existing relationships between SLR and flat residue cover, but observed a 37% difference in measured coefficients compared with wind tunnel results because SLR is a function of wind speed. The SLR is a particularly strong function of wind speed near the threshold wind speed of standing biomass. To avoid this difficulty, the ratio of soil surface to above-biomass friction velocity and a particle interception coefficient were proposed as variables for use in physically-based erosion models (Hagen and Armbrust, 1994). When many leaves or stalks intercept the saltating sand, the interception tends to reduce discharge by increasing the effective threshold for transport capacity from the dynamic towards the static threshold friction velocity. The response of growing crops in a wind stream is particularly complex and, currently, direct measurements of these variables are not available. However, indirect calculations that were based on earlier SLR measurements (Armbrust and Lyles, 1985) have been reported for a few growing crops (Armbrust and Bilbro, 1997). That study showed that the effective plant area index (PAI), defined as the sum of silhouette area index and effective leaf area index, was highly correlated with reduction in the transport capacity of the wind, leading the authors to conclude that PAI can serve as an indicator of the soil protection afforded by growing plants.

Seedlings are most prone to erosion damage, so accurate information during this crop stage is critical. Kinetic energy of impacting sand grains has been suggested as a main factor causing seedling damage (Fryrear and Downes, 1975). However, some preliminary data show that the kinetic energy for a given sand discharge varies, because standing biomass modifies the near-surface wind profile. Burri et al. (2011) found that various densities of vegetative canopies of Perennial Ryegrass (*Lolium Perenne*) strongly affected the vertical profile of particle mass flux in a wind tunnel compared with a bare surface. In agricultural fields flat residue cover also is often present along with growing biomass, but controls erosion somewhat differently than standing biomass (Hagen, 1996). In addition, preliminary tests demonstrated that moving leaves vertically along the stem without changing leaf area can affect threshold and other flow properties (Hagen and Armbrust, 1994). Thus, threshold velocities, interception coefficients, transport capacity, and kinetic energy measurements are needed for typical surface conditions with small seedlings.

The objectives of this study were to determine the effects of number and distribution of leaves on threshold velocities, sand transport rates, and relative abrasion energy among simulated dicotyledonous plant canopies such as typical varieties of beans.

2. Materials and methods

A series of wind tunnel experiments was conducted using sand alone and sand covered by thin canopies of simulated standing leafy biomass protruding above the sand surface. The form of the simulated biomass was selected to resemble young dicotyledonous plants (Fig. 1). The stem height remained constant at 170 mm, while the leaf height and number varied. The four-leaf plant configurations maintained the same 70 mm spacing between the top and bottom leaf pairs for both the 130 mm and the 170 mm top leaf heights. This was done to mimic typical growth patterns for dicotyledonous plants and resulted in the bottom leaves being at different heights when the top leaf heights differed. The maximum leaf heights are referred to as *canopy height* hereafter. The fixed stem height is only referred to as stem height. The tunnel test configurations and biomass characteristics are summarized in Table 1. The leaf area index (LAI) was calculated using the average measured leaf area per plant and then dividing by the total tunnel floor area occupied per plant. The test area in the downwind section of the wind tunnel with the biomass and sensors is illustrated in Fig. 2.

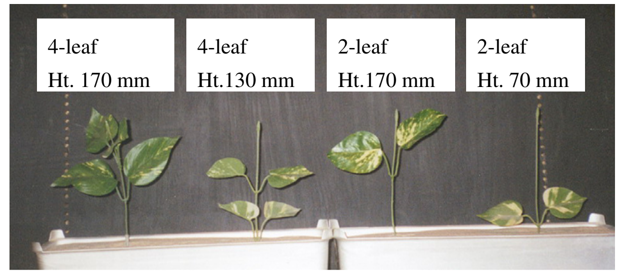

Fig. 1. Four variations of the simulated standing biomass used in wind tunnel tests showing height of top leaf.

In the experiments, quartz sand 0.29–0.42 mm diameter was placed 50 mm deep over the entire floor of a push-type, recirculating wind tunnel with a 1.52 W × 1.82 H × 15.3 L m working section. The free-stream wind velocity as well as wind velocity profiles at four locations near the downwind end of the tunnel, 14 m downstream from the fan section, were measured from near the sand surface to a height of 471 mm. Pitot tubes measuring the velocity profile were located at heights of 20, 31, 41, 61, 86, 111, 140, 151, 161, 181, 206, 231, 260, 271, 281, 301, 326, 351, 380, 391, 401, 421, 446, and 471 mm above the sand surface. The free-stream velocity was measured at 1.3 m above the tunnel floor centered between the tunnel sidewalls, while the velocity profiles were measured at both 0.3 and 0.4 m from the sidewall with two profiles immediately upwind and two profiles immediately downwind of plant rows. The profiles were measured at two different wind velocities below the threshold for sand movement using pitot-static tubes. Electronic transducers were used to measure temperature, barometric pressure, and differential pitot-static tube pressures. The latter transducer had 0–25 mm water pressure range with 0.03% linearity and 0.05% repeatability. The pressure measurements were corrected for barometric pressures and temperature. Finally, simultaneous measurements of the freestream wind speed were used to mathematically eliminate any offset differences among the pressure transducers. The aerodynamic roughness (Z_0), the displacement height (D) and the friction velocity above the biomass (U_{*v}) were calculated from the wind velocity (U) profiles contained in the well-known log-law of the form (Greeley and Iversen, 1985).

$$U = \left(\frac{U_{*v}}{0.4}\right) \ln\left(\frac{Z - D}{Z_0}\right) \quad (1)$$

where Z is height above the sand surface.

For the bare sand surface, D was set equal to zero, and the surface threshold friction velocity (U_{*0t}) for initial sand movement

Table 1
Dimensions and spacing of simulated plants used in wind tunnel tests.

Maximum leaf height[1] (mm)	Leaves per plant (number)	Stem and petiole diameters (mm)	X-spacing, parallel to wind (mm)	Y-spacing, across wind (mm)	Stem and petiole area index ($m^2\ m^{-2}$)	Leaf area index ($m^2\ m^{-2}$)
170[a]	4	2	710	100	0.0076	0.19
130[a]	4	2	710	100	0.0065	0.19
170	2	2	710	100	0.0062	0.095
70	2	2	710	100	0.0034	0.095
170	2	2	710	200	0.0031	0.047
70	2	2	710	200	0.0017	0.047

[a] The lower leaves on the four-leaf plants were at 100 and 60 mm heights, respectively, for 170 and 130 mm maximum leaf heights.

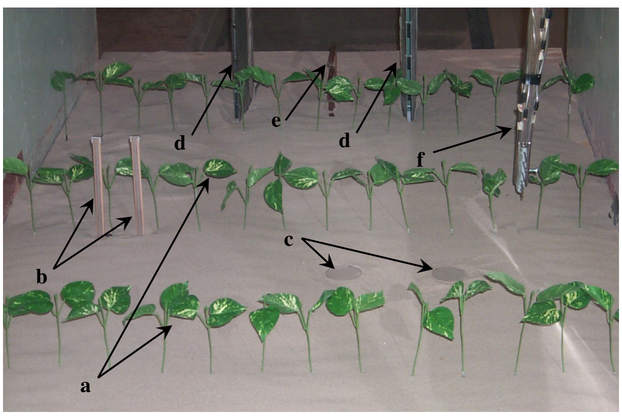

Fig. 2. Downwind end of wind tunnel depicting 2-leaf simulated standing biomass (a), two vertical channel consolidated soil abrasion sensors mounted in plant row (b), two abrasion sensors mounted level with sand surface (c), two vertical slot sand samplers (d), sand profile tube samplers (e), and rake of pitot-static tubes (f).

was obtained by using the slot samplers in the following procedure. The sand discharge, q (g cm^{-1} s^{-1}), was measured for 3 wind speeds slightly above U_{*0t}. Then, U_{*0t} and the coefficient A were calculated by using Table Curve 2D (SPSS Inc., 1997) to fit q and friction velocity, U_*, to a saltation transport equation (Greeley and Iversen, 1985) of the form

$$q = AU*^2(U_* - U_{*0t}) \tag{2}$$

The slot samplers were wedge-shaped with a 5 mm front opening, 44 mm maximum width, and 698 mm height. The sides were vented with fine screens and had sand catch efficiencies of 96–100%.

A two-step process was used to calculate the unknown values in Eq. (1). First, a conservation of mass methodology developed by Molion and Moore (1983) was used to calculate separate D values for each standing biomass canopy. This methodology uses an estimate of the surface aerodynamic roughness below the canopy along with integration by the trapezoidal rule of the wind speed profile measured from the surface to estimate the displacement of the incompressible bulk flow caused by the presence of the canopy. The log-law (Eq. (1)) was then solved for multiple U_{*v} and a single Z_0 in the applicable log-law regions above the bare sand and above each canopy. To minimize errors in estimating U_{*v}, a software algorithm (Ling, 1976) was used that estimates the Z_0 from multiple velocity profiles over a range of three wind velocities below the threshold for sand movement.

For wind velocities above the threshold for sand movement, U_{*v} were assumed to increase in direct proportion to the free-stream velocity. Test runs were typically 3 min duration with the wind velocities averaged and recorded each minute.

For each test surface, total sand discharge at the downwind end of the wind tunnel was measured using two vertical slot samplers. In addition, vertical profiles of the sand discharge were also measured by a series of tube inlets that discharged into containers below the tunnel floor. In the sand discharge tests, 5 wind velocities with 3 replications at each velocity were used. Three wind velocities were selected to insure low levels of saltation to determine saltation threshold and then 2 wind speeds were selected to produce moderate levels of sand transport within each canopy. The sand bed at the upwind end of the wind tunnel was replenished as needed.

To provide a comparable field basis among the tunnel tests, the wind tunnel friction velocities above the biomass were converted to typical weather station wind speeds at 10 m height using an approximation method (Panofsky and Dutton, 1984).

$$U_{*s} = U_{*v}\left(\frac{Z_{0s}}{Z_0}\right)^{0.067} \tag{3}$$

and the log-law (Eq. (1)).

$$U_{10} = \frac{U_{*s}}{0.4}\ln\left(\frac{10^4}{25}\right) \tag{4}$$

where U_{*s} is the station friction velocity, and Z_{0s} is the station aerodynamic roughness assumed to be 25 mm.

During each sand run, the effective kinetic energy transmitted to the surface from sand grain impacts was estimated by weighing the loss of consolidated soil abraded from small trays placed level with the sand surface near the downwind end of the wind tunnel. The abrasion losses from the surface impact trays were evaluated with and without a canopy as measured by the coefficient of abrasion (Can). The Can (m^{-1}) is defined as the tray soil loss from abrasion (kg m^{-2}) divided by the passing saltation discharge (kg m^{-1}). Similarly, vertical profiles of the abraded soil loss were measured with vertical channels filled with consolidated soil. To estimate impacts on plants, the vertical channels were placed in the plant rows, but not covered by any leaves. Total soil loss from the channels was measured by weighing the channels before and after sand runs. The vertical distribution of abraded soil loss from each channel was measured using a micrometer. The abrasion samplers consisted of uniform, weakly consolidated soil without cracks created by puddling and then slowly drying a soil mixture composed of 90% Haynie very fine sandy loam and 10% Kahola silt loam. The abrasion sensors were calibrated by dropping sand grains at terminal velocity on the tilted surfaces of some of the samplers. The abrasion losses from the surfaces were highly repeatable between replicated tests. A test of variance (Holm–Sidok method, Jandel Scientific, 1994) was used to compare the Can of the surface trays and the abrasion loss from the channels within different canopies and without a canopy.

3. Results and discussion

The absolute aerodynamic roughness (Z_0) was largest (16.5 mm) for the 170-mm-tall plants with leaf area index,

Table 2
Means and ±standard deviations of test wind speeds and dimensionless aerodynamic parameters of simulated plants in wind tunnel tests.

Leaf area index (LAI) (m^2/m^2)	Maximum leaf height (H) (mm)	Free-stream wind speeds (m s^{-1})	$\frac{Z_0}{H}$ (mm/mm)	$\frac{D}{H}$ (mm/mm)	$\frac{U_{*0t}}{U_{*v}}$ (m s^{-1}/m s^{-1})
0.19	170	8.89 ± 0.06 11.29 ± 0.04	0.065 ± 0.004	0.518 ± 0.034	0.273 ± 0.008
0.19	130	9.41 ± 0.02 11.82 ± 0.06	0.109 ± 0.015	0.460 ± 0.168	0.221 ± 0.012
0.095	170	7.30 ± 0.13 9.46±.04	0.097 ± 0.004	0.333 ± 0.021	0.297 ± 0.016
0.095	70	7.19 ± 0.05 9.10 ± 0.05	0.062 ± 0.007	0.811 ± 0.054	0.361 ± 0.019
0.047	170	6.68 ± 0.11 7.96 ± 0.06	0.057 ± 0.001	0.261 ± 0.006	0.389 ± 0.018
0.047	70	5.55 ± 0.03 6.69 ± 0.07	0.052 ± 0.001	0.597 ± 0.004	0.502 ± 0.018

LAI = 0.095 (Table 2). More leaf area and particularly less leaf area than 0.095 decreased Z_0. Penetration of turbulent eddies into the plant canopy caused the 170 mm plants with low LAI to have small relative displacement heights (D H^{-1}).

For the sand surface used in this study, the surface threshold friction velocity (U_{*0t}) was 0.24 m s^{-1}. When converted to typical weather station wind speeds at 10 m height, using Eqs. 3 and 4, the canopy threshold velocities ranged from 8.5 m s^{-1} (for 70 mm plants with LAI = 0.047 m^2/m^2) to 17.2 m s^{-1} (for 130 mm plants with LAI = 0.19 m^2/m^2). Threshold velocities required to initiate saltation generally increased with both LAI and canopy height. An exception was the 130 mm-tall, four-leaf canopy that provided more surface protection than the 170 mm-tall, four-leaf canopy. Apparently the shorter canopy improved protection by being more effective at increasing wind drag as well as intercepting saltation due to the closer proximity of the leaves to the surface. At the threshold of sand movement below the canopy, a useful measure of the plant canopy protection is the ratio of surface-to-above canopy friction velocities (U_{*0t} U_{*v}^{-1}) (Table 2). This ratio of plant protection is useful because its variation with wind speed is small (Raupach, 1992). In contrast, the often-reported soil loss ratio (Lyles and Allison, 1980, 1981) is a function of wind speed. As expected, tall canopies with more leaves provided increased surface protection.

The wind tunnel measurements were used to simulate the field response of the canopies to wind directions normal to the rows as outlined in Eqs. 3 and 4 (Fig. 3). The relative protection levels at the saltation threshold wind speeds (Table 2) persisted at the higher wind speeds (Fig. 3) with one exception. As wind speed increased, the tall, sparse canopy (LAI = 0.047, height = 170 mm) protection increased above that of the denser, short canopy (LAI = 0.095, height = 70 mm) (Fig. 3). Apparently, as wind speed increased above threshold, the greater ability of this taller canopy to reduce the friction velocity at the surface began to dominate over the ability of the shorter canopy to intercept more of the saltating particles, resulting in the greater level of protection for the taller canopy at higher wind speeds. This particular tall, sparse canopy (LAI = 0.047, height = 170 mm) had a smaller slope of the sand discharge curve (Fig. 3) than any of the others at higher wind speeds indicating that it was particularly effective at reducing friction velocity at the surface at higher wind speeds compared to the other canopies. Among the canopies tested, the dense, 130 mm-tall canopy provided the most protection against sand discharge.

The canopy modifies the wind speed profile and hence, the profiles of sand discharge. Some examples of discharge profiles normalized by total catch in each profile are illustrated in Fig. 4. The modified sand profiles caused modifications to both the amount

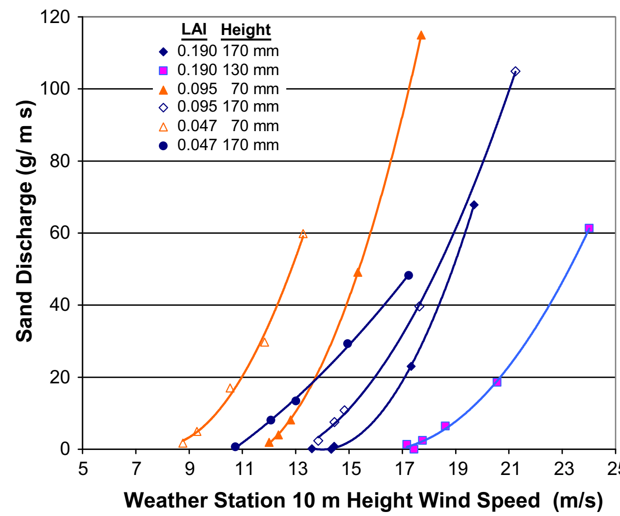

Fig. 3. Sand discharge normal to field rows for simulated 10-m high weather station windspeeds over a range of leaf area indices and maximum leaf heights.

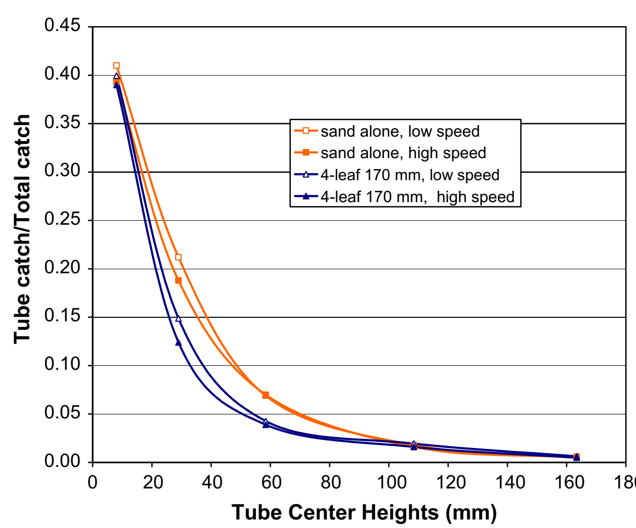

Fig. 4. Comparison of normalized tube catch profile shapes without canopy and within canopy. Calculated wind speeds at a 10 m weather station for sand are 11.8 m s^{-1} (low) and 13.3 m s^{-1} (high) and for 4-leaf canopy 17.3 m s^{-1} (low) and 19.7 m s^{-1} (high).

Table 3
Mean wind speeds and mean abrasion mass loss per unit mass of sand abrader impacting abrasion channels without and with a canopy of simulated plants in wind tunnel.

Leaf area index (LAI) (m^2/m^2)	Maximum leaf height (mm)	Leaves per plant (number)	Low free-stream wind speed ($m\ s^{-1}$)	Low wind speed abrasion loss (g/g)	High free-stream wind speed ($m\ s^{-1}$)	High wind speed abrasion loss (g/g)
0.0	0.0	0	10.19	0.0094a[A]	13.25	0.0262a
0.19	170	4	14.37	0.0089a	16.33	0.0085b
0.19	130	4	14.42	0.0124a	16.85	0.0101c
0.095	170	2	12.93	0.0287b	15.57	0.0294a
0.095	70	2	13.03	0.0096a	15.06	0.0194a
0.047	170	2	11.34	0.0152a	13.08	0.0105d
0.047	70	2	10.40	0.0040a	11.67	0.0056e

[A] Means in each abrasion column followed by different letters are significantly different from the abrasion loss without a canopy ($P < 0.05$).

and distribution of abrasive energy with the canopy compared to without the canopy. At high wind speeds, normalized soil losses from abrasive impacts on vertical channels were generally less within the canopy compared with outside the canopy in 4 of the 6 canopy configurations (Table 3), but were generally the same in low wind speed tests. Over all treatments including no canopy, the normalized abraded channel soil losses were different ($P < 0.05$) and averaged 0.0126 $g\ g^{-1}$ at low wind speeds and 0.0157 at high wind speeds.

Without a canopy, the abrasion profiles created by sand impacts on the vertical channels of soil increased in depth with wind speed but resulted in similar shaped profiles with the height. The maximum impact energy occurred in the region 30–40 mm above the surface. In contrast, the height of maximum impact energy tended to increase with wind speed in the tall canopies. The effect of wind speed on the shape of the abrasion profiles can be clearly illustrated by normalizing (dividing) the depth of soil abrasion by the saltation discharge impacting the vertical channels (Fig. 5). Accompanying the higher wind speed, there was an increase in impact energy in the upper half of the canopy and a slightly reduced peak of maximum impact energy closer to the soil surface.

When plant canopy leaves were near the surface, however, there was a strong depression in the impact energy near the leaf height and a second peak above the maximum leaf height (Fig. 6). This profile shape resulted from leaves intercepting some of the saltating sand and also deflecting some impact energy upward. As a result, the plant areas receiving the most impact energy within the canopy were markedly different between short and tall plant heights. Hence, it may be important when evaluating potential plant damage from sand blasting away from a field boundary, to place the test plants within a canopy of similar plants.

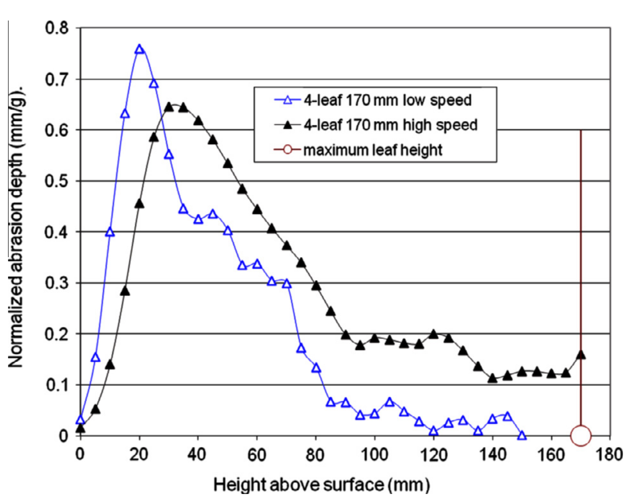

Fig. 5. Abrasion depth variation with wind speed in four-leaf canopies at 17.3 $m\ s^{-1}$ (low) and 19.7 (high) wind speeds calculated for 10 m weather station anemometer height.

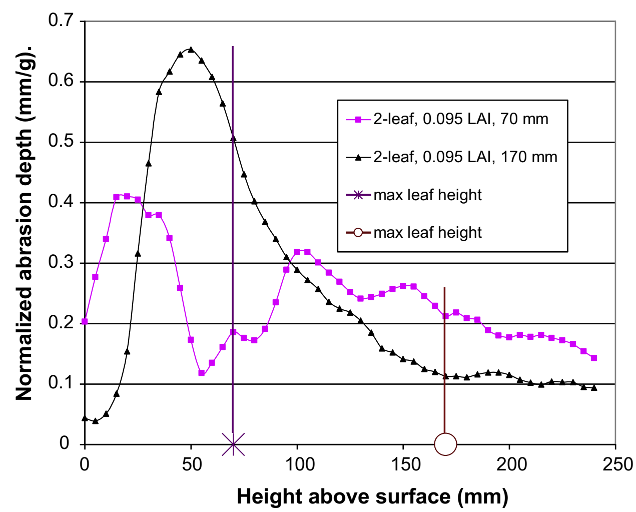

Fig. 6. Abrasion depth variation with height caused by differing leaf heights in two, two-leaf canopies at a 10 m weather station wind speed of 17.6 $m\ s^{-1}$.

For the two leaf canopies, the leaves intercepted saltation when in their lowest position above the surface (70 mm), as evidenced by the distinct valley in the abrasion depth profile (Fig. 5), but not perceptibly when in their highest position (170 mm). However, when they were at their highest position above the surface the sand discharge (transport capacity) was reduced the most (Fig. 3). Thus, the lower leaf height provided the most protection overall from impact energy on plants in the canopy, but plants tested without a canopy—representing the few plants at the windward edge of a field—would have the misleading result of receiving the most abrasion energy when leaves are at the lower position.

The abrasion losses from the surface impact trays were also evaluated with and without a canopy as measured by the coefficient of abrasion (Can). The test of variance showed the Can of the surface trays without the standing biomass was slightly greater than for trays among the standing biomass ($P = 0.02$). The mean and standard deviations of the Can (m^{-1}) for the flat abrasion trays were 0.0106 ± 0.0019 and 0.0068 ± 0.0034 without biomass and with standing biomass, respectively. Thus, the standing biomass reduced the surface loss from abrasion by the saltating sand grains an average of 35%. The soil tray Can values below the canopies under low and high wind speeds averaged 0.0063 and 0.0073 m^{-1}, respectively, and were not significantly different.

4. Conclusions

The canopy aerodynamic roughness increased with plant height, but increasing LAI beyond 0.095 tended to smooth the flow, and thus reduce Z_0, for winds normal to the row direction.

Threshold velocities to initiate saltation generally increased with both canopy height and LAI, except the 130 mm-tall canopy provided more surface protection than the similar 170 mm-tall canopy. The canopy threshold velocities ranged from 8.5 to 17.2 m s^{-1}, when based on a standard 10 m height outdoor weather station located where Z_0 was 25 mm.

The 130 mm-tall canopy provided the most overall surface protection against both initiation and transport of the sand discharge. The protection mechanisms included a combination of low aerodynamic roughness coupled with interception of the saltating sand by the lowest pair of leaves.

Without a canopy, abrasion loss from vertical soil channels increased with wind speed, but the height of maximum abrasion remained nearly constant. Inside the canopy, both the loss amount and impact region varied with wind speed. Within canopies, high wind speeds increased height of maximum abrasion but often still caused less total abrasion per unit sand discharge than over a bare, sandy surface.

Sand interception by leaves also markedly modified the vertical abrasion profiles. Except for tests of field boundary conditions, it may be important to place test plants within a canopy of similar plants when conducting plant abrasion damage tests with a minimum upwind fetch of about 70 canopy heights in a wind tunnel.

Abrasion loss from sand impacts on surface trays was somewhat reduced inside the canopies when compared to tests without a canopy. The surface losses varied only with sand discharge and not wind speed.

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